Modeling the Impact of Climate Change on the Future Heating Demand in Different Types of Buildings in the Belgian Residential Building Stock

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Abstract

In coming years, global warming will have a large impact on many aspects of the environment and human activities in buildings. The objective of the ongoing study, of which some results are presented in this paper, is to upscale the impact of climate change on the Belgian residential building stock and to evaluate its influence on the future heating and cooling demands. In order to quantify the impact of climate change, this study used MAR regional atmospheric model using MPI and BCC as forcing GCMs for Liege city during the period of 2012-2100. Energy simulations are obtained using MATLAB for four different types of residential buildings (Freestanding, semi-detached, terraced and apartment) in four different representative years (2012, 2021, 2050 and 2100). The present paper focuses on results associated with predicted future heating demands.

Key Innovations

- This paper focuses on simulating different types of buildings and assessing the influence of the type of building in different climatic scenarios on the heating demand.
- This study uses MAR regional atmospheric model.

Practical Implications

The Energy simulations are obtained using MATLAB. Thermal coupling between zones is avoided to speed up the simulation time for 992 cases. Each year is simulated individually with a separate weather dataset.

Introduction

In Europe, the energy consumption in buildings is approximately 40% of the total primary energy consumed and so far, in most European countries, the amount of energy required for heating is greater by far than the energy used for space cooling. The outdoor climate and building construction features have a direct influence on the energy use of the building. Several studies have shown the potential decrease of heating demands and increase in the cooling demands given future climate changes (Ward, 2008).

The quality and differences between these studies depend on the different global climate models that are used while assessing the impact of climate change. In the next 100 years, climate change predicts hotter summer and warmer winters. In the different climate European regions, climate change leads to a decrease of residential heating needs and an increase of residential cooling needs. The cooling demand reaches around a tenth of the heating demand for EU28 by the end of this century while taking into consideration the higher level of insulation of buildings in the new evolution of buildings (European Commission. Joint Research Centre, 2018). (Isaac & van Vuuren, 2009) studied the impact of climate change at a global scale on the residential heating and cooling demands, they found that the global heating energy demand is stable and there is an considerable increase in the global energy demand for cooling.

In long term scenarios, energy use is very important to be taken into account especially for the residential sector by looking at end uses in which energy is consumed which gives a better understanding of the evolution of the energy use and the possible impacts and adaptation of the climate change on the energy use.

The main objective of this paper is to assess the impact of climate change on the energy performance, looking first to the heating demand of different building types in the residential building stock in Belgium. The methodology proposed in the frame of this study is based on both a microscopic and a macroscopic approach. Attention is first given at the scale of a single building and then extended to the entire Belgian residential building stock.

In this paper, the model of the building stock is calibrated based on Synthetic Load Profiles (SLP) defined on 1/4 hourly base for electricity and hourly base for gas (*SYNERGRID, Synthetic Load Profiles*, 2020). These synthetic profiles give the real aggregated consumption per an average dwelling using data from 2500 residential dwellings chosen statistically to represent the Belgian residential building stock.

This paper is part of an ongoing study which could be helpful for energy suppliers to predict and quantify the modifications in energy consumption due to the climate change in order to anticipate the changes to be brought to the Belgian electricity grid.

The second part of this paper explains the followed methodology and the thermal model used in the tool. The two different climatic simulations considered are explained in the Weather Data section. All the results are described, analyzed and compared for both climatic simulations.

Methodology

This tool is used to simulate, on a quarter hourly basis, the current Belgian housing stock energy use. This paper focuses on simulating specific case studies representing the different types of buildings. The developed model predicts consumption related to Space Heating (SH), Domestic Hot Water (DHW), Electrical Appliances (EA) and lighting in the Belgian residential housing.

Building Thermal Model

The thermal model used in this paper is based on a physical description of the components and envelope of the building through the use of some parameters (geometry, location, nominal performances...). The physical description of the model is suitable for the identification of technological improvements at the building level. The model developed for the purpose of this work is a dynamic multi-zone model which makes possible to set different temperature set points in the different rooms in order to better reflect the reality and to have a very accurate calculation for the indoor conditions and heating demand.

Zone Thermal Model

The simplified building model of a zone is based on the simple hourly method described in ISO13790-2007 (International Standard Organization, 2007), 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 Figure 1. Different types of walls are considered:

- External heavy opaque walls
- External light opaque walls
- External light transparent walls
- Adjacent and adiabatic vertical walls
- Adjacent and adiabatic vertical walls between adjacent buildings
- Internal and adiabatic vertical walls between zones
- Internal and adiabatic horizontal floor and ceiling slabs

The 5 resistances in the network allow describing the heat transfers coefficients due to ventilation H_{ve}, heat transmission $H_{tr,is}$ due to thermal conductance (between air temperature node θ_{air} and the surface temperature node θ_s), transmission through windows $H_{tr,w}$ and through opaque components $H_{tr,op}$ which is divided in $H_{tr,em}$ and $H_{tr,m}$ (determined in function of the outdoor air temperature θ_e). The thermal mass is represented by a single thermal capacity. The nodes of the network represent the indoor air temperature θ_{air}, the surface temperature θ_s, the mass temperature θ_m, the supply air temperature θ_{sup} and the outdoor air temperature θ_e. Each building zone is described by the aforementioned temperature nodes (Ballarini et al., 2019). The heating/cooling load ($\Phi_{H/C,nd}$) is directly applied on the air node θ_{air}, while the heat flows due to solar radiation and internal sources are considered split into the shares Φ_{ia}, Φ_{st} and Φ_m and they are applied on θ_{air}, θ_s and θ_m respectively.

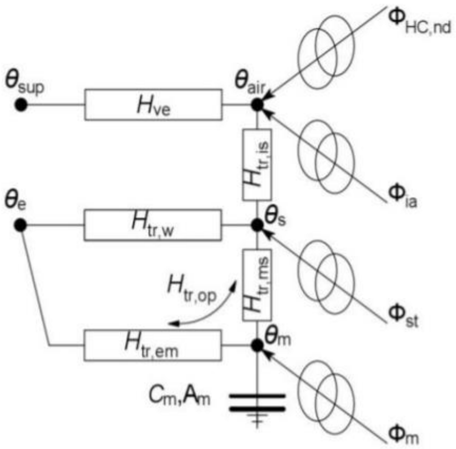

Figure 1: The equivalent 5R-1C network based on the simple hourly method of EN ISO 13790.

Extension of the Model

The multi-zone calculation is carried out without thermal coupling between the different zones, i.e. no heat transfer by thermal transmission or ventilation between zones is considered. There are 6 different zones for the different building types:

- Living area
- Sleeping area
- Kitchen
- Bathroom
- Circulation zone: corridor
- Unheated zone

Heating loads are determined for the first four zones through the RC network described in the previous section. The same heating schedules are applied to all the heated zones. Table 1 shows an example of the different thermal zones

Table 1: Example of different zones for an apartment building

	Living	*Night*	*Kitchen*	*Bath room*	*Corr-idor*	*Unhe-ated*
A_{wall}	30.2	37.3	10.7	0	0	0
A_{wind}	5	9	5	0	0	0
A_{roof}	0	0	0	0	0	0
A_{floor}	29.5	39.4	14.6	4.4	18	0
A_{door}	0	0	0	0	0	0
A_{adj}	0	0	9.3	0	23	0
A_{int}	35.2	46.3	25.1	28.5	44.5	0

Belgian Housing Stock Typology

The proposed approach in this tool for the determination of the building stock is a hybrid approach (mix between "typical" and "representative" approach). The typical approach involves composing a set of typical dwellings closely related to existing buildings and existing building components, chosen for their reference value compared to the examined stock, while the representative approach involves modeling a set of fictional buildings based on average values, the hybrid approach combines the strength of each approach as stated in (Gendebien et al., 2015). Four dwelling types are selected: a free-standing house, a semi-detached house, a terraced house and an apartment. Dwellings of different ages are chosen since these occur in the current dwelling stock. The final tree structure of this tool presents 992 cases of typical buildings. Each case is being characterized according to different factors (year of construction, type, building envelope characteristics and energy vectors). Five construction periods are differentiated for the whole building stock as shown in Figure 2: the period before 1945, 1945-1970, 1971- 1990, 1991-2007 and 2008-2011. The number of cases is 282 for freestanding houses, 282 for semi-detached houses and 282 for terraced houses while only 146 cases are considered for apartments. In this paper, 12 case studies out of the 992 cases are selected for the energy simulation as shown in Table 2. The final definition of each case combines existing typical geometries to average U values and different energy vectors. The model is validated based on comparing the results with the SLP of 2020, the simulation model was able to predict the average electricity consumption of an average dwelling with only less than 3% error compared to the SLP.

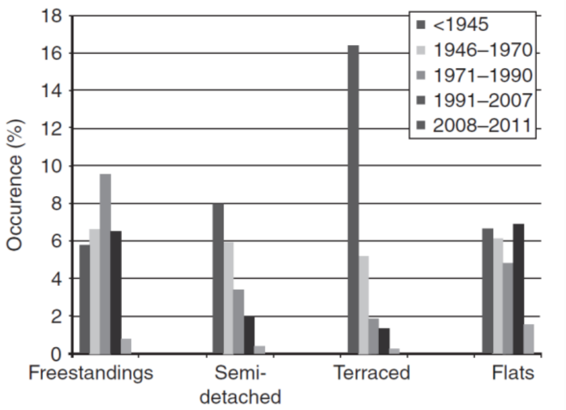

Figure 2: Distribution of the Belgian dwelling types in the different construction periods (Gendebien et al., 2015)

Heating production system

The simplification concerning the energetic vector used for SH and DHW production is to focus only on the main energy vector used in Belgium: gasoil, natural gas and electricity, while there is no simplification in the type of the heating production systems (the heating system is described as centralized or decentralized). Another simplification is in assuming that production of DHW water can be done only by the same type of energy vector as the one used for SH.

Building envelope characteristics

Minor simplifications concerning the insulation characteristics consist in neglecting the partially insulated case. The whole building stock is being divided into insulated and/or non-insulated (wall, roof, floor and window). The chosen U-Values are provided by the Walloon region transposition EPBD and the global repartition of insulation for walls, roofs and floor insulation is given by (Kints, 2008).

Energy Simulation

This paper focuses on simulating real case studies representing the 4 different types of residential buildings (Freestanding, semi-detached, terraced and apartment) from all the building cases of the Belgian building stock tree-structure. The simulations are carried out to investigate the impact of climate change on the future heating demand in different years (2012, 2021, 2050 and 2100) using the MAR regional atmospheric model explained below. This paper focuses on the impact of climate change on the heating demand. The impact on cooling demand constitutes a natural perspective to this work.

Weather Data

The MAR regional atmospheric model is a three-dimensional atmospheric model coupled to a one-dimensional transfer scheme between the surface, vegetation and atmosphere (Ridder & Gallée, 1998). Initially developed for the polar regions in both Greenland (Fettweis et al., 2013) and Antarctica (Kittel et al., 2018; Agosta et al., 2019), it also works very well in temperate regions such as Belgium (Doutreloup et al., 2019; Wyard et al., 2021). The reader can refer to (Kittel, 2021) for a comprehensive description of the MAR model.

Since MAR is a regional model, it needs to be forced by a global model at its lateral boundaries. Therefore, the atmospheric conditions from a general circulation model (GCM) must be directly forced to the boundaries of the MAR domain every 6 hours. The atmospheric variables used by this forcing are temperature, pressure, wind and specific humidity, as well as sea surface temperature. In the framework of this study, MAR is forced by the global models MPI-ESM1-2-HR (called MPI hereafter; (Gutjahr et al., 2019)) and BCC-CSM2-MR (called BCC hereafter;(Wu et al., 2020)) with both scenario historical (1960-2014) and ssp585 (2015-2100) from the CMIP6 project (O'Neill et al., 2016). Compared to the spread of all available CMIP6 GCMs correctly representing the present climate over Western Europe, by 2100 MPI can be considered as a colder GCM than BCC which is in the ensemble mean of all these GCMs. MAR Model runs at 5 km spatial resolution over the Belgian territory as shown in Figure 3, and produces outputs every hour. The datasets are produced from the closest pixel to the main cities of Belgium and the period covered is 2012 – 2100.

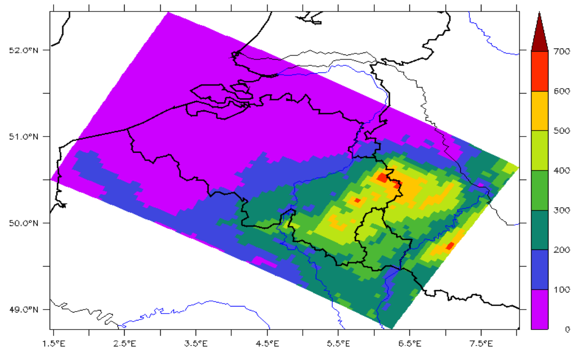

Figure 3: Topography (in meters above sea level) of the MAR domain representing Belgian territory.

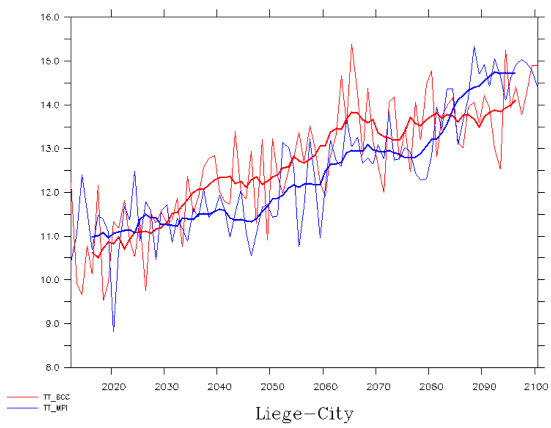

Figure 4: Evolution of annual temperature from 2012 to 2100 using the two MAR simulations (MAR-BCC and MAR-MPI) for Liege city.

In this paper, the MAR model simulations (MAR-BCC and MAR-MPI) are used for Liege city in the energy simulations. Figure 4 shows the evolution of the annual temperature for both simulations from 2012-2100 with (10 year running average) presented by the bold lines. Belgium (Liege) faces a remarkable increase in the temperature regardless the uncertainties on the future climate. The temperatures in 2020 and 2021 are unusually low, while the temperature increases till the end of the century. According to the temperature evolution in 2020 and 2021, the heating demand is supposed to be increasing in the two aforementioned years compared to the period between 2012 and 2019.The representative years for simulations (2012, 2021, 2050 and 2100) are selected according to the temperature evolution.

Internal Gains

Internal gains are mainly due to occupancy, lighting and use of appliances. The total number of occupants corresponds to the size of an average Belgian dwelling

and is set to 2.44. (Vanneste et al., 2007) Unrecoverable losses and recoverable losses are taken into account as a part of internal gains. In this simpler model, the impact of outdoor luminance on lighting use is indirectly taken into account by means of different lighting use probability density functions for summer, winter and shoulder seasons.

Indoor air set points schedule

The heating schedule of a zone is characterized by set point temperatures, morning and evening starting times and durations which differ for weekdays and weekend days. The heating schedule starting times is assumed to be 8h30 in the weekdays and 9h00 in the weekend. The temperature set points are based on Gaussian probabilities, so overall the heating setpoint is defined at 21°C.

Table 2: The various characteristics of the different simulated case studies

Case Number	***Type***	***Year of construction***	***Insulation***				***Space Heating***		***DHW***
			Wall insulation	Windows insulation	Roof insulation	Floor insulation	Energy Vector	Type	Energy Vector
1	Freestanding	<1945	Insulated	Insulated	Insulated	Insulated	Elec	Direct	Elec
2	Freestanding	1946-1970	Not-Insulated	Not-Insulated	Not-Insulated	Not-Insulated	NG	Centralized	NG
3	Freestanding	1971-1990	Not-Insulated	Insulated	Insulated	Not-Insulated	Fuel	Centralized	Fuel
4	Semi-detached	<1945	Insulated	Insulated	Insulated	Insulated	NG	Decentralized	NG
5	Semi-detached	1946-1970	Not-Insulated	Insulated	Insulated	Insulated	Fuel	Centralized	Fuel
6	Semi-detached	1971-1990	Not-Insulated	Insulated	Not-Insulated	Insulated	Elec	Direct	Elec
7	Terraced	<1945	Not-Insulated	Insulated	Not-Insulated	Not-Insulated	Elec	Direct	Elec
8	Terraced	1946-1970	Insulated	Insulated	Insulated	Not-Insulated	NG	Centralized	NG
9	Terraced	1971-1990	Not-Insulated	Insulated	Insulated	Insulated	Fuel	Centralized	Fuel
10	Apartment	<1945	Insulated	Insulated	/	/	Fuel	Centralized	Fuel
11	Apartment	1946-1970	Insulated	Insulated	/	/	NG	Decentralized	NG
12	Apartment	1971-1990	Not-Insulated	Insulated	/	/	Elec	Direct	Elec

Table 3: Thermal transmittance and heat capacity of the building envelope components

Case Number	*Building Type*	**Thermal transmittance of the building envelope components**				**Areal heat capacity of the building envelope components**		
		U_Roof W/(m²K)	**U_Wall W/(m²K)**	**U_Floor W/(m²K)**	**U_Window W/(m²K)**	**C_Roof J/(m²K)**	**C_Wall J/(m²K)**	**C_Floor J/(m²K)**
1	Freestanding	0.48	0.66	0.89	2.75	10916.45	68297.99	79015.99
2	Freestanding	7.7	2.1	7.9	5	11357.18	74715.40	67352.64
3	Freestanding	0.32	1.19	1.42	2.75	12257.14	75945.51	62673.09
4	Semi-detached	0.48	0.66	0.89	2.75	10916.45	68297.99	79015.99
5	Semi-detached	0.47	2.1	0.89	2.75	11617.12	74715.40	79015.99
6	Semi-detached	0.88	1.19	0.59	0.59	11922.42	75945.51	64021.67
7	Terraced	14.1	3.7	7.9	2.75	7211.53	76466.30	67352.64
8	Terraced	0.47	0.6	3.78	2.75	11617.12	69341.45	67352.64
9	Terraced	0.32	1.19	0.59	2.75	12257.14	75945.51	64021.67
10	Apartment	0	0.66	0	2.75	0	68297.99	0
11	Apartment	0	0.66	0	2.75	0	69341.45	0
12	Apartment	0	1.19	0	2.75	0	75945.51	0

Energy Model

As shown in Table 2, there are different parameters characterizing each case study for the different building types. The first parameter is the year of construction, insulation is the second parameters (wall, window, roof and floor). Insulation parameters have been considered (as insulated or not) for the first 3 types of buildings (freestanding, semi-detached and terraced building) while roof and floor insulation are not considered for the apartment buildings. The third parameter is space heating, it consists of the energy vector (electricity, gas or fuel) and the type of the heating production systems (centralized or decentralized). The last parameter is the energy vector for DHW (electricity, gas or fuel). The 12 selected case studies cover almost all the possibilities of different insulation conditions, energy vectors for SH and DHW, and 3 different time periods of the construction years (<1945, 1946-1970 and 1971-1990). Each case-study is simulated 4 times in 4 different years to assess the impact of the climate change on the short term between the past (2012) and the current year (2021) and also in future years in 2050 and 2100.

The heating demand is first computed assuming that unlimited power can be supplied to the zone. Then, this demand is compared to the maximum heating power that can be provided to each zone with a 15 minutes time step.

Results

Results presented in this paper are a part of a main ongoing study to assess the impact of climate change also on the total energy including the cooling energy demand on the whole residential building stock in Belgium.

The results show a significant decrease in the heating energy demand in the 12 case studies in the two different climate simulations. As shown in Figure 5 for (MAR-BCC) for the 3 simulated freestanding houses, there is a decrease in the heating energy demand for the first case which is totally insulated by 946 kWh/a from 2012 to 2021, and it decreases from 3828 kWh/a in 2021 to 3087 kWh/a and 2247 kWh/a in 2050 and 2100, respectively. The first case in freestanding houses has the highest reduction in the heating demand from 2012 to 2100 by 52.94% compared to case 2 and case 3.

The second case study in (MAR-BCC) shows a decrease by 14.04 % in the heating demand from 2012 to 2021 while the highest reduction is from 2050 to 2100 by 20.64%. There is no significant change between the results of the case3 case2: the heating demand decreases from 11468 kWh/a in 2012 to 5819 kWh/a in 2100, i.e; by around 49 %. While the reduction in the heating demand in (MAR-MPI) is higher as the coldest temperatures are considered, in the first case the reduction in the heating demand from 2012 to 2100 is 59.5% compared to 52.9% in (MAR-BCC).

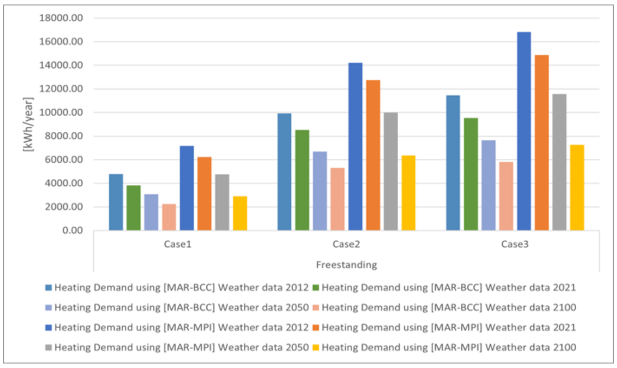

Figure 5: Evolution of Heating Energy demand from 2012 to 2100 in 3 different Freestanding houses using (MAR-BCC) and (MAR-MPI)

For the semi-detached buildings, we can observe more or less the same significant decrease in heating demand. For the first case (case 4) , there is a decrease by around 58% between 2012 and 2100 and by 53% and 50% in the second and third case study, respectively (case 5 and case 6) in the same period between 2012 and 2100 using (MAR-BCC) as shown in Figure 6. In the second simulation (MAR-MPI), the decrease in the heating demand in case 4 is 1628 kWh/a (63 %).

Figure 6: Evolution of Heating Energy demand from 2012 to 2100 in 3 different semi-detached houses using (MAR-BCC) and (MAR-MPI)

Figure 7 shows the terraced buildings results, the decrease in the 3 cases differs between 51.3% in the first case (case 7), 55.4% in the second case and 53.2% in the 3rd case for the period between 2012 and 2100 using (MAR-BCC), while the decrease differs between 58.9% in the first case, 60.93% in the second case and 59.40% in the third case using (MAR-MPI).

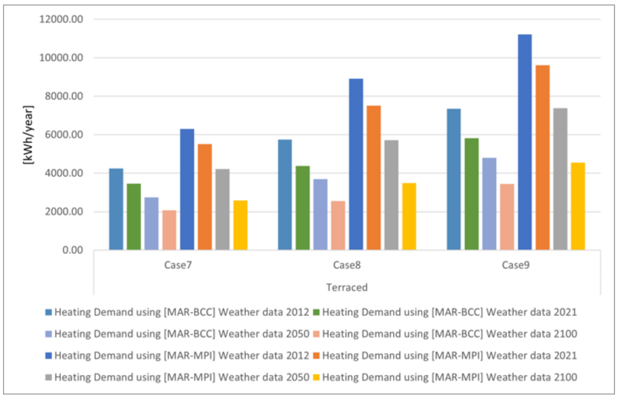

Figure 7: Evolution of Heating Energy demand from 2012 to 2100 in 3 different terraced houses using (MAR-BCC) and (MAR-MPI)

For the results related to apartments shown in Figure 8, the decrease in the heating demand is by 57% for cases 10 and 11 from 2012 to 2100 and by 56% for case 12 for the same time period using (MAR-BCC). The reduction in the heating demand using (MAR-MPI) is by around 63% for cases 10 and 11 and by 62% for case 12 from 2012 to 2100.

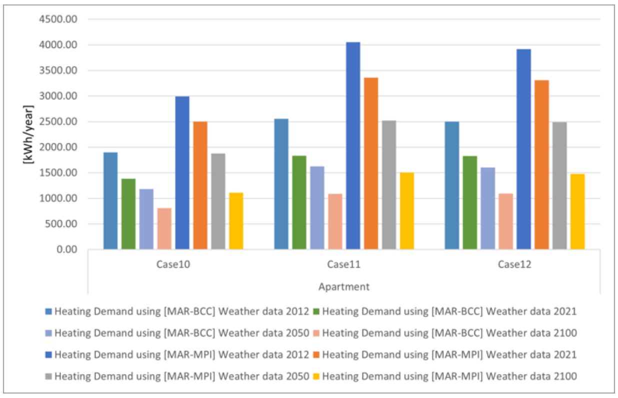

Figure 8: Evolution of Heating Energy demand from 2012 to 2100 in 3 different apartments using (MAR-BCC) and (MAR-MPI)

The heating systems are turned on during the autumn and winter months, starting from October till the end of winter and also the first months of Spring, so the heating systems are turned on from October till (March-April)

On a different scale as shown in Figure 9 for a freestanding house, the results show that by 2100 the heating demand will be 90% lower in October compared to the heating demand in 2021. The highest heating demand in 2021 is in January, the results show a decrease by 36.7% in January 2100.

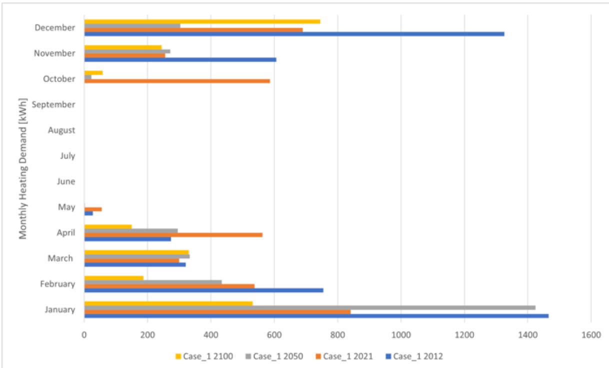

Figure 9: Monthly Heating Demand for a freestanding house from 2012 to 2100 (Case_1) (MAR-BCC)

Unexpectedly the heating demand in October in 2021 is much higher than the heating demand in 2012 while it decreases again in 2050 and 2100. As shown in Figure 10 which represents the evolution of monthly temperature with (5 year running average), the October in 2021 is cold compared to the previous and upcoming year, which is the same case in April 2021, as shown in Figure 9, the heating demand increases in April 2021 and it decreases again in 2050 and 2100, the evolution of the monthly temperature for April proves that, as shown in Figure 10, April 2021 is the coldest April from 2012 to 2100.

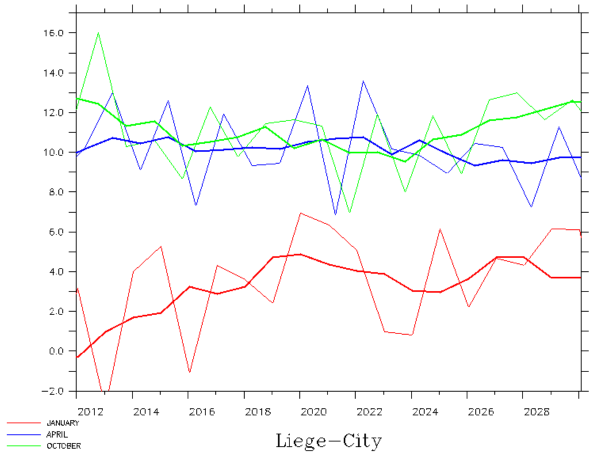

Figure 10: Evolution of monthly average temperatures from 2012 to 2030 for January (in red), April (in blue) and October (in green) using MAR-BCC simulation in Liege city.

Another example (an apartment) is shown in Figure 11, The results show the significant decrease in the heating demand in October, the heating demand in October 2021 is 161 kWh and will decrease by 99.8% in 2100. The heating demand in April is expected to be fluctuating in the next 10 years as shown in Figure 12, the temperature in April in (MAR-MPI) will be low in 2028.

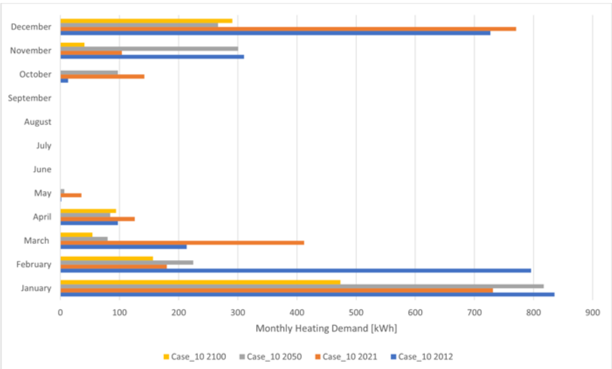

Figure 11: Evolution of monthly heating demand for an apartment from 2012 to 2100 (Case_10) (MAR-MPI)

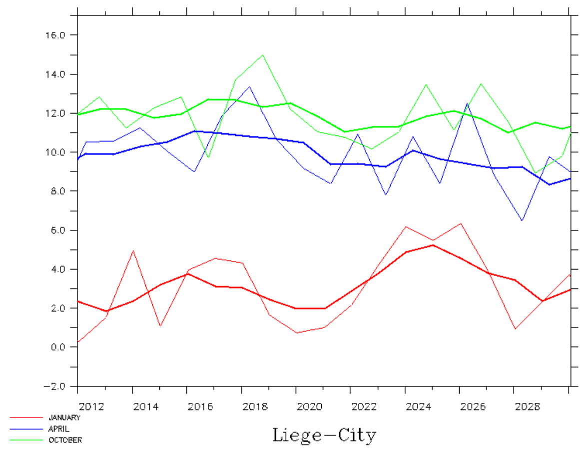

Figure 12: Evolution of monthly average temperatures from 2012 to 2030 for January (in red), April (in blue) and October (in green) using MAR-MPI simulation in Liege city

Conclusion

A dynamic building simulation model is used to focus on the future evolution of building heating energy demands. This study aims to assess the evolution of the profiles of final energy consumptions at the Belgium level with the predicted evolution of the climate until the end of the current century. 12 case studies are simulated representing 4 different building types to assess the impact of climate change on the heating demand in the different types of buildings considering the different factors of insulation and years of construction. The results show a significant decrease in the future heating demand in the upcoming years especially between the period 2050-2100.

The results also show that the building type has an influence on the energy demand: Figure 13 shows that freestanding houses (case 2 and case 3) have the highest reduction in the specific energy demand. Case 2 has a reduction by 51.5 % and 87.8 % in the specific energy demand using (MAR-BCC) and (MAR-MPI), respectively.

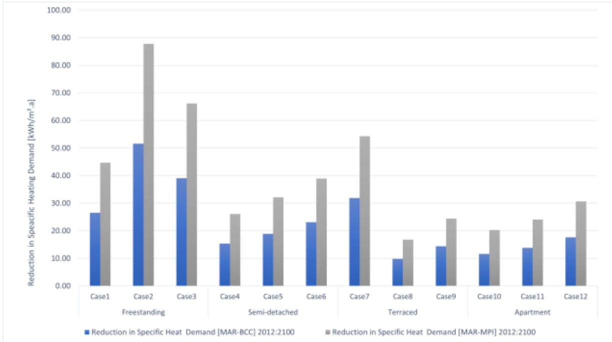

Figure 13: Reduction in specific heat energy demand in the different types of buildings

In some cases explained in the paper, the heating demand will totally decrease and will be zero in Autumn months which is not the case in the previous years and in 2021. That highlights the fact that the future cooling demand is also very important to be assessed. Global warming, causing the extreme weather that can be experienced right now, will affect the future cooling demand and different future measures should be taken into consideration.

Acknowledgments

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