International High Performance Buildings Conference

School of Mechanical Engineering

2022

# Cooling Concepts for Residential Buildings: A Comparison Under Climate Change Scenarios

Essam Elnagar

Vincent Lemort

Elnagar, Essam and Lemort, Vincent, "Cooling Concepts for Residential Buildings: A Comparison Under Climate Change Scenarios" (2022). *International High Performance Buildings Conference.* Paper 406.
https://docs.lib.purdue.edu/ihpbc/406

# Cooling Concepts for Residential Buildings: A Comparison Under Climate Change Scenarios

Essam ELNAGAR[1,]*, Vincent LEMORT[2]

[1]Thermodynamics Laboratory, Aerospace and Mechanical Engineering Department, Faculty of Applied Sciences, University of Liège, Liège, Belgium
essam.elnagar@uliege.be

[2]Thermodynamics Laboratory, Aerospace and Mechanical Engineering Department, Faculty of Applied Sciences, University of Liège, Liège, Belgium
vincent.lemort@uliege.be

* Corresponding Author

## ABSTRACT

Buildings in the EU account for 40% of our energy consumption and 36% of our greenhouse gas emissions, with HVAC systems being the biggest contributors. With the predicted increase in global air temperature up to 4.8 K by the end of this century, cooling will be the most rapidly increasing energy-consuming technology in buildings. Heat pumps are one of the most energy-efficient heating and cooling systems. In this paper, the energy performance of three different cooling concepts including an air-to-air heat pump in a residential building is assessed with the impact of climate change on the heating and cooling energy demands under future climatic scenarios in Belgium. The paper presents the results obtained by simulating heating and cooling systems based on using DesignBuilder while taking into consideration the influence of climate change on the performance of the split AC system. This study uses several weather data sets one forced by a reanalysis model on the past period (1980-2020) and three forced by Earth System Models (ESM) on past (1980-2014) and future periods (2015-2100). The paper also presents a performance comparison between the passive cooling technologies such as natural ventilation and active cooling system such as split AC systems in Belgium. The Indoor Overheating Degree (IOhD) indicator is used to assess the thermal comfort and overheating discomfort in the building. The obtained results showed that the climate plays an important role in the final energy end-use for heating and cooling, the final heating energy end-use decreases by 40% while the final cooling energy end-use increases by 187% by the end of the century. The results also showed that the IOhD using passive cooling scenarios such as natural ventilation decreased by 77% in 2090s compared to the base case where there is only a mechanical ventilation system, while using an active cooling system such as a split AC system could maintain the thermal comfort almost all the time in the future weather scenarios. This paper is part of an ongoing study, 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 energy demands.

## 1. INTRODUCTION

The recent decades have seen a major concern about global warming and climate change. According to the Intergovernmental Panel on Climate Change (IPCC) sixth assessment report, global warming of 1.5 K and 2 K will be exceeded during the 21st century relative to 1850-1900 and the average global surface air temperature in (2081-2100) is predicted to increase within a range of 1 to 5.7 K in relation to (1850-1900) period under various $CO_2$ emission scenarios (*Climate Change 2021*, 2021; Eyring et al., 2016). This increase in temperature leads to a significant increase in energy demand for HVAC systems. Due to the increased $CO_2$ emissions, humidity, wind, and solar radiation are also expected to change over the next years (Karl et al., 2009; Ruosteenoja & Räisänen, 2013; Wyard et al., 2018).

To assess the possible changes in climate in the future, there are different emissions scenarios for the future climate (Nakicenovic et al., 2000; Riahi et al., 2017). These emissions scenarios are calculated using various models for society development which include technological and economic factors. There are five narrative scenarios and a set of radiative forcing. Each scenario consists of different groups characterizing alternative energy technology developments and thus carbon emissions (Riahi et al., 2017).

Buildings in the EU account for 40% of our energy consumption and 36% of our greenhouse gas emissions. Several studies showed that climate change has a major impact on heating and cooling demands. Few studies assessed the impact of climate change on the $CO_2$ emissions of heating and cooling systems (Radhi, 2009). In most European countries, the amount of energy required for heating is greater by far than the energy used for space cooling (Ürge-Vorsatz et al., 2015). In a temperate climate, one of the most predicted effects of climate change is an increase in overheating events and the related health risks for building occupants. Therefore, it is necessary to assess the future thermal performance of buildings and implement robust cooling measures to ensure occupants' comfort.

Several studies showed that, active cooling systems will be necessary for buildings in the future to maintain thermal comfort conditions. (Wang & Chen, 2014) investigated the impact of climate change on heating and cooling consumptions in different residential and commercial buildings in all seven climate zones in the united states, the study showed that by 2080 the heating demand will decrease by 30-65% and the cooling demand will increase by 50-150%, the study also showed that by 2080s, the impact of natural ventilation will not be significant in some cities. (Berardi & Jafarpur, 2020) studied the potential impact of climate change on 16 ASHRAE prototype buildings in Toronto. The results showed that, there is a drop in the annual heating energy use intensity and an increase in the cooling energy use intensity for the different building types, by 2070 the heating demand will decrease by 18%–33% and the cooling demand will increase by 15-126%. (Invidiata & Ghisi, 2016) evaluated the future energy consumption of Brazilian houses in three cities in 2020, 2050 and 2080. The study showed that there will be an increase in the annual energy demand by 112-185% in 2080 in the three cities, and the annual heating demand will decrease by 94% in the coldest city, the study also investigated the possibility of passive strategies to reduce the future annual heating and cooling demand up to 50% compared to the building without strategies. (Elnagar et al., 2022) studied the potential of natural ventilation in Belgium to reduce the internal cooling loads during the summer period. The results show that without natural ventilation, thermal comfort could be reached on average 53.7% of the time, while it could reach 66.2% of the time using single-sided ventilation and 78.8% with cross ventilation.

Despite the numerous studies on assessing the climate change impact on the energy demand in buildings, there have only been a few studies assessing the thermal comfort. As part of the International Energy Agency (IEA) EBC Annex 80 – "Resilient cooling of buildings", this paper assesses the performance of different cooling concepts; passive concepts such as ventilative cooling and active concepts such as air source heat pumps under different climate change scenarios in Belgium. This study uses several weather data sets: one forced by a reanalysis model on the past period (2000-2020) and three forced by Earth System Models (ESM) on past (1980-2014) and future periods (2015-2100). The results presented in this work respond to a growing need for researchers and decision-makers to investigate the relationship between changing future weather conditions and their impact on the energy demand, especially for cooling demand and thermal comfort in buildings.

## 2. METHODOLOGY

The conceptual framework of the study is presented in Figure 1. The first part of the framework introduces the literature review that has been conducted to identify the cooling concepts in this study, three cooling technologies are considered in this work; natural ventilation, mechanical ventilation and air source heat pumps. The second part presents the case study as well as the weather data used in the framework. The building and HVAC models are created with DesignBuilder software, which is a complete and Graphical User Interface (GUI) for the EnergyPlus simulation engine.

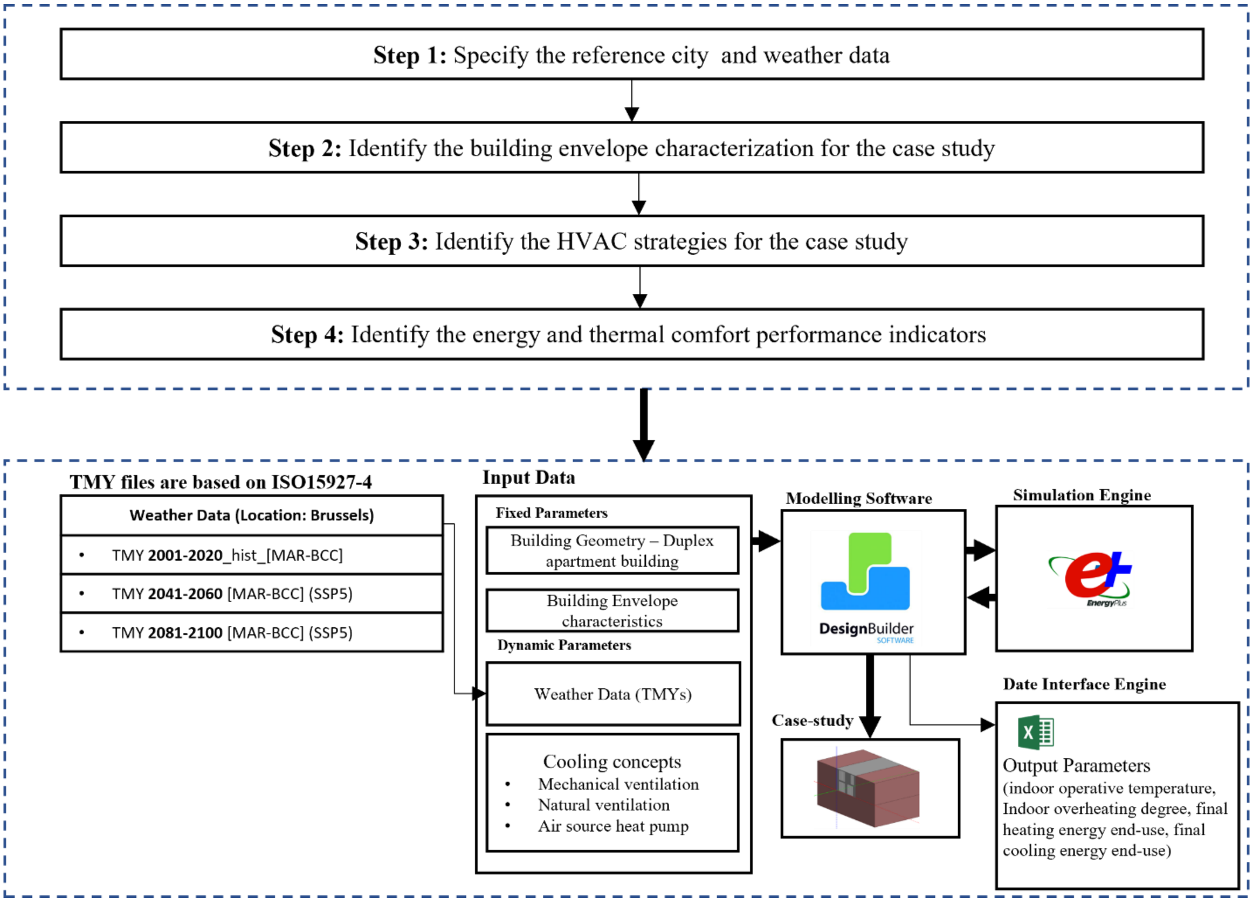


**Figure 1:** Conceptual framework of the study

## 2.1 Building model

This section gives the most important information about the geometry, envelope characteristics and operation features of the studied dwelling. Figure 2 (b) is an upper view of the studied duplex. The building has a North-South orientation and a large window-to-wall ratio (0.6) on the South façade. The dwelling has been divided into seven thermal zones, which have been defined depending on the zone usage, temperature setpoint and orientation. (Elnagar et al., 2022) presented the general characteristics of the building envelope.

The EPBD imposes energy performance standards for buildings. The building walls are compliant with the EPBD 2020 (*Exigences PEB du 1er juillet 2019 au 31 décembre 2020*, 2019). The glazing has been defined in the EPB file of the building as triple-glazing. The frame of the window, made of wood and aluminum, has a U-value of 0.9 $W/m^2 \cdot K$, resulting in a net U-value of 0.6 $W/m^2 \cdot K$, in compliance with the EPBD. The duplex is equipped with a balanced mechanical ventilation system with a heat recovery module of 85% efficiency and a by-pass system. The heating system is traditional with water radiators fed by a gas boiler. There is no mechanical cooling system.

Regarding the operation of the building, it is assumed that the occupants are four adults each emitting 100 W. For lighting, it is good practice to consider the consumption of 6 $W/m^2$, according to norm NBN EN 15193 (The Bureau for Standardisation in Belgium, 2021). The energy consumption linked to electric appliances is assumed to be 3 $W/m^2$. Some operation/occupancy schedules can be applied to that energy consumption. They can be found in standard ISO 17772 (International Organization for Standardization, 2017)

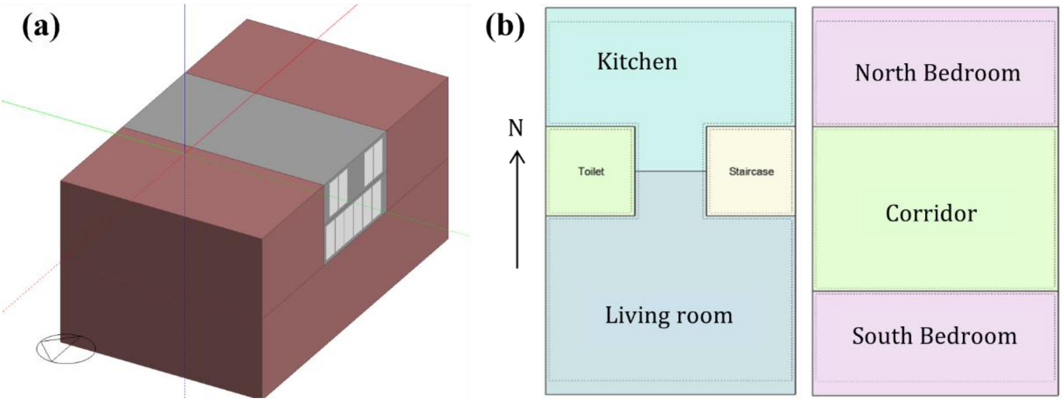


**Figure 2:** The representative case study (a) 3D model of the building (b) Upper view of the building.

## 2.2 Climate data

This study uses "Modèle Atmosphérique Régional" model (hereafter called "MAR") in its version 3.11.4 (Doutreloup et al., 2022). MAR is a three-dimensional atmospheric model coupled to a one-dimensional transfer scheme between the surface, vegetation, and atmosphere (Ridder & Gallée, 1998). This model is validated over the Belgium territory by several studies (Doutreloup et al., 2019; Wyard et al., 2021). For this study, the spatial resolution of MAR is 5 km over an integration domain (120 x 90 grid cells) centered over Belgium as shown in Figure 3.

This MAR model, like any regional model, must be forced at its boundaries by a global model, either a reanalysis model or an ESM. Firstly, the MAR model is forced by ERA5 (called hereafter MAR-ERA5 [30]) in order to have past simulation (1980-2020), and then by 3 Earth System Models (ESMs) from CMIP6 database namely BCC-CSM2-MR (MAR-BCC), MPIESM.1.2 (MAR-MPI), and MIROC6 (MAR-MIR) (Doutreloup et al., 2022)

These ESMs forced MAR simulations can be used to anticipate future periods. MAR simulations can represent the current climate and its interannual variability with success, except MAR-MIR which significantly overestimates temperature and solar radiation in summer. MAR-MPI can be considered as the coldest MAR simulation and MAR-BCC is the ensemble mean of all the MAR simulations (Doutreloup et al., 2022).

Typical Meteorological Years (TMY) are used for the 3 MAR-Simulations for the Shared Socioeconomic Pathway (SSP5.85) (Doutreloup & Fettweis, 2021). There are 3 main scenarios, SSP2-4.5, SSP3-7.0, and SSP5-8.5, which are respectively increasingly warming for 2100. This study used SSP5-85 and MAR-BCC. TMY for the period (2001-2020) based on MAR-BCC simulation is used as the reference scenario.

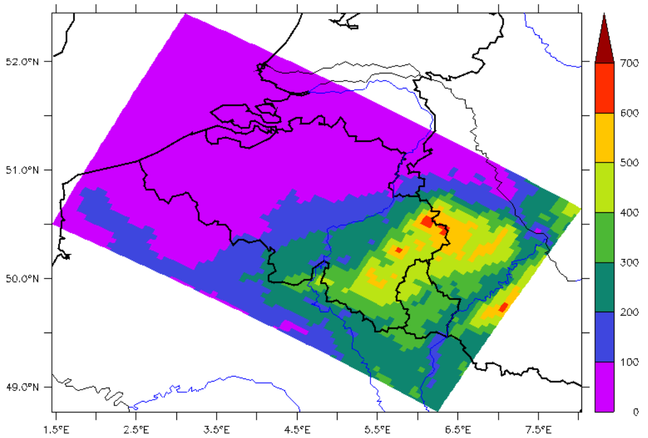


**Figure 3:** Topography (in meters above sea level) of the MAR domain representing Belgian territory (Elnagar et al., 2021).

## 2.3 Thermal comfort

In this work, two comfort models are used to determine the overheating risk in the dwelling and the efficiency of passive cooling. The first comfort model is based on the PMV (according to norm EN USI 7730). The PMV is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale (from -3 to 3), based on the heat balance in the steady-state of the human body. A Steady-state is obtained when the internal heat production in the body is equal to the loss of heat to the environment. The PMV can be used to check whether a given thermal environment complies with comfort criteria, and to establish requirements for different levels of acceptability. Thermal comfort is ensured if the PMV is within the range [-0.5;0.5], which gives a rate of dissatisfied people of 10%.

Contrary to the PMV which is a “static” measurement of thermal comfort, the adaptive comfort theory states that the comfort temperature range can be broadened because the occupants can adapt their behavior depending on the outdoor conditions. The adaptive comfort model is described in norm EN 15251. In a naturally ventilated building without any air-conditioning, the occupants feel more connected to the outdoor environment and can bear higher temperatures in summer. The maximum adaptive comfort temperature can be expressed by a relationship depending on the mean outdoor temperature:

$$T_{comfort,max} = 0.33\, T_{rm} + 21.8 \tag{1}$$

where $T_{rm}$ is a weigh average of the mean outdoor temperature during the previous seven days.

Indoor Overheating Degree (IOhD) indicator is selected to assess the thermal comfort and overheating discomfort in the building as suggested by (Hamdy et al., 2017).

$$IOhD = \frac{\sum_{z=1}^{Z} \sum_{i=1}^{Nocc(z)} [\left(T_{in,z,i} - TL_{comf,z,i}\right)^{+} \times t_{i,z}\,]}{\sum_{z=1}^{Z} \sum_{i=1}^{Nocc(z)} t_{i,z}} \tag{2}$$

where z is the building zone counter, Z is the total number of conditioned zones in a building, i is the occupied hour counter, $N_{occ(z)}$ is the total occupied hours in zone z, $T_{in,z,i}$ is the indoor operative temperature in zone z at hour i, $TL_{comf,z,i}$ is the comfort temperature limits in the zone z at the hour i, t is the time step (typically it is 1 h). Only positive differences of ($T_{in,z,i}$ - $TL_{comf,z,i}$) are taken into the summation

## 2.3 Cooling concepts

Three different cooling concepts are applied in the building. The first concept evaluated the cooling potential of the mechanical ventilation system with heat recovery (basic system in the building) which provides a minimum fresh air flow rate of 25 m3/h according to NBN D50-001 with a minimum temperature difference between inside and outside of 2 K.

The second cooling concept is natural ventilation. The natural ventilation maximum air change per hour (ACH) is explicitly defined for all the naturally ventilated zones. The ACH is modified by controlling the minimum indoor temperature, the temperature difference between the indoor and outdoor temperature ($\Delta T$) in the different scenarios and the operation schedule. The Air change per hour (ACH) was set equal to 5 ACH.

In the third cooling concept, a split Air conditioner (AC) is added to the base case to provide cooling without changing the existing gas boiler system in the building. The conventional split AC consists of an indoor and an outdoor unit. The outdoor unit includes an air-cooled condenser, a compressor and a condenser fan. The indoor unit includes an evaporator, a distribution fan an expansion valve. The split AC in DesignBuilder is implemented by using a unitary air-to-air heat pump module. The unitary air-to-air heat pump model simulates a constant volume of direct-expansion cooling via the DX cooling coil, with rated SHR, rated total cooling capacity, rated air volume flow rate, and rated EER as inputs. The HVAC model input parameters are shown in Table 1. The rated total cooling capacity, rated air volume flow rate and rated SHR are auto-sized.

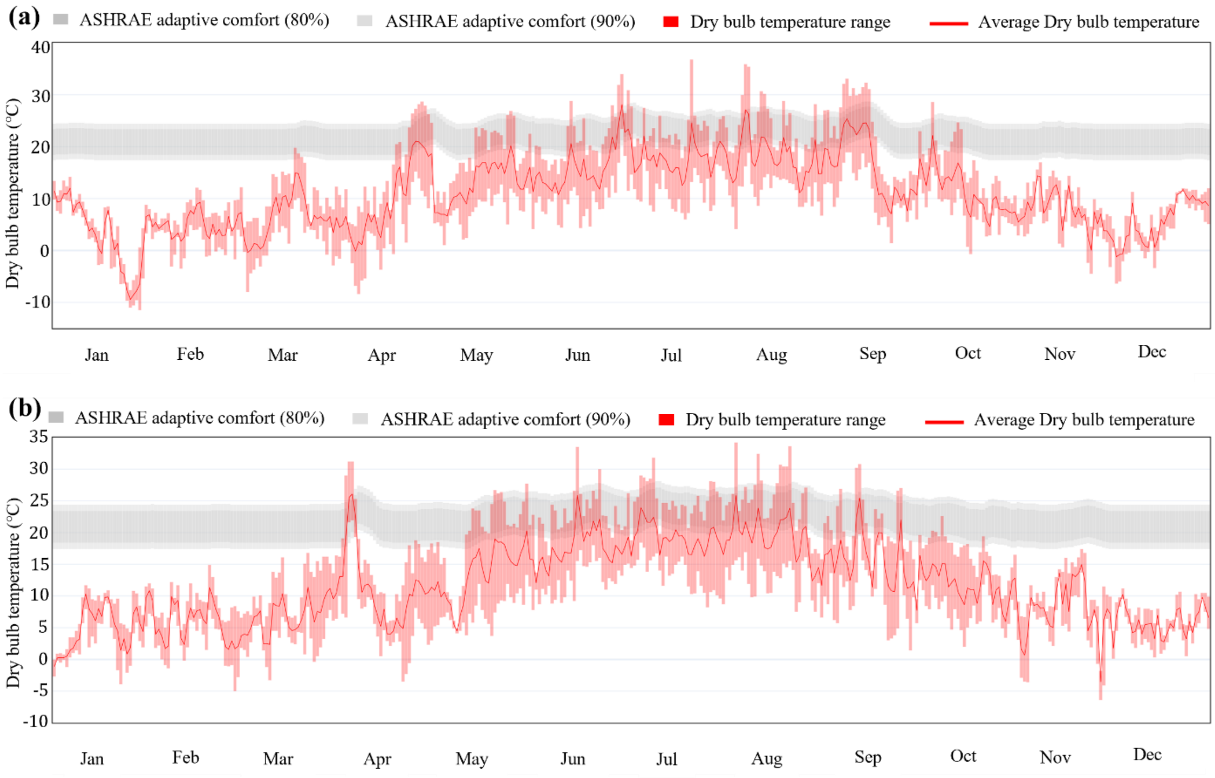
**Table 1:** HVAC Model input

| | **Specifications** |
|---|---|
| Zones (heating) | Kitchen, living, north bedroom, south bedroom |
| Zones (cooling) | Living, north bedroom, south bedroom |
| Zones (ventilation) | Kitchen, living, north bedroom, south bedroom |
| Mechanical ventilation rates | 25 $m^3$/h |
| Natural ventilation rates | 5 ACH |
| Setpoint temperatures | [Min: 20°C, Max: 22°C] for heating (living, kitchen)<br>[Min:19°C, Max:21°C] for heating (north bedroom, south bedroom)<br>[Min: 22°C, Max: 25°C] for cooling (living, north bedroom, south bedroom) |
| Fuel type | Natural gas (heating) and electricity (cooling) |
| Rated EER | 5.8 |
| Boiler Nominal thermal efficiency | 0.88 |

## 3. RESULTS

### 3.1 Evolution of climate

Figure 4 shows the evolution of the daily outdoor temperature representing the distribution of the outdoor temperature in the reference period (2001-2020), the period (2041-2060) and the period 2081-2100. It can be seen that, there is a significant increase in the annual air temperature by 1.6 K in (2041-2060) period and 3.2 K in (2081-2100) period. Following the adaptive comfort model in the ASHRAE 55-2017 Standard (ASHRAE, 2017), the figure also shows the identified range of temperatures (90% and 80%) acceptability limits. The acceptable limits of 80% are for common applications. When a higher level of thermal comfort is desired, the 90% acceptability limits can be used.



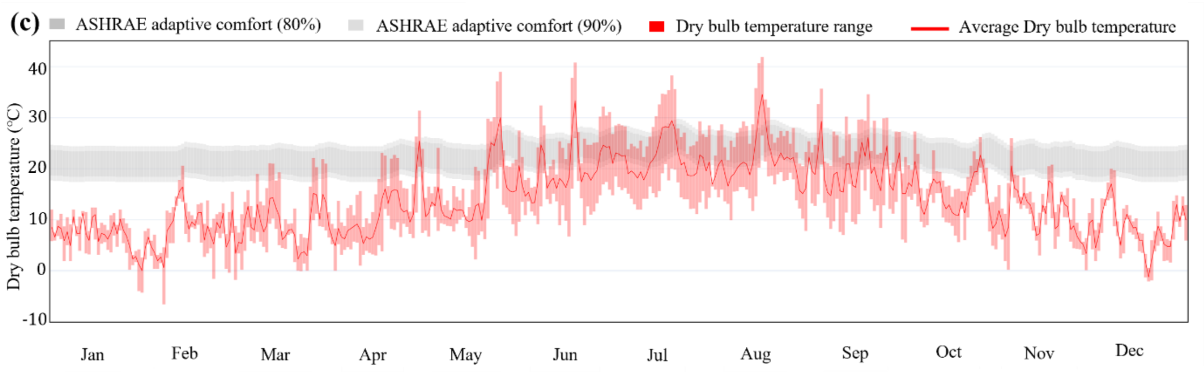


**Figure 4:** Evolution of daily outdoor temperature with the adaptive comfort model for three periods (a) TMY 2001-2020, (b) TMY 2041-2060 and (c) TMY 2081-2100

## 3.2 Thermal comfort assessment

In this section, the result of the thermal comfort assessment for the case study by analyzing the Indoor Overheating Degree (IOhD). Figure 5 presents the IOhD for the different cooling concepts and different weather scenarios. The static comfort model is used for the bedrooms and the adaptive comfort model is used for other zones based on ISO 17772-1. It can be seen that in the base case with only a mechanical ventilation system installed in the building, the IOhD increases from 0.13℃ to 0.8 ℃. In the second scenario using natural ventilation, the IOhD increased from 0.03 ℃ to 0.17 ℃ while in the third scenario by applying an active cooling system using split AC, the IOhD reached only 0.01 by (2081-2100).

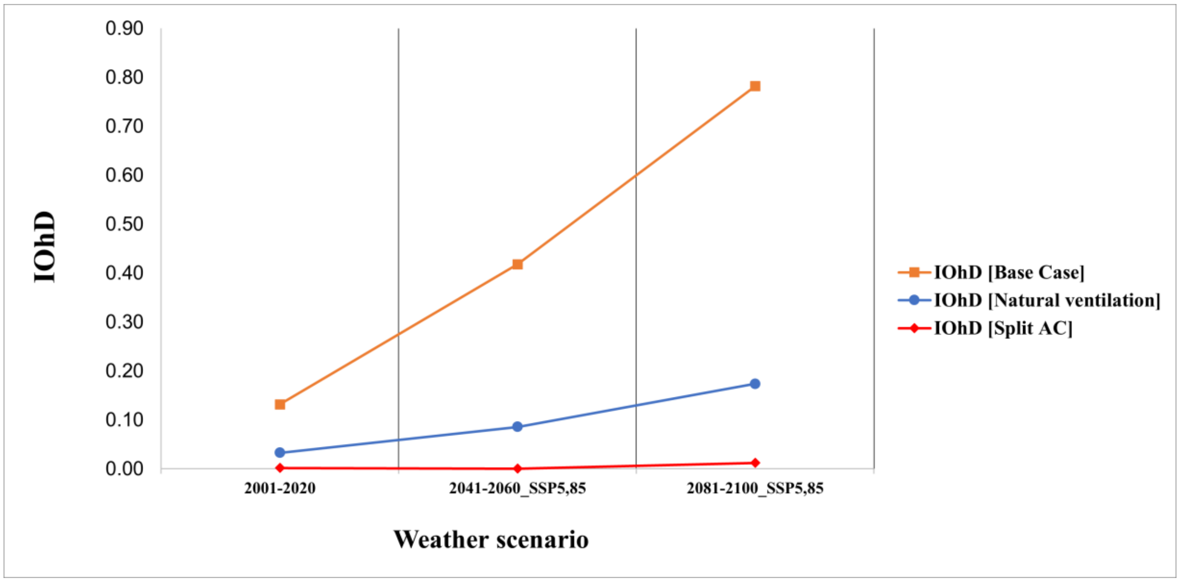


**Figure 5:** IOhD for the different cooling concepts and weather scenarios

## 3.2 Future heating and cooling energy end-use

The final heating and cooling energy end-uses are presented in this section for the third cooling concept where a split AC system is used in the building. Figure 6 shows that, the final heating energy end-use decreases by 26% by (2041-2060) and 40% by (2081-2100) compared to (2001-2020), while the final cooling energy end-use increases significantly by 82% in (2041-2060) and 187% in (2081-2100) compared to (2001-2020). It can also be seen that the final energy end-use decreases in the future scenarios by 32% in (2081-2100) compared to (2001-2020).

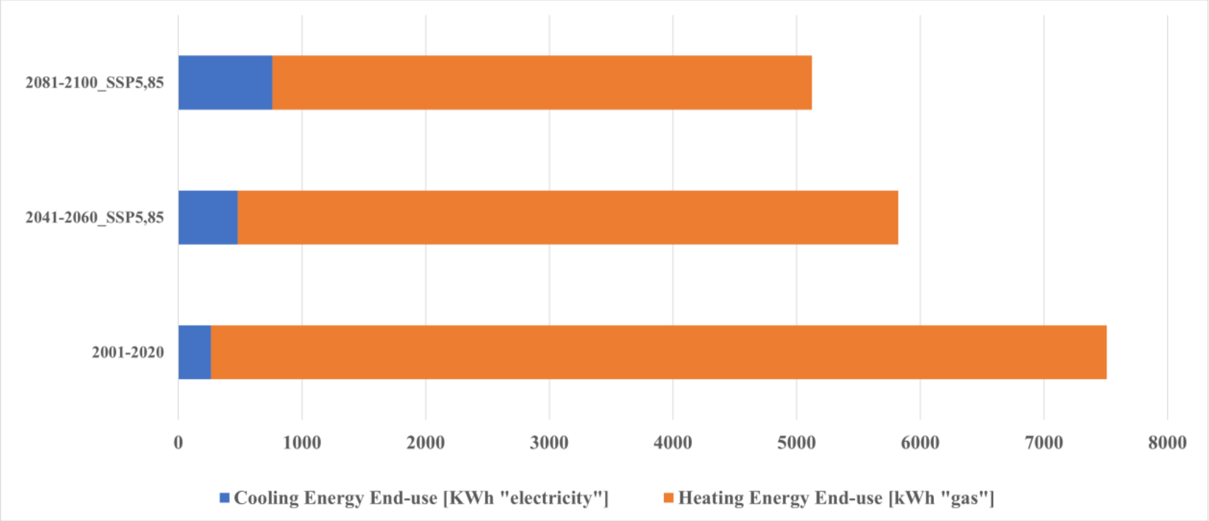


**Figure 6:** Final heating and cooling energy end-use for different weather scenarios for Split AC cooling concept

# 4. DISCUSSION

## 4.1 Findings and recommendations

According to the Intergovernmental Panel on Climate Change (IPCC), global warming of 1.5 K and 2 K will be exceeded during the 21st century. In this paper, using the future weather scenarios in Brussels city for the MAR model, the mean annual air temperature increases by 3.2 K in TMY (2081-2100) compared to TMY (2001-2020). With this significant increase in the temperature and the more frequent heatwaves, it became very necessary to study the future cooling energy demand and the related thermal comfort in buildings.

In this paper, IOhD indicator is used to assess the impact of climate change on thermal comfort using a multi-zonal approach in the case study. Two comfort models are used, the static comfort model for the bedrooms and the adaptive comfort model for other zones. The results showed that the IOhD using passive cooling scenarios such as natural ventilation decreases by 77% in 2090s compared to the base case where there is only a mechanical ventilation system, while using an active cooling system such as a split AC system could maintain the thermal comfort in the future weather scenarios as shown in Figure 5.

Figure 6 showed the final heating and cooling energy end-use. There is a significant increase in the cooling energy end-use and a reduction in the heating energy end-use. As mentioned earlier that buildings in the EU have a major share in the total energy consumption.

To summarize the key findings and provides some recommendations to the building designers and owners regarding the choice and installation of cooling systems:

- It’s necessary to consider highly efficient active cooling systems in combination with passive cooling techniques during the construction of new buildings and the renovation of existing ones.
- Cooling systems coupled with air handling units allow to improve the indoor air quality and are generally suited for residential and commercial buildings.
- IOhD indicator is recommended to be used for thermal comfort assessment.

## 4.2 Strengths and limitations

- The study’s first strength is the validity of the weather data used for the simulations using the MAR model.
- This study also compares different passive and active cooling concepts using a multizonal approach.
- The limitation of this study relies on neglecting the degradation of the HVAC systems in the future.

## 5. CONCLUSION

This paper studied the potential of three cooling concepts (mechanical ventilation, natural ventilation and Split AC) to cover the internal cooling loads during the summer period through different weather scenarios using the TMYs for 2001-2020 (2010s), 2041-2060 (2050s), and 2081-2100 (2090s). The paper showed the necessity to install active cooling systems along with passive measures to maintain a comfortable environment for the occupants. By comparing the three cooling concepts, the Split AC system showed the lowest overheating discomfort estimated by an IOhD of 0.01°C in (2081-2100). The paper also showed that, the final heating energy end-use decreases by 40% while the final cooling energy end-use increases by 187%.

## NOMENCLATURE

| | | |
|---|---|---|
| T | Temperature | (℃) |
| IOhD | Indoor Overheating Degree | (℃) |
| TL | Temperature limit | (℃) |
| EER | Energy Efficiency Ratio | (–) |
| SHR | Sensible Heat Ratio | (–) |

**Subscript**

| | |
|---|---|
| rm | weigh average of the mean outdoor temperature |
| z | buildings zones counter |
| i | occupied hours counter |
| in | indoor conditions |
| t | time step |

## REFERENCES

ASHRAE. (2017). *ANSI/ASHRAE Standard 55-2017—Thermal Environmental Conditions for Human Occupancy*. https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy

Berardi, U., & Jafarpur, P. (2020). Assessing the impact of climate change on building heating and cooling energy demand in Canada. *Renewable and Sustainable Energy Reviews*, *121*, 109681. https://doi.org/10.1016/j.rser.2019.109681

*Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (2021). Cambridge University Press.

Doutreloup, S., Fettweis, X., Rahif, R., Elnagar, E., Pourkiaei, M. S., Amaripadath, D., & Attia, S. (2022). *Historical and Future Weather Data for Dynamic Building Simulations in Belgium using the MAR model: Typical &amp; Extreme Meteorological Year and Heatwaves* [Preprint]. Atmosphere – Meteorology. https://doi.org/10.5194/essd-2021-401

Doutreloup, S., Wyard, C., Amory, C., Kittel, C., Erpicum, M., & Fettweis, X. (2019). Sensitivity to Convective Schemes on Precipitation Simulated by the Regional Climate Model MAR over Belgium (1987–2017). *Atmosphere*, *10*(1), 34. https://doi.org/10.3390/atmos10010034

Doutreloup, Sébastien, & Fettweis, X. (2021). *Typical &amp; Extreme Meteorological Year and Heatwaves for Dynamic Building Simulations in Belgium based on MAR model Simulations* (version 1.0.0) [Data set]. Zenodo. https://doi.org/10.5281/ZENODO.5606983

Elnagar, E., Doutreloup, S., & Lemort, V. (2021, September 1). Modeling the Impact of Climate Change on the Future Heating Demand in Different Types of Buildings in the Belgian Residential Building Stock. *Proceeding of the International Building Simulation Conference*. Building Simulation 2021 Conference. https://orbi.uliege.be/handle/2268/263135

Elnagar, E., Zeoli, A., & Lemort, V. (2022). Performance Evaluation of Passive Cooling in a Multi- Zone Apartment Building Based on Natural Ventilation. *CLIMA 2022 Conference*. https://doi.org/10.34641/clima.2022.263

*Exigences PEB du 1er juillet 2019 au 31 décembre 2020*. (2019). https://energie.wallonie.be/fr/exigences-peb-du-1er-juillet-2019-au-31-decembre-2020.html?IDD=136456&IDC=7224

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

FETTWEIS, X., WYARD, C., DOUTRELOUP, S., & BELLEFLAMME, A. (n.d.). *Noël 2010 en Belgique: Neige en Flandre et pluie en Haute-Ardenne* [Text]. https://popups.uliege.be/0770-7576. Retrieved January 20, 2022, from https://popups.uliege.be/0770-7576/index.php?id=4568&format=print

Hamdy, M., Carlucci, S., Hoes, P.-J., & Hensen, J. L. M. (2017). The impact of climate change on the overheating risk in dwellings—A Dutch case study. *Building and Environment*, *122*, 307–323. https://doi.org/10.1016/j.buildenv.2017.06.031

International Organization for Standardization. (2017). *ISO 17772-1:2017—Energy performance of buildings—Indoor environmental quality*. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/04/60498.html

Invidiata, A., & Ghisi, E. (2016). Impact of climate change on heating and cooling energy demand in houses in Brazil. *Energy and Buildings*, *130*, 20–32. https://doi.org/10.1016/j.enbuild.2016.07.067

Karl, T. R., Melillo, J. M., & Peterson, T. C. (2009). *Global climate change impacts in the United States*. Cambridge University Press. https://www.cabdirect.org/cabdirect/abstract/20103085717

Nakicenovic, N., Alcamo, J., Davis, G., Vries, B. de, Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T. Y., Kram, T., Rovere, E. L. L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., … Zhou, D. (2000). *Special Report on Emissions Scenarios. A SpecialReport of Working Group III of the Intergovernmental Panel on ClimateChange*. Cambridge University Press, Cambridge, UK and New York, NY, USA,. https://escholarship.org/uc/item/9sz5p22f

Radhi, H. (2009). Evaluating the potential impact of global warming on the UAE residential buildings – A contribution to reduce the CO2 emissions. *Building and Environment*, *44*(12), 2451–2462. https://doi.org/10.1016/j.buildenv.2009.04.006

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O’Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., … Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Ridder, K. D., & Gallée, H. (1998). Land Surface–Induced Regional Climate Change in Southern Israel. *Journal of Applied Meteorology and Climatology*, *37*(11), 1470–1485. https://doi.org/10.1175/1520-0450(1998)037<1470:LSIRCC>2.0.CO;2

Ruosteenoja, K., & Räisänen, P. (2013). Seasonal Changes in Solar Radiation and Relative Humidity in Europe in Response to Global Warming. *Journal of Climate*, *26*(8), 2467–2481. https://doi.org/10.1175/JCLI-D-12-00007.1

The Bureau for Standardisation in Belgium. (2021, June). *Standard NBN EN 15193-1:2017—Energy performance of buildings—Energy requirements for lighting*. https://www.nbn.be/shop/en/standard/nbn-en-15193-1-2017-a1-2021_104645/

Ürge-Vorsatz, D., Cabeza, L. F., Serrano, S., Barreneche, C., & Petrichenko, K. (2015). Heating and cooling energy trends and drivers in buildings. *Renewable and Sustainable Energy Reviews*, *41*, 85–98. https://doi.org/10.1016/j.rser.2014.08.039

Wang, H., & Chen, Q. (2014). Impact of climate change heating and cooling energy use in buildings in the United States. *Energy and Buildings*, *82*, 428–436. https://doi.org/10.1016/j.enbuild.2014.07.034

Wyard, C., Doutreloup, S., Belleflamme, A., Wild, M., & Fettweis, X. (2018). Global Radiative Flux and Cloudiness Variability for the Period 1959–2010 in Belgium: A Comparison between Reanalyses and the Regional Climate Model MAR. *Atmosphere*, *9*(7), 262. https://doi.org/10.3390/atmos9070262

Wyard, C., Scholzen, C., Doutreloup, S., Hallot, É., & Fettweis, X. (2021). Future evolution of the hydroclimatic conditions favouring floods in the south-east of Belgium by 2100 using a regional climate model. *International Journal of Climatology*, *41*(1), 647–662. https://doi.org/10.1002/joc.6642

## ACKNOWLEDGEMENT

This research was partially funded by the Walloon Region under the call ‘Actions de Recherche Concertées 2019 (ARC)’ and the project OCCuPANt, on the Impacts Of Climate Change on the indoor environmental and energy PerformAnce of buildiNgs in Belgium during summer. The authors would like to gratefully acknowledge the Walloon Region and Liege University for funding. This study is a part of the International Energy Agency Annex 80 project activities to define resilient cooling in residential buildings.