Impact of integration of electric and gas heat pumps on the final energy consumption of Belgian residential building stock

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Abstract. The paper investigates the evolution of electricity-driven and gas-driven heat pumps technologies used for heating in the residential building stock in Belgium in the market. A base and predictive scenarios are considered. The base scenario includes the current share of the existing heat pumps in the Belgian market while the predictive scenario considers the increased share of the studied heating systems based on the evolution of the buildings envelope over the period 2020-2050. Two different types of heat pumps are considered, one driven by electricity which performance indicators are based on the literature, while experimental data is used for natural gas-driven heat pumps. The latter is modeled in an empirical way based on the system operating conditions and weather data. This paper presents the entire housing stock in Belgium which is divided in 752 cases. A tree structure model defining Belgian housing typology was created, characterizing Belgian residential building stock in terms of various parameters like building age, scale, level of insulation and energy vectors. A weighting factor to represent their occurrence in the existing Belgian building stock is associated to each building type. To study the impact on the load profile and the final energy consumption, the penetration of the selected heat pumps is calculated through the base and predictive scenarios. The penetration rates obtained of 67.6% and 42.7% for electricity and gas-driven HPs respectively, will allow to carry out some production planning for energy suppliers, manufacturers, and policymakers. Finally, the evolution of the sizing criteria in the future will have an impact on the penetration rates of the studied systems and must not be neglected.

Keywords. energy consumption, heating demand, heat pumps, residential buildings
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1. Introduction

Buildings in the EU account for 40% of our energy consumption and 36% of our greenhouse gas emissions [1]. European countries are developing strategies to reduce energy consumption in buildings and the associated CO_2 emissions [2]. In long-term scenarios, energy use is very important to be taken into account, particularly in the residential sector, by looking at energy end uses, which gives a better understanding of the evolution of energy use and the possible impacts and adaptation of climate change on energy use. In most European countries, the amount of energy required for heating is greater by far than the energy used for space cooling [3]. Climate change has drawn great attention in recent years because of its large impact on many aspects of building energy use [4,5]. In Belgium, the residential energy needs for space heating and domestic hot water are mainly met by fuel oil, gas or electricity supplied by the grid. The present research aims at assessing the impact of contrasting penetration scenarios of technologies such as heat pumps.

In Belgium, gas boilers have been for years the most common heating device used due to an extensive gas network available and the relatively low gas prices. Year after year, the European Energy Performance of Buildings Directive (EPBD) imposes more demanding targets, increasing heat pumps installations since it has become more and more difficult to achieve the requirements without using renewable technologies [6].

The benefits associated with these technologies are not only energetic but also environmental. A study by Famiglietti, et al. [7] shows that the impact over the entire life cycle of a Gas Absorption Heat Pump (GAHP) offers a lower environmental impact compared to a traditional boiler mainly because of the lower amount of natural gas (NG) needed in the use phase, representing an average reduction of 27% of $CO_{2\ eq}$ and a reduction of 25% of fossil resource consumption.

Even if the heat pump market share in Belgium remains low (around 10% in 2014), this group of technologies has been growing steadily since 2013. Just in 2018, the market increased by almost 10% compared to 2017 [8], a trend that would continue in the coming years. Even though most of the statistics point to electric heat pumps, the high electricity prices are opening the market to alternative technologies such as thermally driven heat pumps, making them well suited not only for new buildings but also for the existing ones since they can heat water to high temperatures in a very efficient way offering substantial cost and energy savings thanks to the involved technologies [9].

The aim of this paper is to assess the impact of heat pumps evolution in different scenarios (Electricity-driven heat pumps) and (Gas-driven heat pumps) on the annual consumptions of the residential building stock as well as the impact on the CO_2 emissions. In addition to that, A business-as-Usual Scenario (BAU) is investigated up to the horizons 2030 and 2050 by considering the construction, demolition and renovation rates of the buildings. The Energy simulations are conducted with MATLAB.

2. Methodology

The methodology used in this paper is based on the modeling of the energy end-use consumptions. 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). According to ASHRAE, the forward method is more suited for improvements due to it higher level of details, compared to the data-driven method [10].
This paper also used an updated model of the tree structure model representing the Belgian residential building stock developed by Gendebien et. al [11].

2.1 Building Stock (Base Scenario-up to 2012)

The Belgian building stock tree structure is based on a hybrid approach (mix between typical and representative approaches). In the typical approach, a set of typical buildings closely related to the existing buildings are chosen, while a set of fictional buildings based on average values are selected in the representative approach. As shown in Fig. 1, the final tree structure of the base scenario is based on different parameters:

1. Building type (freestanding, semi-detached, terraced and apartment).
2. Year of construction (<1945, 1946-1970, 1971-1990, 1991-2007 and 2008-2012)
3. Insulation level for the building envelope (wall, window, roof and floor).
4. Space heating “SH” (fuel oil, NG, electricity and others (coal, wood,…)).
5. Heating production system (centralized, decentralized).
6. Domestic Hot Water “DHW” (fuel oil, NG, electricity and others (coal, wood,…)).

The final tree structure presents 752 cases representing the whole Belgian building stock till 2012, each case is characterized by the aforementioned parameters.

The simplified building model of a zone is based on the simple hourly method described in ISO13790-2007 [12]. The method is based on the thermal-electrical analogy between the analyzed thermal zone and the equivalent 5R-1C (5 resistances and 1 capacity). The thermal-electrical network is characterized by temperature nodes (θ), thermal resistances (1/H), heat fluxes (Φ) and a capacity (C_m) [13]. The 5 resistances in the network are used to describe the heat transfers coefficients, while the thermal mass is represented by a single thermal capacity C_m.

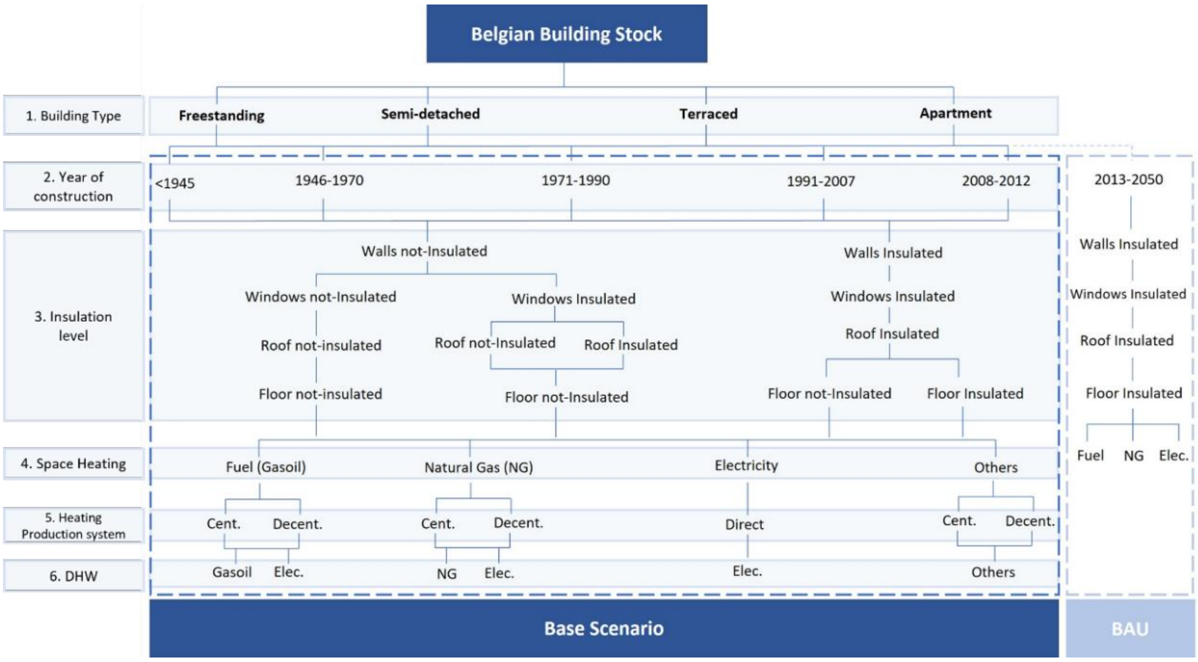

Fig. 1 - Belgian building stock tree structure

Fig. 2 (a) shows the distribution of Belgian dwelling types for the base scenario, it can be seen that the freestanding houses have the highest share by 29.2%. Fig. 2 (b) also presents the energy mix of the different energy sources used for SH; the SH energy needs are mainly met by NG and liquid fuels for boilers by 50.14% and 40.02% respectively, while the electricity and other energy sources represent the lowest distribution.

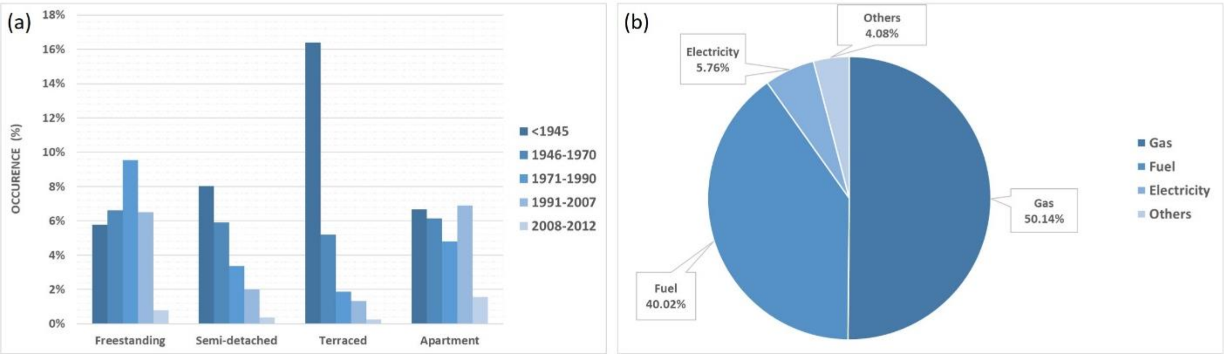

Fig. 2 - Base scenario (up to 2012) (a) Distribution of the Belgian dwelling types differentiating the five construction periods (b) Distribution of energy sources used for SH.

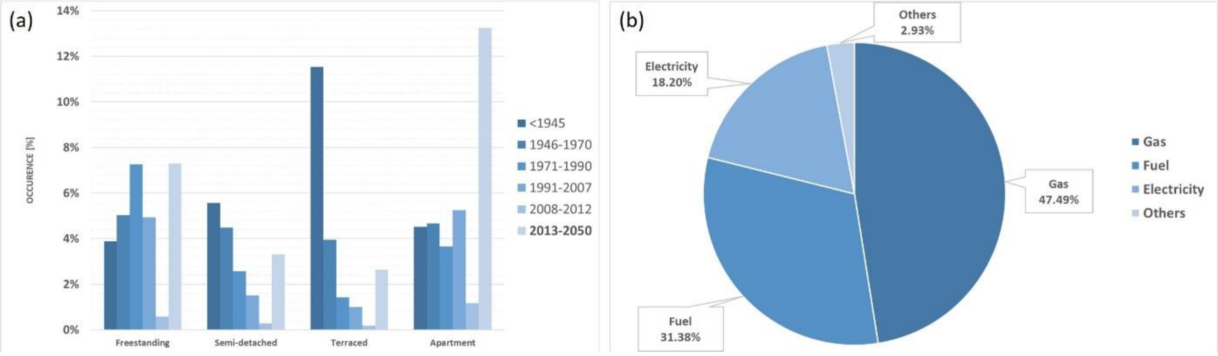

Fig. 3 - BAU scenario (up to 2050) (a) Distribution of the Belgian dwelling types differentiating the six construction periods (b) Distribution of energy sources used for SH.

2.2 Weather Data

The recent decades have seen a major concern about global warming and climate change. This study also aims to upscale the impact of climate change on future heating consumption and to evaluate the minimum indoor temperature used for sizing the heat pumps in Belgium.

The regional climate model used in this study is the “Modèle Atmosphérique Régional” model (hereafter called “MAR”) [14]. Since MAR is a regional model, it must be forced by a global model. Therefore, the atmospheric conditions from a general circulation model (GCM) must be directly forced to the boundaries of the MAR domain every 6 hours. MAR Model runs at 5 km spatial resolution over the Belgian territory as shown in Fig. 4. In this study MAR is forced by the global model BCC-CSM2-MR (called BCC hereafter) [15] with both scenarios historical (1960-2014) and ssp585 (2015-2100) from the CMIP6 project [16]. MAR-BCC is the ensemble mean of all the MAR simulations, compared to MAR-MPI (the coldest) and MAR-MIR (the warmest) [14]. In this study MAR-BCC model is used for the SSP585.

2.3 Future Scenarios

In the future scenarios, the tree structure is then extended for the period 2013–2050 as shown in Fig. 1. The new dwellings that are constructed in this period are fully insulated. In addition to that, two scenarios are assessed to calculate the maximum penetration rate of electricity-driven and gas-driven heat pumps in the building stock and their impact on the overall building stock energy use.

The performance of electricity-driven heat pumps is based on the performance map provided by different manufacturers, while the gas-driven heat pump performance is based on laboratory tests.

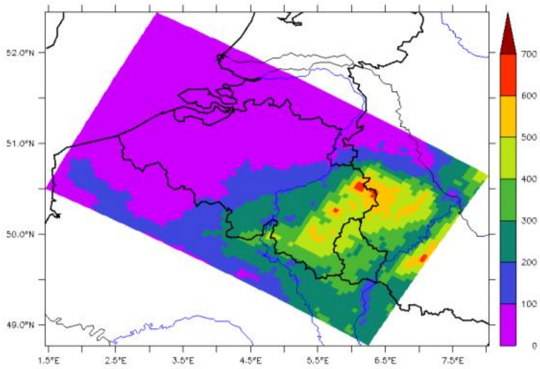

Fig. 4 - Topography (in meters above sea level) of the MAR domain representing Belgian territory [13].

- ***Business-as-Usual (BAU-up to 2050)***

The BAU scenario is the first step to update the building stock for the new dwellings, insulation characteristics and the energy sources used for SH and DHW for the period 2013-2050. Based on the Long term renovation strategies of Wallonia and Flanders in Belgium, an average annual construction and demolition rates are set respectively to 0.8% and 0.075%. In addition to that, a total of 1.3% per year renovation rate is counted to renovate the different buildings. The priority was given first to the older non-insulated and after to the partially insulated buildings.

Fig. 3 (a) shows the expected distribution of the newly constructed dwellings between 2013-2050, the number of dwellings for the reference year 2012 was 4,675,433 buildings which increased by 0.348% in 2050 to reach 6,152,311 dwellings. Fig. 3 (b) represents the distribution of energy sources used for SH in 2050. It can be seen that the electricity share is 18.20% compared to 5.76% in the base scenario because of the policies and regulations to increase the share of electricity and to ban the use of oil boilers for the newly constructed buildings and NG connections for the large apartments as well [17]. The share of NG and fuel is also reduced compared to the base scenario in 2012.

- ***Electricity-Driven Heat Pump Scenario***

The electricity-driven heat pump scenario is characterized by the maximum penetration rate of air-source heat pumps used for SH and DHW production. The heat pumps are modeled using polynomial laws to fit with the performance maps provided by the manufacturers for the different machines.
The model gives the heating capacity at full load and the COP at full load (COP_{FL}) as a function of two variables; the outside air temperature ($T_{air,out}$) and the temperature of the heating fluid at the outlet of the condenser (T_w).

This polynomial model gives accurate results when the working conditions are close to the full load conditions, in order to predict the performance of a heat pump better, a third order low has been chosen. The model has been calibrated with an air-to-water heat pump Viessmann Vitocal 300-A.

The energy input ratio at full load ($EIRFT$) is calculated as a function of ΔT as shown in equation (1) and the capacity at full load ($CAPFT$) is also calculated as a function of ΔT as shown in equation (3).

$$EIRFT = \frac{\mathrm{COP}_n}{\mathrm{COP}_{fl}} = Co + C1 * \Delta T + C2 * \Delta T^2 + C3 * \Delta T^3 \tag{1}$$

$$\Delta T = \frac{T_{air,out}}{T_w} - \left(\frac{T_{air,out}}{T_w}\right) n \tag{2}$$

$$CAPFT = \frac{\dot{Q}_{FL}}{\dot{Q}_n} = Do + D1 * (T_{air,out} - T_{air,out,n}) + D2 * (T_w - T_{w,n}) \tag{3}$$

At part load, the energy input ratio is also calculated ($EIRFPLR$) to give the performance at part load as shown in equation (4).

$$EIRFT = \frac{\dot{W}_{PL}}{\dot{W}_{FL}} = K1 + (K2 - K1) * PLR + (1 - K2) * PLR^2 \tag{4}$$

$$PLR = \frac{\dot{Q}_{PL}}{\dot{Q}_{FL}} \tag{5}$$

Where:
C0 = 1.01283
C1 = -9.6421
C2 = 65.2973
C3 = 359.06
D0 = 0.973861827
D1 = 0.025752873
D2 = -0.00340588
K1= 0
K2= -0.82

In this scenario, the priority of the production is given to the DHW as the backup is used for SH (if there is a backup system in the building) and for SH and DHW simultaneously if there is no backup system in the building.
Three different types of heat pumps were considered for the sizing depending on the overall U-value of the building as shown in Tab. 1, Low temperature heat pumps are selected when the average U-value is below 0.3 W/m^{2}K which is related to the EPB legislation in Belgium, high-temperature HPs are selected for U-value higher than 0.8 W/m^{2}K and medium temperature for U-value between 0.3 and 0.8 W/m^{2}K.

Tab. 1 – Electricity-driven HP selection and sizing.

U-value [W/m^2]	**HP Type**	**Heating power [kW] ($\dot{Q}_{in}$)**
U$_{avg}$ <0.3	Low T HP (Air 7°C/ Water 35°C)	4.4 to 16
0.3 < U$_{avg}$ > 0.8	Medium T HP (Air 7°C/ Water 45°C)	11 to 16
U$_{avg}$ > 0.8	High T HP (Air 7°C/ Water 65°C)	11 to 16

The criteria for determining whether or not a heat pump may be placed in a given building is based on a stationary balance that takes into account the building SH and DHW loads, by considering a maximum rating power of 8.6 kW at -10°C, and 80% of the loads at these conditions. Currently, the minimum outdoor temperature used in sizing in the heating seasoni s -10°C according to the ecodesign requirements [18].

Gas-Driven Heat Pump Scenario

In order to expand the energy sources used for the same technology, a gas-driven absorption heat pump (GAHP) is proposed as a second scenario. Designed for SH and DHW production for residential applications, the appliance has been tested and the results obtained are used to develop a model compatible with that of buildings. The GAHP has a nominal heating capacity of 18.9 kW and its main features are shown in Tab. 2.

Tab. 2 - Main characteristics of the selected GAHP.

Heating power	Air 7°C / Water 50°C 17.6 kW Air 7°C / Water 35°C 18.9 kW
GUE efficiency (relative to LCV)*	Air 7°C / Water 50°C 157% Air 7°C / Water 35°C 169%
Elec. Power absorption	0.35 kW
Heating capacity	11.4 kW (nominal, relative to LCV, 1013 mbar – 15°C) 11.2 kW (real)

** Gas utilization efficiency; efficiency index of gas heat pumps, equal to the ratio between the thermal energy produced and the energy of fuel used (relative to low calorific value).*

The system is based on the Water-Ammonia absorption cycle using outdoor air as the low-temperature heat source and NG combustion as high-temperature heat source; the delivered hot water is the medium-temperature heat sink. The working principle of the system is represented in the diagram shown in Fig. 5.

To reduce its pressure, the refrigerant leaving the COND is throttled by means of a restrictor valve and cooled down inside the Pipe-in-Pipe heat exchanger (PiPHx); then, by means of a second restrictor valve, is brought to the ideal pressure and temperature conditions before entering the Evaporator (EVAP) where the liquid refrigerant is evaporated by taking heat from the surrounding air. Then, the low-pressure vapor ammonia is overheated in the PiPHx before being sent to the Solution Cooled Absorber (SCA), where it meets the poor refrigerant solution coming from the GEN. The pressure of the incoming solution is reduced by a third restrictor valve.

Since the absorption process is an exothermic reaction, the solution is sent to the Water Cooled Absorber (WCA) where a considerable amount of thermal energy is transferred to the water of the heating circuit. Once the absorption is completed, the solution is pumped back to the GEN using a Solution Pump (SP).

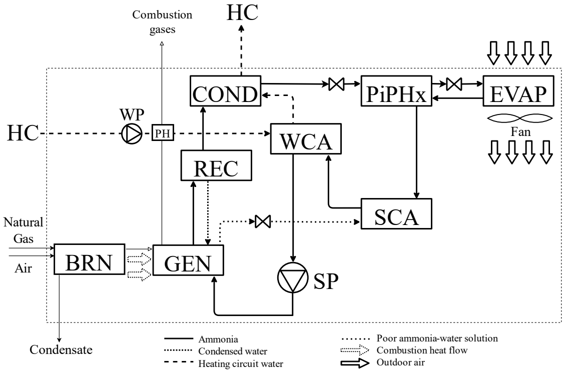

Fig. 5 - Gas absorption heat pump schematic.

The system is installed and tested in a climatic chamber to vary and control the temperature and humidity conditions. From the performance map and the tests conducted in the laboratory, a simple model based on an ordinary least squares linear regression is developed.

The model should give the Heating Capacity at full load ($\dot{Q}_{HC,FL}$) as a function of outdoor temperature (T_{out}), delivery water temperature ($T_{delivery}$) and specific humidity (ω), as shown in Equation (6) The COP at full load (COP_{FL}) depends on the same variables as shown in Equation (7).

$$Q_{HC,FL} = f(T_{air,out}, T_w, W_{out}) \tag{6}$$
$$COP_{FL} = g(T_{air,out}, T_w, W_{out}) \tag{7}$$

The part load ratio (PLR) is the ratio of the heating capacity at part load ($\dot{Q}_{HC,PL}$) to the heating capacity at full load as expressed in Equation (8). This ratio is an input and must be a number between 0 and 1 since the heating capacity varies proportionally with the modulation of the system.

$$PLR = \frac{\dot{Q}_{HC,PL}}{\dot{Q}_{HC,FL}} \tag{8}$$

The same approach is used to model the inputs to the system, in this case, the gas heat input and electrical input (consumption of fans and electronics) are defined as $\dot{Q}_{gas}$ and $\dot{W}_{in}$ in Equations (9) and (10). The gas heat input varies according to the water delivery temperature and outdoor temperature, in addition to the modulation of the system; the electrical consumption depends on the modulation of the system thus it is modeled as a function of the part load ratio and represented as a linear proportion.

$$\dot{Q}_{gas} = h(T_{out}, T_{delivery}, PLR) \tag{9}$$
$$\dot{W}_{in} = i(PLR) \tag{10}$$

The obtained coefficients for the linear model are such that the residual sum of squares between the observed targets in the dataset and the targets predicted by the linear approximation is minimized. The results are shown in Equations (11), (12), (13) and (14). The R^2 of each formula is defined as $1 - (u/v)$, where u is the residual sum of squares and v is the total sum of squares; the best possible score for

R^2 is 1.

$$\begin{array}{lcr} & R^2 & \\ \dot{Q}_{HC,FL} = 0.0958\,T_{out} - 0.1809\,T_{delivery} + 146.192\,\omega + 25.0752 & 0.89 & (11) \\ COP_{FL} = 0.0059\,T_{out} - 0.0118\,T_{delivery} + 15.1612\,\omega + 1.6759 & 0.86 & (12) \\ \dot{Q}_{gas} = -0.00287 T_{out} - 0.0164\,T_{delivery} + 11.9143 PLR + 2.9169 & 0.89 & (13) \\ \dot{W}_{in} = 0.2762\,PLR + 0.0540 & 0.91 & (14) \end{array}$$

The obtained formulas are evaluated for the experimental conditions from which the performance map is obtained. The results are within the order of magnitude and show the same trends and behavior observed during the experimental tests performed with small variations explained by the R^2 value of each formula.

In this scenario, the same criteria has been used to determine if a heat pump can be installed or not by considering a maximum rating power of 16.9 kW at -10°C, based on the manufacturer data. In addition to that the same sizing criteria is also used to size the GAHP according to the overall U-value of the building.

3. Results and Discussion

The results of the base scenario are shown in Fig. 6, comparing the total SH and DHW energy consumption in 3 different periods. It can be seen at Fig. 6 (a) that there is a slight change in the distribution of energy sources used for SH and DHW as there was no change in the building stock, while there is a significant decrease in the total SH and DHW consumption. In the base scenario with a reference year using TMY (2001-2020), the total SH and DHW consumption was 102184 GWh and it decreased to 81320 GWh and 77825 GWh in (2041-2060) and (2081-2100) respectively.

Fig. 6 (b) also shows the average consumption per dwelling in the 3 periods for the base scenario. It decreased from 21.86 MWh in (2001-2020) to 17.40 MWh in (2041-2060) and 16.65 MWh in (2081-2100). It can also be seen that the CO_2 emissions decreased for an average dwelling from 5.10 ton CO_2 to 3.88 ton CO_2. The emission factors for electricity, gas, fuel and others in Belgium are 0.160 kg/kWh, 0.202 kg/kWh, 0.267 kg/kWh and 0.342 respectively [19,20].

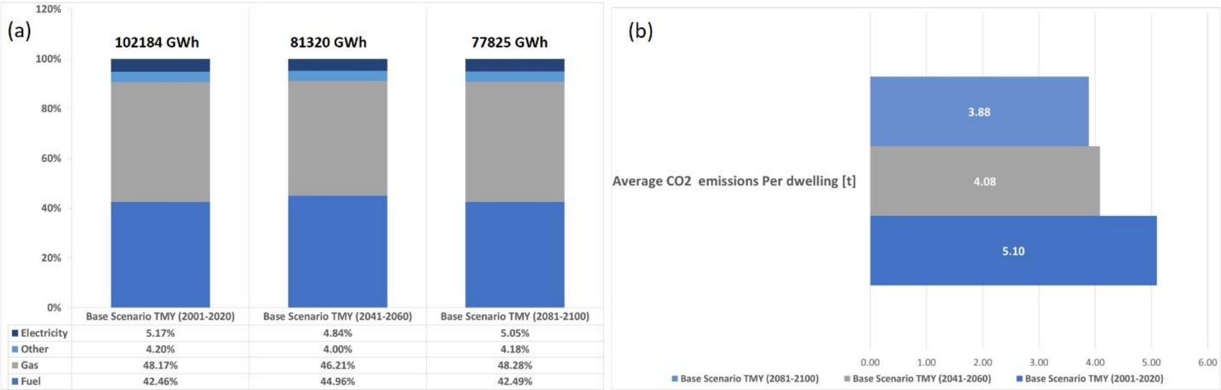

Fig. 6 - Comparison between the SH and DHW energy consumption in the Base Scenario in different years (a) Total SH and DHW energy consumption (b) average CO2 emissions per dwelling.

For the BAU Scenario, the building stock has been updated as shown before in Fig. 3. The new distribution of the buildings has been used to simulate the electricity-driven heat pumps scenario and to calculate the maximum penetration rate of both heat pumps in the building stock and their impact on the overall building stock energy use.

Fig. 7 shows the maximum penetration rate of the electricity-driven heat pumps. Based on the criteria mentioned before, 67.6% is the maximum possible penetration rate of the electricity-driven HPs in 2050 Horizon. It can also be seen that in the electricity-driven HPs scenario, the NG and fuel share amongst the whole building stock decreased to 15.5% and 15% respectively compared to their share in the BAU scenario as shown in Fig. 3.

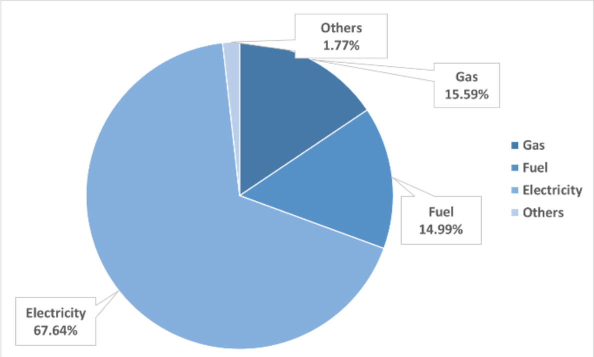

Fig. 7 – Electricity-driven HP scenario - distribution of energy sources used for SH.

The increase of the electricity share has also an impact on the total SH and DHW energy consumption of the building stock as shown in Fig. 8.
It can be seen that electricity represents 45.4% of the total SH and DHW energy consumption in the

electricity-driven HPs scenario compared to 13.64% in the BAU scenario.

The total SH and DHW energy consumption decreased by 3.23% in the electricity-driven HPs scenario compared to the BAU scenario and the consumption per average dwelling decreased from 15.6 MWh in the BAU scenario to 15.1 MWh in the electricity-driven HPs scenario.

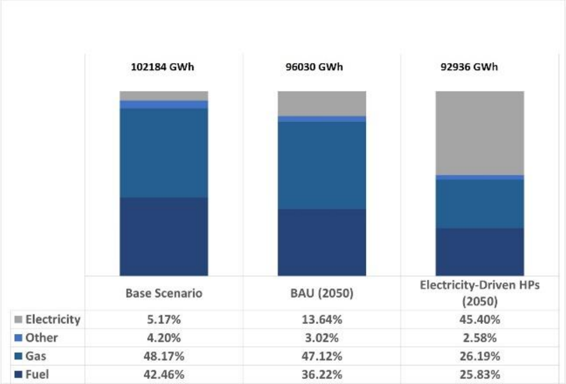

Fig. 8 - Comparison between the total heating energy consumption in the Base scenario, BAU scenario and electricity-driven HPs scenario.

For the gas-driven HPs scenario, based on the same criteria of installing a GAHP with a maximum power of 16.9 kW at -10°C. The maximum penetration rate of GAHP is 42.7% by 2050, compared to the distribution of NG source in BAU scenario in 2050 which is 47.5% as shown in Fig. 3(b). The share of the GAHP represents 89.92% of the total number of buildings that use NG for SH and DHW purposes as shown in Fig. 9.

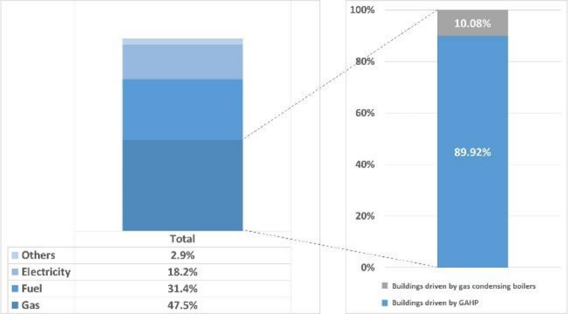

Fig. 9 – Gas-driven HP scenario – share of GAHP amongst the buildings that use NG for SH and DHW.

Fig. 10 compares between the total heating energy consumption in the gas-driven HP scenarios, BAU scenario as well as the base scenario. The total heating consumption for SH and DHW in the gas-driven HP scenario is 4.5% lower than the BAU scenario.

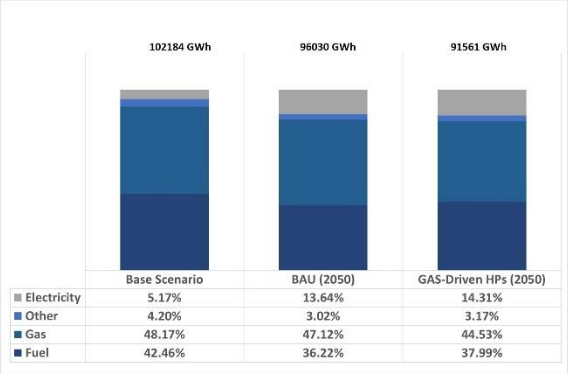

Fig. 10 - Comparison between the total heating energy consumption in the Base scenario, BAU scenario and gas-driven HPs scenario.

The results also show that the minimum outdoor temperature is increasing in the coming years. Compared to the reference year TMY(2001-2020), there are 26 hours when the Temperature is below -10°C, while in the period (2081-2100), the minimum outdoor temperature is -5°C for 3 hours. Based on those results, the minimum outdoor temperature used in the criteria to determine the maximum penetration rate of HPs is updated to -5°C. The change in the maximum penetration rate is not significant, it has been found that the electricity-driven heat pumps penetration rate increases from 67.6% to 68.9% and the gas-driven heat pumps penetration rate will increase from 42.7% to 43.5%.

4. Conclusion

In this paper, a bottom-up approach has been updated to describe the Belgian building stock with the base scenario and BAU scenario. The results show that, climate change has a significant impact on the energy use of buildings, by 2100 the SH and DHW energy consumption for the whole building stock decreased by 23.8%.

In the second step, the evolution of the building stock till 2050 has been updated while taking into consideration the construction, demolition and renovation rates in the BAU 2050 scenario. The distribution of energy sources used for SH and DHW has been changed compared to the base scenario.

The paper also investigates two different scenarios to calculate the maximum penetration rate of heat pump technologies used for SH and DHW in the residential buildings in Belgium. In the first scenario, the maximum penetration rate of electricity-driven HPs is 67.6%, while the maximum penetration rate of GAHP is 42.7%.

The evolution of temperatures in the coming years showed that increasing the minimum indoor temperature used in the sizing criteria for the HPs to -5°C instead of -10°C, will also have an impact on the maximum penetration rate of both HPs.

5. Acknowledgment

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