Numerical assessment of self-sufficiency of residential buildings in Belgium by using heat pumps, photovoltaic panels and energy storages

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Abstract. Residential buildings claim a significant share of the total energy use worldwide. In order to have more realistic energy performance predictions, increased attention is paid to the analysis of the building’s energy use through comprehensive, transient detailed numerical simulations. In this article, the self-consumption and self-sufficiency values of three detached residential buildings are assessed through numerical models made in the programming language Modelica and software tool Dymola. The three buildings have the same structure and different space heating energy demands of 15 kWh/m²/year, 30 kWh/m²/year and 45 kWh/m²/year. The energy use of the buildings coincides with the occupancy profile where domestic hot water use dominates over the space heating demand provided by an air to water heat pump. The discrepancy between renewable energy production and energy consumption is mitigated by means of thermal load shifting and electrical energy storage. In this research, the self-consumption and self-sufficiency of the studied buildings have been analysed as a function of the economically favourable energy storage sizing. For the use of an electrical battery with the installed capacity of 2.5 kWh and thermal energy storage of 250 l, the self-sufficiency results to be 40%, 38.5% and 37% for the three buildings respectively at the specific simulated energy demand conditions.

1. Introduction

1.1. Energy use and legal policies

The energy use by residential buildings account for 25.71% of the European Union’s (EU) final energy use in the year 2016 making it the largest energy demanding sector after transport [1]. On the global level, the energy use by the residential sector had a continuous growth. Due to the increased trend of using energy efficient products, the introduction of renewable energy sources and applications of energy policies, the final energy use of the residential sector notes a declining trend in the EU [2]. Several energy saving policies have been bindingly introduced among the member states of the EU at the local,
The energy and climate “20-20-20” targets have been imposed by the European Commission in 2007. The package sets three key targets: 20% cut in greenhouse gas emissions from 1990 levels, a share of 20% of energy use out of renewable sources and 20% improvement in the energy efficiency of the applied technology. The targets were set as a goal to be reached in a period of 13 years (2007-2020) [3]. In the meanwhile, the EU legal forces have introduced new, more challenging targets within “The 2030 climate and energy framework”. According to this policy, the member countries of the EU are encouraged and obliged to apply strategies that will lead to at least: 40% cuts in the greenhouse gas emissions from the 1990 levels, 32% share of renewable energy and 32.5% improvement in energy efficiency [4].

In the residential sector, the energy demand is a function of several factors such as weather and climate conditions, characteristics of the building structure, occupant behavior and economic potential for upgrading the existing heating systems. Space heating (SH) and domestic hot water requirements (DHW) have the highest share in total energy use among other typical energy consuming appliances of household facilities. Statistical surveys carried out by the official organization of the EU have shown that the final used energy in the dwellings is mostly taken by space heating (64.7%) and domestic hot water production (14.5%), while consequential production of energy for covering both of the thermal needs accounts for 79.2% of the total final energy use in residential buildings. In Belgium, the residential buildings sector is responsible for 17.5% of the total energy use. The energy demand is mostly covered by the supply of the natural gas fossil fuel source with the share of about 40% [5].

The Energy performance of buildings directive (EPBD) requires that all new residential buildings must be built as nearly zero energy buildings (NZEB) starting from the year 2020 [6]. This policy results in a substantially lower energy demand. Fortunately, most of the present world society has a clear awareness of the transient of the fossil fuel energy sources and the importance of energy savings. With the help of the local subsidies, new buildings across the EU are being constructed targeting a lower heating demand. As a consequence, the policy resulted in the application of alternative building system technologies which were already known on the market but not applied to their full remarkable capabilities.

1.2. Scope and definitions
At the present time, renewable energy systems (RES) such as photovoltaic panels (PV), heat pumps (HP) and solar thermal panels (STP) are finding an outstanding breach on the residential building market [7]. With their ability to generate the energy on site, a building becomes less dependent on the external grid thus leading to a certain potential of self-sufficiency value. The yearly electricity demand can be partly covered by a PV system, while the heating demand can be covered by a HP, possibly in combination with a STP system. The level of autonomy or self-sufficiency is, however, limited due to the time mismatch between the optimal on-site energy generation and energy demand.

Figure 1 shows a schematic outline of energy demand profile and an energy generation profile of a grid-connected residential building provided by on-site renewable electricity production through PV panels. Areas A and C represent the net energy need where the energy demand C is directly covered from the renewable energy source. Area B represents surplus energy production injected into the grid. The energy demand represented by area A is covered by the energy imported from the grid.

From figure 1, two metrics that denote the interaction between the household and the grid can be defined: self-consumption (SC) and self-sufficiency (SS). Although energy is not consumed but used and transformed to another energy form, the authors accepted to use the established expression ‘self-consumption’. Self-consumption is defined as the ratio between the used instantaneous renewable energy produced on site to the total instantaneous renewable energy generation on site (area C against the sum of the areas B and C) while the self-sufficiency denotes the ratio of the used instantaneous renewable energy produced on site to the total instantaneous electrical energy demand of the building (area C against the sum of the areas A and C).
In order to increase the values of SC and SS in the context of residential buildings, two main techniques are illustrated in figure 1 as well. At first, the load shifting technique refers to the movement of the time period with surplus energy consumption to periods with surplus energy production. This may refer to appliances such as washing machines that are often on during night at lower price tariffs. The second technique represents the energy storages implementation which are charged at the times of surplus energy production or at lower billing tariffs and later utilized in the peak moment of energy demand. The increment of SC and SS values generally leads to the lowering of the grid peak load and to the total increase of the efficiency of energy supply reflected in energy transport savings.

In this article, self-consumption and self-sufficiency of three detached low-energy demand residential buildings will be analyzed by means of using the thermal load shifting and the electrical energy storage strategies. The load shifting has been accomplished by the use of a thermal energy storage (TES) supplied by an air to water heat pump to meet the heating requirements of the dwelling while the electrical energy storage is realized with the use of a battery. In this work, special attention is given to the building system equipment sizing, configuration and controlling strategy.

2. Case study

2.1. Building structure
The three different building structures have the same architectural layout. The building structure layout is based on a real building that is a part of the social housing district Venning located in Kortrijk, Belgium built as a low-carbon district [9]. The building is configured as a detached building with two floors and a gable type roof. Figure 2 shows the floor plans of the ground floor and the first floor. The house is divided into 9 zones out of which 5 are heated. On the ground floor, the living room and kitchen are treated as a single zone thus further jointly referred to as the living zone. Besides the living zone, three bedrooms and the bathroom zone, located on the first floor, are heated as well. The zones which do not require space heating are the entrance, the toilet room, storage room located on the ground floor and as well as the attic space, available through the hatch door on the first floor.
Figure 2. Architectural layout of the used building structure. Ground floor (left), first floor (right).

The conditioned floor area of all three houses is estimated to be 99.8 m$^2$ individually. However, the three houses differ in the insulation thickness and airtightness which lead to three differing energy performances of the building being the medium energy demand building, low energy demand building and a passive house. Table 1 represents the properties of the three building types.

| Building | B45 | B30 | B15 |
|----------|-----|-----|-----|
| Air tightness | 1.4 ACH | 1 ACH | 0.6 ACH |
| Overall heat transfer coefficient | 0.391 W/(m$^2$K) | 0.282 W/(m$^2$K) | 0.184 W/(m$^2$K) |
| Heating demand | 4477 kWh/year | 2991 kWh/year | 1511 kWh/year |
| Specific heating demand | 44.9 kWh/m$^2$year | 30.0 kWh/m$^2$year | 15.1 kWh/m$^2$year |

The airtightness of the building is determined by the number of air changes per hour (ACH) at the overpressure value of 50 Pa. The structural heat transfer properties are represented though the overall heat transfer value for the three buildings. The energy performances are defined by specific annual heating demands of approximately 45 kWh/m$^2$year, 30 kWh/m$^2$year and 15 kWh/m$^2$year respectively. Due to simplicity reasons, the buildings will be referred to as respectively B45, B30 and B15.

2.2. Input data and boundary conditions
All three buildings were simulated at the same boundary conditions. The yearly moderate climate data of the city Uccle in Belgium were used to simulate the weather conditions. The time step of the weather data is 1h with the lowest reached temperature of -7.61°C.

A synthetic user profile is developed for each of the zones which is based on the time survey data for a profile that matches a young family with two adults and two children. The occupant behavior includes coherent profiles for the set point temperatures of the zones, convective and radiative internal heat gains of the occupants and appliances, the electricity demand of appliances and lighting, DHW demand and occupancy presence of the zones. The used time-step is 10 minutes for the temperature set points and occupancy and 1 minute for the internal heat gains, electricity demand and DHW demand. The set point temperatures vary over the different zones. The living zone is heated to 20°C with a night setback to
15°C, coherent with the occupancy profile of the living zone. All occupancy profiles are generated by the Python Strobe package [10].

On the household level, the internal heat gains of appliances and occupants amount to 4442 kWh annually. With the average internal heat gain value of 403 W, the living zone has the largest internal heat gains due to the presence of multiple appliances such as fridge, oven, television etc. On the other hand, the annual electricity demand for lighting and appliances is 4351 kWh for each household. The DHW use was modelled to be dominant in this case study. With the constant supply of municipal water at 10°C, and demand temperature set point of 40°C, the annual DHW demand corresponds to 6732 kWh of heating energy or 67.5 kWh/m²a expressed via the conditioned floor area of the property.

2.3. Description of building systems

2.3.1. Ventilation system. Due to the high airtightness, the ventilation system has become one of the essential systems to form a part of low energy buildings [11]. Even though the ventilation system is not in the focus of this work, a simple ventilation system is modelled and kept constant throughout the whole study. The system includes the fresh air supply to all the zones of the dwelling and an equal amount of air exhaust. In order to prevent excessive waste of heat carried by the exhaust air, an air to air heat exchanger is modelled as part of the system. The heat exchanger is modelled as a heat recovery unit with the constant efficiency of 84%. The streams of the supply and exhaust air sides are not in physical contact nor mixed.

2.3.2. Heating system design and sizing. The heating system installation applied in the buildings is considered for meeting both space heating and DHW energy demand in sequential order. Both of the systems are provided by an inverter controlled air to water heat pump unit. The space heating system is enabled in the 5 heated zones through underfloor heating system installation circuits designed in the serpentine formation. As an aspiration towards better efficiency of the heat pump unit, the chosen design temperature regime of the underfloor system is 35/25°C. A heating curve is implemented to adjust the production to the demand. Table 2 represents the overview of the design heating loads for the heated zones of the three case buildings.

| Zone        | B45   | B30   | B15   |
|-------------|-------|-------|-------|
| Living zone | 1435 W| 1283 W| 943 W |
| Bedroom 1   | 724 W | 524 W | 397 W |
| Bedroom 2   | 521 W | 364 W | 260 W |
| Bedroom 3   | 367 W | 268 W | 204 W |
| Bathroom    | 532 W | 374 W | 273 W |
| Building level | 3579 W | 2813 W | 2076 W |

The DHW is provided through a 300 l vessel. The vessel is heated by an integrated heating coil supplied from the heat pump as well as with the additional electrical heater of 3 kW located at the top of the DHW tank. The DHW demand has a priority against the space heating demand. The heat pump, therefore, supplies the hot water either to the DHW vessel tank or to the space heating thermal energy storage (TES) which is further used to satisfy the space heating needs (to be elaborated further).

2.3.3. Electrical system. The electrical system is modelled as grid-connected PV battery system. The PV panel is modelled with the 5-parameter model of De Soto et al., based on temperature dependent diode equivalent circuit [12,13]. The calculations are based on the manufacturer data for the nominal power of the PV panel of 230 Wp with the surface of 1.4 m². In this study, a total amount of 20 PV
panels is applied in order to cover about 90% of the Southside roof area of the building. The PV panels are oriented directly southwards with an inclination angle of 34°. In the model, the power loss due to the conversion of the generated direct current to the alternating current is also accounted for with the constant inverter efficiency of 95%. The electrical energy storage (EES) is modelled as a Li-ion battery which has the charging efficiency of 87.4%, discharging efficiency of 98% and a self-discharge of 3% per month. The operating range of the battery is 80% of its rated capacity.

3. Modelling tools and controlling principle
All the models and simulations are built in the programming language Modelica and software tool Dymola [14]. Most of the used models are parts of the two Modelica open-source libraries: IDEAS [15] and Buildings [16] library. Still, a custom made auxiliary HP electrical heater was used in this study.

On figure 3, a simplified hydraulic scheme of the heating system can be observed. The switch between satisfying either DHW or SH demand causes mainly two actions. At first, the main three way valve located in front of the HP diverts the flow towards one of the circuits while the set point temperature of the HP switches from the value given either by the heating curve or by the DHW set point temperature of 50°C. Since the DHW has priority over the SH demand, the performance switch occurs whenever the DHW bottom tank temperature TBotDHW drops below 40°C and switches back to SH when TBotDHW is above 46°C. The electrical heater contained within the DHW water tank switches on when the top tank temperature TTopDHW drops below 40°C and switches off when TTopDHW is above 42°C. Further, the DHW to the suppliers is provided with the temperature of 40°C achieved by the three way mixing valve utilizing the water from the DHW tank and freshwater.

![Figure 3. A simplified hydraulic scheme of the heating system circuit.](image)

On the SH side, the TES storage depicted in figure 3 is either used as a buffer vessel or as the TES storage if the load shifting strategy is considered in the simulation. In general, the HP is controlled based on the top (TTopTES) and bottom (TBotTES) tank temperatures and the tank set temperature (TSetTES). In the case when the buffer vessel is used, TSetTES is 2°C higher than the supply temperature for space heating (TSup), which is determined by the heating curve. The HP switches on when TTopTES drops below TSetTES and switches off when TBotTES has become higher than TSetTES. To be able to reach the switch-off condition, the HP condenser temperature TSetHP for space heating is set 5°C higher than TSetTES. The TES also contains a 3 kW electrical heating element that activates when TTopTES drops below TSup. The third three way valve is mixing the water from the top of the tank with water that is returned from the underfloor heating system to achieve the TSup provided to the underfloor heating system. The HP has an internal electrical heater of 3 kW that assists the HP on the coldest days, only when the outside temperature is below -5°C.
On the side of the electrical installations, the EES is charged when there is an extensive PV generation of electricity. Last only occurs when the instantaneous renewable energy production is larger than the instantaneous sum of the electrical loads of the HP, electrical heaters, appliances and lightning. The charging of the battery takes place until the battery is fully charged. When the buffer tank is used as TES, as part of the load shifting strategy, the TES is charged by the HP which then changes its water set point temperature to 55°C thus overheating the TES. The TES is charged when there is a persistent overproduction of PV for longer than 10 minutes and the battery is fully charged. In this way, the electrical energy storage is prioritized over the TES.

4. Results

The three case buildings were simulated at the same weather conditions, occupancy behaviour, appliances and DHW demand and with the mismatching space heating energy demand. In the study, the comparison in the potential reach of SS and SC was referenced to the basic case. The basic case implies all three case buildings with the overall referenced electricity demand of 7406.8 kWh (B15), 7769.2 kWh (B30) and 8116.4 kWh (B45). Electrical demand is covered either from the PV generation out of 28 m² of panels or from the grid. Therefore, the basic case considers the installation without the use of TES and EES. In figure 4, the results of the SS and SC for the 3 building cases are presented for varying, economic capacity of the TES and EES. In total, 12 simulations were made for the varying EES and TES capacity of up to 2.5 kWh and 250 l respectively.

![Figure 4](image.png)

**Figure 4.** Self-consumption (left) and self-sufficiency (right) simulation results for the three building energy performance levels.

Figure 4 clearly shows the rise in the SC and SS values with the use of EES and TES. The impact of a small EES is much more significant than the impact of a small TES. In each of the four storages size combinations, the B15 building achieves approximately 1.5% higher SS than the B30 building and approximately 3% higher SS than the B45 building. On the other hand, SC values are much less influenced by the different building energy performances. This means that the absolute self-consumption remains rather constant. The increase in SS is thus the consequence of the reduced reference overall electricity demand due to the reduced space heating demand. SH demand is the highest during the winter and it is often covered by the electricity imported from the grid since the PV generation is lower during the winter season. A lower space heating demand thus results in less grid imported electricity, which translates in a higher SS value.

For the case without EES and TES, SC slightly increases with better building energy performance, meaning that the absolute self-consumption is slightly higher in the case of the higher energy performance of the building. This also means that the building with a lower reference electricity demand thus has a slightly lower grid energy supply need. The main cause is that the HP is sized in accordance with the space heating demand, while it must also cover the DHW heating demand. For the building with a lower space heating demand, the HP has less capacity and must therefore operate at full capacity for longer periods of time to sufficiently heat the DHW tank. This means that the HP load results in a
slightly flatter curve with fewer power peaks. A more constant electricity demand curve results in the better overlap between the demand and generation and thus in slightly higher SC.

5. Conclusion
In this work, self-sufficiency (SS) and self-consumption (SC) was numerically evaluated for the three residential buildings with different energy performance. The buildings were simulated under the same boundary conditions for the space heating and daily hot water (DHW) energy demand. In order to inspect the impact of thermal load shifting and electrical energy storage on the case buildings, a thermal energy storage of 250 l and electrical energy storage of 2.5 kWh were applied. The self-sufficiency results to be 40%, 38.5% and 37% for the buildings with the space heating energy demand of 15 kWh/m²-year, 30 kWh/m²-year and 45 kWh/m²-year respectively for the specific energy demand conditions. The SC values are much less influenced by the building energy performance. One of the reasons is that the electricity demand for powering the space heating system is only a portion of the total electricity demand. In this research, the buildings were set to be DHW energy demand dominated. The results emphasize the importance of the other energy demands of the building with respect to the building energy performance. In addition to the space heating demand, lowering the electricity demand for lighting and appliances and lowering the DHW demand may result in higher overall SS values.

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