IMPACT OF THE INTEGRATION OF VARIOUS HEATING TECHNOLOGIES ON THE ENERGY LOAD PROFILES OF THE BELGIAN RESIDENTIAL BUILDING STOCK

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Abstract

Nowadays, the integration of renewable energy sources leads to the decentralization of energy supply systems. In particular, the increase in solar PV collectors and wind turbines has an important impact on the management of the electricity grid, and especially on its balancing, because of their variability. A possible solution to the increasing balancing needs is the smart modulation of the electrical load.

It appears that buildings can become key systems for smart energy management at the distribution grid level. In Belgium, the residential energy needs for space heating and domestic hot water are mainly met by fuel oil, gas boilers or electricity supplied by the grid. The aim of the present research is to assess the impact of contrasting penetration scenarios of technologies such as heat pumps, micro-CHP units, thermal storage systems, PV and solar thermal collectors on hourly and quarter-hourly gas and electrical load profiles and annual consumptions of residential buildings. The Belgian stock is chosen to illustrate the applied methodology.

The first part of this work consists in the development of validated dynamic simulation tools to predict the electricity and gas consumption of the residential building stock on a quarter-hourly basis. The model is based on a bottom-up approach where the occupants' behavior is depicted by stochastic profiles. Calibration of the model is carried out based on available Belgian synthetic load profiles.

In the second part, the utility of the proposed model is illustrated by defining four scenarios: an electricity-based scenario characterized by an increased use of heat pumps for space heating and domestic hot water, a solar scenario with integration of PV collectors and a gas scenario with micro-CHP units. A fourth scenario that combines all three technologies is also investigated. Their impact on the electricity and gas profiles is estimated.

In a future work, the simulation tools will be further improved to be used for demand side management purposes and the assessment of peak shaving potential at a national scale.

Introduction

Recently, there have been great incentives towards the introduction of renewable energy sources in the energy supply mix. The resulting decentralization of the electricity production systems and variability of the renewable production have an important impact on the management of the electricity grid and leads to increasing balancing needs. It appears that the smart modulation of the electrical load could be a possible solution to cope with these needs, and in particular, buildings could become key systems at the distribution grid level.

Indeed, in Europe, in 2004, buildings consumption accounted for 40% of the total energy demand, among which the residential sector represented a share of over 70% [1]. Since 1993, the International Energy Agency has launched the Demand-Side management Programs [2] which, in terms of building load management, aims to establish strategies to shift the electric demand from peak to off-peak periods through the management of the utilities use. These domestic loads, namely energy consumption for space heating, domestic hot water production and large electrical appliances (dishwasher, clothes drier,...), present an important potential of modulation. The implementation of such strategies should reduce the investments for power grid reinforcement and be economically profitable for end-users.

Several studies have been carried out at the building level, with particular attention given to heat pumps coupled to thermal storages. Arteconi et al. [3] presented a study focusing on the influence of switching off a heat pump coupled to thermal energy storage during peak hours on the occupants' thermal comfort and on the electricity load curve in the UK. The same authors carried out a state of the art of thermal storage systems (TES) for management of electrical load [4] and their coupling for air-conditioning or heating purposes. Usman et al. [5] investigated different strategies of control of all-electric Net-Zero Energy Buildings equipped with heat pumps and photovoltaic collectors with or without thermal storage in order to assess the self-consumption and flexibility potentials. It was shown that with proper control strategy, such system could offer great benefits in terms of supply and demand matching. A different approach was investigated by Baetens and Saelens [6], who presented a study over the impact on the low voltage distribution grid (transformer overload, voltage quality,…) of the integration of heat pumps and PV collectors in a residential neighborhood. Twenty-one feeder configurations were investigated in order to assess the penetration levels from which such problems would occur and demand side management techniques would be required.

To the best knowledge of the authors, very few studies have considered the investigation of load management potential in residential buildings at the national scale. The aim of the present research is to assess the impact of contrasting penetration scenarios of different HVAC technologies (heat pumps and µ-CHP) coupled to themal storage systems and PV collectors on daily load profiles and annual consumptions of residential buildings. The Belgian stock is chosen to illustrate the applied methodology. In a future work, the developed tool will be used for demand side management purposes at a national scale.

Methodology

The methodology proposed in this study is based on a so-called "forward bottom-up" approach. The first part of the work consists in the development of a simulation tool able to simulate the current Belgian housing stock energy use. In the second part, several scenarios of HVAC technology penetration are considered.

Forward bottom-up approach

The "forward bottom-up" approach consists in the modeling of end-use consumptions based on a physical description of the components and envelope of a building and in its extrapolation to larger sets of buildings [7]. First, a tree-structure characterizing the Belgian residential building stock in terms of buildings age, size, insulation level and energy vectors was established. This step is further detailed in a previous work [8]. A set of 992 typical buildings was described and their respective share in the current building stock was assessed (Figure 1).

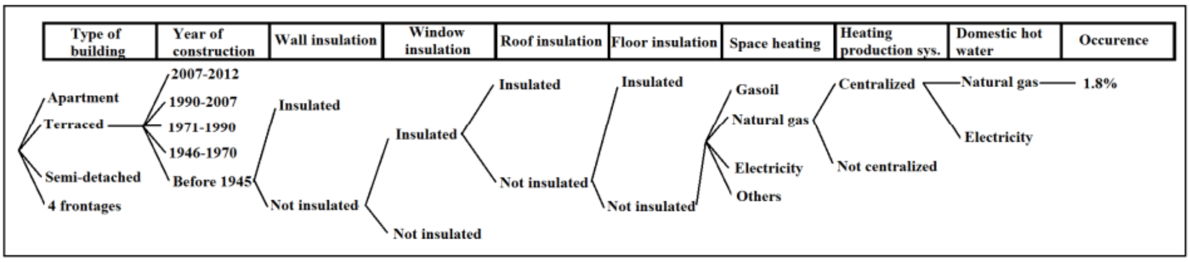

Figure 1: Building stock tree-structure

Then, a quasi steady-state building model based on simple normative methods (ISO13790 simple dynamic hourly building model [9]) was implemented. The validity of the model for the prediction of the heating load was checked using the BESTEST procedure [10]. The developed model provides the energy consumption associated to space-heating and domestic hot water needs. Internal loads related to occupancy, use of electrical appliances and lighting are modeled based on stochastic profiles further detailed in a previous paper [8]. Energy load profiles are generated for each type of building by the sub-mentioned model and aggregated with their respective share in the tree structure in order to obtain electricity and gas profiles per average dwelling.

The latest are then compared to available Synthetic Load Profiles (SLP) for Belgian residential end-users [11]. These synthetic profiles give the real aggregated consumption per average dwelling of a set of 2500 dwellings. They are chosen statistically to represent the Belgian residential consumers, and data are provided on a 1/4 hourly base for electricity and hourly base for gas. Good agreement was found in terms of annual consumption (Table 1) and average daily profiles (Figure 2) for the reference year chosen (2010). However, the 1/4 hourly reproduction remains uncertain for certain days, especially for electricity use since it depends on the highly unpredictable occupants' behavior.

Table 1: Annual consumption - comparison between target consumption and simulation results for 2010

	Annual electricity consumption [kWh/dwelling]	Annual gas consumption [MWh/dwelling]
Target consumption	4400	23
Simulation results	4275	20
Relative deviation [%]	3	12

Finally, the evolution of the building stock is investigated until 2030. The tree structure is consequently modified to include demolition, construction and envelope retrofit options represented by yearly rates between 2010 and 2030. With respective rates of 0.075, 0.9 and 1.3%, the annual consumptions obtained in 2030 are 17.8 MWh/dwelling for gas and 3.55 MWh/dwelling for electricity. These results are mentioned as part of the “Business as Usual” scenario (BAU scenario) underneath.

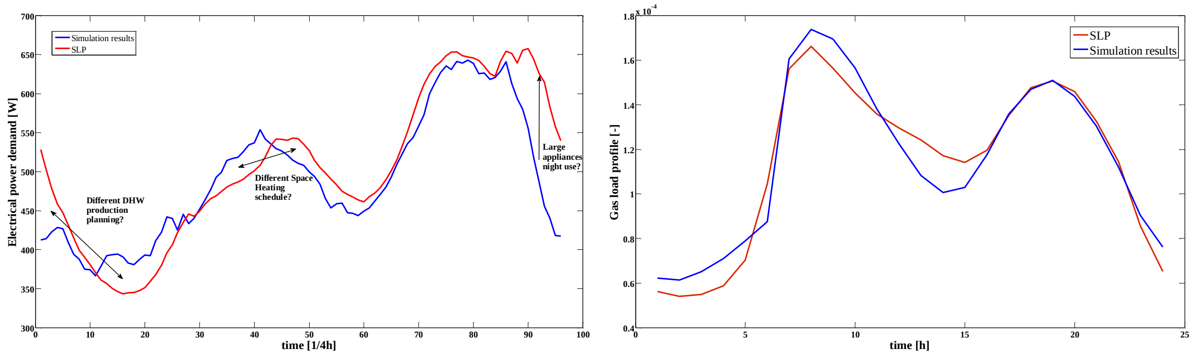

Figure 2: Electricity (left) and gas (right) profiles per average dwelling for an average day in 2010 - comparison between Synthetic Load Profiles (SLP) and simulation results.

Contrasting scenarios for 2030 - models

Three contrasting scenarios and their combination are investigated in this work:

- heat pump scenario,
- µ-CHP scenario,
- PV collectors scenario.

Heat pump scenario

The heat pump scenario is characterized by an increased use of heat pumps for space heating and domestic hot water production. The heat pumps are modeled using an empirical model inspired from “Conso Clim” model [12] and fitted to performance maps provided by manufacturers. The model predicts the performances of heat pumps via three different polynomials. The coefficient of performance (COP) and the heating capacity at full load are predicted as a function the outside air temperature at the supply of the evaporator and the temperature of the heating fluid at the outlet of the condenser.

The criteria to determine if a heat pump can be installed in a specific building is based on a stationary balance taking into account the building air change rate and the space heating and domestic hot water loads. Considering residential heat pumps currently available on the market, the maximum rating power is 8.6 kW under -10°C outdoor air temperature, and must correspond to 80% of the load in such conditions. A gas backup boiler is used in a bivalent parallel configuration. The priority of the production is always given to domestic hot water and the backup is used for space heating when a simultaneous demand occurs. For each type of houses, a choice of a particular technology (low, medium and high temperature) was done based on the overall heat transfer coefficient of the building (Table 2).

Table 2: Heat pump technology selection

Overall building U value [W/m²K]	**Heat pump technology (T_{evap} -T_{cond})**
< 0.3	Low temperature (7-35)
0.3 - 0.8	Medium temperature (7-45)
> 0.8	High temperature (7-65)

µ-CHP scenario

The µ-CHP units chosen comprises Stirling engine, a gas back up boiler and a storage system (water tank) and its architecture is represented in Figure 3 (left). As described by Lombardi et al. [13], the system is controlled based on the water tank temperature as explained in Figure 3 (right). The units are characterized by 1 kW of electricity generation, 5.7 kW of heat generation and a 850 liters storage tank. Start and stop losses ([14] and [15]) are taken into account by dividing arbitrarily the year in five equal periods with efficiencies of 96%, 87%, 78%, 87% and 96% respectively.

Two criteria have been used to determine if a μ-CHP could be installed in a specific building:

- μ- CHP could only be installed in buildings supplied by gas.
- economic criterion: the use of a μ-CHP of 5.7 kW_{th} is cost effective only if it works more than 4000 hours per year [16].

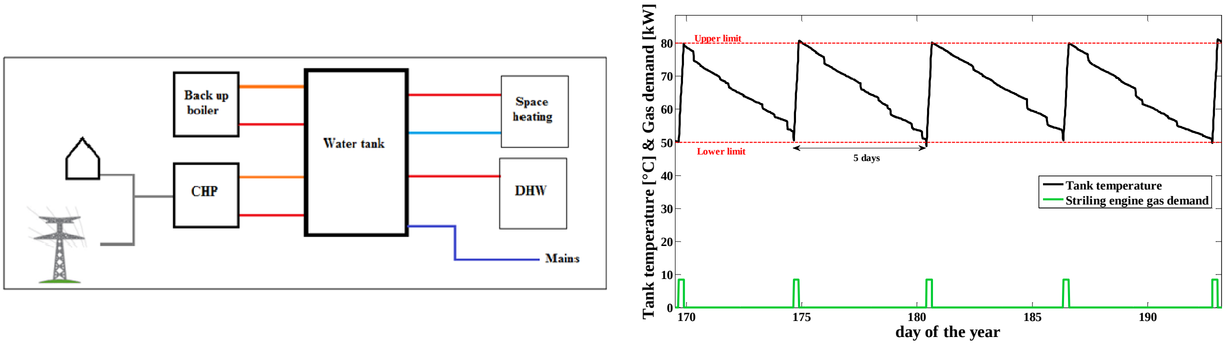

Figure 3: Schematic representation of the μ-CHP units architecture and working principle (left) - tank temperature evolution (right)

Solar photovoltaic scenario

For PV collectors, the most widespread technology in Belgium so far is first generation collectors made of poly- or mono-crystal silicon [17]. Common simulation models are 5 parameters models function of the cell temperature and the total irradiance [18]. This model is part of the TRNSYS library (type 194), and was used to generate yearly performance for weather conditions in Uccle. The simulation results are shown in Figure 4 (left). Regressions were applied to these performance curves, and the equations obtained were used in the present simulations. Power generated are shown in Figure 4 (right) for winter and summer at 35° tilt angle and south and east orientations.

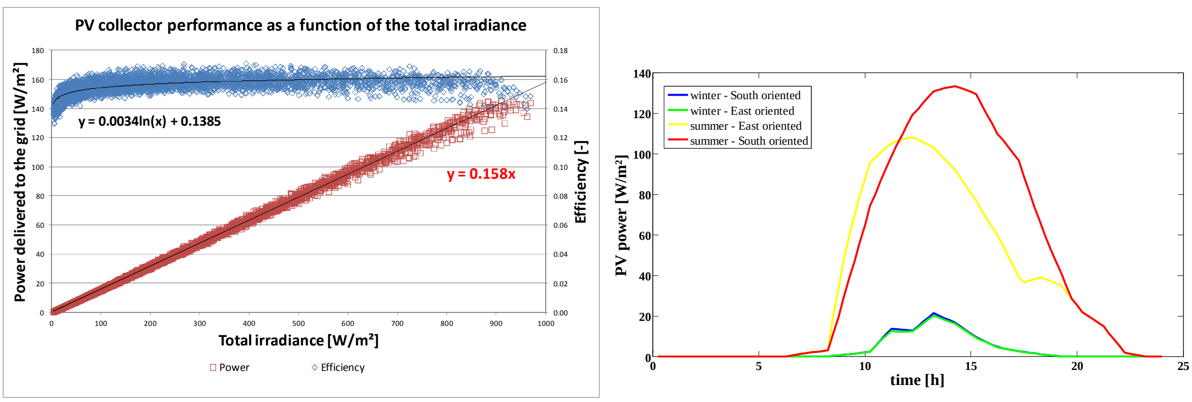

Figure 4: Power delivered to the grid and global efficiency of a 1m² PV collector as a function of the total irradiance (left) - power generated for typical winter and summer days - 35° tilt angle - south and east orientations (right).

Results and discussion

Three contrasting scenarios of penetration of different technology have been implemented, and the results are summarized in this section. It should be noted that no load shifting strategies have been implemented yet.

Heat pump scenario

In the heat pump scenario, the total penetration rate in 2030 was set to the maximum value possible, estimated to 54% with the criteria mentioned above. The resulting reduction in final energy consumption per average dwelling, compard to the BAU scenario, reaches only 15% (-3 MWh/dwelling). The relatively low reduction observed can be explained by the fact that the 54% of dwellings equipped with heat pumps represent only 25% of the total consumption of non-electrical energy vectors in the regular BAU scenario. The seasonal COP is of around 2.75 for space heating and 2.6 for domestic hot water production. A 14% drop in CO2 emissions is observed.

The electricity share in the energy mix increases by 10%, and the average consumption rises particularly in the winter and mid-season (Figure 5). As illustrated in Figure 6, the peak demand with 54% penetration of heat pumps reaches up to 186% in average of the regular demand (BAU) for the month of January and between 20 to 30% in the mid-season. This is susceptible to prompt important constraints on the electricity grid. However, the shape of the load profile remains similar, except during the first 24 ¼ hours of the day, for which the planning of the domestic hot water preparation differs.

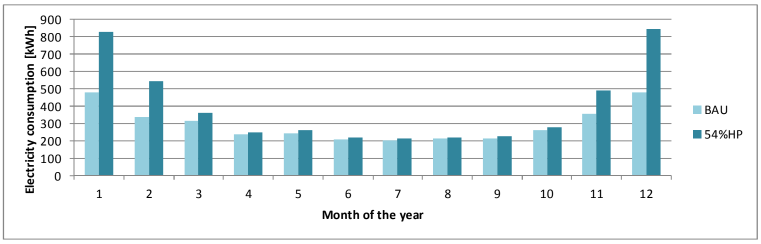

Figure 5: Electricity consumption per month per average dwelling for BAU and heat pumps scenarios.

µ-CHP scenario

Given the economic criteria for the use of a µ-CHP presented earlier, the maximum penetration rate by 2030 is 14.4 %. Compared to the BAU scenario, the energy consumption per average dwelling is modified as follows:

- the electricity consumption, defined as the instantaneous difference between the consumption of the dwelling and the power produced by the µ-CHP, decreases by 17%,
- the electricity production surplus, defined as the share of electricity not instantaneously self-consumed in the dwelling, reaches 186 kWh per dwelling, i.e. 24% of the electricity produced by the µ-CHP unit.
- the gas consumption increases by 11%.

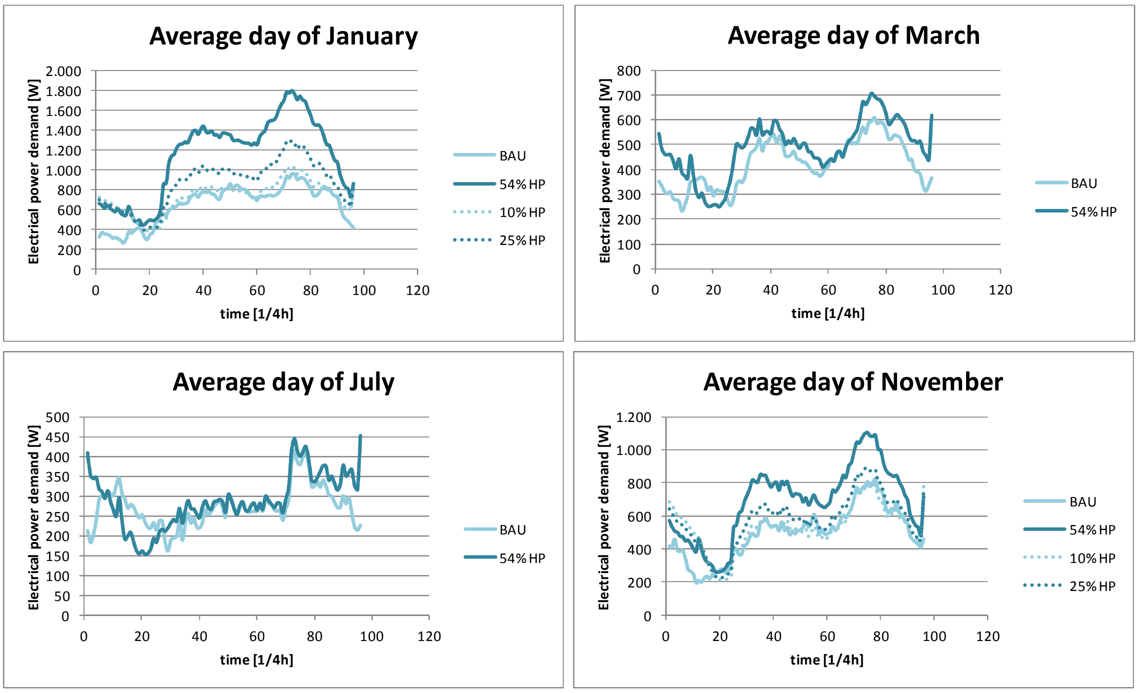

Figure 6 : Electricity demand per average dwelling for an average day per month for BAU and different heat pumps penetration scenarios.

Therefore, if the production surplus is not taken into account, the total energy consumption per average dwelling increases by 2% and reaches 23.78 MWh/dwelling. The resulting increase is due to the larger gas consumption caused by both the decrease in performance of the CHP unit in the mid-season and in the summer (Figure 7 - bottom) and the increase in the storage tank ambient losses because of its size and higher temperature set points. The electrical power production is thus more constant during the winter, and negligible in the summer (Figure 7 - top). Indeed, in the summer, the µ-CHP only starts in order to reheat the tank for domestic hot water use, which occurs around once a week.

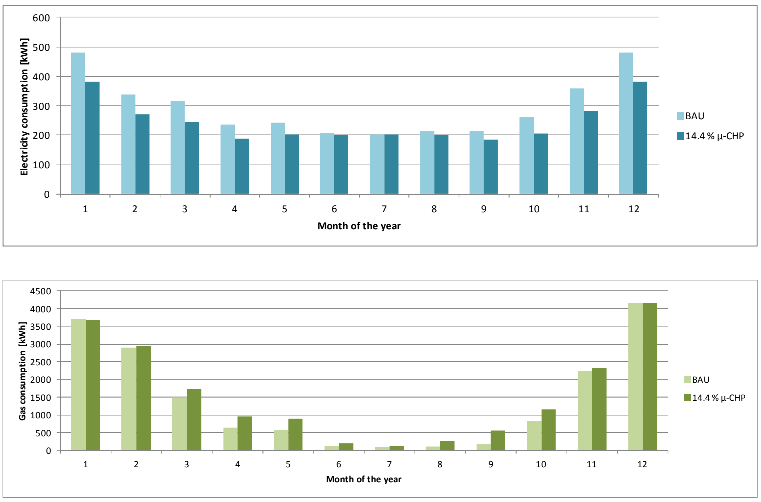

Figure 7 : Comparison of electricity (top) and gas (bottom)consumption per average dwelling in 2030 with integration of 14.4% µ-CHP (left) - Tank temperature evolution and Stirling engine gas demand for summer period (right)

If the shape of the electricity demand profiles remains similar, the gas profiles, however, presents a reduction in the morning peak demand. This is due to the presence of a storage tank, which confers a larger inertia to the system for space heating, hence the diminution visible in Figure 8.

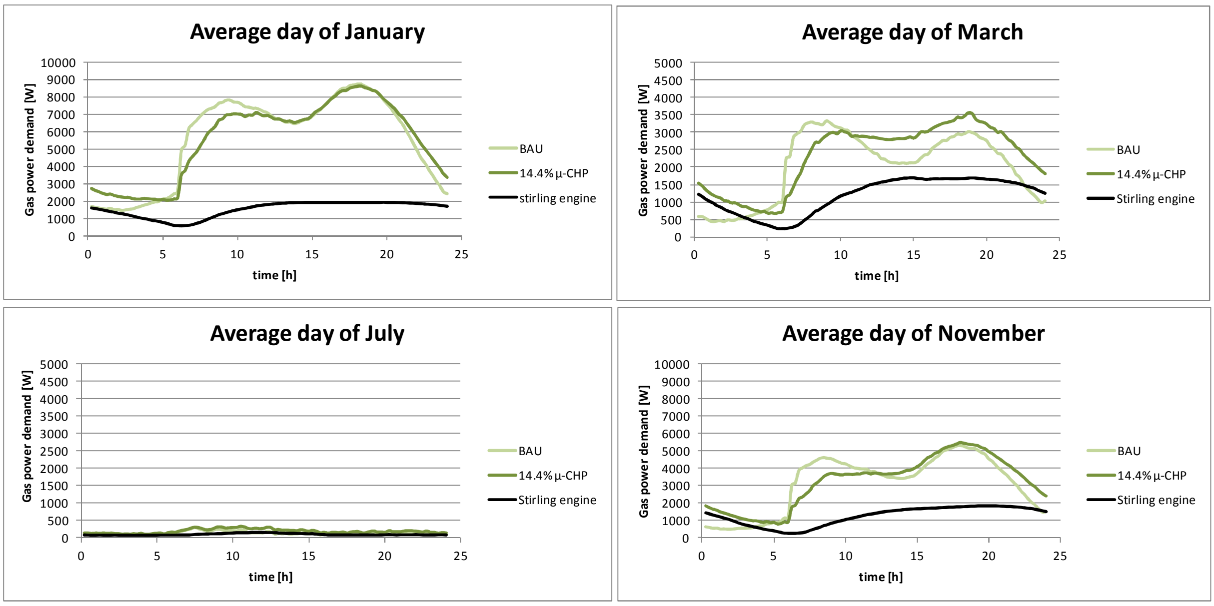

Figure 8 : Gas demand per average dwelling for an average day per month for BAU and µ-CHP secnarios.

PV collectors scenario

Currently in Belgium, 6.5% of the dwellings are equipped with PV collectors[19]. Scenarios with respectively 10, 25 and 50 percent of the dwellings equipped with PV collectors were considered. The installed surface was determined to 34 m², based on the average annual electricity consumption of 3550 kWh per dwelling. The proportions of orientations were arbitrarily set to 25 and 75 % respectively for east and south, and the slope assumed to be the optimal 35°.

The PV production was withdrawn from the instantaneous electrical consumption, and considered as surplus when exceeding the demand. The production surplus increases faster than the demand reduction with the number of installed collectors. Therefore, more electricity is unused simultaneously by the residential sector and released on the grid, with important consequences on its balancing. Moreover, Figure 9 shows that most of the PV power is produced in the middle of the day, whereas the peak consumption occurs at night. In the winter, the PV production is low and a weak proportion of the demand can be satisfied. It can be noted that there may exist better orientations to optimize the winter production and the simultaneity with the demand, even though the total annual production may be lower.

Combined scenario

In the combined scenario, the following penetration rates are chose:

- 25% heat pumps,
- 10% µ-CHP,
- 25% PV collectors.

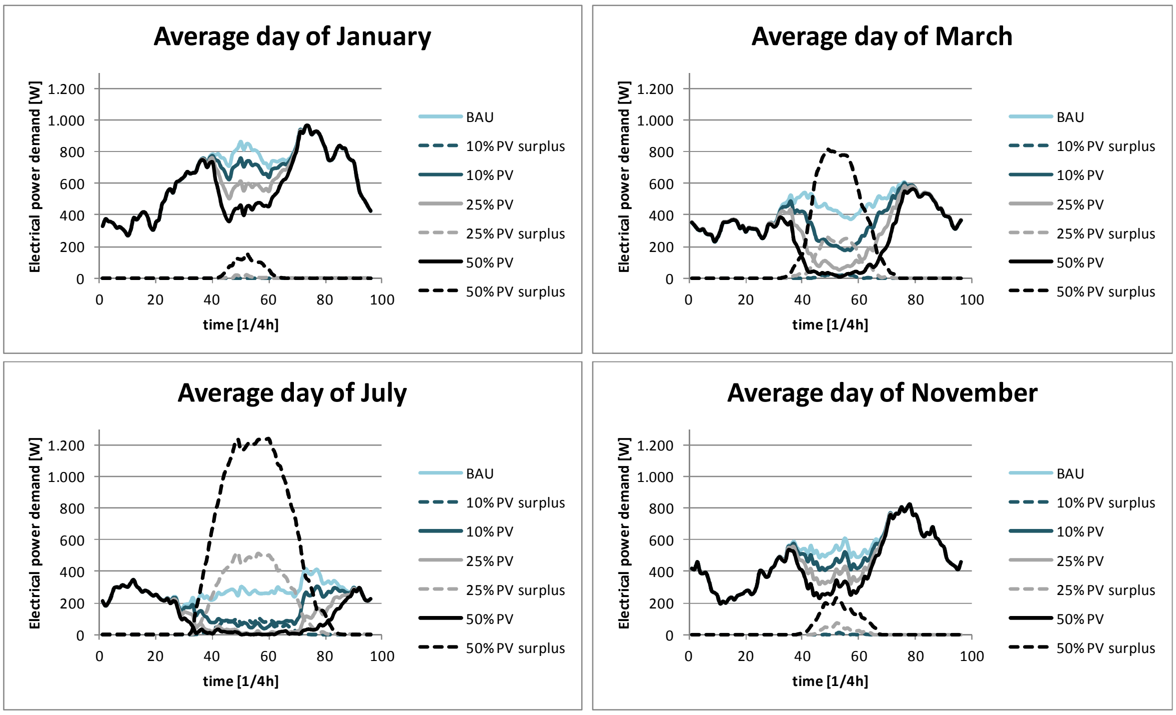

Figure 9: Electricity load profiles per average day per month for different penetration rate of PV collectors.

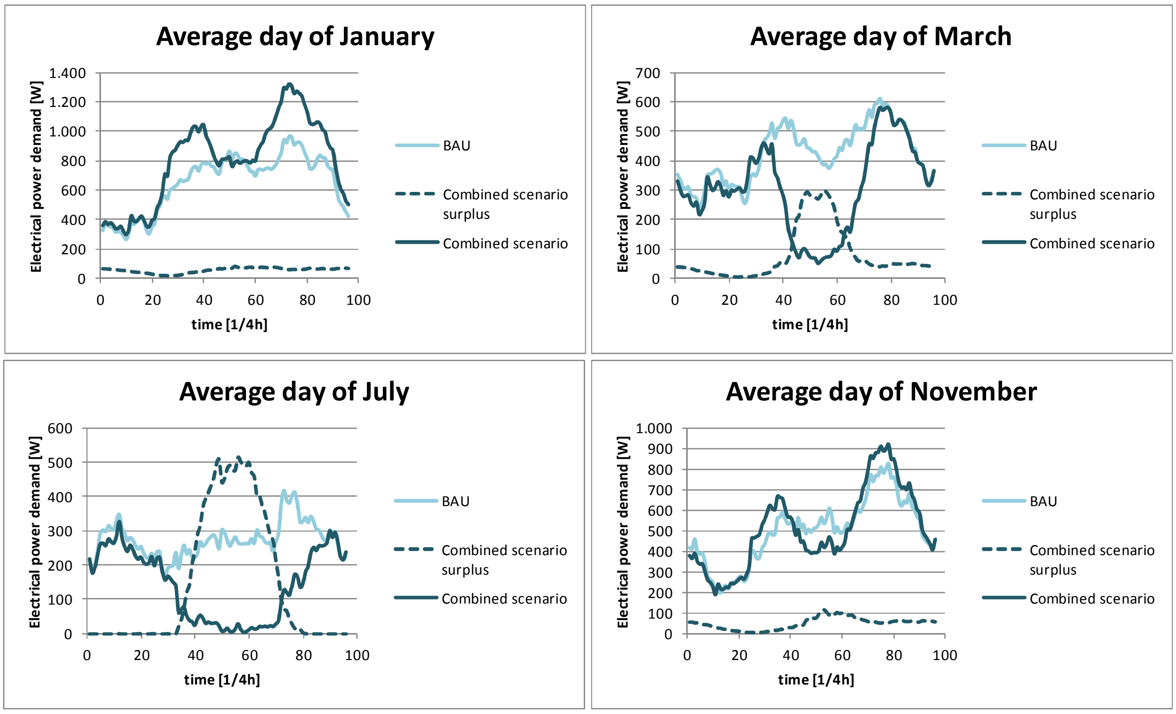

Figure 10: Electricity load profiles per average day per month for the combined scenario (25% heat pumps, 10% μ-CHP and 25% PV collectors).

The energy consumption per average dwelling is reduced by 9% compared to the BAU scenario and reaches 19.5 MWh. The electricity and gas consumptions are reduced by 13% and 6% respectively. The electricity load profiles are modified as shown in Figure 10. For the average day of January, without load planning strategies, the electricity produced by the PV collectors and the μ-CHP doesn't fully counterbalance the important rise in peak consumption caused by the introduction of heat pumps.

Conclusions

A bottom-up approach of the Belgian residential building stock has been carried out. Energy load profiles have been derived for the reference year 2010. Evolution of the building stock until 2030 following the current trends (BAU scenario) has been implemented, and different scenarios of penetration of technologies were investigated. For the heat pump scenario, the analysis allows drawing an important conclusion: if by 2030 most dwellings replace their traditional boilers by heat pumps without changing the time of use planning of the system, benefits will be retrieved at the end-users' scale, but at a macro-scale, with the assumptions made in this work, the gain is not proportional to the penetration rate, and the additional constraints for the electricity grid are significant. The latest should be further assessed.

For the µ-CHP scenario, using a common storage tank for both domestic hot water and space heating causes it to be extremely oversized in the summer, and limits retrievable benefits. On the other hand, the electricity production in the winter could be easily shifted to meet the peak demand.

For the introduction of PV collectors, it seems that the south orientation is not optimal to meet the winter demand, and overproduction occurs in the summer. A compromise should be investigated between annual production and simultaneity of production with peak demand.

Future work will be devoted to the establishment of modulation strategies of the load profiles to facilitate the balancing with fluctuating renewable energy sources.

Acknowledgements

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