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Smart grid energy flexible buildings through the use of heat pumps and building thermal mass as energy storage in the Belgian context

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ABSTRACT

The management of electricity grids requires the supply and demand of electricity to be in balance at any point in time. To this end, electricity suppliers have to nominate their electricity bids on the day-ahead electricity market so that the forecast supply and demand are in balance. One way to reduce the cost of electricity supply is to minimize the procurement costs of electricity by shifting flexible loads from peak to off-peak hours. This can be done by offering consumers time-of-use variable electricity tariffs as an incentive to shift their demand. This study provides typologies of smart grid energy ready buildings within the context of the Belgian residential building stock and the Belgian day-ahead electricity market. Typical new residential buildings are considered, equipped with air-to-water heat pumps that supply either radiators or a floor heating system. Five heating control strategies are compared in terms of thermal comfort, energy use, cost, and flexibility. Flexibility is quantified in terms of load volumes shifted and in terms of procurement costs avoided. The first three are rule-based control strategies, whereas the last two are a smart grid-oriented optimal predictive control strategy responding to a time-varying electricity price profile. The results show that the smart grid control strategies allow reduction of procurement costs by up to 15% and the consumer's cost by 13%. The flexibility, defined in terms of loads volume shifted, is increased by 3% to 14% with the same thermal comfort. The impact of building insulation level and thermal mass is also evaluated. The flexibility for load shifting is higher when shifting from a low-energy (average U-value of 0.458 W/m^{2}K) to a very-low-energy house (average U-value of 0.152 W/m^{2}K).

INTRODUCTION

In the context of integration of renewable energy sources, energy supply systems tend to become decentralized. The variability of these sources has a significant impact on the management of the electricity grid. To ensure grid balancing, several levels of action take place at different times. On the day-ahead electricity market, electricity suppliers have to nominate their electricity bids such that the forecast supply and demand are in balance. At the intraday-level, mismatches between the forecast and actual supply and demand can be compensated by using reserve capacity or by real-time demand response.

Smart grid energy ready buildings can help minimize the cost of electricity supply at the distribution grid level in three different ways. First, a smart meter allows gathering information for better prediction of electricity demand profiles of local consumers. Second, the electrical load of such buildings can be shifted based on time-of-use (ToU) variable electricity tariffs (Newsham and Bowker 2010; Merciadri et al. 2014). Finally, imbalance costs resulting from mismatches between forecasted supply and demand can be tackled by real-time demand response (Conejo et al. 2010).

In the frame of this article, the flexibility of the heating load associated to residential buildings is investigated through the use of heat pumps. From an electricity grid system operator point of view, such loads are identified as thermostatically controlled loads and represent a large potential for robust local reserve and reduce the need for new transmission lines (Kamgarpour et al. 2013). Load modulation can be initiated in response to different triggers: signals from the grid, such as power exchange (Miara et al. 2014) and voltage level (De Coninck et al. 2014), or price signals (Halvgaard et al. 2012).

Different control strategies of HVAC equipment can be implemented and coupled with storage systems. Two storage options are commonly investigated: building thermal mass (Braun 1990) or water tanks (Miara et al. 2014). As emphasized by Braun (1990), conventional control strategies do not consider the use for thermal storage in the building structure as a means for operating cost-reduction potential. However, optimal control of building thermal mass storage allows for significant energy cost reduction through load shifting and peak shaving. Embedded model predictive control has been identified as an appropriate methodology for such optimization problems in several studies. For example, Ma et al. (2012) used model predictive control (MPC) to optimize building thermal comfort while decreasing peak demand and reducing total energy costs in the context of energy-efficient buildings equipped with thermal storage. Updated predictions of weather, occupancy, renewable energy availability, and energy price signals were included. As pointed out by Bruninx et al. (2013), attention should be given to the modeling of the additional heat storage losses caused by load shifting.

In this article, the impact of building thermal mass storage on the electricity consumption is evaluated for typical new residential buildings in Belgium. These buildings are equipped with air-to-water heat pumps and use either radiators or a floor heating system. Belgium's climate is characterized by a yearly average outdoor temperature equal to 10°C. The average outdoor temperature during the heating season equals 6.5°C, and the length of the heating season, defined as the number of days with outdoor temperature lower than 15°C, is 242 days per year.

In the first part of this work, three rule-based control (RBC) strategies are considered:

(1) a clock-driven intermittent heating strategy,

(2) an optimized intermittent heating strategy taking into account the storage in the thermal mass of the envelope, and

(3) a heating strategy using the additional storage capacity of a water tank.

The choice of intermittent heating can be motivated by the trend to adapt heating schedules to occupancy patterns. In Belgium, day/night occupancy patterns are quite widespread (Aerts et al. 2014).

A cost-weighted energy consumption function is considered. In the second part of the article, an optimal predictive control (OPC) strategy for price-responsive heat pumps is implemented in the context of the Belgian day-ahead electricity market. The flexibility of the systems under study is quantified in terms of load volumes shifted and in terms of procurement costs avoided.

CONTEXT AND CASE STUDIES

Context—the Belgian electricity market

Since 2007, the electricity market has been fully liberalized. With the opening of the European electricity market, Belpex, a power exchange for short-term trading, has been launched and provides the market with transparent prices. One of its segments focuses on day-ahead trading and is called the Belpex Day-Ahead Market. In 2012, the installed capacity for electricity production in Belgium was composed of about 40% gas, 35% nuclear, 9% hydropower, 6% liquid and solid fuels, and 10% waste and renewables. Nuclear plants are used for the base load, and gas power plants or gas turbines ensure peak demand (called marginal power plants). The volatility of the day-ahead spot market prices depends directly on these marginal plants.

Different tariff structures are already implemented for residential customers, mostly flat and day–night (DN) pricing. Historically, the DN pricing scheme has been introduced as incentive to promote energy consumption during off-peak hours. In this article, a third novel pricing scheme is introduced: the perfect prediction (PP) tariff, reflecting the Belpex day-ahead spot market clearing prices. The three tariffs are illustrated in Figure 1. Given the energy mix for electricity production in place in Belgium, the spot market price daily profile is on average close to the DN pricing.

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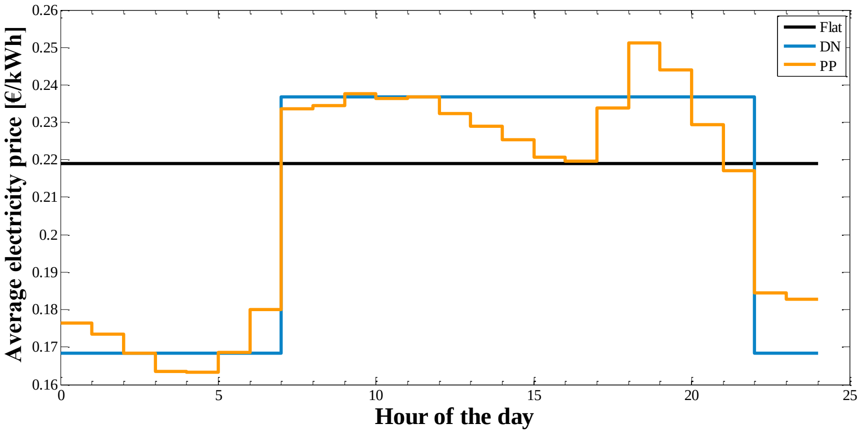


Fig. 1. *Tariff structure for residential customers: flat, day/night (DN) and perfect prediction (PP) tariffs.*

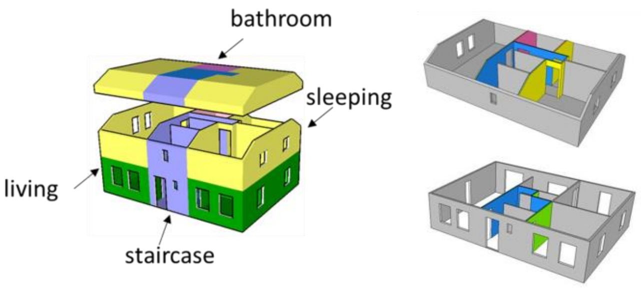


Fig. 2. *Perspective view of the test house heated volume shared into four zones (left) and layout of the ground and first floors showing zone separating walls.*

The 2020 European climate and energy package translated to Belgium aims at introducing up to 13% renewable energy sources. This progressive increase in renewable energy sources for electricity production brings additional challenges for the management of the electricity grid. Demand response programs are investigated as one possibility to reduce grid reinforcement needs and investment costs.

Test case study

A typical freestanding new residential building is considered with a total heated volume of 457 m^3 (Figure 2). It is divided into four zones: a living zone, a staircase, a sleeping zone, and a bathroom. This typical geometry is used with a concrete structure. Vertical walls are composed of 20cm hollow concrete blocks, a variable thickness of rigid insulation panels, and brick as a finishing material for the external façade. The ground floor and the upper floor are made of precast concrete, while the roof is a wooden insulated structure. Three levels of insulation and air tightness are considered:

(1) K45 corresponds to an average U-value of 0.458 W/m^2K and is associated with n_{50} = 6 air change rate (ACR),

(2) K30 corresponds to an average U-value of 0.305 W/m^2K and is associated with n_{50} = 3 ACH, and

(3) K15 corresponds to an average U-value of 0.152 W/m^2K and n_{50} = 0.6 ACH.

The K45 level was the Belgian standards for newly built houses before 2014. The K30 level corresponds to the improved test case, close to the new standard. Finally, K15 corresponds to the passive house standard. The site is considered as wind half-sheltered. Most houses in Belgium have a concrete structure. The external walls of new built houses are generally provided with external insulation.

The heat production system is an air-to-water heat pump connected to radiators in the different zones, except in the living zone where it can be connected either to radiators or to a heating floor.

METHODOLOGY

Building and heat pump models

Two types of models are presented in this section: a detailed dynamic simulation model and simplified gray-box model. In the detailed dynamic model of the building, both external and internal walls are modeled through a 2R-1C network, as illustrated in Figure 3 (left), with R as the wall thermal resistance and C the wall capacitance. Two additional parameters, φ and θ, are introduced and define, respectively, the proportion of the wall capacity accessed by a 24-h time period outdoor temperature sinusoidal oscillation and the position of that capacity in the wall. They are calibrated to fit the real and imaginary parts associated to the wall admittance. Windows and doors are assumed to behave as purely resistive components. Infiltration is computed through a simplified model taking into account wind pressure, buoyancy effects and transfer between zones (Masy and André 2012).

The building is equipped with an air-to-water heat pump. A simplified empirical model of the heat pump based on the ConsoClim method (Bolher et al. 1999) is calibrated based on manufacturer data. The nominal coefficient of performance (COP) is equal to 3.95 for the following nominal conditions: outdoor temperature of 7°C and condenser water exhaust temperature of 35°C. The model allows calculating the available heat power from the condenser, the electric power consumed by the compressor, and the COP at full load and part load as functions of the outdoor temperature and condenser water exhaust temperature. The nominal heat power of the condenser equals 9.3 kW for the highly insulated house (K15 average U-value of 0.152 W/m^{2}K), 11.5 kW for the middle insulated house (K30 average U-value of 0.305 W/m^{2}K), and 13.8 kW for the less insulated house (K45 average U-value of 0.458 W/m^{2}K).

Ventilation is performed through a dual\-flow system provided with a central recovery heat exchanger for which effectiveness is considered constant and imposed to 80%. The supply airflow is 171 m^3/h for the living zone and 144 m^3/h for the sleeping zone. The extracted air flows are 78 m^3/h from the living zone, 50 m^3/h from the bathroom, and 187 m^3/h from the staircase.

A traditional day/night occupancy profile is considered for ordinary days:

- the living zone is occupied from 7:00 a.m. to 10:00 p.m.,
- the sleeping zone is occupied from 10:00 p.m. to 7:00 a.m. on ordinary days and from 11:00 p.m. to 8:00 a.m. on weekends,
- the bathroom is occupied from 6:00 a.m. to 7:00 a.m. and from 8:00 p.m. to 10:00 p.m. on ordinary days and from 7:00 a.m. to 8:00 a.m. and from 9:00 p.m. to 11:00 p.m. on weekends, and
- the staircase is never considered occupied.

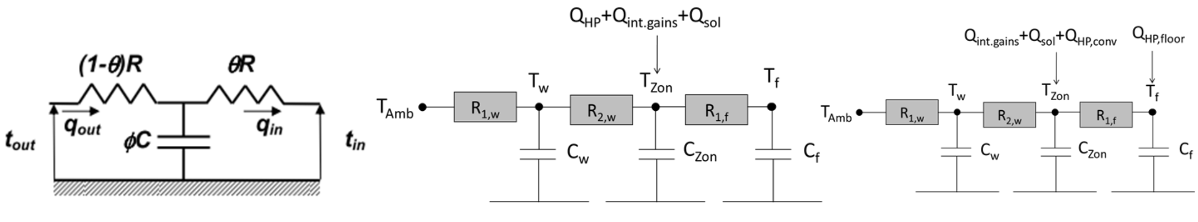


Fig. 3. *Capacitive wall representation, 2R-1C network (left) and gray-box model representation for a house equipped with radiators only (center) and with radiators and a floor heating system (right).*

Installed power of 6 W/m^2 is considered for lighting. It is gradually operated when the external illuminance measured on a horizontal plane decreases from 12,000 to 800 lux, i.e., from 120 to 8 W/m^2 of external global solar intensity measured on a horizontal plane.

By-pass control of the heat recovery exchanger as well as window opening for free cooling are both performed to avoid an overestimation of the heating storage potential in the building envelope thermal mass. Both strategies are applied as soon as the indoor temperature exceeds the heating set-point by 2 K, provided the outdoor air temperature is higher than 16°C.

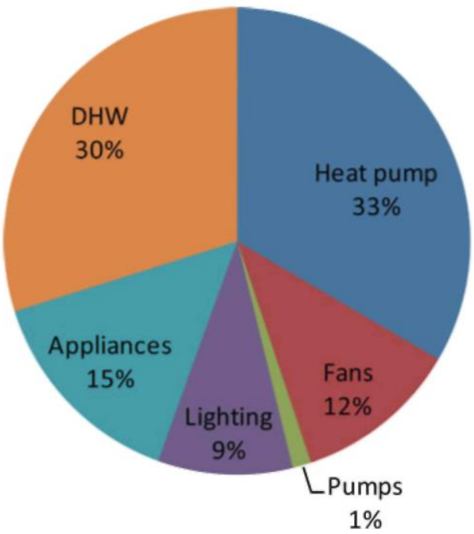
This detailed model is used as simulation tool for implementation of the RBC strategies and as an emulator in the feedback loop the optimal control strategies presented in the section entitled "Control Strategies and Definition of Flexibility."

A simplified gray-box model is needed for the OPC strategies ("Control Strategies and Definition of Flexibility" section) to speed up calculation time. The model structure is illustrated in Figure 3 (right), where Cz_{on}, C_w, and C_f are, respectively, the zone, wall, and floor thermal mass capacities; $R_{1,W}$ and $R_{2,W}$ are the wall thermal resistances; $R_{1,f}$ is the thermal resistance between the internal mass and the zone; and T_{Amb}, T_{Zon}, T_w, and T_f, respectively, are the outdoor air temperature, zone temperature, wall mass temperature node, and internal mass temperature. The convective heat gains are composed of the solar heat gains (Q_{sol}), the internal heat gains $(Q_{int.gains})$, and the convective share of thermal energy provided by the heat production system $(Q_{HP}$ or $Q_{HP,conv})$· $Q_{HPfloor}$ represents the share of thermal energy provided by the heat production system supplied to the heating floor. All parameters are identified by minimizing the root mean square error (RMSE) between the zone temperature predicted by the detailed model and the gray-box model. The minimum RMSE is inferior to 0.41°C for a year training period.

Simulation parameters and breakdown of electricity use

Simulations are performed over a whole year on a quarter-hourly basis. Weather data correspond to climatic conditions for the year 2012. Figure 4 shows the results corresponding to a reference case: insulation level K45, external insulation, air tightness n_{50} = 6 ACH, continuous occupancy, radiator space heating with intermittent control, and domestic hot water heating through electric resistance.

Predicted percentage of dissatisfied (PPD) values based on ISO 7730 (ISO 1995) are also computed to ensure that that the internal comfort is maintained, taking into account the wall surface temperature and indoor air temperature.



	kWh/yr	kWh/rm .yr
Heat pump	3813	26
Fans	1304	9
Pumps	147	1
Lighting	1065	7
Appliances	1669	11
DHW	3405	23
Total	11403	78

Fig. 4. *Breakdown of electricity consumption for the test case study with reference conditions.*

Control strategies and definition of flexibility

Five heating systems control strategies are considered.

• RBC 1 is an intermittent heating strategy, where heating temperature set-points in the whole house are only maintained when the living zone is occupied. The heating temperature set-points are equal to 21°C in the different zones, except in the bathroom where the set-point equals 24° C; otherwise, the set-points are 18°C in the whole house. The intermittent heating strategy is optimized to reach the indoor temperature set-point at the beginning of occupancy in the living zone. The time required to cover the building heat losses and to load its thermal mass is continuously evaluated during the night set-back period, taking into account the influence of the outdoor temperature on the heat pump performance.

• RBC 2 is a continuous heating strategy with a constant indoor temperature set-point of 21°C in all the zones, except in the bathroom where the set-point equals 24°C.

• RBC 3 is an intermittent heating strategy with an additional water tank. The intermittent heating strategy is considered, and a water storage tank is added in parallel to the system to store energy during night set-back periods and release it during daytime occupancy. The tank volume is 1000 L; it is

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assumed to be homogenously mixed. The heat pump condenser exhaust temperature is varying and maintained 5°C higher than the tank water temperature, with a maximum value equal to 55°C for the radiator heating system and 45°C for the floor heating system. The tank is charged during the night when the electricity price is low, from 12:00 p.m. until the restart of the heating system. The heat is released during daytime when electricity price is high, from 10:00 a.m. to 12:00 p.m.

• OPC 1 is a smart grid control strategy with continuous heating. Heat pump operation is optimized by means of model predictive control for two different tariff structures, a DN electricity tariff and a ToU electricity price based the actual spot market price in Belgium for the day-ahead electricity market (Belpex Day-Ahead Market). The OPC uses a simplified representation of the building dynamics (gray-box model) with a feedback loop from the detailed emulator (Figure 5), introducing a correction for the possible model mismatch between the simplified model and the emulator. Perfect weather predictions are assumed. A continuous heating strategy where the zone temperature remains between 20°C and 22°C is implemented.

• OPC 2 is a smart grid control strategy with intermittent heating. As for OPC 1, heat pump operation is optimized by means of model predictive control for two different tariff structures, namely a DN electricity tariff and a ToU electricity price for the Belpex Day-Ahead Market. The difference resides in the implementation of an intermittent heating strategy for which the zone temperature is constrained to remain between 20°C and 22°C only between 8:00 a.m. and 12:00 a.m.

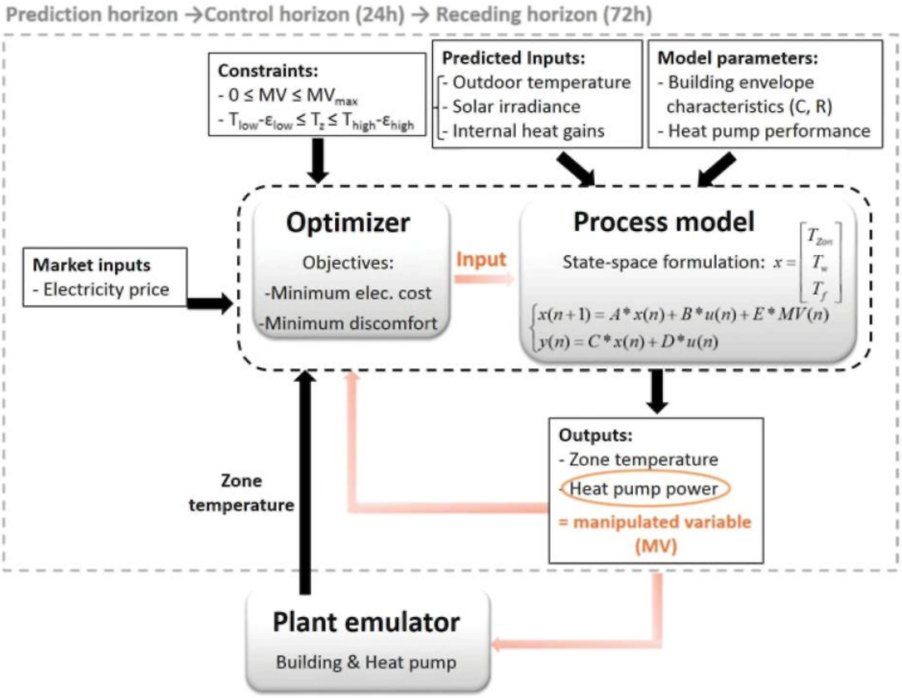

Fig. 5. *Smart-grid control strategy scheme*.

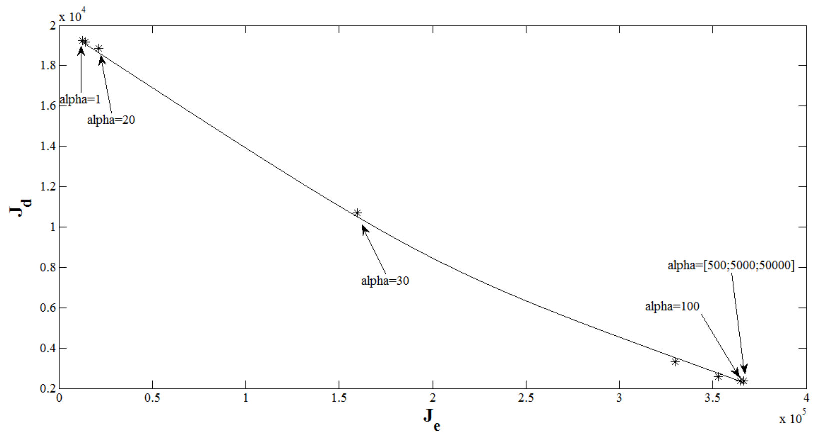

Fig. 6. *Pareto curve for bi-objective function; J_e is the price objective and J_d the comfort objective.*

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First approach—traditional RBC methods and definition of the flexibility

Flexibility of the building space heating demand characterizes its ability to shift the heat pump electric loads from peak to off-peak hours. The electricity price on the "spot" market is varying along the day. A PP electricity tariff for the consumer is defined from the hour-by-hour electricity procurement cost (PP) on the "spot" market during the year 2012 (Figure 1).

The average cost of the electricity consumed by the heat *pump,* $p_{el,avg}$, is defined by Equation 1 as well as the maximum ($p_{el,\max}$) and minimum ($p_{el,min}$) cost values, respectively, calculated using the maximum and minimum hourly values of the electricity cost of the current day. The integration is performed over the whole year:

$$p_{el,avg} = \frac{\int_0^t p_{el} * \dot{W}_{el} dt}{\int_0^t \dot{W}_{el} dt} \quad p_{el,\max} = \frac{\int_0^t p_{el,\max} * \dot{W}_{el} dt}{\int_0^t \dot{W}_{el} dt} \quad p_{el,\min} = \frac{\int_0^t p_{el,\min} * \dot{W}_{el} dt}{\int_0^t \dot{W}_{el} dt} \tag{1}$$

The flexibility of the space heating demand is defined in Equation 2. The flexibility is equal to 1 when all the electricity required by the heat pumps is used at the time of the day with the lowest price:

$$Flexibility = \frac{p_{el,\max} - p_{el,avg}}{p_{el,\max} - p_{el,\min}} \tag{2}$$

As flexibility strategies use the building envelope thermal mass for heat storage purposes, they usually yield an over-consumption. Overconsumption associated to RBC is defined as the consumption increase when compared to intermittent heating:

$$Overconsumption = \frac{E - E_{\text{int}}}{E_{\text{int}}} \tag{3}$$

Second approach—optimal control schemes (OPC) and definition of the flexibility

Both optimal control strategies OPC 1 and OPC 2 rely on model predictive control. The resolution scheme is depicted in Figure 5. The objectives are:

- the minimization of the cost of electricity, expressed by

$$J_e = \sum_{i=1}^{N=p} p_{el}(i) * \dot{W}_{el}(i) \tag{4}$$

with *p* the receding horizon, W_{el} (the heat pump electrical power) the manipulated variable, and p_{el} the electricity price for the consumer based on ToU tariffs (DN tariff and PP tariffs from the day-ahead spot market Figure 1);

- the minimization of thermal discomfort during occupancy periods:

$$J_d = \sum_{i=1}^{N=p} f_{occ}(i) * (\varepsilon_{low}(i) + \varepsilon_{high}(i)) \tag{5}$$

where f_{occ} expresses the presence of occupants in the house and is set to 1 during occupancy periods and 0 otherwise.

The following constraints are set:

- the zone temperature should remain between the upper and lower limits; hard constraints on zone temperature are softened using ε_{low} and ε_{high} to ensure the robustness of the optimizer:

$$T_{low} - \varepsilon_{low} \le T_Z \le T_{high} + \varepsilon_{high} \tag{6}$$

with T_{low} and T_{high} set, respectively, to 20° C and 22° C continuously for continuous heating strategy (OPC 1) and between 7:00 a.m. and 10:00 p.m. for intermittent heating (OPC 2), and ε_{low} and ε_{high} are constrained to be positive;

- the heat pump electrical power should not exceed the maximum electrical power imposed to 3 kW.

The final cost function is defined by

$$C = J_e + \alpha * J_d \tag{7}$$

where α is a weighting factor used to modify the relative importance of each sub-function in the final cost function. It was manually tuned to confer similar weight to both sub-functions J_e and J_d but to ensure thermal comfort in priority. It was set to 5000 based on the Pareto front illustrated in Figure 6.

The resulting minimization problem is convex (due to the simplification of constant COP) and linear. The solver used is the CPLEX (IBM 2013) solver with the M ATLAB-compatible open-source Yalmip Toolbox (Löfberg 2004).

As stated, model mismatch between the plant and process is taken into account. Indeed, on top of the Gaussian noise error inherent to the identification of the simplified system, the assumption of a constant COP causes a significant error on the prediction of the heat pump performance. Therefore, a feedback loop from the emulator is included after each control horizon to update the initialization of the process model for the next optimization horizon.

Flexibility is quantified in terms of load volumes shifted and in terms of procurement costs avoided in the context of the Belgian day-ahead electricity market. A reference power demand profile is determined for a flat electricity tariff for the consumer, and the related procurement costs are estimated based on the Belpex (Belgian power exchange) spot market. Similarly, maximum and minimum procurement costs are estimated. Therefore, the flexibility is expressed as follows:

- in terms of procurement costs avoided,

$$flexibility_{PC} = \frac{PC_{max} - PC}{PC_{max} - PC_{min}} \tag{8}$$

with *PC* as the total procurement cost for the year with optimal control and PC_{max} and PC_{min}, respectively, the maximum and minimum procurement costs;

- in terms of volume shifted,

$$flexibility_{VS} = \frac{flexibility_{PC} - flexibility_{PC,ref}}{flexibility_{PC,ref}} \tag{9}$$

with $flexibility_{PC,ref}$ as the flexibility computed in terms of procurement costs for the reference profile based on a flat electricity tariff.

The same overconsumption is determined in comparison with the flat tariff reference value.

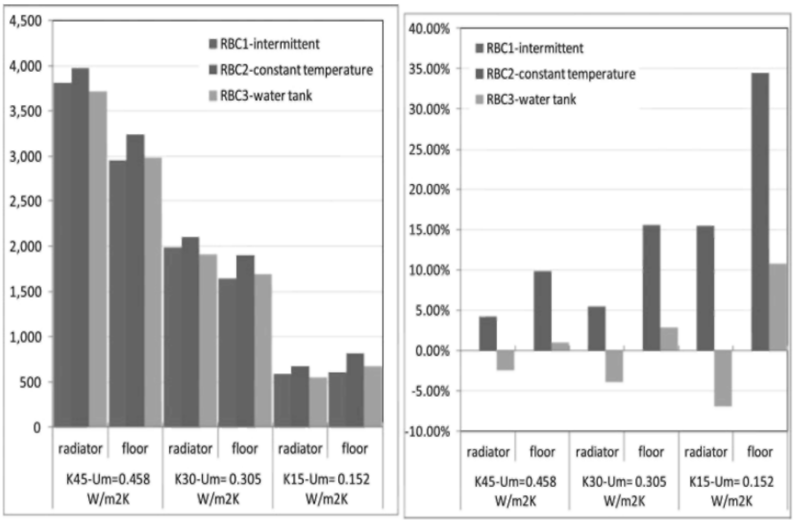

Fig. 7. *Heat pump electricity consumptions in kilowatthours/year for different control strategies, heating systems, and building insulation levels (left) and overconsumption compared to intermittent heating (right).*

RESULTS

First approach—traditional RBC methods results

Figure 7 displays the electricity consumption in kilowatthours/year for different control strategies (intermittent heating, constant temperature heating, and heat storage in the water tank), heating systems (radiator and floor heating), and building insulation levels, as well as overconsumption compared to intermittent heating. The floor heating system is made of a concrete slab at the ground floor in the living zone. The consumption level is strongly related to the building insulation level. It is not surprisingly higher for continuous heating with a constant set-point temperature. Floor heating systems require lower electricity consumption than radiator systems because they work at lower temperature levels (40°C) than radiators (55°C), so that the seasonal COP of the heat pump is higher (Figure 8). Water tank storage provides energy savings when associated to a radiator heating system. It can save up to 7% on electricity consumption.

Water tank storage can save up to 19% electricity consumption cost when coupled with radiators when the building insulation level is high (Figure 9). Despite its higher electricity consumption level compared to intermittent heating when associated to a floor heating system, water tank storage can save up to 2% on electricity consumption cost. Energy savings provided by a water tank are very sensitive to the water tank set-point. Cost savings are sensitive to the ratio between nighttime and daytime electricity tariffs and to the variation of the heat pump COP in relation with the outdoor temperature. The tank size also affects the results. The tank size and the water tank set-point should therefore be optimized. Cost savings due to water tank storage are not so much collected in the heart of winter because the heat pump COP is lower during the night when the outdoor air temperature is low. They are mostly collected in mid-season. A problem might then occur when the heat stored during the night or early in the morning is not totally released during the next daytime because solar heat gains are sufficient to reach the indoor temperature set-point. This underlines the need for predictive control to forecast the heating needs for better heat storage control.

Despite its higher electricity consumption level compared to intermittent heating, continuous heating at a constant temperature can provide a similar electricity consumption cost due to higher COP values as the heat pump works at a lower part load factor (Figure 8).

Figure 10 displays the flexibility associated to the different control strategies, as defined in Equation 2. The minimum affordable electricity price for the consumer, computed as the yearly average value of the daily minimum electricity cost values, is €0.162/kWh, while the corresponding maximum is €0.249/kWh. Intermittent heating strategies are associated with higher electricity prices, i.e., lower levels of flexibility, while water tank storage control strategies are associated to lower average electricity prices, particularly when the building insulation level increases.

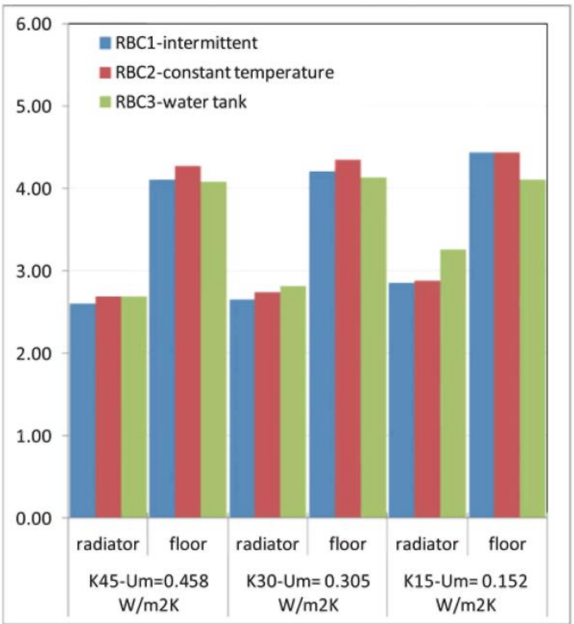

Fig. 8. *Heat pump seasonal COP for different control strategies, heating systems, and building insulation levels.*

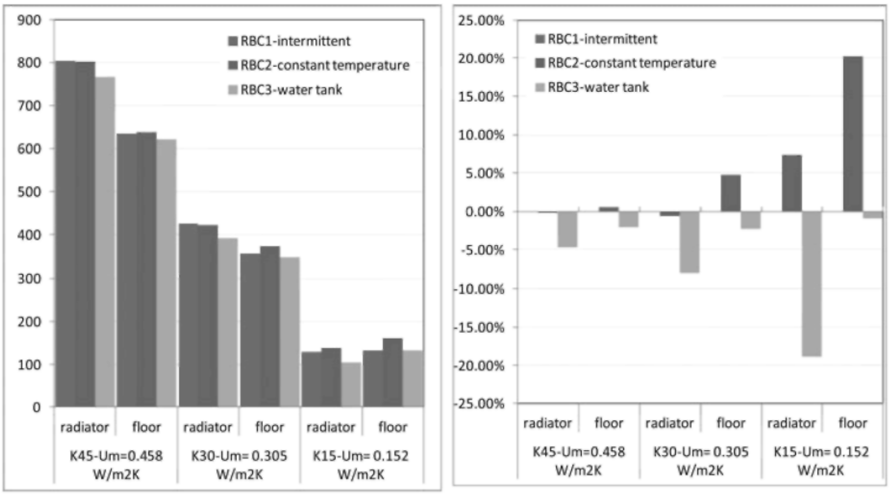

Fig. 9. *Heat pump electricity consumption cost for different control strategies, heating systems, and building insulation levels (left) and cost savings compared to intermittent heating (right).*

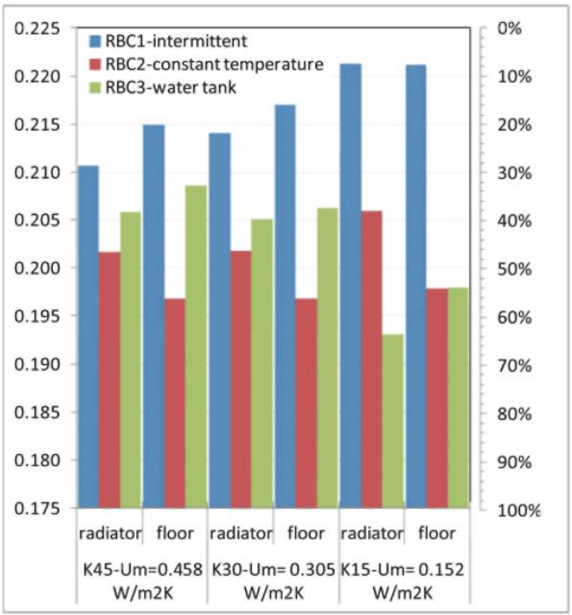

Fig. 10. *Average electricity cost in Euros/kilowatthours (left) and flexibility (right) related to different control strategies, heating systems, and building insulation levels.*

Table 1. *Optimal control results—intermittent heating strategy.*

	Electricity tariff	Energy (kWh/year)	Flexibility (%)	Overconsumption (%)	Procurement cost (%)	Consumer's cost (%)	Volume shifted (%)
Floor heating K30,	Flat	1065	48				
U_m = 0.305 W/m²K	DN	1249	70	17	-4	-3	44
	PP	1260	77	18	-10	+ 1	58
Radiator K30,	Flat	1730	48				
U_m = 0.305 W/m²K	DN	1974	73	14	-10	-7	51
	PP	1985	77	15	-14	-3	60
Floor heating K45,	Flat	1933	48				
U_m = 0.458 W/m²K	DN	2246	74	16	-9	-6	55
	PP	2272	79	18	-15	-3	67
Radiator K45,	Flat	2922	48				
U_m = 0.458 W/m²K	DN	3281	70	12	-9	-6	46
	PP	3266	72	12	-11	-3	50

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Second approach—smart grid control (OPC) method results

Since K45 and K30 insulation levels represent, respectively, the previous and current insulation standards for new construction, these cases have been further investigated and used as case studies for optimal control response. The focus of this section is the influence of the electricity tariff structure on the load-shifting potential. The results of the optimization strategy are presented for each type of house and heating emission system for three electricity tariffs: flat, DN, and PP. Flat and DN tariffs are already implemented in Belgium; the PP tariff corresponds to the actual power exchange rate on Belpex spot market. Both intermittent heating with night set-back and continuous heating are considered.

Table 2. *Optimal control results—continuous heating strategy.*

	Electricity tariff	Energy (kWh/year)	Flexibility (%)	Overconsumption (%)	Procurement cost (%)	Consumer's cost (%)	Volume shifted (%)
Floor heating K30,	Flat	1121	66				
U_m = 0.305 W/m²K	DN	1217	74	9	**+ 1**	-13	12
	PP	1240	79	11	-3	-8	20
Radiator K30,	Flat	1830	63				
U_m =0.305 W/m²K	DN	1985	74	8	-3	-12	17
	PP	2010	78	10	-7	-8	24
Floor heating K45,	Flat	2038	66				
U_m = 0.458 W/m²K	DN	2220	75	9	-1	-13	15
	PP	2257	80	11	-5	-9	22
Radiator K45,	Flat	3119	62				
U_m = 0.458 W/m²K	DN	3329	72	7	-3	-12	15
	PP	3336	73	7	-5	-9	18

Based on the results from Tables 1 and 2, different observations can be made.

- Impact of building envelope: The percentage of volume shifted increases with the insulation level of the building envelope.

- Impact of the tariff: Both DN and PP tariffs yield similar results in terms of flexibility (72% to 78%) compared to the flat tariff (about 62% to 66%). The reason for such similarity is to be found in the type of power plants used as a base load and as marginal power plants, which directly influences the electricity tariff, as explained in the section entitled "Context—The Belgian Electricity Market." With nuclear power as the base load and gas turbines as marginal plants, the spot market price daily profile is on average close to the DN pricing for the current energy mix, though more volatile on a day-to-day basis. Therefore, for the case studies proposed here, there seems to be little advantage of having access to the PP pricing, and similar results can be obtained with a DN tariff structure in terms of flexibility. However, the PP tariff seems to bring higher benefit for the energy supplier, whereas DN pricing seems better suited to maximize the consumer's benefit for continuous or intermittent heating. Further integration of renewable energy sources in the energy mix is likely to modify the assignment of the base load and marginal power production, and the access to spot market prices will have a more significant impact on demand response programs. Conclusions could also differ with a morning/evening type of intermittent heating.

- Impact of the heating strategy: The percentage of volume shifted is more than doubled with intermittent heating compared to continuous heating. Continuous heating yields lower relative overconsumption due to load shifting, but the absolute energy consumption is higher than for intermittent heating.

- Impact of the emission system: Flexibility is slightly higher with floor heating than radiators. The overconsumption due to load shifting is larger for floor heating, but the absolute consumption remains inferior to radiators due to a lower water supply temperature (35°C with floor heating and 55°C with radiators), which yields better heat pump performance. Cost saving for both energy supplier (procurement costs) and consumer are higher with radiators. It should be noted, however, that a control based on the zone temperature is not accurate in terms of thermal comfort with floor heating. A correction to take into account that the operative temperature should be added and may change the conclusions.

Figure 11 illustrates the results for intermittent heating in the case of a K30 house with radiators for an average winter weekday. As expected, differences can be observed between the emulator and the gray-box models, confirming the importance of the feedback loop to correct the initial state of the optimizer.

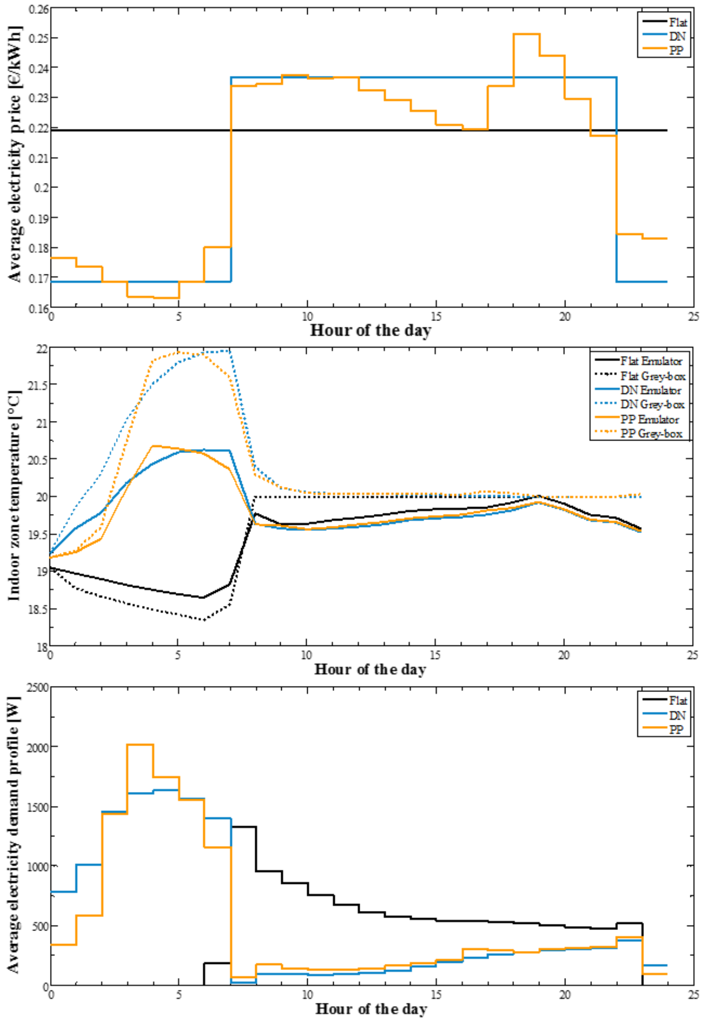

Fig. 11. *Illustration of load shifting for different tariff structures for K30 house with radiators; top: tariff structure, center: average indoor temperature, bottom: heat pump electric power.*

Discussion

Although energy mix and electricity prices differ strongly from one country to another, electricity market models are similar within the European countries. The methodology presented here could therefore easily be applied to other countries. However, the conclusions may differ, due to the following factors:

- the volatility of the spot market price for the scenario using the PP tariff;

- the technology of heat pumps used; indeed, other types of heat pump technology could be used depending on the climate and country resources, such as cold climate heat pumps or ground source heat pumps, as their performances differ from traditional air-to-water heat pumps and will affect the results;

- the type of buildings, since thermal capacity of buildings is the main thermal storage in this study; light-structure buildings, such as wooden-frame houses, will offer lower flexibility potential; an additional water storage tank may significantly increase load-shifting potential in such cases.

CONCLUSIONS

This article presents a method to assess the flexibility potential of several types of buildings equipped with different emission systems (radiators and floor heating) and an air-to-water heat pump. Five control strategies have been implemented. Flexibility has been defined as the ability to shift the heat pump electric load from peak to off-peak hours in terms of electricity price. Three tariffs have been considered: flat, DN, and spot market. Results show that the use of prices as incentive to promote load shifting is appropriate for this application. In particular, RBC strategies have outlined the global impact of the building envelope characteristics. The higher the insulation level is, the larger the flexibility potential is, provided the building thermal mass is heavy and accessible. Compared to intermittent heating, water tank storage can save up to 2% electricity consumption cost when associated to a floor heating system and up to 19% electricity consumption cost when coupled with radiators. The results emphasize the need to optimize the temperature set-point and the size of water tank storage, as well as the need for predictive control to forecast building heating demand.

The smart grid control method showed that optimizing the load profile based on electricity pricing results in an increase in electricity consumption (up to 20%) but a reduction of procurement costs of up to 15% for the electricity supplier and 13% for the consumer. In particular, there is an important potential for cost reduction and load shifting associated to the PP tariff. At the optimum, up to 80% of the electricity consumption is shifted to off-peak periods. In terms of flexibility, similar results are obtained for DN and dynamic tariff structures for the current energy mix (mostly nuclear and gas). These results are likely to change with the introduction of a higher share of renewable energy sources and coming changes in energy market structure.

The proposed method can easily be applied to other types of buildings, technologies of heat pumps, and climates. In future work, the results should be validated by adding weather prediction mismatch. The methodology will be extended to the intraday and real-time markets.

NOMENCLATURE

C = wall heat capacity ($J/m^2.K$)

E = energy consumption (kWh/year)

E_{int} = energy consumption corresponding to intermittent heating strategy (kWh/year)

n_{50} = infiltration air change rate at 50 Pa (acr or h^{-1})

p_{el} = electricity price for the consumer based on a time-of-use tariffs (€/kWh)

$p_{el,avg}$ = average cost of the electricity consumed (€/kWh)

$p_{el,\min}$, $p_{el,\max}$ = minimum, maximum cost of the electricity consumed (€/kWh)

PC = total procurement cost of electricity for the year with optimal control (€/year)

PC_{min},PC_{max} = minimum, maximum procurement cost of electricity for the year (€/year)

R = wall heat transfer resistance ($m^2.K/W$)

T_{low}, T_{high} = lower and upper set-point limits for zone temperature (°C)

T_z = zone temperature (°C)

U = wall overall heat transfer coefficient ($W/m^2.K$)

W_{el} = electrical power of the heat pump compressor (W)

θ = accessibility of wall overall heat capacity (-)

φ = useful proportion of wall overall heat capacity (-)

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