Smart Grid Energy Flexible Buildings through the use of Heat Pumps 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 such that the forecasted 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 (ToU) variable electricity tariffs as an incentive to shift their demand. Smart control of HVAC equipment with embedded model predictive control (MPC) can be used in that context. They have to be provided with dynamic building simulation models.

This study provides typologies of Smart Grid Energy ready Buildings within the context of the Belgian building stock and the Belgian day-ahead electricity market. A typical new residential building is considered, equipped with an air-to-water heat pump that supplies either radiators or a floor heating system. Five heating control strategies are compared in terms of thermal comfort, energy use and flexibility, where the 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 latter two are 'smart-grid' model predictive control strategies responding to a time-varying electricity price profile. The results show that the 'smart-grid' control strategies allow to reduce the procurement costs by 2 to 18% and increase the flexibility by 8 to 24% (volume shifted) with the same thermal comfort. The impact of building insulation level and thermal mass is also evaluated. The flexibility for load shifting is about 8 to 10% higher when shifting from a low-energy (K45) to a very-low-energy house (K30).

1. 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 level of actions take place at different times. On the day-ahead electricity market, electricity suppliers have to nominate their electricity bids such that the forecasted supply and demand are in balance. At the intraday-level, mismatches between the forecasted and actual supply and demand can be compensated for by reserve capacity or by real-time demand response.

Smart Grid Energy ready Buildings can help minimizing the cost of electricity supply at the distribution grid level in three different ways. A first one is to predict electricity demand profiles associated to local consumers equipped with smart metering devices as accurately as possible. A second one 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 (ToU) variable electricity tariffs as an incentive to shift their demand. A third one is to minimize the imbalance costs resulting from mismatches between forecasted supply and demand, by real-time demand response. In the frame of this paper, the flexibility of the heating load 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).

Different control strategies of HVAC (Heating, Ventilation and Air-Conditioning) equipment can be implemented and coupled with storage systems. As emphasized by Braun (1990), conventional control strategies don't consider the use for thermal storage in the building structure as a mean 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.

In this paper, the impact of building thermal mass storage on the electricity consumption is evaluated for a typical new residential building in Belgium equipped with an air-to-water heat pump and alternatively radiators or a floor heating system. In the first part of the work, the flexibility is assessed according to a cost-weighted electricity consumption of the heat pump for three rule-based control (RBC) strategies: intermittent heating strategy, continuous heating strategy and storage heating strategy. A ranking of the building characteristics affecting its flexibility is deduced as well as recommendations to avoid overconsumption associated to energy storage. In the second part of the paper, the flexibility obtained with model based predictive control (MPC) strategies is evaluated.

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 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. In such control strategies, the cost function to optimize is of major importance.

In this study, the MPC minimizes the heat pump energy cost to satisfy thermal comfort, based on the day-ahead electricity price profile. 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 for year 2012.

2. METHODOLOGY

2.1 Test case study: building and heat pump models

A typical freestanding new residential building is considered with a total heated volume of 457 m^3 (Fig. 1). It is divided into four zones: a living zone, a staircase, a sleeping zone and a bathroom. Vertical walls and floors are all made of precast concrete (external as well as internal) while the roof is a wooden insulated structure. External vertical walls are supposed to be insulated either on the internal surface or on the external surface. Two levels of insulation and air tightness are considered: K45 corresponds to an average U-value of 0.458 W/m^2K and is associated with n_{50}= 6 ACH, and K30 corresponds to an average U-value of 0.305 W/m^2K and is associated with n_{50}= 3 ACH. The first level corresponds to the Belgian standards for newly built houses while the second one is an improved test case. The site is considered as wind sheltered.

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

Two occupancy profiles are considered for ordinary days in the living zone: continuous occupancy from 7 AM to 10 PM and two-slot occupancy from 7 to 9 AM and from 4 to 10 PM. The following occupancy schedules are also considered for both occupancy types:

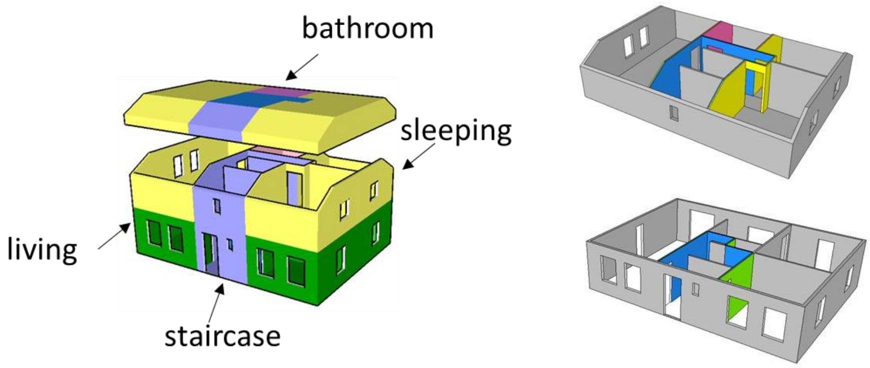


Figure 1: Perspective view of the test house heated volume shared into four zones (left) and layout of the ground and first floors showing zone separating walls.

- The living zone is occupied from 8 AM to 11 PM in the week-end.
- The sleeping zone is occupied from 10 PM to 7 AM on ordinary days and from 11 PM to 8 AM in the week-end.
- The bathroom is occupied from 6 to 7 AM and from 8 to 10 PM on ordinary days and from 7 to 8 AM and from 9 to 11 PM in the week-end.
- The staircase is never considered as occupied.

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. Five heating systems control strategies are considered:

- RBC 1: An intermittent heating strategy: heating temperature set points in the whole house are only maintained when the living zone is occupied. Otherwise, the set points are 16°C in the whole house. When the living zone is occupied, heating temperature set points are equal to 21°C in the different zones, except in the bathroom where the set point equals 24 °C. The required restart time is a quarter of hour for the radiators and 2 hours for the heating floor.
- RBC 2: A continuous heating strategy: heating temperature set points are constant and equal to 21°C in the whole house, except in the bathroom where the set point equals 24 °C.
- RBC 3: A storage heating strategy: heating temperature set points are constant such as for the continuous heating strategy, but an increase of 1K is gradually added to the set point during off-peak hours, while a decrease of 1K is gradually imposed during peak hours.
- MPC 1: An optimal control strategy: heat pump operation is optimized by means of model predictive control for a day-night electricity tariff structure. The MPC uses a simplified representation of the building dynamics (no model mismatch considered) and perfect weather predictions.
- MPC 2: A smart grid strategy: heat pump operation is optimized by means of model predictive control for a time-of-use electricity price based the actual spot market price (Belpex day-ahead market). The MPC uses a simplified representation of the building dynamics and perfect weather predictions.

An 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 12000 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 in order 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 2K, provided the outdoor air temperature is higher than 16°C.
In the detailed dynamic model of the building, both external and internal walls are modeled through 2R-1C network as illustrated in Figure 2 (left) with R 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 in order 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 & André, 2012 and Masy, 2008).

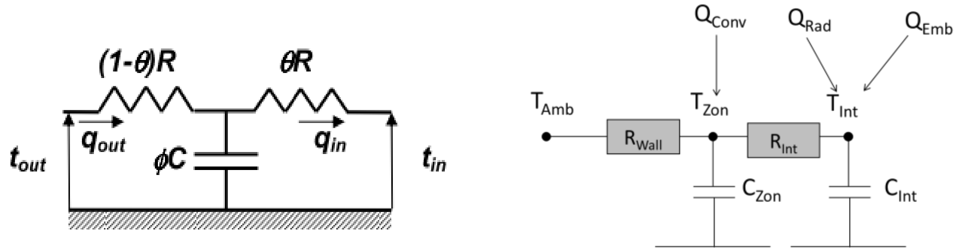


Figure 2: Capacitive wall representation, 2R-1C network (left) – Grey-box model representation (right)

The grey-box model used in the MPC was identified using the Greybox Toolbox (De Coninck, 2013) and is illustrated in Figure 2 (right). The governing equations are

$$C_{Zon}\frac{dT_{Zon}}{dt} = \frac{1}{R_{Wall}}(T_{Amb} - T_{Zon}) + \frac{1}{R_{Int}}(T_{Int} - T_{Zon}) + Q_{Conv} \quad (1)$$

$$C_{Int}\frac{dT_{Int}}{dt} = \frac{1}{R_{Int}}(T_{Zon} - T_{Int}) + Q_{Rad} + Q_{Emb} \quad (2)$$

where C_{Zon} an C_{Int} are respectively the zone and internal mass thermal capacities, R_{Wall} the wall thermal resistance, R_{Int} the thermal resistance between the internal mass and the zone and T_{Amb}, T_{Zon} and T_{Int} respectively the outdoor air temperature, the zone temperature and the internal mass temperature. The convective heat gains (Q_{Conv}) are composed of the solar heat gains and convective fraction of internal heat gains, whereas the radiative heat gains (Q_{Rad}) are simply the radiative fraction of internal heat gains. Finally Q_{Emb} represents the heat input from the heat production system.

The building is equipped with an 8 kW air-to-water heat pump. A simplified empirical model of the heat pump based on ConsoClim method (Bohler et al., 1999) is calibrated based on manufacturer data. The nominal 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.

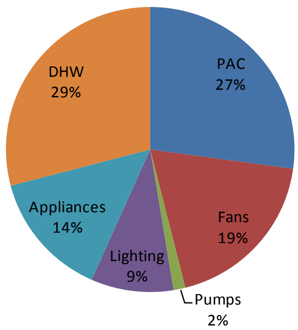
2.2 Breakdown of the yearly electricity consumption

Simulation is performed with EES (Engineering Equation Solver, S.A. Klein) solver over a whole year on a quarter-hourly basis. Weather data corresponds to climatic conditions for year 2012. Figure 3 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, domestic hot water heating through electric resistance.

Values of the Predicted Percentage of Dissatisfied (PPD) based on ISO 7730 (1995) are also computed in order to insure that that the internal comfort is maintained. However, wall surface temperature isn't directly accessible in the models, and was assumed to be equal to the indoor air temperature.

2.3 First approach – traditional RBC control methods and definition of the flexibility

The flexibility of the building space heating demand characterizes its ability to shift the heat pump electric loads from peak to off-peak hours. Considering an average hour-by-hour electricity price on the "spot" market for an ordinary day and for the week-end, a weighting factor *f* of electricity price is defined in order to reach 1 when the price is maximum (Figure 4).



	kWh/yr	kWh/m^2.yr
Heat pump (PAC)	3171	22
Fans	2208	15
Pumps	155	1
Lighting	1079	7
Appliances	1665	11
DHW	3396	23
Total	11673	80

Figure 3: Breakdown of electricity consumption for the test case study with reference conditions.

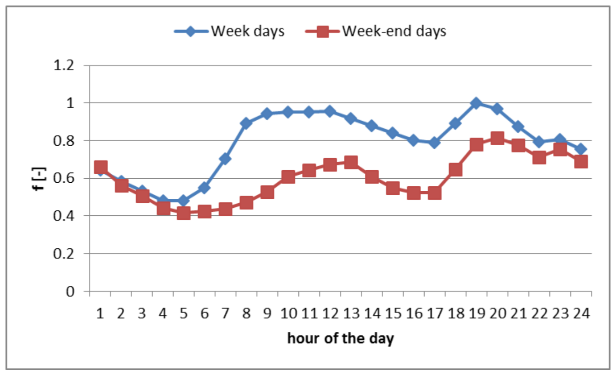


Figure 4: Weighting factor of electricity price on the « spot » market.

A cost-weighted electricity consumption of the heat pump, E_{cw}, is defined by equation (3) as well as maximum ($E_{cw,max}$) and minimum ($E_{cw,min}$) values with the maximum or minimum weighting factors of the current day:

$$E_{cw} = \int_0^t f * \dot{W}_{el} dt \qquad E_{cw,\max} = \int_0^t f_{\max} * \dot{W}_{el} dt \qquad E_{cw,\min} = \int_0^t f_{\min} * \dot{W}_{el} dt \tag{3}$$

The flexibility of the space heating demand is defined in equation (4). It reaches 1 when all the electricity required for the heat pump is consumed at the hour of the day when the price is the lowest.

$$Flexibility = \frac{E_{cw,\max} - E_{cw}}{E_{cw,\max} - E_{cw,\min}} \tag{4}$$

As flexibility strategies use the building envelope thermal mass for heat storage purpose, they usually yield an overconsumption when compared to a reference building envelope which would be purely resistive with the same level of insulation, but without any thermal mass. Overconsumption is defined as the consumption increase due to thermal mass (E) divided by the reference consumption of an equivalent purely resistive building (E_{stat}) in equation (5).

$$Overconsumption = \frac{E - E_{stat}}{E_{stat}} \tag{5}$$

2.3 Second approach - Smart grid control scheme

In this section, a smart-grid control strategy based on model predictive control is implemented. The resolution scheme is depicted in Figure 5. The objectives are:

- the minimization of the cost of electricity, expressed by

$$J_e = \sum_{i=1}^{N=p} p_{el}(i) * \dot{W}_{el}(i) \tag{6}$$

with p the receding horizon, $\dot{W}_{el}$ the manipulated variable, i.e the heat pump electrical power and p_{el} the electricity price for the consumer based on a time-of-use tariff.

- the minimization of thermal discomfort during occupancy periods

$$J_d = \sum_{i=1}^{N=p} f_{occ}(i) * (\varepsilon_{low}(i) + \varepsilon_{high}(i)) \tag{7}$$

under the following constraints:

- the zone temperature should remain between the upper and lower limits. Soft constraints are used to ensure the robustness of the optimizer:

$$T_{low} - \varepsilon_{low} \leq T_Z \leq T_{high} - \varepsilon_{high} \tag{8}$$

  with T_{low} and T_{high} set respectively to 21 and 24°C, and ε_{low} and ε_{high} constrained to be positive.

- the heat pump electrical power should not exceed the maximum power imposed to 3kW and should not work during non-suitable periods.

The final cost function is defined by

$$C = J_e + \alpha * J_d \tag{9}$$

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, and was set to 5000.

The resulting minimization problem is convex (due to the simplification of constant COP) and linear. The solver used is a MUltifrontal Massively Parallel Sparse direct solver (Amestoy et al., 2001 and Amestoy et al., 2006) based on LU decomposition method.

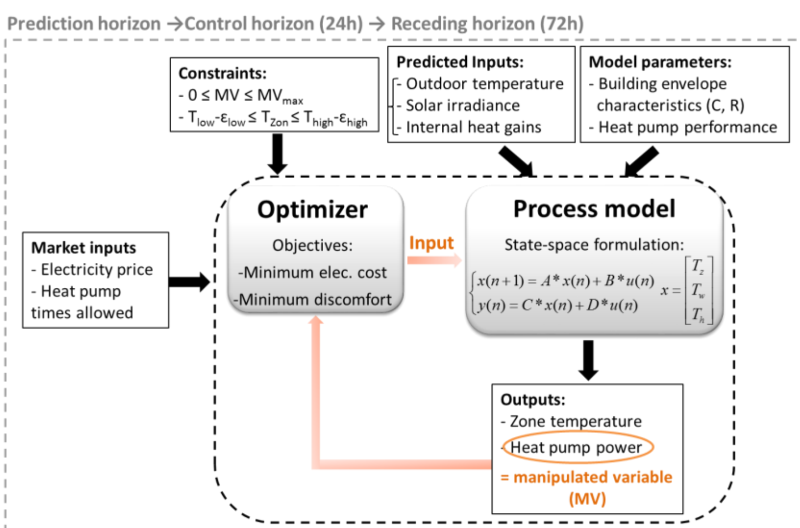


Figure 5: Smart-grid control strategy scheme

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:

$$flexibility_{PC} = \frac{PC_{\max} - PC}{PC_{\max} - PC_{\min}} \tag{10}$$

with PC 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:

$$flexibility_{VS} = \frac{flexibility_{PC} - flexibility_{PC,ref}}{flexibility_{PC,ref}} \tag{11}$$

with $flexibility_{PC,ref}$ 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.

3. RESULTS

3.1 First approach – traditional RBC control methods results

Results presented in Figures 7 and 8 show low flexibility values for an intermittent heating strategy, mean flexibility values for continuous heating and higher flexibility values, ranging from 60 to 80 % for a storage heating strategy. Storage strategies usually yield an increase of heating consumption, which is higher for heating floor systems, especially for standard insulation level K45. The higher overconsumption associated to heating floors, compared to radiators, is explained by the increase of the transmission losses since the heating pipes are integrated in the floor and are no longer part of the heated space. Improving the insulation at the bottom of the heating floor could reduce the storage overconsumption and hence increase the flexibility. Some negative values of overconsumption can be observed for well insulated houses (K30) with continuous occupancy all day long and provided with intermittent heating: those buildings are able to store solar heat gains during daytime in a useful way so that the heat recovery due to solar heat gains compensate the overconsumption due to intermittent heating in building provided with high thermal mass. A ranking of the building characteristics allowing it to improve the flexibility associated to its space heating demand are first, a heating floor system instead of radiators, second, an improved envelope insulation, and third, external walls insulation in order to provide access to the thermal mass from the indoor.

The percentage of dissatisfied (PPD) is illustrated in Figure 6 and is below 11% in average. In perfect thermal comfort conditions, the latest would reach 5%.

Based on the results obtained, it can be concluded that external insulation offers slightly larger flexibility and lower overconsumption, and that the storage control strategy offers the largest flexibility. Therefore only case studies with external insulation will be investigated for the MPC strategy.

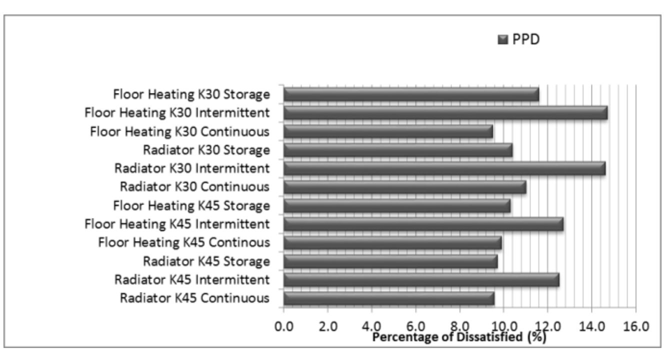


Figure 6: Percentage of dissatisfied for different heating strategies for continuous occupancy

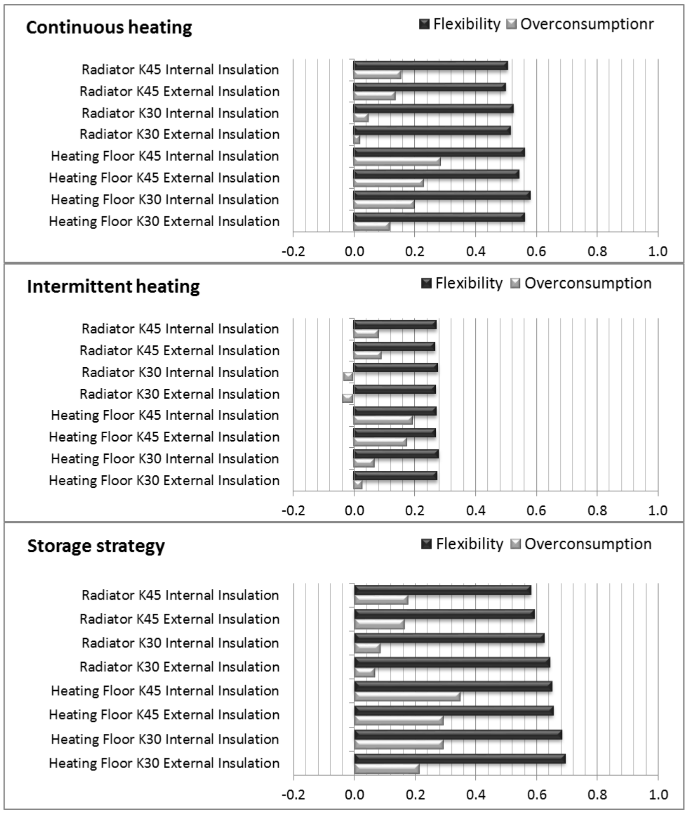


Figure 7: Flexibility and overconsumption related to different heating strategies for continuous occupancy.

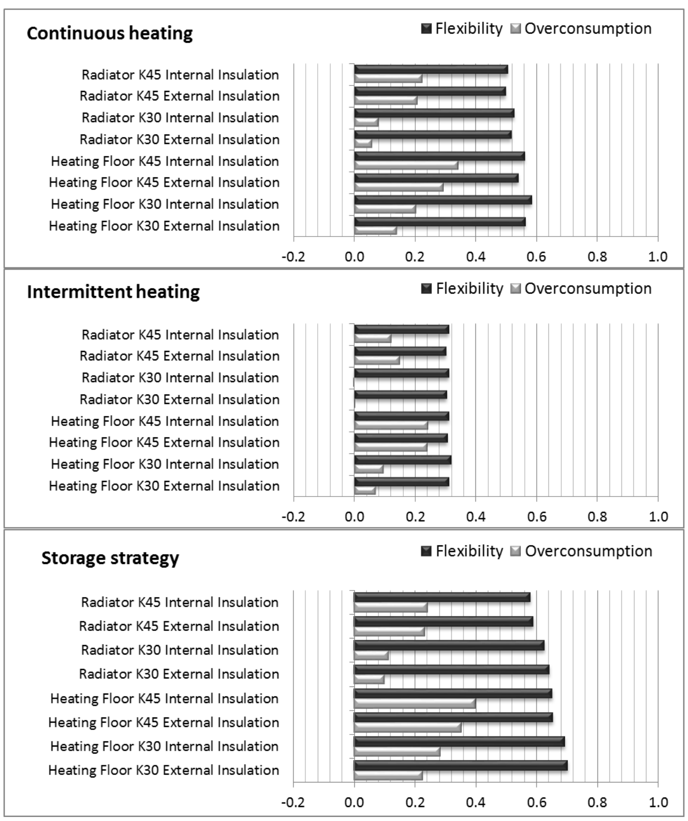


Figure 8: Flexibility and overconsumption related to different heating strategies for two slots occupancy.

3.2 Second approach – smart-grid control method results

The results of the optimization strategy are presented in Table 1 for each type of house and heating emission system for three electricity tariffs: flat, day & night (DN) and perfect prediction (PP - which corresponds to the actual Belpex power exchange rate).

Table 1: MPC optimization results

	Electricity Tariff	Energy [kWh/year]	Procurement cost (Eur)	Flexibility (%)	PPD (%)	Over-consumption	Cost reduction	Volume shifted
Floor Heating K30	Flat	1605	84	62.2	6.4			
	DN	1719	80	72.8	6.7	7%	5%	17%
	PP	1712	72	81.6	6.9	6.6%	14%	24%
Radiator K30	Flat	1945	102	60.2	6.2			
	DN	2065	95	71.8	6.5	6.1%	7%	19%
	PP	2071	84	82.6	6.6	6.5%	18%	37%
Floor heating K45	Flat	2884	150	61.3	6.2			
	DN	2999	147	66.3	6.6	4.0%	2%	8%
	PP	2984	136	72.9	6.7	3.5%	9%	16%
Radiator K45	Flat	2682	141	61.6	6.1			
	DN	2803	137	67.3	6.4	4.5%	3%	9%
	PP	2794	126	74.2	6.4	4.2%	11%	20%

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: the results are sensitively different for day/night optimization and perfect prediction tariffs. There is an important potential (more than double) for cost reduction and load shifting associated to the perfect prediction tariff.
- Overconsumption and volume shifted: load shifting to reduce cost with both DN and PP tariffs typically yields an additional energy consumption increase of 3.5 to 7%. When subjected to the PP tariff, the shifted volumes are higher and so is the cost reduction for the energy supplier (9 to 18%). Therefore, the Belpex-based price currently seems to offer some benefit for the consumer/energy supplier.
- Thermal comfort: the percentage of dissatisfied for the different buildings remains almost the same when going from minimal energy (‘flat’) to minimal energy cost (‘DN’ and ‘PP’). It should be noted that these values are calculated for the heating season only.
- The values obtained here with MPC for load shifting (flexibility of 60% to 83% in terms of procurement costs) and for the thermal discomfort (PPD of 6 to 7%) are the same order of magnitude as the values obtained with the RBC (section 3.1). This suggests that a properly tuned RBC can approximate the cost optimal solution, at least in case of the current electricity price tariffs.

Note: Floor heating systems show an increased electricity use compared to radiators in this case, because of the transient losses inherent to the floor heating inertia. This result is however obtained assuming a constant supply water temperature of 35°C when calculating the COP of the heat pump (both for radiators and floor heating). Since floor heating systems allow lower supply water temperatures, the actual electricity consumption with floor heating systems will be lower.

4. CONCLUSIONS

Five control strategies have been implemented to assess the flexibility potential of two types of buildings equipped with different emission systems (radiator and floor heating) and an air-to-air heat pump. Rule based control strategies have outlined the global impact of the building envelope characteristics: the higher the insulation level, the larger the flexibility potential. The smart-grid control method showed that optimizing the load profile based on electricity pricing results in an increase in electricity consumption (3.5 to 7%), but a reduction of procurement costs of 2 to 18%. In particular, there is an important potential for cost reduction and load shifting associated to the perfect prediction tariff. At the optimum, around 70 to 80% of the electricity consumption is shifted to off-peak periods. These conclusions are likely to change with the introduction of a higher share of renewable energy sources. The results should be validated by adding model and prediction mismatch. In a future work, the methodology will be extended to the intraday and real time markets.

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