Upscaling the flexibility potential of space heating in single-family houses

Jérome Le Dréau*, Ilyas Mellas¹, Marika Vellei¹, Johann Meulemans²

¹ LaSIE UMR CNRS 7356 / La Rochelle University, France
² Saint-Gobain Research Paris, 39, quai Lucien Lefranc BP 135, 93303 Aubervilliers, France

*corresponding author: jledreau@univ-lr.fr

Abstract. Energy flexibility from residential buildings is foreseen as a solution to facilitate the integration of variable energy sources in the grid. In fact, the energy use in residential buildings is still high despite the different building regulations and some of their usages can be shifted in time. Among these usages, space heating showed an interesting potential for flexibility, especially in France, where 45% of the heating systems is electrical. The objective of this study is to evaluate the flexibility potential in typical French houses, looking at both the energy shifted and thermal comfort. Large differences are highlighted, mainly due to the thermal properties of the envelope and the type of emitter. The temperature drops are quick in poorly insulated building. Underfloor heating systems show a good flexibility potential due to the inertia of this type of emitter. Finally, quantitative data, such as the mean power decrease and power profiles, is provided to help the integration of flexible buildings in future energy grids.

1. Introduction

Energy flexibility can be defined as the “ability of a building to manage its demand and generation according to local climate conditions, user needs and grid requirements” [1]. Space heating (61% of the energy use in residential buildings in France) can play an important role in providing flexibility to the energy grids. Prospective studies on future electrical systems rely on a large penetration of space heating flexibility in the residential sector to allow the uptake of renewable energy sources/systems. The French TSO estimates that up to 25% of electrical heating systems should be equipped with a dynamic controller by 2030 [1]. The deployment is even projected to increase up to 75% by 2050 [3]. Different labelling systems are also under development to qualify the energy flexibility of buildings (e.g. smart-readiness indicator in Europe, or GoFlex in France).

However, the flexibility offered by different buildings varies much with the building typologies, energy classes, heating and control systems. This large diversity was previously highlighted by different researchers (e.g. see [4][5][6] and references therein), but additional data are required for energy outlook. The main objective of this study is thus to estimate the flexibility potential for demand response at the building level and to help designing future energy systems.

The main challenge for grid operators is to deal with the evening peak (resulting mainly from cooking activities). Different strategies will thus be tested to decrease the heating energy use between 6pm and 9pm. The demand-response (DR) events will be performed on different building typologies (energy class and thermal mass) heated up with either radiators or underfloor heating systems. Multi-criteria
analysis will be conducted to characterize both energy use and thermal comfort during the DR events. Finally, the results of the simulations will be compared to values derived from demonstration projects.

2. Materials and methods

Different building typologies were selected to perform modulations of the space heating and investigate the flexibility potential of single-family houses. The envelope properties of the three simulated buildings (Table 1) are representative of different building regulations (BR), from an old house slightly insulated (BR 1982) up to a state-of-the-art building (BR 2020). The level of thermal mass was kept constant ($C_m = 55\, \text{Wh/K.m}^2_{\text{floor}}$) and all houses were insulated from the inside, which is typical in France. Internal heat loads from occupants and equipment were accounted for. As a consequence of the level of insulation and airtightness, the annual heating needs of the buildings ($Q_{\text{heating need}}$) range from 157 down to 27 kWh/m$^2_{\text{floor.y}}$ (continental climate of Nancy).

### Table 1. Thermal properties of the simulated buildings.

| BR 1982 | BR 2005 | BR 2020 |
|---------|---------|---------|
| **Insulation walls** | | |
| 6 cm IWI | 10 cm IWI | 15 cm IWI |
| (U=0.51 W/m².K) | (U=0.30 W/m².K) | (U=0.19 W/m².K) |
| **Insulation roof** | | |
| 8 cm | 10 cm | 30 cm |
| (U=0.54 W/m².K) | (U=0.50 W/m².K) | (U=0.15 W/m².K) |
| **Insulation floor** | | |
| 3 cm | 15 cm | 20 cm |
| (U=0.81 W/m².K) | (U=0.24 W/m².K) | (U=0.15 W/m².K) |
| **Windows** | | |
| Double glazing | Double glazing | Triple glazing |
| (U=0.31 W/m².K & g=0.75) | (U=0.36 W/m².K & g=0.60) | (U=0.8 W/m².K & g=0.54) |
| **Ventilation** | | |
| Mechanical ventilation by extraction | Mechanical ventilation by extraction |
| (airflow 195 m³/h) | (humidity controlled, mean 125 m³/h) |
| **Infiltration [ACH]** | 0.35 | 0.18 | 0.05 |
| **Heat Loss Coefficient [W/K]** | 330 | 193 | 97 |
| **Characteristic time [h]** | 24 | 37 | 67 |
| **$Q_{\text{heating need}}$ [kWh/m²_{floor.y}]** | 157 | 84 | 27 |

In order to evaluate the influence of the emitter, these houses are equipped with either radiators or underfloor heating. The sizing of these systems is performed according to the design temperature (with a sizing factor of 25%). The operative temperature of each room is controlled at a constant temperature of 21°C with a proportional controller (proportional band of 1.5 K). A temperature-controlled system was chosen over a power-controlled one, because this type of controller is relatively common for electrical heating systems and ensures a minimum temperature level in the house.

As the objective of flexibility is to decrease the peak observed at the national level at the end of the afternoon, two strategies are considered, namely:

i. a downward modulation, with a decrease of the operative temperature set-point from 21°C down to 19°C between 6pm - 9pm (during 3 hours);

ii. an upward modulation before 6 pm, with an increase of the operative temperature set-point during the afternoon (during 1-3 hours).

One of the main drawbacks of the second strategy is that the discharge of the thermal mass is not controlled, leading to a poor reliability for demand-response purpose. Thus, the cases of upward modulations will not be detailed in this article, but results are available in the supplementary materials and in [7]. In total, 42 cases were simulated.

The different building types were modelled using a Building Energy Simulation (BES) software (EnergyPlus 8.8), in which each room is modelled as a thermal zone. The inertia of the ground is taken into account by applying sinusoidal temperature variations to some boundary conditions and the attic is modelled as a thermal zone with increased infiltration. The radiators are modelled as a convective/radiative heat source (80%/20% respectively) and the underfloor heating system is implemented as an active layer (usually located 5-6 cm below the finishing layer). The simulation time-
step was set to 2 minutes to capture the dynamic of the control systems. The temperature set-points were prescribed through a Functional Mockup Interface (FMI) using PyFMI.

3. Comparison of the flexibility potential of different buildings
In this first section, the flexibility behavior of the different buildings is illustrated for a typical winter week (26th to 29th of January) to highlight the major differences within the building stock. The first day is relatively sunny, whereas the two others are cloudy. The simulation results are evaluated with different key performance indicators, either related to thermal comfort (including dynamic features) or to the heating power. It should be noted that the results are expressed in terms of heating needs (i.e. efficiency of the systems not accounted for) in order to focus on the interaction between the emitter and the envelope.

3.1. Influence of the building energy class
Figure 1 compares the heating power and the operative temperature with and without modulation for the BR 1982 and BR 2020 buildings. The grey-shaded areas correspond to the three hour-long DR events (6pm – 9pm). In the BR 1982 building, the indoor temperature drops quickly, faster than the acceptable limit set by ASHRAE 55-2013 (1.1°C/15 min) [8]. During cold days, the temperature drops of 2°C within 20 minutes with a maximum rate of change as high as 16°C/hr (evaluated over 2 minutes). These rapid rates of change can elicit negative alliesthesia and lead to discomfort [9]. Conversely, the temperature drop is smoother in the BR 2020 building due to the larger time constant: the maximum rate of change is 5°C/hr. It should also be noted that passive solar heat gains influence the flexibility potential of both buildings, as shown on the 26th of January.

The variation of the heating power is also different in the two buildings. Due to larger heat losses and differences in sizing, the power decrease is higher in the BR 1982 building. However, long periods with the heater switched off cannot be sustained in the old building as the lower threshold of 19°C for thermal comfort is quickly reached. In the BR 2020, the heating system can be switched off for more than one hour, even during cold days. In both buildings, the rebound effect when setting back to the original set-point is yet relatively strong (around twice the power without modulation). Different solutions exist to handle this issue, such as a limitation at the controller level or the desynchronization of the ripple control (beyond the scope of the present study).

3.2. Influence of the emitter
Figure 2 compares the heating power and the operative temperature for the BR 2005 building equipped with either radiators or underfloor heating. The dynamic behavior of the two systems is quite different, despite the same level of thermal mass. In the BR 2005 equipped with underfloor heating, the heating power can be totally switched off between 6pm and 9pm. The operative temperature of the single-family house does not actually change much during downward modulations, due to the time lag between the
energy use and the heat emission in the space. The concrete screed acts as a buffer, resulting in temperature gradients as low as 2°C/hr (compared to 10°C/hr for the radiators). Similar behavior can be observed in the BR 1982 and BR 2020 buildings, with longer switch-off times. However, floor heating systems lead to slightly higher energy need (around 5-10%) due to back losses and overheating. This overheating risk is especially high in the BR 2020 building, but it is not specific to the demand-response strategy.

Additional simulations with external insulation (resulting in a thermal mass of $C_m = 75 \text{ Wh/}K\text{.m}^2$) were also performed. Differences were only observed for very long upward or downward modulations (over 6 hr). Finally, the temperature and power changes with a P and a PI controller were compared, but little influence on the flexibility potential was observed (not reported here for the sake of brevity).

Figure 2. Heating power and operative temperature in the BR 2005 building equipped with radiators (left) or underfloor heating system (right).

4. Flexible buildings and energy grid
In this section, quantitative data are provided to facilitate the integration of energy flexible buildings into energy prospective scenarios. The different days of the heating season are thus analyzed to get a more holistic perspective on the flexibility potential. It should also be noted that the heating season consists of 220 days for the BR 1983, 180 days for the BR 2005 and 135 days for the BR 2020. Different indicators are provided: the median decrease of heating power, the dimensionless power profile and the share of heating energy that can be displaced.

4.1. Available heating power
Figure 3 shows the mean decrease of heating power that can be achieved in the different buildings for both radiators and underfloor heating system during the DR events (one modulation a day). For all cases, a large scattering of the data can be observed; the decrease of power varies much over the heating season. As expected, the better the energy class of the building, the lower the available heating power. However, there is no linear relationship between the annual heating energy use and the available power. When comparing the radiators and the underfloor heating system, a larger decrease of power is possible with the high-inertia heating system. In fact, it can sustain longer switch-off periods without altering much the indoor environment (Figure 2). Only the BR 2020 building equipped with an underfloor heating system does not perform better than with radiators. In fact, the asymmetry between day and night heating demand is stronger with the underfloor heating system, leading to little energy demand in the beginning of the evening. This asymmetry is due to the slight overheating, which could be better handled with a more advanced controller (sluggish PI or MPC).

In order to verify that the simulations provide realistic power decrease, the results were compared to data measured during demonstration projects in residential buildings (equipped with electrical radiators). The main results are summarised below:
- “Une Bretagne d’avance” (2012-2015): 420 households and 15 000 DR events monitored, for an average power decrease of 1.1-1.6 kW per household;
- “Modelec” (2012-2015): 500 households and 22 000 DR events monitored, for an average power decrease of 1.25 kW;
- “Smart-Electric Lyon” (2012-2016): 1000 households monitored, for an average power decrease of 1 kW.

These measured results can be considered as representative of the flexibility potential of a residential building (single-family house or apartment block, average floor area 86 m²) located in France (oceanic or continental climate) for a switch-off flexibility strategy. As the simulated results correspond to a temperature-controlled case, the measured power decrease could be expected to be higher than the simulated one. This discrepancy could be explained by the user behaviour, which is simplified in the simulations. Occupants might not heat up continuously, or at a lower set-point, or some spaces might be unheated. Modelling properly the user behaviour towards heating is however challenging, as different criteria need to be accounted for, such as number of occupants, comfort preferences, type of heater and controller, type of building, incomes, etc. Correction coefficients on space heating intensity of use such as the one proposed by [10] or [11] could be used to account for such behaviour (≈0.6 in a BR 1982 building). Yet, their reliability for demand response estimation can be questioned.

![Figure 3. Decrease of the power need between 6 pm - 9pm, buildings equipped of radiators (up) and underfloor heating system (down).](image)

4.2. Dimensionless heating power profiles

Being able to predict and control the rebound effect (after a downward modulation) is of main interest for grid operators. Figure 4 shows the dimensionless heating power during and after modulations for the different days of the heating season. With radiators the rebound is relatively strong (up to 150%) but predictable and limited in time (below 20% after 3 hours), whereas the pattern is more diffuse (below 20% after 6 hr) but less predictable with underfloor heating. This relatively long rebound of underfloor heating can be interesting for performing upward modulations (pre-heating).

![Figure 4. Dimensionless heating power in the BR 2005 building equipped with radiators (left) or underfloor heating system (right).](image)
4.3. Share of displaced heating energy
When performing downward modulation from 6pm every day of the heating season, the share of displaced heating energy corresponds to around 8% for the radiators (2-10 kWh/m²\text{floor}·y) and 12% for the underfloor heating system (2-20 kWh/m²\text{floor}·y). Most of this energy displaced is used later in the evening, and the energy savings are, as expected, negligible (between 0.5-1.9%).

5. Conclusion
The objective of this study was to estimate the flexibility potential of single-family houses and provide quantitative data for energy prospective purposes. In a first part, the main differences within the building stock were highlighted. The level of insulation and airtightness greatly influence both the indoor environment and the power needs. The operative temperature drops quickly in poorly insulated buildings, with rates of change as high as 16°C/hr. A three hour switch-off of the heating system should not be considered in the BR 1982 building, but is possible in the BR 2020 building. Additionally, the influence of the emitter was highlighted. An underfloor heating system extends the flexibility capabilities of a building, and long switch-off periods can be reached without compromising thermal comfort. However, robust controllers are required to handle the overheating risk. In a second part, quantitative data are provided to facilitate the integration of energy flexible buildings in the energy grid: the median power decrease and the dimensionless power profiles were given for various buildings and emitters. One of the challenge for grid operators will be to handle/predict the variation of the flexibility potential during the heating season.

Supplementary materials
The simulated results (for downward and upward modulations) are available for interactive visualisation on: https://gitlab.univ-lr.fr/jledreau/FlexHeat.

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