Characterisation of the flexibility potential from space heating in French residential buildings

Jérôme Le Dréau, Johann Meulemans

To cite this version:

Jérôme Le Dréau, Johann Meulemans. Characterisation of the flexibility potential from space heating in French residential buildings. 7th International Building Physics Conference, IBPC 2018, 2018, Syracuse, United States. hal-01988209

HAL Id: hal-01988209
https://hal.archives-ouvertes.fr/hal-01988209

Submitted on 17 Jun 2019

Characterisation of the flexibility potential from space heating in French residential buildings

Jérôme Le Dréau[1,*], Johann Meulemans[2]

[1] LaSIE UMR CNRS 7356 / University of La Rochelle, France
[2] Saint-Gobain Recherche, France

[*] *Corresponding email: jledreau@univ-lr.fr*

ABSTRACT

Demand response (DR) at the building level (also named energy flexibility) will play an important role in facilitating energy systems based mostly or entirely on renewable energy sources. Flexibility is thus deemed necessary to control the energy consumption to match the actual energy generation from various renewable energy sources such as solar and wind power. However, there is lack of comprehensive knowledge about how much energy flexibility different building types and their usage may be able to offer to the present or future energy systems. In this study, the flexibility potential of space heating is characterised among the building stock in France. Five different typologies of buildings were chosen (post-1945, BR 1982, BR 2005, BR 2012 and BR 2020) with different levels of insulation, air-tightness and thermal mass. Building energy simulations were performed, with modulations (i.e. increase or decrease) of the space heating set-point during the heating season. From this study, the large influence of the envelope properties on the flexibility potential was highlighted: the storage efficiency for upward modulations and the rebound rates for downward modulations range from 40% up to 90% in poorly insulated and well-insulated buildings, respectively. This study describes a generic method and provides quantitative data to estimate the flexibility potential for demand response at the building level and to help designing future energy grids.

KEYWORDS

Energy flexibility; Demand response; Space heating; Building stock; Building envelope

INTRODUCTION

In order to decrease the environmental footprint of buildings, the European Union is encouraging the development of demand side management (DSM). These strategies consist in energy conservation measures to decrease the energy use of buildings on the long term and demand response (DR) to improve the operation of buildings taking into consideration the energy grids constraints. Demand response at the building level will play an important role in facilitating energy systems based mostly or entirely on renewable energy sources. Space heating, which accounts for 61% of the energy use in residential buildings in France (ADEME, 2013), can play an important role in providing flexibility to the energy grid. Recent studies in Denmark (Le Dréau and Heiselberg, 2016) and Belgium (Reynders et al., 2017) showed that the flexibility potential ranges from 50 up to 140 Wh/m^2_{floor} for 4-hour modulations. Similarly, some field tests carried out in France (e.g., Modelec and Smart Electric Lyon projects) estimated this potential from 1 up to 3 kW per household (ADEME, 2016). However, these studies focussed on the type of control system and selected one or two building typologies to draw their conclusions. There is thus a lack of comprehensive knowledge about how much energy flexibility different building types and their usage may be able to offer to the present or future energy systems. The objective of this study is to evaluate the energy flexibility potential of single-family houses with respect to their thermal characteristics, accounting for different types (i.e., upward or downward modulations) and durations of DR events. The objective of upward modulations is to fill the valleys, whereas the objective of downward modulations is to shed the peaks. The flexibility potential will be characterised by a virtual storage capacity as defined in previous studies (Le Dréau and Heiselberg, 2016; Reynders et al., 2018, 2017).

METHODOLOGY & DESCRIPTION OF BUILDINGS

Five buildings were selected to perform modulations of the space heating and can be classified according to the year of construction and the building regulation: 50's (no building regulation), BR 1982 (first building regulation in France), BR 2005, BR 2012 and BR 2020 (extrapolated from the actual building regulation in France). These five classes of buildings represent a large share of the building stock of single-family houses in France (around 30% of the single-family houses have been built within these periods). The main thermal characteristics of these buildings can be found in Table 1. The level of insulation of the buildings increases with the building regulations and the airtightness decreases. All buildings are insulated from the inside since this is a common feature in France. The building built in the 50's relies only on natural ventilation to ensure a good indoor air quality, whereas other buildings are equipped with a mechanical extraction (with either an automatic or a hygrometric regulation). It should be noted that the building layout varies with the cases (3 different geometries with a floor area from 110 up to 140 m²). Realistic occupation and internal loads scenarios were defined, resulting in a total sensible heat load of around 5000 kWh/year (which corresponds to an average load of 4.8 W/m^2_{floor}). Due to these different characteristics, the space heating needs of the simulated buildings range from 21 kWh/m^2_{floor}.year up to 290 kWh/m^2_{floor}.year in Nancy (continental climate).

Table 1. Thermal properties of the simulated buildings.

	50's	BR 1982	BR 2005	BR 2012	BR 2020
Insulation walls	1 cm IWI *(U=2.75 W/m².K)*	4 cm IWI *(U=0.64 W/m².K)*	10 cm IWI *(U=0.32 W/m².K)*	18 cm IWI *(U=0.18 W/m².K)*	22 cm IWI *(U=0.14 W/m².K)*
Insulation roof	2 cm *(U=1.3 W/m².K)*	8 cm *(U=0.58 W/m².K)*	16 cm *(U=0.23 W/m².K)*	28 cm *(U=0.13 W/m².K)*	30 cm *(U=0.10 W/m².K)*
Insulation floor	2 cm *(U=1.93 W/m².K)*	8 cm *(U=0.45 W/m².K)*	20 cm *(U=0.19 W/m².K)*	16 cm *(U=0.23 W/m².K)*	15 cm *(U=0.20 W/m².K)*
Windows	Double glazing *(U_w=3.1 W/m².K & g=0.75*	Double glazing *(U_w=3.1 W/m².K & g=0.75*	Double glazing *(U_w=1.6 W/m².K & g=0.60)*	Double glazing *(U_w=1.5 W/m².K & g=0.63)*	Triple glazing *(U_w=0.8 W/m².K & g=0.54)*
C_m [$Wh/K.m^2_{floor}$]	75 (heavy)	46 (medium)	59 (heavy)	67 (heavy)	62 (heavy)
Ventilation	-	Mechanical ventilation by extraction (airflow 195 m³/h)		Mechanical ventilation by extraction (humidity controlled, mean 125 m³/h)	
Infiltration [ACH]	0.4	0.35	0.18	0.12	0.05
HLC [W/K]	602	336	167	122	91
G [W/m^3_{heated} .K]	1.87	0.93	0.53	0.40	0.30
$\tau_{ISO\ 13790}$ [h]	16	19	47	65	81
$Q_{heating\ needs}$ [$kWh/m^2_{floor}.y$]	288	141	66	41	21

This study focusses on the flexibility that can be gained by controlling the space heating energy use. The heating system consists of radiators located in each room and emitting heat both by radiation (30%) and convection (70%). Upward and downward modulations (i.e. by increasing/decreasing the operative temperature set-point from 21°C to 23°C/19°C) were investigated for durations between 1 and 12 hours. These modulations do not jeopardise the thermal comfort of the occupants (as defined in the standard EN 15251). The starting time of the modulations (noon) was chosen to match with the peak of production in an energy production system dominated by solar panels. The controller of the radiators is a "perfect" rule-based controller, which pre-calculates at each time-step the amount of heat to be injected in the thermal zone to reach the set-point (taking into consideration the limitations of the heating system). Each building was modelled by 11 thermal zones using a Building Energy Simulation (BES) software (EnergyPlus 8.8). The simulation time-step was set to 2 minutes. Two different climatic zones in France were considered: Nancy (continental climate) and Nice (Mediterranean climate). The results obtained for both climates were quite similar, so only the results from Nancy will be presented here for the sake of brevity.

From the simulations, the heating power and operative temperature with and without modulation are compared. An example is given in Figure 1 (left), where an upward modulation for 2 hours (grey area) is performed in the building built according to the BR 2012. Three indicators are then derived from these simulations to characterise the virtual storage capacity of each building: the energy charged in or discharged from the thermal mass during the modulation ($\Delta q_{heating\,DR}$), the energy change after the modulation ($\Delta q_{heating\,post-DR}$) and the efficiency ($\eta$) of the modulation. In case of an upward modulation, the efficiency is referred to as the storage efficiency. In case of a downward modulation, the efficiency is referred to as the rebound rate. The dimensionless power profiles were also plotted for the different days of the heating season (Figure 1, right) and a large variability can be observed.

$$\Delta q_{heating\,DR} = \int_{start\,DR}^{end\,DR} \Delta P_{heating}.\,dt\ \left[Wh/m^2{}_{floor}\right] \tag{1}$$

$$\Delta q_{heating\,post-DR} = \int_{end\,DR}^{\infty} \Delta P_{heating}.\,dt\ \left[Wh/m^2{}_{floor}\right] \tag{2}$$

$$\eta = \frac{-\Delta q_{heating\,post-DR}}{\Delta q_{heating\,DR}}\ [-] \tag{3}$$

$$\overline{\Delta P_{heating\,DR}} = \frac{\int_{start\,DR}^{end\,DR} \Delta P_{heating}.dt}{\int_{start\,DR}^{end\,DR} dt}\ \left[W/m^2{}_{floor}\right] \tag{4}$$

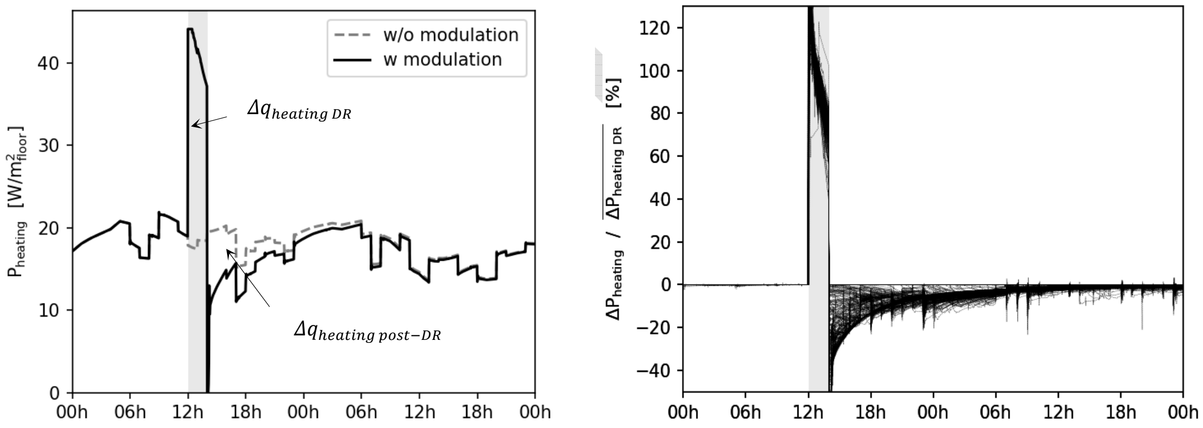

Figure 1. Heating power (26th of January) and dimensionless power profile (200 days of the heating season) for the building BR 2012.

RESULTS WITH SINGLE MODULATIONS

In a first part, single modulations were performed for each day of the heating season (resulting in more than 200 simulations for each building, each type and duration of modulation). By performing single modulations, the thermal mass has enough time to fully recover its initial state (which can last for several days) and interactions between different modulations can be dismissed.

Upward modulations

Figure 2 shows the discharged energy (post-DR) and the storage efficiency for the different buildings and the different upward modulation durations. In order to show the variability of the potential over the heating season, boxplots were used. The box shows the 25th, 50th and 75th percentiles, the whiskers extend up to 0.5 times the interquartile range and the dots represent outliers. A large number of outliers can be observed especially during the transition season, which can be explained by the large diversity in power profiles as shown in Figure 1 (right). In terms of energy, the longer the modulation, the larger the energy shifted, and the lower the storage efficiency. The influence of the building envelope can also be clearly observed: the higher the level of insulation, the higher the storage efficiency. In other words, the additional energy use when activating the building thermal mass varies much, from 50% losses in a 50s' building down to 10% losses for a BR2020 building (for a 6-hour modulation). It can also be observed that the BR 2020 building is able to store more heat during long modulation times due to the intermittent heating.

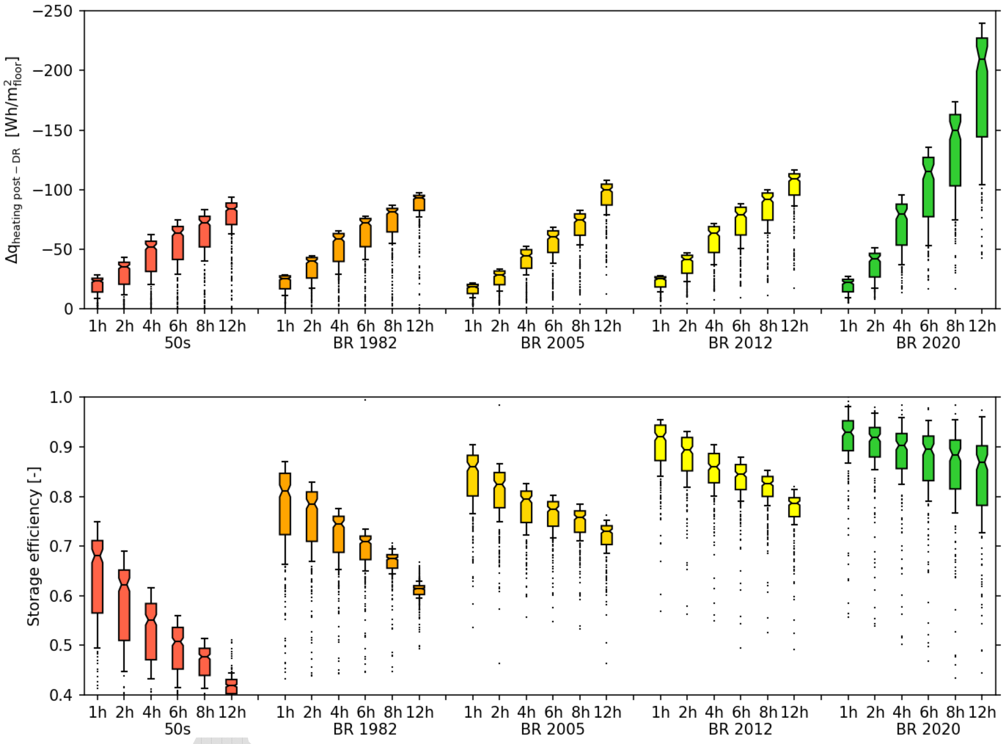

Figure 2. Heating energy post-DR (top) and storage efficiency for upward modulations (bottom).

Downward modulations

In order to harvest flexibility from buildings, downward modulations can also be performed to shave the peaks or shift part of the load. Figure 3 represents the discharged energy (during the DR) and the rebound rate for the different buildings and the different modulation durations. The lower the insulation level, the higher the energy savings. However, these higher savings come at the cost of a lower operative temperature in the building: the temperature decreases quickly in poorly insulated houses due to their lower time constant (cf. Table 1). It can also be observed that the energy shifted with downward modulations is lower than the one shifted with upward modulations, especially in relatively well insulated buildings: intermittent heating is more pronounced for well-insulated buildings. The rebound rate was also evaluated (Figure 4, bottom). A rebound rate of 100% means that the savings achieved during the downward modulation have to be fully "paid back" (resulting in no energy savings). The rebound rate exhibits a large variability within the building stock, ranging from 43% up to 87%.

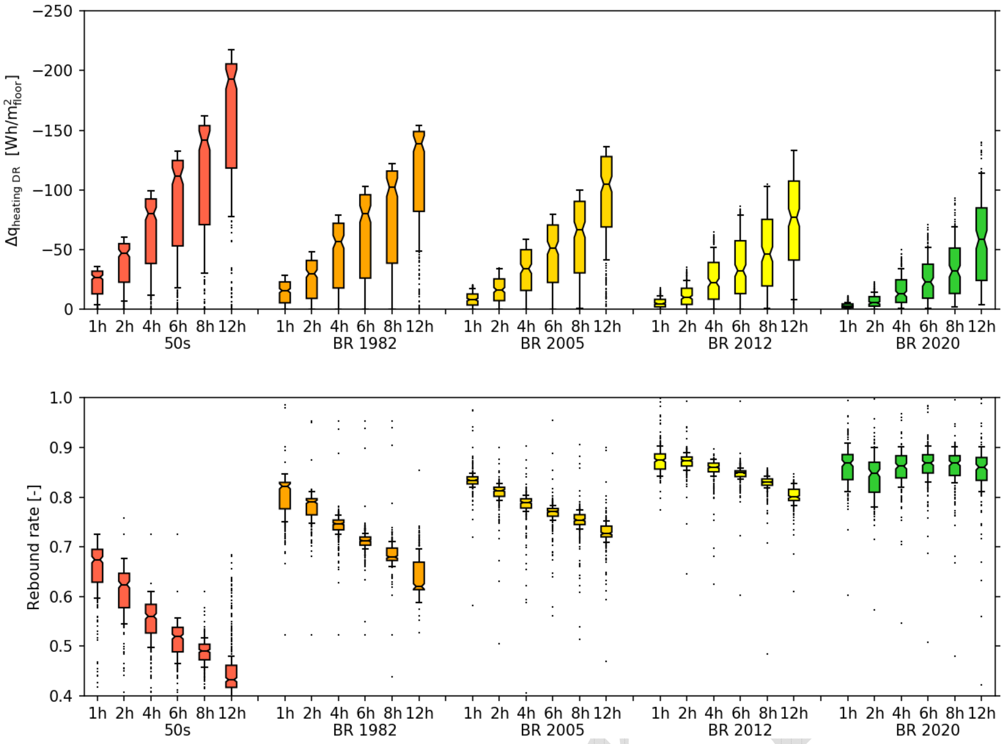

Figure 3. Heating energy DR (top) and storage efficiency for downward modulations (bottom).

RESULTS WITH DAILY MODULATIONS

In order to test a possible control strategy, the flexibility of buildings is activated once a day, starting at noon. The objectives of these simulations are both to validate the flexibility potential observed in the previous section and investigate the influence of flexibility on the yearly heating needs (energy flexibility vs. energy savings).

Figure 4 represents the annual space heating needs with upward modulations. The decreased energy use after the modulation (i.e. discharged energy) is almost constant in the building stock (around 12 kWh/ m$^2_{\text{floor}}$.year). However, the additional energy use by performing upward modulations differs and ranges from 4 up to 10% (2 up to 13 kWh/ m$^2_{\text{floor}}$.year). Figure 5 shows the resulting total energy needs with daily downward modulations. The energy savings are relatively small, around 3-4%. It can be explained by the high rebound rates (Figure 3, bottom).

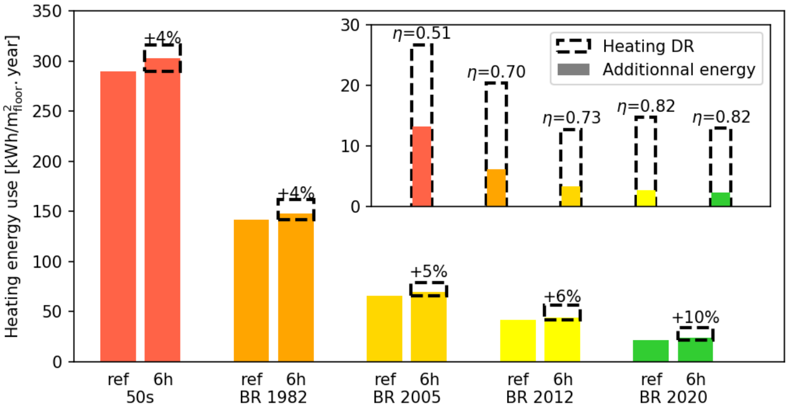

Figure 4. Annual heating need with a DR scenario (one upward modulation a day during 6 hours).

A good agreement can also be observed between the results of single and daily modulations in terms of efficiency and shifted energy. The results of single activations can thus be used by building designers to predict the flexibility potential. An example of the estimated charged energy is given below, for the BR2005 building and 6-hour upward modulations:

- from the single activations, 59 Wh/m^2/ 0.77 $\times$ 180 DR event $\approx$ 13.8 $kWh/m^2.year$
- from the daily modulations, 12.7 $kWh/m^2.year$

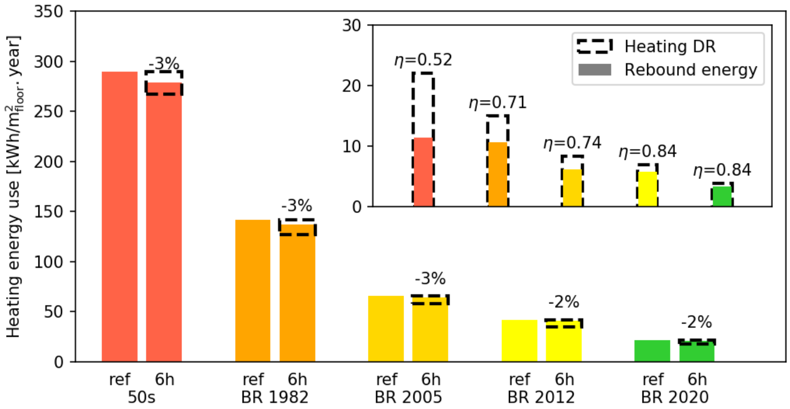

Figure 5. Annual heating need with a DR scenario (one downward modulation a day during 6 hours).

CONCLUSIONS

The energy flexibility potential of the space heating system was evaluated based on building energy simulations. Both upward and downward modulations were performed in buildings with different levels of insulation. A better characterization of the link between energy flexibility and envelope properties was achieved. Upward modulations in poorly insulated buildings should be avoided, as it leads to large storage losses (around 50% in average). Downward modulations can be performed, but they will induce rapid changes in indoor climate, which can exceed the acceptable limit set by ASHRAE (1.1°C/15 min). For relatively well-insulated buildings (built after the BR 2005), the efficiency and the stored energy did not change much and a good trade-off for flexibility was observed. If modulations are performed once a day for 6 hours, the decreased energy use as a consequence of the DR events amounts from 4 up to 22 kWh/m^2_{floor}.year. This work also provides quantitative data to building designers to estimate the flexibility potential under a specific DR scenario and to help designing future energy grids.

ACKNOWLEDGMENT

The authors would like to gratefully acknowledge IEA EBC Annex 67 - Energy Flexible Buildings for providing excellent research networking.

REFERENCES

ADEME, 2016. Systèmes Electriques Intelligents : Premiers résultats des démonstrateurs.

ADEME, 2013. Chiffres-clés du bâtiment.

Le Dréau, J., Heiselberg, P., 2016. Energy flexibility of residential buildings using short term heat storage in the thermal mass. Energy 111, 991–1002.

Reynders, G., Amaral Lopes, R., Marszal-Pomianowska, A., Aelenei, D., Martins, J., Saelens, D., 2018. Energy flexible buildings: An evaluation of definitions and quantification methodologies applied to thermal storage. Energy Build. 166, 372–390.

Reynders, G., Diriken, J., Saelens, D., 2017. Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings. Appl. Energy 198, 192–202.