Aalborg Universitet

CLIMA 2016 - proceedings of the 12th REHVA World Congress

volume 10

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Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Heiselberg, P. K. (Ed.) (2016). *CLIMA 2016 - proceedings of the 12th REHVA World Congress: volume 10*. Department of Civil Engineering, Aalborg University.

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Demand-Side Management of the Heating Need in Residential buildings

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Abstract

In the coming years, an increased share of renewable energy sources (RES) is expected in the grid, bringing up the challenge of variability and fluctuation in the energy supply. The building thermal mass could be used as a storage solution to optimise the use of fluctuating energy sources. The objective of this study is thus to define how long the activation can last without compromising the comfort of users. Using Building Energy Simulation (BES) tools, the potential of three residential buildings with different levels of insulation and air-tightness has been assessed. A price signal (i.e French spot market price) has been used as an indicator of the availability of electricity. During the time of high-price, the set-point decreases, whereas the set-point increases during time of low price. Different periods of modulations have been tested: 30 minutes, 1, 2, 4, 6, 12 and 24 hour(s).

The time constants of the buildings differ much depending on the level of insulation. This characteristic implies differences in the control strategy in order to make use of the flexibility potential without compromising comfort. The maximum time of activation varies from a couple of hours for a poorly-insulated building, up to 24 hours for a well-insulated building. From the grid perspective, a high flexibility potential has been observed: it is possible to move the heating need from hours with a high spot price to hours with a low spot price. Additionally, a sensitivity study has been conducted to observe the influence of the comfort criteria, the weather and the availability of electricity.

Keywords - energy flexibility; heat storage; heat conservation; thermal mass

1. Introduction

Many European countries have set high goals for 2050 in term of energy production from renewable energy sources (RES): Denmark aims at covering the entire energy supply (electricity, heating, industry and transport) with RES, and Germany has the objective to reach at least 80% of power from renewable sources in the electricity supply system. In France, 23% of the energy should be produced by RES by 2020, and no objective has been set yet for 2050. One of the main issue with RES is to deal with their variability, and ensure the stability of the network during periods of low production. Therefore, flexible energy systems and “smart-grids” shifting the energy system from demand-response to production-response are extensively investigated nowadays.

Some researchers pointed out the potential of the building thermal mass to store this excess energy in form of heat. Numerical studies have highlighted the influence of the level of insulation [1][2] and the type of emitter [3][4]. Moreover, demand-side management of the heating power has been tested in a few pilot projects (e.g. 3000 households in the west part of France [5][6], and 300 households in the south [7]). The response of the users to the activations were relatively positive, and the effect could be measured at the grid level. However, the periods of activation were relatively short (between 20 minutes up to 2 hours). The objective of this study is thus to define how long the activation can last without compromising the comfort of users.

As the residential sector uses a large share of energy for heating, this work focuses on single-family houses. Three buildings with different levels of insulation and air-tightness have been modelled in order to account for the diversity of the building stock. The indoor temperature set-point has then been set as a function of a price signal: the set-point decreases during high market price, whereas it increases during low market price. This price signal corresponds to the spot market price observed in the French electricity market. Different periods of modulation have been tested, ranging from 30 minutes up to 24 hours.

In a first part, the building and system parameters will be described, together with the simulation tools. Then, the results will be analysed in order to define an optimum period of activation. Finally, the robustness of the strategies chosen will be tested for different types of users, price signals and climates.

2. Case study

Three single-family houses (SFH) have been selected from the French building stock of the Tabula database [8]. The three buildings are located in France and the ambient boundary conditions correspond to the weather in Trappe for the Typical Meteorological Year (TMY). These three buildings are representative of different periods of construction (Fig. 1):

- The first house (a) corresponds to a typical building from the 80’s, and has been built according to the first French building regulation (1974). The envelope is poorly insulated (40 mm insulation on the walls), the openings are quite large and equipped with low quality double-glazing windows, and the level of air-tightness is low. The heating need is equal to 130 kWh/m².year (for 130 m²).
- The second house (b) has been built in 2014, according to the current building regulation. The envelope is better insulated (e.g. thermal resistance of the external wall of 4 m².K/W), and the openings are smaller. The air-tightness has improved and the heat losses from the

ventilation system are partly recovered using a heat pump. The heating need is equal to 50 kWh/m².year (for 105 m²).

- The third house (c) corresponds to the future building regulation, and has been named 2020+. With better envelope and systems, the heating need deceases down to 30 kWh/m².year (for 105 m²).

The three buildings are all characterised by a low level of thermal mass because the external walls are insulated from the inside. However, the time constants of the buildings are different as the heat losses vary. The detailed characteristics of the buildings can be found in Table 1.

Fig. 1. Pictures of the three single-family houses: a) 1980 b) 2014 c) 2020+

Table 1. Buildings, systems and loads characteristics.

		1980	2014	2020+
Constructions	U floor	0.42 W/m².K	0.23 W/m².K	0.23 W/m².K
	U outer wall	0.64 W/m².K	0.25 W/m².K	0.25 W/m².K
	U ceiling	0.54 W/m².K	0.17 W/m².K	0.12 W/m².K
	U-g windows	2.8 W/m².K - 0.75	1.51 W/m².K - 0.63	0.78 W/m².K - 0.47
	Pct. windows (gross area)	27%	18%	18%
	Thermal mass (C_m)	49 Wh/K.m²	47 Wh/K.m²	48 Wh/K.m²
	Time constant	21 h	39 h	57 h
Air flow	Infiltration	0.05 ACH	0.1 ACH	0.05 ACH
	Ventilation	0.4 ACH (natural)	0.4 ACH (mechanical)	0.4 ACH (mechanical)
	Heat recovery	-	η = 0.25	η = 0.8
Loads	People load	3 persons (100 W per person)		
	People schedule	Varying weekdays (nobody from 8am to 4pm), weekends		
	Equipment load	Total annual: 3660 kWh - Average load: 3.26 W/m² [9]		
	Equipment schedule	Daily, weekly and seasonal variations [9]		
Heating	Max. heating power	63 W/m²	35 W/m²	24 W/m²
	Inlet water tmp. rad.	60°C	45°C	41°C
	Inlet water tmp. u.h.	40°C	34°C	30°C

Two types of water-based heating systems have been modelled: a radiator (rad.) and an underfloor heating (u.h.). The control parameter is the flow for the radiator and the inlet temperature for the underfloor heating. The heat exchange between the radiator and the thermal zone is modelled using a UA heat exchange coefficient. For the underfloor heating, pipes are modelled as 2D heat sources and equivalent resistances are calculated. The sizing of heat emitters has been performed with a special care, as this parameter influences the thermal behaviour of the building. The sizing follows the French guidelines, with an indoor set-point of 19°C, an outdoor temperature of -7°C and an oversizing factor of +25% (Table 1).

The simulation of the building, systems and occupants is performed using EnergyPlus. Each building has been modelled with eight thermal zones, and the mean values are calculated based on area-average. Inter-zonal heat transfer through doors are modelled (airflow 0.1 m^3/m^2). In order to model accurately the phases of charges/discharges, conduction through walls is calculated using the Finite Difference Method and short time-step (2 minutes). The control of the heating set-point is handled by an external interface named BCVTB.

3. Scenarios of modulation

In order to have a reference heating need, a first simulation is performed with a constant temperature set-point of 21°C, which corresponds to the average temperature observed in French residential buildings [10]. Then, different simulations are performed to observe the influence of the set-point modulation on the energy flexibility of the building. A price signal (i.e French spot market price in 2015 [11]) has been used as an indicator of the availability of electricity. The spot market price has then been divided into three categories: low, normal and high price. A low price corresponds to a price, which is lower than the first quartile (evaluated over two weeks). A high price corresponds to a price, which is higher than the third quartile. Based on this arbitrary price definition, different periods of modulation have been tested: 30 minutes, 1, 2, 4, 6, 12 and 24 hour(s). These periods of modulations correspond to the maximum time that the set-point can be changed from its original setting (i.e. 21°C). During the time of high-price, the set-point can be decreased by 2 K, whereas the set-point can be increased by 2 K during time of low price. This range of temperature set-point has been chosen to fit with a normal level of expectation for the occupants (less than 10% dissatisfied [12]). Moreover, this temperature span of ±2K ensures that the variation of thermal comfort in time is within the comfort range (below 2.1 K/h [13]). These upward and downward modulations can be repeated over the day after a waiting period.

An example of set-point and temperature variations can be observed in Fig. 2. Based on the evaluation of the low and high spot prices (cf. figure down), the set-point is modulated over the day, with a maximum period of modulation of 2 hours. It can be observed that the temperature in the single-family house from 1980 is affected by these changes of set-point. The high inertia of the underfloor-heating system can also be observed: a more constant indoor temperature is maintained despite the modulations in power.

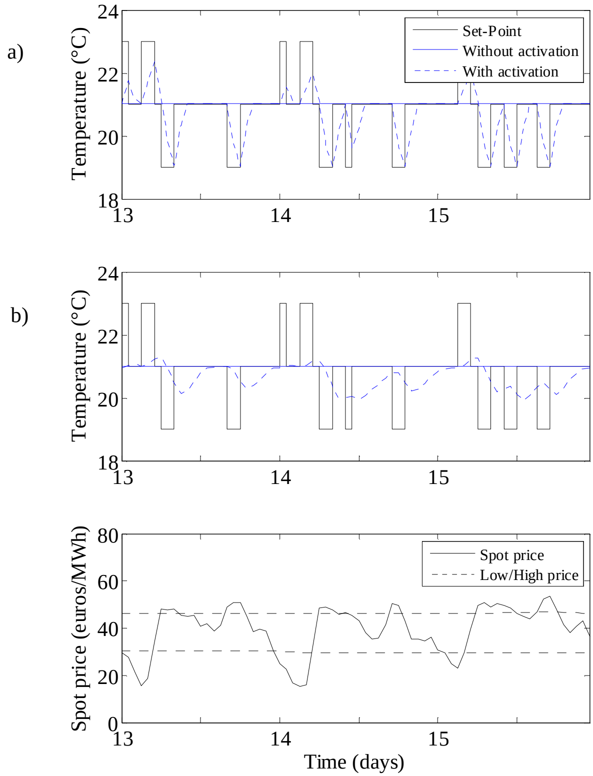

Fig. 2. Temperature and price variations during week 3 with periods of modulations of 2 hours with a) radiator, b) underfloor heating (SFH from 1980)

4. Results and comparison

The repartition of the yearly heating need between low, normal and high price can be observed in Fig. 3 for the single-family house from 1980, in Fig. 4 for the one from 2014, and in Fig. 5 for the 2020+ building. The results are expressed in term of heating need. It corresponds to the net heating need of the emission system, and not to the energy used by the heating system (i.e. the system efficiency and losses are not accounted for).

First of all, it can be observed that there is a potential for shifting the energy use from high price to low price hours. For modulations up to 24 hours, there is almost no more energy use during high price hours, except for the house from 1980 equipped with a radiator. A good shifting capability is also observed with shorter modulations (4 hours). When comparing the two types of emitters, it can be observed that the radiator uses more energy during the high price hours than the underfloor heating system, even without modulation strategy. In fact, the underfloor heating system takes advantage of its inertia, and uses less energy during daytime when the prices are usually higher. Finally, it should be added that these modulations only slightly increase the total energy use (i.e. 1-2 kWh/m^2.year).

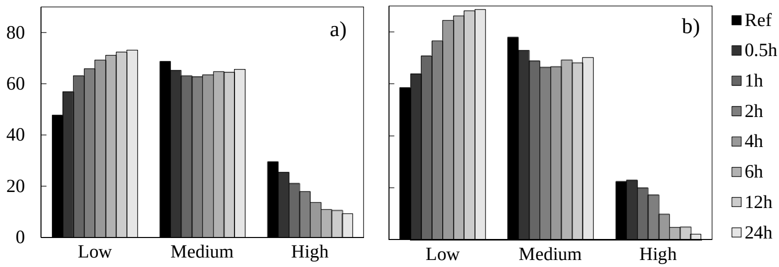

Fig. 3. Heating need, in kWh/m^2, with a) radiator, b) underfloor heating (SFH from 1980)

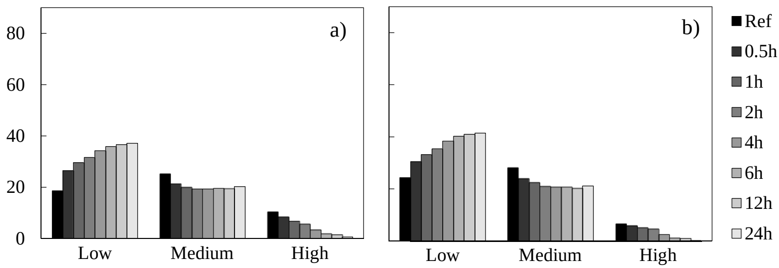

Fig. 4. Heating need, in kWh/m^2, with a) radiator, b) underfloor heating (SFH from 2014)

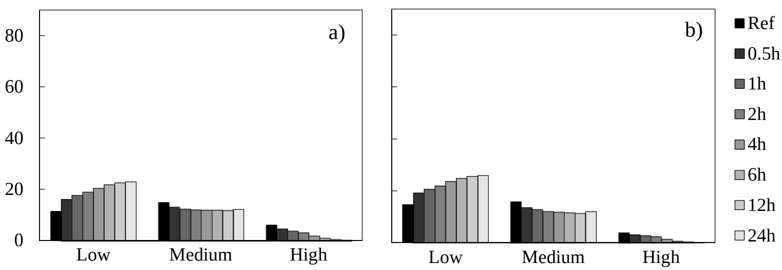

Fig. 5. Heating need, in kWh/m^2, with a) radiator, b) underfloor heating (SFH from 2020+)

In order to evaluate and compare the flexibility of the different buildings, a flexibility factor has been calculated (Eq. 1). This factor illustrates the ability to shift heating use from high to low price periods. If the heating use is similar in low and high price periods, the factor is 0. If no heating is used in high price periods, the factor is 1. If no heating is used in low price periods, the factor is -1.

$$Flexibility\ factor = \frac{\sum q_{heating\ need\ \{low\}} - \sum q_{heating\ need\ \{high\}}}{\sum q_{heating\ need\ \{low\}} + \sum q_{heating\ need\ \{high\}}} \quad (1)$$

This flexibility factor has been calculated for the different buildings and scenarios of modulation (Fig. 6). This factor increases with the number of hours of activation, with a quick rise within the first hours: the factor increases from 0.38 to 0.57 when increasing the period of modulation of the radiator from 30 minutes to 2 hours (SFH from 1980). This figure also confirms that the underfloor heating system has a higher flexibility potential than the radiators. Finally, it can be observed that there is only small differences between the 2014 and the 2020+ buildings, suggesting that time constant of actual buildings is sufficient to provide flexibility (considering the spot price from 2015 as a reference).

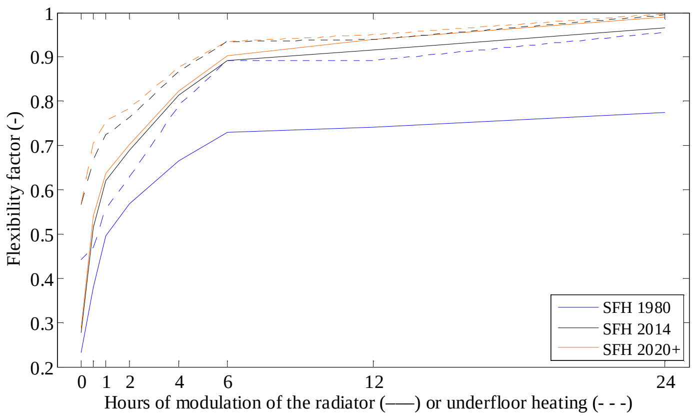

Fig. 6. Flexibility factor as a function of the duration of modulation.

However, looking only at the changes in energy use is not enough, and the indoor temperature change should also be evaluated. The 5% and 90% percentiles of indoor temperature are shown in Fig. 7, in order to illustrate variations of temperature due to the modulation (respectively due to the decrease and increase of set-point). The minimum and maximum temperatures are not shown, in order to give the general trend and not the extremum values.

First of all, it can be observed that the type of building highly influences the variation in comfort. The SFH from 1980 is quite sensitive towards a decrease of set-point due to large heat losses. Well-insulated buildings tend to be more sensitive towards an increase of set-point. The influence of the type of emitter can also be observed: the indoor temperature is less affected by an underfloor heating system than by a radiator due to its inertia. Finally, similarly to the flexibility factor, the largest variations of comfort can be observed during the first hours of activation. For modulations longer than 6 hours, the changes in indoor temperature are not so large anymore due to the limited storage possibilities.
It can also be noticed that these temperature changes are in line with the one observed during the project Greenlys [7], where the indoor temperature decreased from 0.1 up to 0.2°C during modulations of 30 minutes.

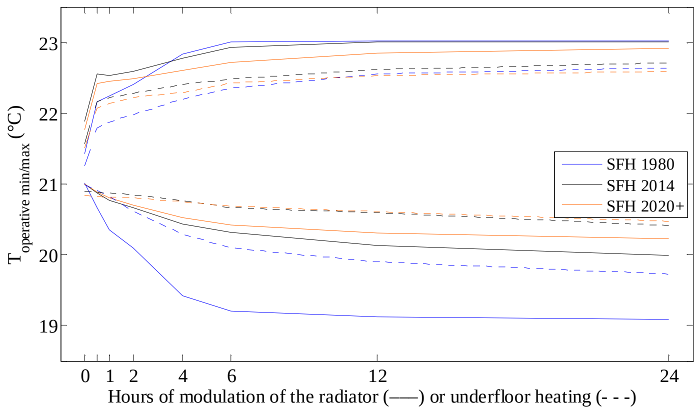

Fig. 7. 5% and 90% percentile of indoor temperature, heating season only.

In order to maximise flexibility and minimise the variations of indoor temperature, optimum scenarios have been selected for further analysis:

- 2 hrs modulations for the SFH from 1980
- 12 hrs modulation (without increase of set-point) for other buildings.

These scenarios have been chosen to have variations of the indoor temperature of less than 1°C. The increase of set-point has been avoided in new buildings, in order to prevent overheating. It results in a decrease of the flexibility factor of -0.05 pts, but the use of energy during low price hours is still avoided.

5. Sensitivity study

In order to evaluate the flexibility potential of the different buildings under varying conditions, a sensitivity study has been performed by changing one-factor-at-a-time (Table 2). The influence of the occupants (comfort settings and use of the building), the weather conditions (7 French cities) and the spot price (6 different years) has been evaluated.

Table 2. Variation of the flexibility factor under different conditions.

		1980		2014		2020+	
		Rad.	U.H.	Rad	U.H.	Rad	U.H.
No modulation		0.23	0.44	0.28	0.57	0.29	0.57
Reference modulation		0.57	0.63	0.83	0.89	0.88	0.91
Variations compared to the reference modulation	Normal set-point of 20°C	+0.03	+0.02	+0.02	+0.01	+0.01	+0.01
	Comfort band of ±1K	-0.06	0	**-0.16**	-0.01	**-0.12**	-0.01
	Bedrooms (×2) and office unheated	-0.09	-0.04	-0.12	**-0.09**	-0.11	**-0.08**
	Internal loads profile	+0.01	0	+0.01	-0.01	0	-0.01
	Other weather data from France	-0.06 **+0.12**	-0.06 **+0.11**	-0.09 +0.06	-0.05 +0.04	-0.09 +0.03	-0.06 +0.04
	Spot prices 2010-2014	-0.08 +0.04	-0.07 +0.06	-0.09 +0.12	-0.05 **+0.09**	-0.10 +0.09	-0.06 **+0.08**

From this table, it can be observed that the flexibility factor is mainly influenced by external factors (i.e. the weather conditions and the spot price). The milder the climate, the higher the flexibility (e.g. the flexibility potential is higher in the south of France than in the north). The spot price influences also much the flexibility factor: the longer the periods of high or low price, the higher the flexibility potential. In fact, long periods of modulation lead to a deeper activation of the building thermal mass. This sensitivity on the grid scenarios also highlights the fact that the future spot price should be estimated with care in order to get a reliable evaluation of the flexibility potential of buildings. Moreover, if the building is not fully occupied, the flexibility factor tends to decrease because of the heat transfer between heated and unheated spaces. Finally, the comfort settings have a little influence on the flexibility factor, except for the radiator. In that case, and if the users require changes of set-point lower than ±1K (instead of ±2K), the flexibility potential will decrease much.

6. Conclusion

The objective of this study was to evaluate the potential of buildings to support the development of renewable energies, by using their thermal mass as a storage medium. Therefore, different scenarios of modulations of the indoor temperature set-point have been tested in three typical residential buildings in France. A price signal (i.e. spot market price) has been used as an indicator of the availability of electricity, and variations of the set-point between 19°C up to 23°C have been performed. Flexibility factors have been calculated to evaluate the flexibility potential of the different cases.

A better understanding of the dynamic behaviour of buildings has been achieved in this paper. The building stock showed a high potential for moving the heating need from high to low price periods, without comprising much the indoor climate. The autonomy of an old building is relatively short, but modulations of 2 hours allow to move a large part of the heating need from high to low price hours. Well-insulated buildings have a larger time constant, and decreasing the set-point by 2°C for 12 hours does not affect much the indoor temperature (between 0.2 up to 0.5°C). In addition to the type of building, the flexibility potential and the thermal comfort are also affected by the type of emitter. An underfloor heating system maximises the use of the thermal mass, and showed the highest potential to flatten the variations.

Additionally, a sensitivity study has been conducted to observe the influence of the occupants and the external conditions. It has been observed the large influence of the weather, the spot price profile and the unoccupied spaces. Further investigation on the grid scenarios is needed.

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