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Energy flexibility of residential buildings using short term heat storage in the thermal mass

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ABSTRACT

The objective of this study is to assess the potential of buildings to modulate the heating power and define simple control strategies to exploit the flexibility potential considering both energy and thermal comfort. Two residential buildings with different levels of insulation and air-tightness have been modelled. This wide range of thermal properties covers the global performance of the residential building stock, and does not only focus on state-of-the-art buildings. Two strategies of modulation have been investigated: heat storage (i.e. increase of set-point) and heat conservation (i.e. decrease of set-point). Additionally, the effect of the time of activation and the type of emitter (radiator or underfloor heating) has been evaluated.

A better understanding of the dynamic behaviour of buildings has been achieved in this paper. Contrary to other storage solutions (e.g. battery, hot water tank), the modulation potential of the thermal mass depends on several factors (level of insulation, type of emitter, etc) and varies over time (cold vs. transition season). The autonomy of a poorly-insulated building is relatively short, whereas passive houses have a long time constant. This characteristic implies differences in the control strategy to make use of the flexibility potential without violating comfort.

1. Introduction

In many countries, the share of renewable energy sources (RES) in the grid is increasing, bringing up the challenge of variability and fluctuation of the energy supply. In Denmark, renewable energies accounted for 25% of the adjusted gross energy consumption in 2014 [1]. Denmark has the objective to cover the entire energy supply (electricity, heating, industry and transport) by RES by 2050 [1]. In Germany, the goal is to reach at least 80% of power from renewable sources in the electricity supply by 2050 [2]. However, fluctuating production can affect the electrical network by overloading power lines and/or transformers. Local differences between electricity production and demand may also lead to problems in voltage stability or resource utilization. Similar issues will appear in the new generation district heating networks [3]. Therefore, flexible energy systems and "smart-grids" shifting the energy systems from the traditional production-response to future demand-response are extensively investigated [4,5].

Buildings can be part of the solution in these future energy grids. First of all, many buildings will be both user and producer of energy (heat or electricity): these types of buildings are so called "prosumers". Buildings also offer different storage potentials, either in the structure itself (thermal storage) or in individual units (e.g. hot water tank, battery). Finally, buildings and their users can adjust their energy consumption to have a flexible energy demand. Different types of energy use can be shifted in time: Marszal and Heiselberg [6] and Mohsenian-Rad et al. [7] have studied the effect of modulating the plug load, Clement-Nyns et al. [8] have investigated the interaction between an electric vehicle and the building energy production, Evens and Kärkkäinen [9] and De Coninck et al. [10] have evaluated the effect of adjusting the hot water production, and other researchers [11–24] have evaluated the potential of adjusting the heating power. The objective of these modulations is to decrease the energy use in case of shortage (energy conservation) and/or increase the energy use in case of excess production (energy storage).

This paper will focus on the potential of the building thermal mass to modulate the energy use (thermal or electrical) of the heating system. The use of the thermal mass has been identified by Arteconi et al. [25], Hewitt [5] and Hedegaard et al. [26] as a

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promising and cost-effective solution to gain flexibility. Moreover, modulation of the heating demand can have a large influence on the grids. In fact, the heating need still represents 25% of the total energy use in Denmark despite the tightening of the building regulation [27]. This share varies with the level of insulation: the heating need of an old building amounts to around 50% of the total building energy demand (including equipment load), whereas this share goes down to 10% for passive houses [28].

Previous research projects investigating the thermal mass potential have used various approaches depending on the level of analysis. When the focus is on the grid characterisation, building models are often quite simple [16,23,26,29]. These models cannot capture the fine dynamics of buildings, especially when using low order RC-models [30]. When the focus is on the building side, optimisations are usually performed at the parcel level. The main disadvantage of these approaches is that they are constrained by the chosen grid scenario, despite the high uncertainty on this parameter [31,32]. Moreover, many case studies rely on the use of advanced controllers and optimisation functions to define the set-point [13,15,19,22]. One of the drawback of this type of approach is that the dynamic behaviour (periods of charges and discharges) is not clearly characterised. Only a few publications treat in details the different phases of the heat transfer [18,20]. Finally, further research is still needed to observe the influence of the building design parameters on the flexibility potential [17,18].

Despite these differences in methodologies, some trends can be observed in the modulation of the heating power. The level of insulation of the building has an important influence [14,18,33,34]. For a poorly insulated building, the effect is limited in time and in intensity: “the thermal demand is reduced by almost 20% for a timeframe of four hours at an ambient temperature of 0 °C” [20]. On the other hand, well-insulated buildings showed a long-lasting effect [34]: “the storage approaches allow more than eight hours without heating demand” [21].

Finally, some researchers have compared the dynamic behaviour of different heat emission systems and highlighted their large influence on thermal comfort: “not only the availability of the thermal mass, but also the interaction between the heating system and the thermal mass is of significant importance” [17]. Different heat emission systems have been compared: radiators vs. underfloor heating [11,17,18], radiator vs. TABS [12,21].

The objective of this paper is to get a better understanding of the thermal behaviour of buildings and heating systems, under different scenarios of activation. This study evaluates the amount of heat modulated and the duration of the effect on the grid. This characterisation will then be used to set simple control strategies to exploit the storage potential, considering both energy and thermal comfort. The diversity of the building stock will be evaluated by comparing the thermal response of a building from the 80's to a passive house. It has been decided to focus on the building itself and not on the energy grid, because of the difficulty to define future grid scenarios. This work, which provides a deep analysis of the storage potential in the thermal mass, can be used to compare different storage solutions (e.g. hot water tank, district heating network) and better assess the role of buildings in the future energy grids.

In a first part, the scenarios of activations, the building models and emitters will be presented. Both radiator and underfloor heating systems will be evaluated, as they interact differently with the building structure. In a second part, the scenarios of heat conservation and heat storage will be analysed in term of capacity, efficiency, autonomy and influence on thermal comfort. Finally, these results will be used to validate the strategy: the potential for shifting the energy use in time will be tested on a price scenario from 2009.

2. Scenarios of modulation

2.1. Concept

The objective of this study is to evaluate the storage potential in the thermal mass, without considering the availability of energy. Different types of activation are tested for each day of the heating season and with different starting time and duration. The variability of the performance of the modulations over the days can thus be observed. These activations are performed by a direct change of set-point. Two main modulations are evaluated:

- Heat storage (or upward modulation): the set-point is increased by 2 K for a period of time. This range corresponds to an acceptable temperature change on the hot side of the comfort zone
- Heat conservation (or downward modulation): the set-point is decreased by 2 K for a period of time. This range corresponds to an acceptable temperature change on the cool side of the comfort zone.

This range of temperature set-point has been chosen to fit with a normal level of expectation for the occupants (less than 10% dissatisfied [38]). Moreover, this temperature span of ±2 K combined with the thermal mass of buildings ensures that the variation of temperature in time is within the comfort range (below 2.1 K/h [39]). In field measurements during the heating season, relatively large temperature fluctuations can also be observed, both for poorly and well-insulated buildings [40–44]. However, one of the remaining question is to know if the occupants would accept these temperature changes based on an external signal. The first studies with short activations (20 min per day) showed a relatively good acceptation of the users [35].

Different durations of activation have been considered, ranging from 2 up to 24 h. No simulation has been performed below 2 h of activation because of the inertia of the heating system [36] and because of the limited amount of energy into play. Activations over 24 h have not been considered as occupants might not accept a long change in comfort. Moreover, the effect on the grid will be less significant after 24 h of activation, as there will be less inertial effect.

In practise, these changes of set-point can be performed in different ways with existing control systems. One of the most straightforward ways to achieve a change of set point is to modify the control of the home automation system, in order to respond to an external signal. Another solution is to control the temperature of the primary circuit (e.g. change the weather compensation [36]). Finally, a more demanding solution is to set-up a communication system with the controller of each emitter.

2.2. Implementation in the simulation environment

In order to have a reference, a first simulation is performed with a constant heating set-point of 22 °C. This set-point corresponds to a neutral thermal sensation [38]. Afterwards, a scenario of modulation is chosen (e.g. increase of set-point by 2 K for 6 h starting from midnight) and 365 simulations are performed to observe the variation of performance over the different days of a whole year. The simulations are run independently to make sure that there is no influence of the previous activation over the next one. The simulation results are then analysed by comparing the chosen scenario to the reference case. For each modulation, different information can be extracted: storage capacity, efficiency, change of operative temperature, autonomy, etc. In total, 48 scenarios of modulations have been performed for each building (changing the