Applied Energy 198 (2017) 192–202

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings

Glenn Reynders [a,b,*], Jan Diriken [c,b], Dirk Saelens [a,b]

[a] KU Leuven, Building Physics Section, Kasteelpark Arenberg 40 box 2447, BE-3001 Heverlee, Belgium
[b] EnergyVille, Thor park 8310, BE-3600 Genk, Belgium
[c] VITO, Unit Energy Technology, Boeretang 200, BE-2400 Mol, Belgium

HIGHLIGHTS

- A generic method for the bottom-up quantification of energy flexibility was developed.
- A set of reference boundary conditions is described enabling the evaluation in a design stage.
- The method is applied to typologies of the Belgian building stock, including renovation scenarios.
- Storage capacities and efficiencies depend mainly on the insulation level, the heating system and duration of the event.
- The methodology allows to evaluate the impact of dynamic boundary conditions on energy flexibility.

ARTICLE INFO

Article history:
Received 6 December 2016
Received in revised form 13 March 2017
Accepted 20 April 2017

Keywords:
Energy flexibility
Active demand response
Thermal storage

ABSTRACT

The use of structural thermal storage is often suggested as a key technology to improve the penetration of renewable energy sources and mitigate potential production and distribution capacity issues. Therefore, a quantitative assessment of the energy flexibility provided by structural thermal energy storage is a pre-requisite to instigate a large scale deployment of thermal mass as active storage technologies in an active demand response (ADR) context.

In the first part of the work, a generic, simulation-based and dynamic quantification method is presented for the characterization of the ADR potential, or energy flexibility, of structural thermal energy storage. The quantification method is based on three ADR characteristics – i.e. available storage capacity, storage efficiency and power-shifting capability – which can be used to quantify the ADR potential in both design and operation.

In the second part of the work, the methodology is applied to quantify the ADR characteristics for the structural thermal energy storage capacity for the different typologies of the Belgian residential building stock. Thereby an in-depth analysis demonstrates the relation between the building properties and its energy flexibility as well as the dependence of the energy flexibility on the dynamic boundary conditions.

1. Introduction

In order to avoid potential grid stability issues [1] associated with a high penetration of renewable energy sources and the electrification of the energy demand, active demand response (ADR) is often suggested [2,3]. In that context buildings may also play a significant role as they not only represent 40% of the total energy use world-wide, but – by taking into account their potential for thermal energy storage – they also show an important flexibility for active demand response[1] [4–6]. Using conversion technologies such as energy efficient heat pumps to convert power to heat, thermal energy storage is shown to be a low-cost alternative for direct electrical storage [7]. Moreover, thermal energy storage is widely distributed in the building sector as hot water storages or the thermal mass of the building structure, referred to as structural thermal energy storage (STES).

* Corresponding author at: KU Leuven, Building Physics Section, Kasteelpark Arenberg 40 box 2447, BE-3001 Heverlee, Belgium.
E-mail address: glenn.reynders@kuleuven.be (G. Reynders).
URL: http://www.bwk.kuleuven.be/bwf (G. Reynders).

[1] Active demand response (ADR) is defined as a temporary deviation of the energy demand compared to the reference scenario, without influencing the normal operation of the building.

http://dx.doi.org/10.1016/j.apenergy.2017.04.061
0306-2619/

The potential of thermal energy storage – and more specific structural thermal energy storage – for ADR is commonly evaluated in case studies, demonstrating the impact of using STES to shift the peak heating and cooling demand, to increase the passive use of solar and internal gains or maximize the benefits of varying energy prices [8,4,9,10]. On the one hand, these studies demonstrate significant energy cost savings, increased uptake of renewable production and greenhouse gas emission reductions when the available flexibility of the thermal mass of the building is used to optimize the buildings energy demand profile. On the other hand, a comparison of these studies shows that the results are highly case dependent. Conclusions based on this type of studies on the available flexibility of STES for ADR are difficult to generalize since energy (cost) savings demonstrated in those case studies depend upon amonst others the specific energy market context or the penetration rate and mix of renewable energy sources.

To allow a case independent analysis of the energy flexibility – enabling the comparison of the potential for ADR between different buildings and even between different storage technologies – recent studies have proposed generic quantification methods for the ADR potential of thermal energy storage. In general these quantification methods approach the assessment of the demand response potential or energy flexibility by quantifying the properties of an equivalent storage unit. This approach is introduced in Heussen et al. [11]. The study presented the 'power node framework' that models demand response technologies as generic virtual storage units, characterized by the storage capacity C, the state of charge, the efficiency of the conversion process and the storage losses or storage efficiency. A similar, generic approach – i.e. the concept of 'Energy Hubs' – was introduced in the 'Vision of Future Energy Networks' project [12]. Their main strength thereby lays in the generic description of demand response and storage technologies, allowing for a combined evaluation of a large mix of technologies. Nevertheless, in the context of structural thermal storage in buildings the challenge however still lays in finding an appropriate translation from the buildings thermal properties and dynamic thermal response to the equivalent storage, or power node, properties. As a first step, this work aims at gaining insight into this relation between building thermal properties and the resulting demand response potential, by providing and applying a comprehensive quantification framework for demand response characteristics.

As an alternative to [11], Oldewurtel et al. [13] extended the use of traditional performance indicators for storage systems – such as the energy capacity, the maximum (dis)charge power, and the autonomy – to demand response technologies, contrasting amongst others the power capacity, energy capacity, ramp rate and response time of both storage and DR technologies. Using a similar, optimal control-based approach, De Coninck et al. [14] assess flexibility by quantifying the available storage capacity in relation to the (energy) cost associated to activating the storage capacity. While the latter methods show large similarities with the ADR characteristics and quantification methods developed in this paper, De Coninck et al. [14] and Oldewurtel et al. [13] start from an optimal control formulation for the quantification methods. In this paper, the quantification methods are developed from the analysis of single ADR events. Moreover, the formulations used in this paper start form a rule-based control. Although the authors acknowledge that the optimal control formulation has important benefits in operational control applications and analysis of more complex systems, the rule-based control approach is exploited in this paper to establish a comprehensive analysis of the relation between the building design and its energy flexibility. Such an in-depth analysis of this relationship performed by a quantification of the energy flexibility of building typologies has to the authors knowledge not yet been established.

In this work, based on a review and the identified overlap of the literature presented above, 3 ADR characteristics are deduced and applied to quantify the ADR potential of STES in the Belgian residential sector. Section 2 presents the definitions and quantification methods for the ADR characteristics. Section 3 briefly summarizes the Belgian building stock model and the simulation approach used to quantify the indicators. The results are discussed in Section 4 for a theoretic case using respectively simplified (Section 4.1) and dynamic (Section 4.2) boundary conditions. The simplified boundary conditions are used to highlight the impact of the building design on the ADR potential, the latter demonstrate the impact of dynamic boundary conditions. The main conclusions and suggestions for future research are summarized in Section 5.

2. Definition of generic ADR characteristics

In this section, 3 performance indicators or characteristics for ADR are defined and quantification methods for the ADR potential of structural thermal storage are presented. These characteristics are chosen as they cover 3 main dimensions of energy flexibility that were identified in the literature review in Section 1, i.e. the dimensions of size, time and cost. In this work specifically the available storage capacity (C_{ADR}), the storage efficiency (η_{ADR}) and the power shifting capability (PSC) are presented. Thereby C_{ADR} and PSC cover the dimension of size as they represent respectively the energy and the power that can be shifted. In addition, the PSC includes the relation between the dimensions of size and time. The storage efficiency (η_{ADR}) is defined to acknowledge that activating thermal storage for demand response will induce storage losses and hence a cost for activating this storage capacity.

Note that the definitions given below are readily extended to cooling application. Also, since this study focuses on the relation between the ADR potential and the thermal properties of the building structure rather than the thermal system properties, the heating power in this paper corresponds to the net heating power emitted by the emission system to the building and not the produced power of the heating system. In other words, potential system losses or the impact of ADR on for instance the coefficient of performance of heat pumps are not taken into account in this work. A distinction has been made between radiator and floor heating systems, as the use of these systems has a major impact on how the structural thermal storage capacity is activated.

2.1. Available structural storage capacity

The available storage capacity expresses the amount of energy that can be added to the STES during a specific ADR event. Thereby, the heat that can be stored within a dwelling not only depends upon the thermal properties of the building fabric, but also on the properties and actual use of the heating and ventilation systems. Moreover for structural thermal mass these performance indicators are, in contrast to f.i. batteries, not constant but vary with the climatic boundary condition and occupant behavior. The definition therefore explicitly takes into account the time-depend aspect. The evaluation of such discrete events was also evaluated in [13–16] and was found to be a comprehensive manner to capture the ADR potential from the dynamic response of the building mass, governed by multiple time constants.

2.1.1. Definition

The available capacity for active demand response (C_{ADR} [kW h]) is defined as the amount of energy that can be added to the storage system, without jeopardizing comfort, in the time-frame of an ADR-event and given the dynamic boundary conditions.