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.

Quantifying the active demand response potential: impact of dynamic boundary conditions

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Abstract

The use of thermal energy storage using the thermal mass of buildings is often suggested as a key technology to improve the penetration of renewable energy sources and counter grid stability problems. Therefore a quantitative assessment of the flexibility provided by structural thermal energy storage and its relation to the building design is a prerequisite to instigate a large scale deployment of dwellings as active storage technologies that can be used in a demand response context.
In this work a generic, simulation-based, dynamic quantification method is presented to characterize the potential of structural thermal storage for active demand response (ADR). Thereby it is shown that, in contrast to traditional storage technologies, the ADR characteristics are not constant but vary significantly as result of the dynamic boundary conditions.

Keywords - Energy flexibility, demand-response, thermal storage

1 Introduction

In order to avoid potential grid stability issues associated with a high penetration of renewable energy sources and the electrification of the energy demand, active demand response is often suggested [1]. 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 have also shown to have an important flexibility for active demand response [1] [2, 3, 4]. This potential of thermal energy storage – and more specific structural thermal energy storage (STES) – for active demand response (ADR) is commonly evaluated in case studies, demonstrating the impact of using STES to shift the peak heating and cooling demand,

[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

to increase the passive use of solar and internal gains or maximize the benefits of time of use pricing [5, 2, 6]. Whereas 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, the results are highly case dependent. Since energy (cost) savings demonstrated in those case studies depend upon f.i. the specific energy market context or the penetration rate and mix of renewable energy sources, conclusions on the flexibility of STES for ADR are difficult to generalize.

To allow a case independent analysis of the flexibility – enabling the comparison of the potential for ADR between different buildings and even between different storage technologies – recent studies [7, 8, 9] have proposed generic quantification methods for the ADR potential of thermal energy storage. In an ADR context, Oldewurtel et al. [7] extended the use of traditional performance indicators for storage systems – such as the energy capacity, the maximum (dis)charge power, the autonomy etc. – 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. [8] assess flexibility by quantifying the available storage capacity in relation to the (energy) cost associated to activating the storage capacity. Nevertheless, in the context of structural storage the challenge however still lays in a detailed and accurate specification and quantification of the required flexibility characteristics.

Based on a review of the methodologies presented above, 4 generic performance indicators for energy flexibility were deduced in [9] and applied to quantify of the ADR potential of STES under simplified (steady state) boundary conditions. The goal of this paper is to extend the method to a dynamic evaluation of the ADR characteristics, focusing on the impact of dynamic boundary conditions. Thereby the emphasis is put on the dynamic characterization of the available storage capacity and the storage efficiency, since these two indicators were found to give important insight to the flexibility of buildings in the design phase.

In section 2, the definition and quantification method for the available storage capacity and storage efficiency are presented. Both indicators are quantified in section 3 for a set of example dwellings, showing firstly (§ 3.1) the reference results for simplified constant boundary conditions and secondly the impact of dynamic climate and comfort conditions (§ 3.2). The main conclusions are summarized in section 4.

2 Active demand response characteristics

In this section the key performance indicators for active demand response are defined and quantification methods for the ADR potential of structural thermal storage are presented. In this work specifically the available storage capacity (C_{ADR}) and the storage efficiency (η_{ADR}) are presented.

The definitions and quantification methods for C_{ADR} and η_{ADR} are based on a simulation of an ADR-event and a comparison of the resulting heating power to a reference case with the building in normal operation. As such, the ADR-event is defined as a temporary deviation from normal oper-

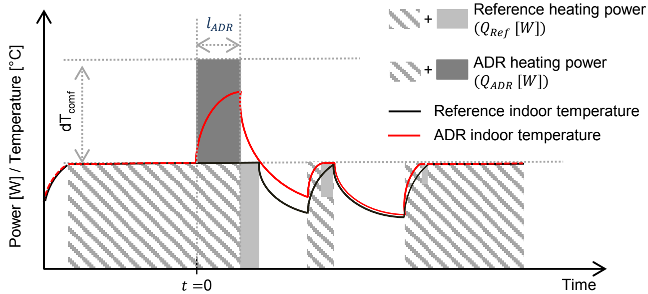

Figure 1: Scheme of the simulations used to quantify C_{ADR} and η_{ADR}

ation, in this case an increase of the set-point temperature for heating and is used to activate the thermal mass as schematically shown in Fig. 1. Assuming – without loss of generality – that for heating applications a reference (optimal) control would maintain a minimum temperature allowed by thermal comfort in order to minimize the energy use. An ADR-event will then always result in a temporary increase of the indoor temperature compared to this reference. Note that the definitions given below can be readily extended to cooling application.

2.1 Available structural storage capacity - C_{ADR}

C_{ADR} represents the amount of heat that can be stored without exceeding the maximum comfort temperature, given the building design parameters, the heating system and the dynamic boundary conditions for climate and occupant behaviour. Due to the latter, it is evident that C_{ADR} – as well as η_{ADR} defined below – are not constant, but vary in time depending on the boundary conditions, in contrast to f.i. batteries.

Definition The available structural storage capacity for active demand response (C_{ADR} [kWh]) is defined as the heat that can be added to the structural thermal mass of a dwelling, without jeopardising thermal comfort, in the time-frame of an ADR-event and given the dynamic boundary conditions.

Quantification methodology To quantify the available storage capacity – as well as the storage efficiency shown in the following paragraph – two scenarios are simulated as demonstrated in Fig. 1. A first simulation (black line) represents the reference scenario whereby the heating system is controlled to maintain the minimum comfort temperature, resulting in the reference heat demand of the dwelling ($\dot{Q}_{Ref}$). The second simulation (red line) represents an ADR-event whereby, the temperature set-point for the heating systems is increased by dT_{comf} [°C] for the duration l_{ADR} [s] .

The available storage capacity is then given by the integral of the difference between the heat input during the ADR-event ($\dot{Q}_{ADR}[W]$) and the reference heat input during normal operation ($\dot{Q}_{Ref}[W]$), represented by the dark grey area in Fig. 1:

$$C_{ADR}(t, l_{ADR}, U(t), dT_{comf}(t), \theta) = \int_0^{l_{ADR}} (\dot{Q}_{ADR} - \dot{Q}_{Ref})dt \quad (1)$$

$$\dot{Q}_{ADR} = f(t, l_{ADR}, U(t), dT_{comf}(t), \theta) \quad (2)$$

$$\dot{Q}_{Ref} = g(t, U(t), \theta) \quad (3)$$

with l_{ADR} the duration of the ADR-event, $U(t)$ the dynamic boundary conditions such as climate and occupant behaviour, $dT_{comf}(t)$ the comfort range available for ADR which may vary in time, and θ the building and system design parameters.

2.2 Storage Efficiency

As shown in [6, 10], the activation of the thermal mass results in increased indoor temperatures and thus in increased transmission and ventilation losses. Consequently, only a part of the heat that is stored during an ADR-event can be used effectively to maintain thermal comfort and reduce the heating power in the period following the ADR-event.

Definition The storage efficiency (η_{ADR} [-]) is defined as the fraction of the heat that is stored during the ADR-event that can be used subsequently to reduce the heating power needed to maintain thermal comfort.

Quantification methodology The efficiency is calculated using the same set of simulations that are used to quantify C_{ADR}:

$$\eta_{ADR}(t, l_{ADR}, U(t), dT_{comf}(t), \theta) = 1 - \frac{\int_0^{\infty} \left(\dot{Q}_{ADR} - \dot{Q}_{Ref}\right) dt}{\int_0^{l_{ADR}} \left(\dot{Q}_{ADR} - \dot{Q}_{Ref}\right) dt} \quad (4)$$

The integral in the denominator is equal to the heat stored in the ADR-event (C_{ADR}), shown as the dark grey area in Fig. 1. A part of this heat can be used after the ADR-event to reduce the heating power needed to guarantee thermal comfort as indicated by the light grey area in Fig. 1. The storage losses induced by activating the thermal mass – used as the numerator in equation 4 – thus correspond to the fraction of the heat stored during the ADR-event that is not recovered after a long period.

Note that since this study focuses on the performance of the building rather than the heating system, the heat supplied by the emission system to the building and not the energy use of the heating system is used to quantify the efficiency. Nevertheless, the method can be readily extended to include thermal systems.

3 Impact of boundary conditions

To demonstrate the impact of dynamic boundary conditions on the potential for ADR using the STES, C_{ADR} and η_{ADR} are quantified for 4 dif-

Table 1: Summary of the total floor area (A_{floor}), volume, heat loss coefficient (HLC) and effective thermal capacity[4](C_{eff}) as obtained in [11].

Property	Detached				Terraced			
	pre 1945		1991-2005		pre 1945		1991-2005	
	Org.	Ren.	Org.	Ren.	Org.	Ren.	Org.	Ren.
A_{floor} [m]	279	279	258	258	226	226	192	192
Volume $[m^3]$	766	766	710	710	621	621	527	527
HLC [W/K]	1293	229	550	194	771	228	360	214
C_{eff} [MJ/K]	176	176	171	171	124	124	158	158

Table 2: Deterministic schedule for indoor temperature setpoints

Zone	Setpoint occupied	Setpoint unoccupied	Occupied period
Day-zone	21 °C	16 °C	07:00–22:00
Night-zone	18 °C	16 °C	21:00–09:00

ferent building typologies equipped with radiator heating systems[2]. For this paper typical Belgian detached and terraced houses built before 1945 and between 1991-2005, because they cover a significant spread in the total heat loss coefficient and the available thermal mass. Two building characteristics with the largest impact on C_{ADR} and η_{ADR} [9]. Additionally for each typology, the original and thoroughly renovated building scenarios are compared. The main thermal properties are derived from the TABULA building stock description as presented in [11] and are summarized in Tab. 1, a detailed description is found in [11]. In order to limit the computation time, 9^{th}-order grey-box models that distinguishes between day- and night-zones are used. These models have been identified and validated as described in [11].

As a reference, C_{ADR} and η_{ADR} are quantified first (§3.1) assuming simplified, constant boundary conditions. Thereby, the impact of the duration of the ADR-event, the allowed temperature deviations as well as the static outdoor temperature on C_{ADR} and η_{ADR} are analysed. In the second part (§3.2), both ADR characteristics are quantified for dynamic boundary conditions, i.e. a typical climatic year for Uccle (Belgium) and a deterministic schedule for the comfort settings (Tab. 2). As an example, an ADR-event of 2 h with a comfort range of 2 °C. Note however that the maximum allowed temperature for ADR is always based on the set-point temperature during the occupied period.

3.1 Reference results for static boundary conditions

The results for C_{ADR} and η_{ADR} are shown here to demonstrate the comprehensive comparison of the ADR potential of different buildings that is obtained using simplified, static boundary conditions. Fig. 2 shows the relation between the C_{ADR} and η_{ADR} for an outdoor temperature of -10 °C, 0 °C and

[2]Heating systems are sized according to EN12831 using a reheating factor of 11 W/m^2

[4]the effective thermal capacity is defined as the fraction of the thermal mass that actively contributes to the dynamic response of the dwelling [11]

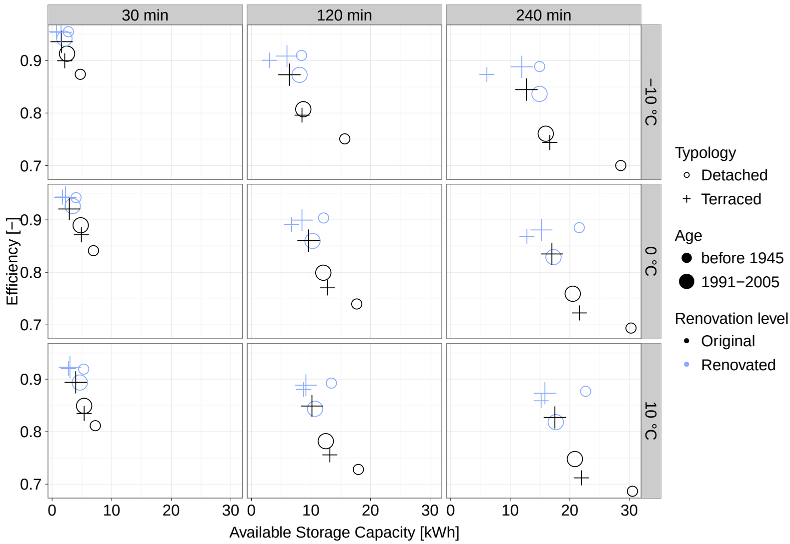

Figure 2: η_{ADR} as function of C_{ADR} for increasing outdoor temperatures (-10, 0, 10 °C) and durations of the ADR-event (30, 120, 240 min) and for the different buildings.

10 °C and a duration of the ADR-event of 30 min, 2 h and 4 h. The results show that as the outdoor temperature rises the available capacity increases while the corresponding storage efficiency decreases. The increase in C_{ADR} for increasing outdoor temperature stems from the increasing excess in heating power that is available. For an outdoor temperature of -10 °C, the heating power needed to maintain the minimum comfort temperature is close to the nominal power of the system. Consequently, the potential for ADR is limited. The increase in C_{ADR} is more pronounced when the temperature rises from -10 °C to 0 °C than for an increase from 0 °C to 10 °C. For the latter, not the available heating power but the upper comfort boundary is the limiting factor requiring the heating power to be reduced when the maximum comfort temperature is reached, hence limiting C_{ADR}.

Evidently, the available capacity increases with the duration of the ADR-events. Thereby it is emphasized that although the maximum comfort temperature is reached after less than 2 h, the available capacity keeps increasing for longer durations since the stored heat is still able to penetrate further into the thermal mass. Nevertheless, the heating power must be limited to avoid overheating and thus the rate of increase of the available capacity decreases.

In parallel, a reduction of the storage efficiency is found for increasing duration of the event and for increasing outdoor temperatures. As the duration of the ADR-event is limited (less than 30 min), storage efficiencies above 85 % are obtained in winter conditions with outdoor temperatures below 0 °C.

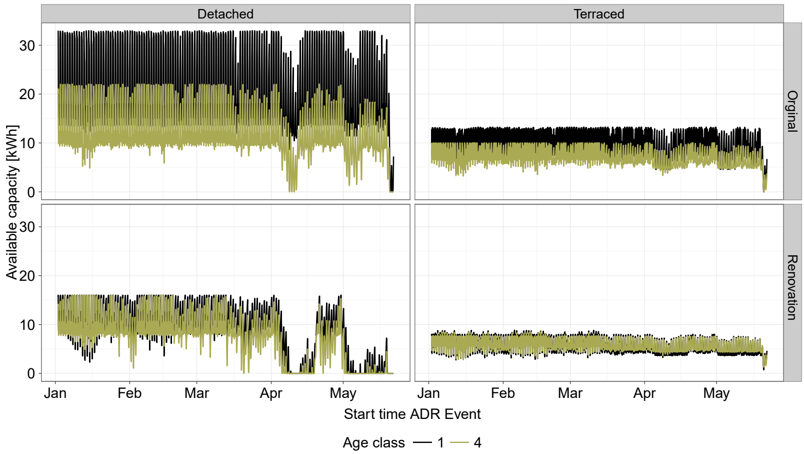

Figure 3: $C_{ADR}(t)$ for the original (top) and renovated (bottom), detached (left) and terraced (right) dwellings. The line-colour represent buildings built before 1945 (Age class 1) and between 1991-2005 (Age class 4).

As the outdoor temperature rises, the daily heat demand of the dwellings decreases. Consequently, it will take longer before the stored heat is recovered, reducing the storage efficiencies.

Finally, the building design shows a significant impact on the ADR potential. In line with the results of [9], the highest η_{ADR} is generally obtained for the terraced buildings since the ratio of the heat loss coefficient of the building over the available thermal mass is lower. For the renovated buildings, storage efficiencies up to 94 % are obtained for 30 min ADR-events in cold conditions and above 82 % for an ADR-event of 4 h and an outdoor temperature of 10 °C. C_{ADR} is found to be higher for the uninsulated buildings due to the higher heat power. It must be pointed out that for an outdoor temperature of 10 °C and a 4 h ADR-event, C_{ADR} equals 46 % of the daily heat demand[5] for the renovated terraced building, but only 12 % of the daily heat demand for the uninsulated detached dwelling.

3.2 Results for dynamic boundary conditions

While the results of §3.1 already show a correlation of C_{ADR} and η_{ADR} with the static outdoor temperature, this section analyses the impact of dynamic boundary conditions. Fig. 3 shows C_{ADR} – obtained for Belgian outdoor climate data and assuming the occupancy schedule of Tab. 2 – as a function of the start time of the ADR-event. Thereby significant variations on two time scales are shown. A long-term variation – showing decreasing values in mid-season and summer – and an important daily variation are shown.

[5]Note the daily demand here is obtained for simulation with the static boundary conditions.

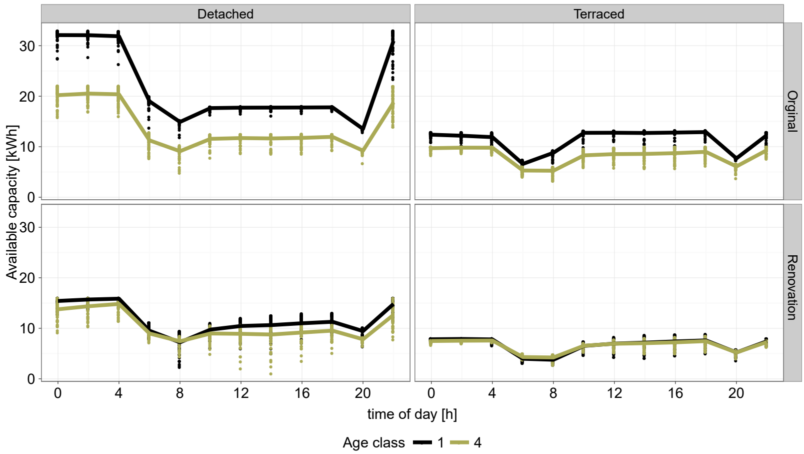

Figure 4: Daily averaged profile of C_{ADR} for the results of Fig. 3.

The averaged daily profile is discussed further in Fig. 4.

The long-term variations result from the increasing outdoor temperatures and high solar gains in mid-season. As such, the free-floating indoor temperature will rise above the minimum comfort temperature, reducing the temperature difference that is available to activate the thermal mass. The impact is more pronounced for the detached dwelling due to the higher glazed area and hence the higher solar gains. In the renovated scenario, the high solar gains for the detached dwelling and the fact that shading is not included in the model, results in indoor temperatures above 22 °C for the period between April 2^{nd} and April 12^{th} and after May 4^{th}. Consequently, the heating system can no longer be used to activate the thermal mass and the resulting available capacity for ADR is 0 kWh.[6]

In addition to the long-term variations, daily fluctuations induced by the occupancy schedule are illustrated in Fig. 3. Since, the maximum temperature in the ADR-event ($T_{max,ADR}$) is calculated based on the temperature set-point for the occupied period, hence a larger range of temperature variations is available during the set-back periods leading to an increase of C_{ADR}. To analyse this effect in more detail, Fig. 4 shows the average daily profile of C_{ADR} corresponding to Fig. 3. A difference is found between the profile of the terraced and the detached dwelling. Where for the detached dwelling

[6]Note that active cooling systems can be considered for ADR at this point, however this has not been investigated in this Belgian context. Moreover, one may argue that the use of shading devices may avoid the overheating and prolong the active use of the structural thermal energy storage capacity. In both cases, it is the authors opinion that passive strategies should always be given priority to deliver thermal comfort. This statement is supported by the results of the storage efficiency shown further in Fig. 5.

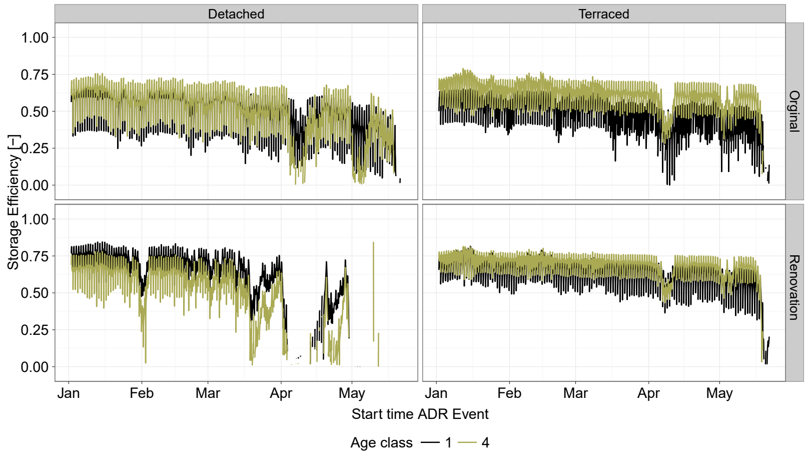

Figure 5: Obtained η_{ADR} corresponding to the cases of Fig. 3

C_{ADR} is almost 2 times higher between 10 PM and 4 AM than at night, C_{ADR} is almost equal during the day as at night for the terraced dwellings. This can be explained by the significant difference between the share of the day- and night-zone in the total heating power and implies the need for a multi-zone dynamic quantification in practice. For the detached dwelling the heating power for the day-zone is on average twice as high as for the night-zone. Consequently, the additional capacity that is available in the day-zone during the temperature set-back at night, is higher than the additional capacity that is available in the night-zone between 9 AM and 9 PM. For the terraced buildings, both zones have an equal share in the heating power.

The reduction in the capacity between 6AM and 8AM and at 8 PM, coincide with the start-up of respectively the day- and night-zone. During this period the heating in the reference case already operates at its maximum capacity to recover from the temperature setback and is therefore not available for ADR.

4 Conclusions

A generic, dynamic quantification method has been developed to assess the active demand response potential of structural thermal energy storage. The main added value of this methodology is that it enables a comprehensive comparison between different buildings and can even be extended to different storage technologies.

The available storage capacity and corresponding efficiency, as defined in this paper, allow a comprehensive comparison of the impact of the building design on the ADR potential assuming simplified, static boundary conditions. While such an approach enables a fast evaluation during the design phase, a detailed, dynamic quantification of the ADR characteristics under dynamic boundary conditions is found to be a prerequisite for control applications. Both C_{ADR} and η_{ADR} show significant dependence on the solar gains, outdoor temperature and the occupancy behaviour. Thereby the reduction in C_{ADR} and η_{ADR} as the outdoor temperature rises and solar gains increase demonstrates that the practical applicability of structural thermal storage should be limited to cold periods during the heating season to guarantee high storage efficiencies. Daily variations in C_{ADR} and η_{ADR} are found to be mainly induced by the heating schedules. For both types of variations, proper design of the control strategy to anticipate on changes in the occupant behaviour and outdoor climate should be considered.

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