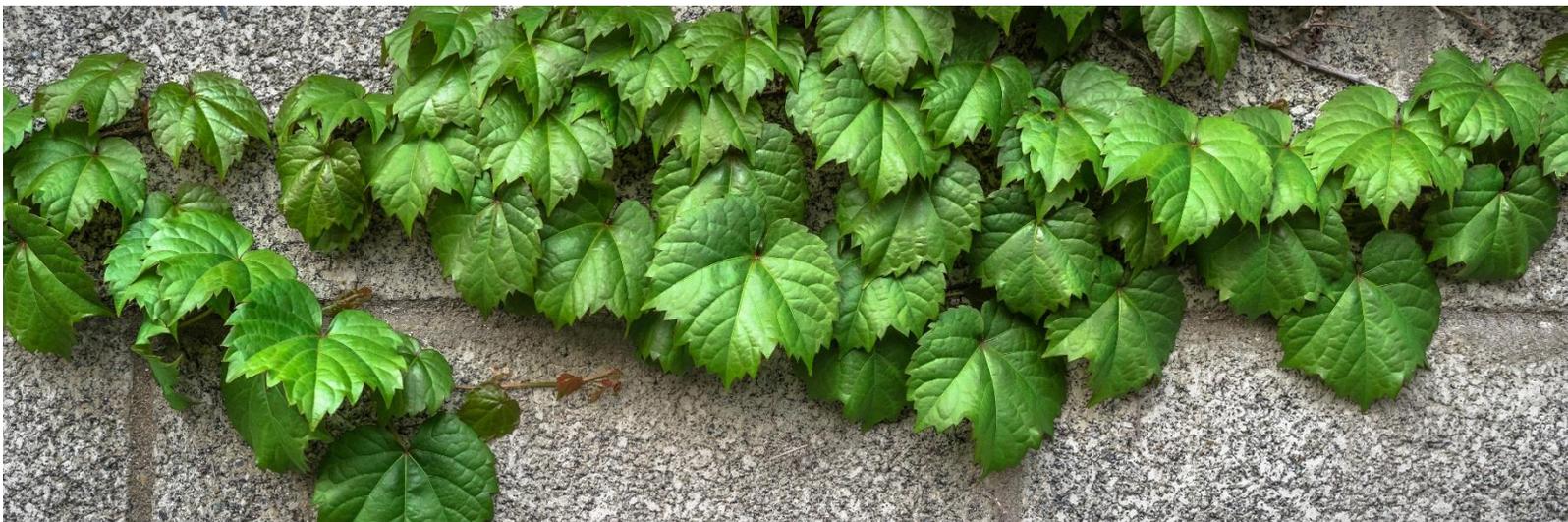


FINAL REPORT

STRUCTURAL THERMAL ENERGY STORAGE IN
HEAVY WEIGHT BUILDINGS – ANALYSIS AND
RECOMMENDATIONS TO PROVIDE FLEXIBILITY TO
THE ELECTRICITY GRID





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EXECUTIVE SUMMARY

To overcome the growing unbalance between energy demand and renewable energy generation, an increased flexibility is required from the demand side (i.e. the consumer). Orchestrated in a new energy infra- and market structure, e.g. so-called smart grids, buildings can play a significant role in demand side flexibility. Given the available inertia provided by heavyweight construction materials, and given the increasing electrification of heating and cooling systems, structural thermal energy storage (STES) in buildings can be one of the key actors for a successful demand response energy market, without additional investments in storage devices. However, the current version of the Energy Performance of Buildings Directive (EPBD) does not include the concept of structural thermal energy storage used for active-demand response (ADR).

Considering this absence, The Concrete Initiative commissioned a study to show the potential of using the structural thermal mass of heavyweight buildings, such as concrete buildings, in terms of potential increase of renewable energy penetration in the grid, avoiding grid peaks, and flexibility benefits in a smart grid context.

This report is the result of this study, and consists out of three main steps: (i) a comprehensive review of the relevant literature, (ii) the analysis of the findings and (iii) recommendations with regard to the exploitation of structural thermal energy storage.

Scientific literature demonstrates a substantial benefit in pre-cooling and pre-heating of buildings under specific conditions, i.e. for a specific type of building, equipment, control setup, comfort range, time periods for pre-cooling or pre-heating, and limited season (heating and cooling season). Most studies focus on the benefits and possible limitations in term of energy consumption savings during grid peaks, and discuss the requirements to use thermal mass to create flexibility on grid level to its full potential.

In summary, those requirements are the sufficient thermal insulation of the building, an adapted fabric cover over the underfloor heating/cooling pipes, a suitable heating/cooling system providing flexibility such as electrical heat pump or a flexible district heating, a smart controlling, the possibility to aggregate individual loads, and adapted energy prices incentives.

When fulfilling these requirements, the flexibility provided by the thermal mass of the building fabric can lead to significant benefits such as the balancing of the grid infrastructure (e.g. peak reduction up to 50% of cooling load), investment and operating cost savings (operational savings up to 40%), higher RES penetration and CO₂ emission reductions (up to 25% CO₂-reductions per dwelling).

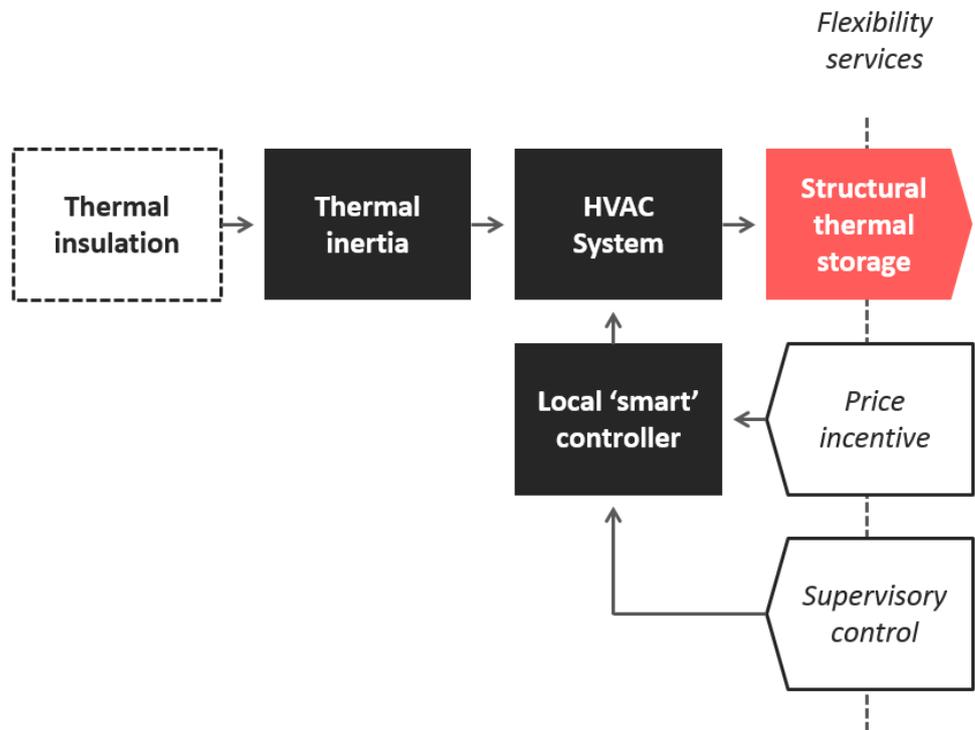


Figure 1: Schematic overview of the requirements related to the optimal use of Structural thermal energy storage

Nevertheless, different limitations are to be considered with pre-heating or pre-cooling strategies in buildings: a total electricity consumption increase due to storage losses, limited storage duration and utilization in mid-season, and comfort limitations. However, when the active demand response program is properly managed, those downsides of structural thermal storage can be addressed in order to tap the economic and environmental benefits.

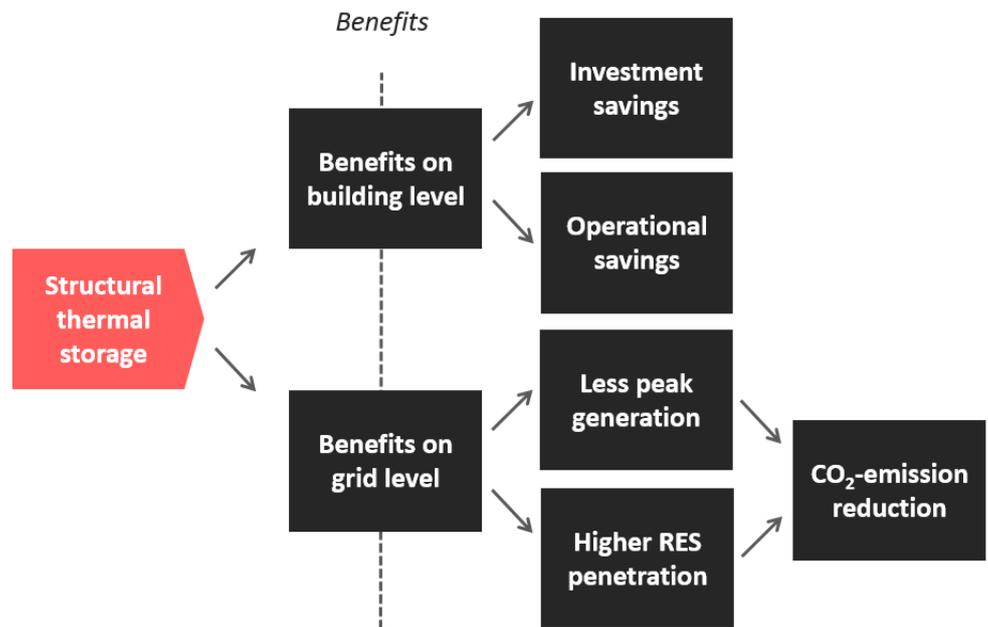


Figure 2: Schematic overview of the benefits resulting from the optimal use of Structural thermal energy storage

The current review of the EPBD is an opportunity to raise ambitions with regards to the exploitation of structural thermal storage to its full potential with the following policy recommendations:

- Evolve to new energy performance calculation models to take thermal energy storage into account.
- Insist on new energy performance calculation models to take into account the dynamic use of thermal energy storage in a load shifting context.
- Improve the recognition of the benefits of structural thermal storage by taking the “available structural storage capacity” into account in the Directive.
- Promote the interoperability between building heating/cooling systems and the energy market in order to deploy ADR.
- Encourage energy storage incentives in order to make it economically viable for end-users today.

The following policy recommendations would allow better use of the storage capacity but they are considered to be out of the scope of the EPBD.

- Encourage experimental studies / pilot projects in real buildings to demonstrate the benefits of ADR using structural thermal energy storage in operation.
- Encourage energy tariff structure reflecting the demand-supply unbalances in order to provide an incentive for ADR.
- Align storages regulatory frameworks in order to maximize the storage opportunities, especially at peak.

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1 INTRODUCTION

1.1 BACKGROUND AND PROBLEM DEFINITION

The energy system is moving from a fossil-fuel-based, highly-energy-consuming, centralised system towards a renewable-energy-based, energy efficient, more decentralised, and interdependent system. A growing number of intermittent renewable energy sources (RES) are necessary to achieve a decarbonized energy system but this also puts additional pressure on the electricity grid: the grid infrastructure has been designed to absorb centralized electricity generation and balance the grid by adapting this generation, while the unbalance between energy demand and supply can become a profound issue because of RES. To overcome this unbalance and guarantee the stability of the electricity grid, an increased flexibility is required from the demand side (e.g. the consumer). Orchestrated in a new energy infra- and market structure, e.g. so-called smart grids, buildings can play a significant role in this context of demand side flexibility.

Buildings in Europe are currently responsible for about 40% of the total energy consumption. Space heating and cooling take significant portions of this consumption. Given the possible inertia of these thermal demands and the increasing electrification of heating and cooling systems, thermal energy storage systems (TES) in buildings are one of the key actors for a successful demand response energy market (1).

Opportunities are missed when seeing buildings as basic individual units using energy when needed. The building stock in general and new buildings in particular are in a transition phase when it comes to the design of the energy system. Buildings are moving from being highly-energy-demanding and unresponsive elements in a system to becoming highly-efficient micro energy-hubs consuming, producing, storing and supplying energy, making the overall system more flexible and efficient (1). There is also an increasing potential for flexibility when using loads that can be shifted like space heating and cooling, domestic hot water, white goods (such as dish-washers or refrigerators), or electrical vehicles. The capacity of buildings to store energy is therefore an important factor in the development of smart grids.

Considering the load-shifting potential in buildings with regard to heating and cooling, the available thermal energy storage capacity exploiting the fabric thermal mass of a building can be used to pre-heat or pre-cool a building. "Structural thermal energy storage" (STES) is the appropriate term for this kind of storage since the thermal energy is mostly stored in the mass of the structural elements – i.e. walls, slabs and ceilings – and re-released on a later moment (2). In its passive form, structural thermal energy storage has actually been tapped by building designer for ages: passive night cooling of heavyweight building is a traditional way to tap the thermal mass of stone or concrete under hot climate. In a smart grid context, the active and intelligent utilisation of structural thermal energy storage is also promising. Because it is exploiting the mass of a material that has been built for other purpose; it does not require additional investment in storage devices.

The current Directive on the Energy Performance of Buildings (EPBD) is mainly aiming at the reduction of the energy use of the individual building. For instance, in order to reduce the global energy consumption of buildings, the EPBD states that all new buildings should be nearly-zero energy buildings (nZEB) by 2021. In the calculation methodology to verify if this goal is reached, it is mandatory to include thermal characteristics, heating and air-conditioning installations, renewable energy technologies, passive heating and cooling elements, shading, indoor air-quality, etc. Specifically relevant for this study, it also refers to thermal capacity in the building construction, used to improve indoor climatic conditions. (3)

Nevertheless, the current version of the **EPBD does not include the concept of structural thermal energy storage (STES) used for active-demand response (ADR)**. This study therefore focusses on the advantages and limitations of structural thermal energy storage, in order to suggest policy recommendations to include this in the EPBD-revision.

1.2 OBJECTIVES

This study, commissioned by the Concrete Initiative, presents the potential of using the structural thermal mass of heavyweight building, such as concrete buildings, in terms of potential energy efficiency and flexibility benefits in a smart grid context.

The **objective** of this study is **threefold**:

- Provide a clear definition of the concept of 'structural thermal energy storage', 'thermal mass', 'thermal capacity' and 'thermal inertia' based on current EPBD-legislation and in a smart grid context.
- Several benefits and limitations of structural thermal energy storage can be found in the scientific literature. Those benefits and limitations shall be aligned, structured and clarified in order to withhold the most promising applications.
- Provide recommendations on policy measures that would allow to tap the potential of structural thermal energy storage in buildings in order to reduce further the CO₂ emissions associated to building consumption. The Energy Performance of Buildings Directive (EPBD) is a particularly relevant target for those policy recommendations since it is under revision in 2016.

1.3 SCOPE

This study targets structural thermal energy storage (STES) in heavyweight type of buildings such as concrete buildings.

Structural thermal energy storage differentiates from the current EPBD-regulation, as **thermal capacity in the EPBD is described as a measure against overheating**. This means that the EPBD refers to the passive working of thermal inertia, which is the case in for example concrete structures where there is a lot of available thermal mass.

Structural thermal energy storage intends to activate thermal mass, in order to increase the use of thermal mass on top of its passive behaviour to store energy. This can be done through the use of Thermal Activated Building Systems (TABS) as emission system, where water tubes are integrated in a structural element in order to provide heating/cooling to a building. Known concepts based on this emission type are concrete slabs emitting heating and cooling to the floor above and below, and also floor heating where a few centimetres of a cement based solution is heated in order to heat the room above the floor.

This approach of activating thermal mass, enables an **interesting potential on grid level due to the time delay between heating/cooling and emission**. It enables structural thermal energy storage, which can be used in a smart grid context where moving loads can create flexibility for the grid through active-demand response (ADR).

Active-demand response programs, managing flexibility between buildings and the grid, are mostly applicable in a building equipped with an electric system for heating and/or cooling purposes in a smart grid electricity context. Similar active demand-response programs are also explored in the context of new generations of district heating systems (smart thermal systems), where local storage and demand-side management are proposed to increase the global efficiency of the district thermal system and increase the RES penetration (4). In order to move loads, it is important that the production unit is steered by a smart control. Whether this is a district heating/cooling system or a heat/cold source located in a single building, makes little difference in this context of load shifting.

In order to further align the scope of the study, it is important to elaborate on the working of an ADR. An active demand response (ADR) program is actively exploiting the demand side flexibility (in heating and cooling, among others) and its main impact could be summarized into three key results:

- **Peak shaving or peak clipping**, denoting the reduction of the total required peak power of buildings by reducing the required peak power for heating and cooling in buildings or by reducing the simultaneity of these peak loads with other electrical loads.
- **Load shifting**, denoting the introduction of a time delay between the system activation and the energy demand in the room by pre-heating or pre-cooling.
- **Valley filling**, denoting temporal increase of the load during off-peak periods, for example when photovoltaic own consumption cannot be valorised otherwise.

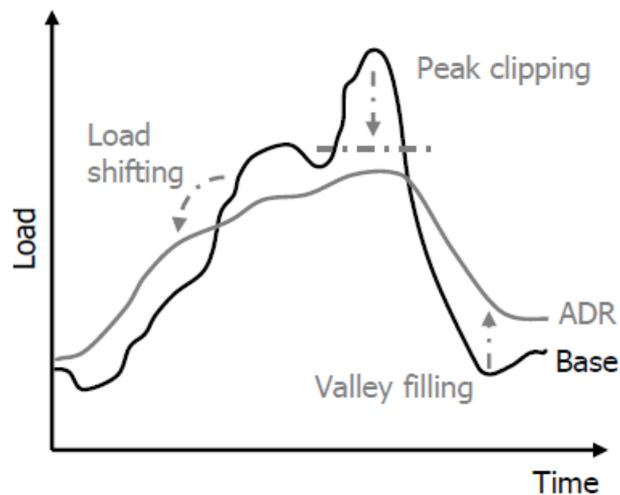


Figure 3: Conceptual daily load profile with and without active demand response (ADR) (2)

Whereas peak shaving could enable smaller equipment because of lower power requirements (system ducts, plant size, smaller grid cables) thus enabling a reduced investment (CAPEX), it can also induce a reduction of the operational cost when the electricity price contains a capacity factor. Similarly, load shifting induces a market impact and a reduced operational cost (OPEX) when the necessary price incentives exist.

Despite the incentive for several stakeholders, advantages on cost-level could be considered of limited relevancy for policy recommendations as these often focus on social welfare maximization and environmental benefits when aiming towards a sustainable horizon. For example, the potential increase of renewable energy penetration enabled by structural thermal energy storage could be considered as more relevant in this context.

The study therefore includes estimations towards cost savings, but **mainly focuses on the environmental impact that load shifting induces**, *i.e.* the possible increase of RES penetration on grid level, the decrease in peak-power generation and the induced CO₂ emission reduction.

This means that the study goes beyond the single-building energy efficiency scope and takes into account its flexibility by looking at the synergies between buildings, the electricity grid, the electricity market and the generation of electricity when studying the potential and limitations of structural thermal energy storage.

In this frame it is relevant to note that other technologies than STES can also be used to store energy in a demand-response context (for example batteries or hot water tanks) but a comparison with other storage technologies is not part of the scope of this study. The use of thermal energy storage is shown to be cost effective compared to battery storage (2). Amongst the comparative advantages of structural thermal energy storage, the low investment cost needed compared to other storage devices and the very long lifetime of the storage that is virtually the same as the lifetime of the building.

In addition to the scope described in this chapter, two examples are added in 7.4

2 METHODOLOGY

Following the definition of structural thermal energy storage and how it differentiates from the current EPBD, this chapter describes the applied approach to define policy recommendations on structural thermal energy storage.

The methodology to achieve the above goal consists of a comprehensive review of the relevant literature and the analysis of the findings, in order to draw recommendations around the active utilization of the thermal mass of a building (in addition to the current validated passive working). The approach can thus be summarized in three main steps:

1. The **Literature Review (Chapter 3)** consists of a comprehensive overview of the results of scientific papers and studies carried out in the EU and North America on the utilization of (active) thermal mass and structural thermal energy storage. The list of relevant studies that have been reviewed are available in the Bibliography in Annex 7.3. Both simulation and experimental studies from the literature have been taken into account. This review aims to collect:
 - The relevant indicators to quantify the potential of thermal mass in terms of flexibility,
 - Qualitative and quantitative results in term of flexibility and associated savings,
 - Qualitative and quantitative impact assessment in terms of environmental benefits.
2. The **Analysis of Findings (Chapter 4)** and the comparison of the different benefits and limitations of the structural thermal energy storage on building and grid level. This discussion aims to:
 - Discuss the requirements that will enable the utilization of the flexibility provided by the thermal mass to its full potential.
 - Compare the relevant findings and analyse their implications for different stakeholders and assess the evolution of those consequences in the longer term.
 - Explain the benefits that were identified in the scientific literature
 - Discuss the drawbacks and current limitations and address them when possible
3. The **Policy Recommendations (Chapter 5)** are formulated based on the literature findings and their analysis. Those recommendations are focusing on the EPBD document and its implementation at member state level.

3 LITERATURE REVIEW

Many studies have demonstrated a substantial benefit in pre-cooling and pre-heating of buildings under specific conditions, *i.e.* for a specific type of building, equipment, control setup, comfort range, time periods for pre-cooling or pre-heating, and limited season (heating and cooling season). Most of those studies are focussing on the benefits and possible downsides in term of energy consumption savings at peak, while many different additional indicators are used in the literature and a wide range of results for similar indicators can be found.

The following table provides an overview of the indicators and related quantitative results that have been found in the relevant literature.

Table 1: Overview of results from ADR using structural thermal energy storage

Strategy	Relevant Indicators	Results	Type of building (E) : Experimental (S) : Simulation	Source
Pre-heating	Structural storage capacity (load shifting – 4h period)	12 – 30 kWh/period (radiator)	Dwellings (S)	(2)
		16 – 66 kWh/period(underfloor heating)		
	Electricity costs savings	-34 %	Service building (E)	(5)
		30 – 100 €/participant per year	Dwellings (S)	(6)
		-26% to -40%	Dwellings (S)	(2)
	Heat demand fraction covered by RES	+25 %	Dwellings (S)	(2)
		+19% to +30%	Service building (E)	(5)
		up to +6.7 %	Dwellings (S)	(7)
CO ₂ emission reduction	0.25 - 0.55 t/y/building	Dwellings (S)	(2)	
	-15 % CO ₂ on average	Dwellings (S)	(2)	
Total electricity use by HP	+1.5% to +7.5% +5% on average	Dwellings (S)	(2)	
Pre-cooling	Reduced energy supply capacity (peak shaving)	-25%	Office buildings (S)	(8)
		-25% to -50 %	Commercial buildings (E)	(9)
		-15% to -35 %	Office building (S)	(10)
	Reduced consumption at peak (load shifting)	-25% to -40%	Office building (S)	(9)
	Electricity cost savings	-40 %	Office building (S)	(10)

Based on this literature findings, there are **five important observations** that can be made regarding the potential for use of building thermal mass that resulted from the studies:

- (i) There is a lack of experimental studies on real buildings available in the scientific literature, as most results have been based on simulations.
- (ii) Together with the available thermal storage capacity, the cost savings potential is very sensitive to the insulation level, control strategy, heating system characteristics, price incentives, and market set-up. In other words, there are some specific requirements that will enable the utilization of the flexibility provided by the thermal mass to its full potential.
- (iii) There is a good potential for load-shifting and peak shaving when utilizing structural thermal energy storage for pre-heating or pre-cooling (up to 50% under optimal circumstances) and the associated cost savings can be significant (up to 40%)
- (iv) The global benefits in terms of RES penetration and CO₂ emissions reduction can be quantified when analysing the RES curtailment and peak generation that can be avoided through the demand-response programs.
- (v) Load shifting can lead to an increase of the total electricity used by the heat pump because of the storage losses.

4 ANALYSIS OF FINDINGS

4.1 REQUIREMENTS AND FACILITATORS

Before analysing the identified benefits and limitations around the utilization of structural thermal energy storage, this chapter discusses requirements and facilitators that are considered essential to tap structural thermal energy storage potential. The thermal mass of building materials has been tapped by building designers for ages and building users can benefit from the flexibility provided by the passive thermal storage in some conditions without any specific design optimization or demand-response strategy. Nevertheless, there are some specific requirements that will enable the active utilization of the flexibility provided by structural thermal energy storage.

Thermal insulation

A performant insulation and ventilation system are a prerequisite to guarantee an optimal thermal storage efficiency for structural thermal storage (2), (11). Storing energy in the building material will always induce passive thermal losses. In order to improve not only the energy efficiency of the building, but also its structural thermal energy storage efficiency, the building envelope must be performant with adequate thermal insulation and air-sealing in order to contain the thermal losses to the external environment to a minimum. The total losses will also depend on the desired storage duration and the type of heating system, as discussed later.

Sufficient fabric cover

When using heating or cooling systems integrated in a concrete slab (e.g. TABS), the heating/cooling fluid and the ambient air are separated by a concrete cover. The thickness of this cover (and the resulting thermal capacity that can be activated) plays an important role in the thermal storage duration: Increasing the thickness of the cover will enable load shifting over longer durations for both heating and cooling (12).

For example, a potential storage duration of about 10 hours has been tested for a concrete cover of 15 cm thick compared to a duration of 5 hours for a cover of 5 cm (12). This thickness can be an advantage or a disadvantage depending on the load shifting strategy.

Suitable heating/cooling system

An electrical heating and/or cooling system is a prerequisite to tap flexibility on the electricity market. This will be materialized in an electricity driven heat pump. According to the European Heat Pump Association (EHPA), more than 7 million heat pumps were already operating in Europe in 2014 and the market is currently growing 10% annually. An expected increase in the penetration of energy efficient heat pump

systems for space heating will play an important role in the further electrification of the European energy market. (2)

Outside the electricity market, demand-response programs are also explored in the context of district heating systems. Local thermal storage and demand-side management are then proposed to increase the performance of the district thermal system and increase the penetration of renewable production sources (4).

Underfloor heating combined with available thermal mass for thermal storage show slightly higher storage performances compared to radiator heated system. Simulations show that a median efficiency value of 93 % is obtained for dwellings equipped with a radiator and 96 % for dwellings equipped with floor heating system. (2)

Smart control

In a smart grid context, the optimal utilization of structural thermal energy storage requires an optimization of the control strategies with adequate building automation, such as a model predictive control (MPC). This control adapts the heating and cooling by taking into account key parameters and their evolution in the future: future heat/cold demand, internal and external gains, comfort requirements, prices incentives for demand-response, storage capacity. This thus requires a communication channel between the building and e.g. a cloud computing infrastructure (2).

Load aggregation framework

When evaluated on a stand-alone basis and as a single building, the energy and power advantage as a result of operating a demand response strategy (kW or kWh) is insignificant when compared to grid-wide system requirement (MW or GWh requirements). However, an aggregated community of buildings can meet the requirements.

For example, a Dutch experiment (8) realised a cooling power peak shaving of up to 7 kW for a medium size office building while the Dutch power systems guidelines require potential to deliver a minimum bid of 1 MW, 4 MW and 20 MW for participation in power grid support services for primary-, secondary- and tertiary- reserve respectively (13). Effective load aggregation framework for multiple buildings is therefore required to participate in large demand side flexibility (DSF) schemes. On comparative scale, aggregation of simultaneous cooling loads from hundreds to a few thousand similar buildings are required for participation in provision of primary-, secondary- and tertiary- reserve respectively.

Aggregation of shiftable loads involving thousands of buildings is a challenge because of the communication required, the number of factors, appliances, equipment and buildings. This challenge should be solved with the recent and future developments in terms of building automation, communication technology, distributed control and micro-processor capabilities.

Energy price incentive

Pre-heating and pre-cooling strategies are interesting when incentives are existing, e.g. when time-of-use prices are low or when own renewable production is high. Energy cost savings cannot be realized with demand response if the energy price is flat.

Under the current tariff structure applied for the majority of European consumers, the incentive is still limited compared to its potential. Currently, typical examples of situations with incentives for the operation of a heat pump are: (i) at night when cheaper night tariff is available and (ii) on sunny days when photovoltaic own production is in excess.

In the near future, the grid operator or electricity supplier can provide incentives to consumers such as capacity tariffs and time-of-use prices that are reflecting the time-of-use grid congestion and the production prices.

4.2 BENEFITS

Transmission and distribution infrastructure

Electricity demand-response programs have shown to have a positive impact on the electricity grid. They reduce the required investment in the electricity grid capacity: by decreasing the grid congestion, peak shaving defers costly investment in network reinforcement and increase long-term network reliability. Stability issues on the distribution grid are also avoided and overall losses are reduced.

In case of district heating demand response program, similar benefits can be obtained on the pipeline network: DSM can defer costly investments in additional distribution capacity (14).

Investment cost savings

The reduction of heating or cooling peak load is considered to be one of the main benefits of a demand response strategy using structural thermal mass since there is a significant potential for investments cost savings at two levels. Both (i) the heating/cooling unit peak capacity requirement at building level and (ii) the need for additional electricity peak production units at system level are lower, leading to economic benefits.

Demand response using the structural thermal mass is able to reduce the required capacity on average by 30%, by shifting the heat pump operation away from peak periods (2). Some tests on experimental buildings have shown that there is a potential for load reduction of up to 50% in peak hours (9).

The economic benefit of peak shaving are estimated by assuming that the investment cost for a peak power plant is 1250 €/kW installed capacity (i.e. for a combined cycle gas turbine). Assuming that the avoided investment costs are shared among all the demand-response participants annually, with a plant life time of 25 years and a discount rate of 3.5%, the cost saving per household fluctuates around € 300 per year, until 50% ADR penetration. Above this penetration level, the savings per participant decrease since they are shared among a bigger number of participants (6).

Similar investment cost savings in installed capacity (close to 1000 €/kW) have been analysed for district heating (14).

Operating cost savings

Opportunities for reducing operating costs through use of building thermal mass for heating or cooling are due to four effects: (i) by replacing expensive on-peak electricity by cheaper off-peak electricity, (ii) by participating in the reserve markets, (iii) by reducing mechanical cooling resulting from the use of cool night-time air for ventilation precooling, and (iv) by improving efficiency with increasing operation at more favourable part-load and ambient conditions. However, these benefits must be balanced with the increased energy losses¹ that occurs with pre-heating or pre-cooling of the thermal mass. The resulting operating cost savings associated with load shifting and demand reductions depend upon both the method of control and the specific application. (10)

In general, better opportunities for operating costs savings exist for higher ratios between on-peak and off-peak rates and longer on-peak hours. However, the savings are more sensitive to the ratio of on-peak to off-peak rates than to the length of the on-peak period. Cooling simulations tapping the optimal control of the structural thermal energy storage have shown energy costs savings ranging from 0 to 35% depending on utility rates (10). Similar electricity savings of 34% have been observed on an experimental service building in Portugal following a pre-heating strategy to avoid consumption during peak-periods. (5)

Several studies have also shown a clear correlation between the amounts of renewable energy produced in the system (i.e. RES penetration) and the aforementioned operating costs savings potential (6), (7). Higher RES penetration tends to make the electricity prices more volatile, increasing the ratio between on-peak and off-peak rates and thus increasing the potential operating costs savings.

Higher RES penetration

The use of structural thermal energy storage has the potential to significantly increase the penetration of renewable energy sources (RES) in the electricity production mix, mainly due to a reduction of the curtailment losses (2), (5). Curtailment is a waste of renewable energy corresponding to a surplus of renewable generation compared to the electricity demand. It mainly occurs during windy night in areas with high wind energy penetration or during sunny days in areas with high photovoltaic penetration. Some scientific studies have been able to quantify the potential increase of demand covered by RES with an adapted pre-heating strategy using the structural thermal mass of the building.

For example, the use of structural thermal energy storage in Belgian dwellings could result in a 25% increase in the fraction of the heat demand covered by RES. (2)

In a country with higher RES penetration like Portugal, recent studies have found that significant part of the surplus renewable energy generated during night and early morning (19–30%) can potentially be

¹ This increase in total energy requirements is discussed in chapter 4.3

absorbed by applying a pre-heating strategy. During the cooling period, a temporary shut-down of the space conditioning can also substantially compensate the intermittences of wind power generation and wind forecasting errors during the first hour of unbalance, giving enough time for the other resources of the electrical system to adapt. (5)

This last finding is very promising for the European market since wind power already covers a significant part of the demand for electricity in many areas of Europe. Wind power often presents large variations of generation with extreme ramp rates and large forecasting errors and the wind generation exceeds the electricity demand several times a year.

CO₂ emission reduction

Due to the increased penetration of renewable energy sources and the reduction of the use of fossil fuel, the introduction of heat pumps, replacing fossil fuel heating systems, combined with demand response significantly affects the CO₂-emissions.

Simulations on Belgian dwellings have shown that active demand response strategy using structural thermal energy storage allows higher RES penetration (i.e. less curtailment) reducing the operation CO₂ emissions by 15% on average. It was shown that the individual reduction per household was ranging from 0.25 ton/year to 0.55 ton/year or from 6% to 25% depending on the building design and heating system. The best results being obtained for buildings with floor heating and the best insulation (2).

Since heating or cooling during very cold or hot periods is often carried out with peak-load marginal electricity generated with fossil fuel power plant, large reductions of CO₂-emissions may also be obtained by shaving those peaks tapping the storage potential of heavyweight buildings. For dwellings with floor heating, simulations have demonstrated a potential to reduce 550 kWh peak electricity consumption from gas-fired power plants per building per year (15). This electricity reduction roughly corresponds to a reduction of 0.275 ton/year per household.

4.3 LIMITATIONS

Energy consumption increase

In any kind of storage, one of the downsides is the global increase in the total energy consumption because of the storage losses. On a building level, the consumption increase can be explained by higher thermal losses that correspond to an increase in the indoor temperature when the building is pre-heated.

As discussed in paragraph 4.1, performant insulation is therefore essential to curb the losses that are usually in a range of 1.5% - 7.5%. For example, pre-heating strategy in Belgian dwellings would potentially increase the global electricity use of heat pumps by 5% on average (2). A less pronounced consumption has been observed when the heat pump is combined with underfloor heating systems compared to (low-temperature) radiators (15).

At country level in Belgium, the calculated absolute electricity demand increase would be in a range between 20 to 150 GWh annually (6), a very limited amount compared to the total electricity demand of about 88 TWh (0.02% to 0.17%).

One may argue that the benefits of thermal storage are wasted in higher thermal losses. To see whether this is the case, the decrease in RES curtailment per building can be plotted against the increase in electricity consumption per building.

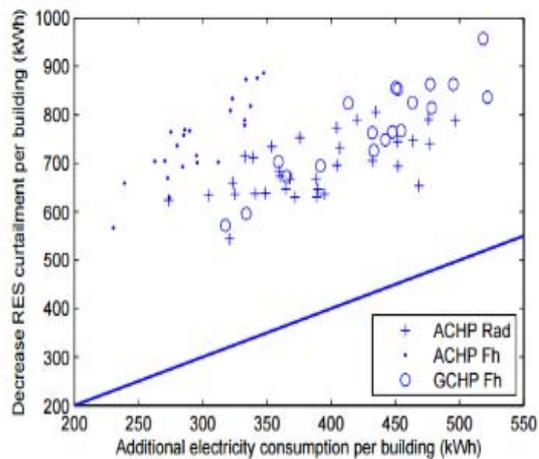


Figure 4: Decrease in curtailing RES per building with respect to extra electricity consumption per building when applying ADR. The figure shows that the decrease in RES curtailment is higher than the extra electricity consumption for all the simulations. (15)

From the above figure, the decrease in curtailment is always higher (above the line) than the increase in electricity consumption due to ADR. For example, applying active demand response causes a building to consume 230 kWh additional electricity but reduces almost 600 kWh of RES curtailment, then on a net basis, 370 kWh fossil fuel generation is saved. Hence on a net basis, less electricity from gas-fired power plants is used.

Limiting conditions

There are several limitations related to the range of utilization of structural thermal energy storage: storage duration is limited in time and often limited to specific seasons.

A minimal duration of an ADR event exists and is specific to the design of the HVAC system. This potentially limits the applicability of the proposed potential of flexibility to certain ADR market designs.

Also **a maximal duration of an ADR event** should be considered. On the one hand, the maximal duration is limited by the storage efficiency that significantly decreases with the flexibility event duration (2). Above a certain duration and depending on the heating system, insulation and available thermal mass, the thermal energy losses will be too high to be covered by the benefits in terms of cost savings and RES penetration. On the other hand, the duration is also limited by the comfort limits as will be discussed in the next chapter. With an estimation of about 2h storage for every 1°C of pre-cooling² (10), a comfort limit set to 4°C below the maximum temperature is limiting the pre-cooling duration to 8h.

There are also obvious **mid-seasonal limitations**: the available structural storage capacity and its efficiency significantly decreases with e.g. the decreasing heat demand (increasing outdoor temperatures and solar gains). In mid-season and summer the potential for ADR by activating the structural storage capacity using the heating system is marginal, due to low storage capacity and efficiency. For Northern Europe countries, ADR using structural storage capacity for the heating systems can only be used efficiently in winter. For Southern Europe countries, ADR using structural storage capacity for the cooling systems can only be used efficiently in summer (2).

The impact of **self-consumption of the photovoltaic (PV) production** is found to be limited for pre-heating strategies because periods with high PV-production coincide with low heat demands, due to the use of passive solar gains in the buildings. Consequently, the potential for load-shifting using the heating system is limited when the target is to consume PV local production. (2)

Comfort

When using the structural thermal energy storage capacity, the indoor temperature is influenced by the pre-heating/cooling strategy. This influence may not compromise thermal comfort and occupant satisfaction.

This means that, on the one hand, the indoor temperature should for instance not increase more than 1.1°C in 0.25 h or 2.1°C in 1 h as described in ASHRAE Std. 55-2004, although higher values may be allowed if this change is the result of control or adjustments by the user (2). On the other hand, absolute comfort bands can be defined but strongly depend on the outdoor climatic conditions.

² Typically, internal gains are on the order of 30 –70 W per square meter of floor space. The thermal capacity for typical concrete building structures is on the order of 12– 24 Wh/°C/m². (10)

These requirements however do not necessarily limit the applicability of STES-based ADR. It has been demonstrated that the associated operational benefits of flexibility can be grasped without compromising stated local comfort bands (6). This includes examples of heavyweight buildings where the heating in winter period remains out for up to 7 days before the heating reactivates to avoid going out of the comfort band (16). Even more, the value of the additional available flexibility given by comfort temperatures outside these bands can decrease because of lower storage efficiencies associated with higher temperatures.

4.4 IMPACT ON STAKEHOLDERS

The benefits and limitations are felt differently depending on the position of the stakeholders. The following table summarizes the qualitative impact of ADR using structural thermal energy storage on several stakeholders.

Table 2: Stakeholder table with the present and future qualitative impact of ADR on those stakeholders

Stakeholder	Present		Future	
Baseload generators³	+/-	Little incentive and see Demand Response (DR) only as a means of hedging to unplanned outages	+/-	Idem
RES generators	+	ADR is very interesting to avoid curtailment	++	Curtailment will be a growing issue with increasing RES share
Peaking generators⁴	-	See ADR as direct competition	--	Might possibly disappear with performant ADR
Transmission System Operators⁵ (TSO)	+	ADR facilitate supply and demand balance and improve reliability	++	ADR necessity shall increase since supply and demand unbalance will be a growing issue
Distribution System Operators⁶ (DSO)	+	ADR can be used to relieve network congestion and improve local reliability or quality of supply and reduce network investments	++	Idem but with increasing challenges related to energy transition
Energy retailers	+	ADR is interesting as a means to balance their contracted supply with the demand of their customers	+	Idem
Building users	+/-	ADR can be used to reduce the operation costs. Incentives to respond depends on the price incentive offered by the retailer or the DSO	+	Price incentives shall be more elaborated in the future
Building owners	+	ADR targeting peak shaving can decrease HP investment cost	+	Idem

³ Electricity producers that operate power plants consistently generating the electrical power needed to satisfy minimum/base load demand.

⁴ Electricity producers that operate power plants generating the electrical power needed to satisfy peak demand.

⁵ TSO: Operator that transmits electrical power from generation plants over the high- and medium voltage electrical grid to regional or local electricity distribution system operators.

⁶ DSO: Operator that distributes electrical power from substations to the electricity consumers over lower voltage electrical grid.

5 POLICY RECOMMENDATIONS

5.1 EPBD REVISION

The review of the Energy Performance of Buildings Directive (EPBD) is an opportunity to raise ambitions with regards to the exploitation of structural thermal storage to its full potential.

- **Evolve to new energy performance calculation models to take thermal energy storage into account:** Current energy performance calculation models that are based on a steady-state analysis do not consider storage effects which are of value on a grid level, such as the storage and release of thermal energy in the elements of the building. Dynamic calculation methods should be preferred in order to allow designers to make thermal mass available in their energy management strategy. Specifically for structural thermal energy storage, this requires the addition of the concept of *active* thermal capacity compared to the current definition of thermal capacity in the EPBD.
- **Insist on new energy performance calculation models to take into account the dynamic use of thermal energy storage in a load shifting context:** Given the stated dynamic calculation methods which allow designers to make use of thermal mass in their energy management strategy; the effective implementation of a storage-based ADR should be evaluated and rated.
- **Improve the recognition of the benefits of structural thermal energy storage by taking the “available structural storage capacity” into account in the Directive:** Thermal capacity is presently recognised in the Directive as only contributing to the energy efficiency of buildings at the same level as other solutions (i.e. insulation, heating and cooling systems, renewable energy) while the available structural storage capacity is a key indicator for their ability to participate in ADR in a smart grid context. The relation between buildings and the grid should be emphasized and promoted in a dialog between all actors in the energy sector and building industry.
- **Promote the interoperability between building heating/cooling systems and the energy market in order to deploy ADR:** Aggregation of shiftable loads involving thousands of buildings is a challenge because of the communication required, the number of factors, appliances, equipment and buildings. This communication can occur through a supervisory and control and data acquisition (SCADA) system for remote monitoring and control that operates with the grid and market signals and insures the interoperability of a massive amount of buildings.
- **Encourage energy storage incentives in order to make it economically viable for end-users today:** In the near future, the grid operator or electricity supplier can provide incentives to consumers such as time-of-use prices that are reflecting the time-of-use grid congestion in order to encourage them in participating in balancing the grid.

5.2 OTHER RECOMMENDATIONS

The following policy recommendations would allow better use of the storage capacity but they are considered to be out of the scope of the EPBD.

- **Encourage experimental studies / pilot projects in real buildings to demonstrate the benefits of ADR using structural thermal energy storage in operation.**
- **Encourage energy tariff structure reflecting the demand-supply unbalances in order to provide an incentive for ADR.**
- **Align storages regulatory frameworks in order to maximize the storage opportunities, especially at peak.**

6 CONCLUSION

The literature provides several examples of the growing potential for flexibility using building loads that can be shifted, like space heating and cooling. In a smart grid context, the structural thermal energy storage capacity of heavyweight buildings have a promising potential for load shifting or peak shaving in active demand response programs. Scientific studies demonstrated that pre-cooling strategies have a potential to reduce a buildings electricity peak by up to 50% while the total energy costs can decrease by 40% in best case. Some studies go further by translating those energy and cost savings into global benefits such as renewable energy systems increase and associated CO₂ emission reduction.

Nevertheless, it was emphasized that there are some **specific requirements enabling the utilization of the flexibility** provided by the thermal mass of a building to its full potential. An efficient thermal insulation is a basic requirement to avoid storage losses and to keep the structural thermal energy storage efficiency within acceptable ranges. When using underfloor heating system or thermally activated building systems, the fabric layer thickness is another important parameter to determine the duration of the thermal storage. In order to access the flexibility market, the building also needs suitable heating and cooling systems such as electrical heat pump or new generation district heating systems and a smart controller using optimization strategies targeting the benefits. As an individual heating or cooling system load is relatively small compared to the market needs, the load has to be aggregated e.g. in order to be able to access the balancing market. The market should provide price incentives to the building user such as time-of-use prices encouraging to consume electricity during off-peak period.

In a second step, the **main benefits of this flexibility** have been further analysed. The positive impact on the electricity grid is well known: Active demand response can reduce the required investment in the electricity grid capacity, stability issues and overall losses. Also, the reduction of heating or cooling peak load is considered to be one of the main benefits of a demand response strategy using structural thermal mass since there is a significant potential for investments cost savings at two levels: (i) the heating/cooling unit peak capacity requirement at building level and (ii) the need for additional electricity peak production units at system level are lower, leading to economic benefits. Opportunities for operating costs savings through use of building thermal mass for heating or cooling are also significant: (iii) by replacing expensive on-peak electricity by cheaper off-peak electricity, (iv) by participating in the reserve markets, (v) by reducing mechanical cooling resulting from the use of cool night-time air for ventilation precooling, and (vi) by improving efficiency with increasing operation at more favourable part-load and ambient conditions. Additionally, the use of structural thermal energy storage has the potential to significantly increase the penetration of renewable energy sources in the electricity production mix, mainly due to a reduction of the curtailment losses (i.e. due to an increase of up to 25% in the fraction of the heat demand covered by renewable energy sources). Simulations have shown that this higher renewable energy sources penetration could reduce the CO₂ emissions related to the heating of buildings by about 15%.

However, there are also **limitations** associated with the implementation of pre-heating or pre-cooling strategies. In any kind of storage, a downside is the global increase in the total energy use because of the storage losses. On a building level, the consumption increase (+5% on average) can be explained by higher thermal losses that correspond to an increase in the indoor temperature when the building is pre-heated. One may argue that the benefits of thermal storage are counteracted with higher thermal

losses, but the increased use of renewable energy largely exceeds the consumption increase. Also several limitations occur related to the range of utilization of structural thermal energy storage: the storage duration is limited to design-specific time ranges and its profitability is often limited to pronounced seasons (e.g. heating and cooling season). Lastly, the buildings thermal comfort and occupant satisfaction may not be compromised by the fluctuations in indoor temperature induced by the pre-heating (or pre-cooling) strategy.

Based on these findings, the capacity of heavyweight buildings to store energy in its structural elements shows to be an important factor in the development of so-called **smart grids**, providing the required flexibility to increase further the penetration of renewable energy sources and reduce the CO₂ emissions. Building energy efficiency policies should therefore encourage the development of energy performance calculation models which take into account structural thermal energy storage and its dynamic behaviour in a context of automated demand response. The EPBD should improve the recognition of the benefits of structural thermal storage by taking the “available structural thermal energy storage capacity” into account. The utilization of optimal controlled strategies should also be promoted, as well as the interoperability between the building control systems and the energy market. Lastly, energy storage market incentives need to be further developed and harmonized to make it economically viable for end-users. Those recommendations can foster the utilization of structural thermal energy storage which play a significant role in the energy transition.

7 ANNEXES

7.1 ABBREVIATIONS

ACHP	Air Conditioning Heat Pump
ADR	Active Demand Response
CEMBUREAU	The European Cement Association
DR	Demand Response
DSF	Demand Side Flexibility
DSM	Demand Side Management
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EU	European Union
GCHP	Ground Coupled Heat Pump
HP	Heat Pump
MPC	Model Predictive Control
nZEB	Nearly Zero Energy Buildings
RES	Renewable Energy Systems
SCADA	Supervisory Control and Data Acquisition
SRI	Smart Readiness Indicator
STES	Structural Thermal Energy Storage
TABS	Thermal Activated Building Systems
TES	Thermal Energy Storage

7.2 GLOSSARY

- **Active thermal energy storage:** TES based on a control system to administer the heat charging and discharging.
- **Available structural storage capacity for active demand response [kWh]:** the amount of heat that can be added to the structural mass of a building, without jeopardising thermal comfort, in the time-frame of an ADR-event and given the dynamic boundary conditions.
- **Demand response:** The ability to shift energy demand by reducing peak consumption and avoiding grid imbalance.
- **Demand Side Management:** DSM is inclusive of all undertakings on the demand side of an energy system undertaken in close collaboration of the consumers and power system utilities in efforts to alter load pattern using incentives, subsidies or cash benefits.
- **Flexibility:** the ability to cost effectively balance electricity supply and demand continually while also maintaining acceptable service quality to connected loads. This is inclusive of the ability for periodic energy availability to the grid over a defined time, response to random unscheduled load and provision of additional reserves to manage uncertainties arising from inaccurate forecasting or sudden change in the weather.
- **Heavyweight building:** construction made of loadbearing elements mainly composed with heavyweight materials such as reinforced concrete, concrete masonry, stone, bricks or rammed earth. Those heavyweight materials mostly have a high thermal mass compared to other materials.
- **Passive thermal energy storage:** means that building parts with high heat capacity can absorb and emit heat when the temperature in the environment changes. This is a phenomenon that always takes place, even if no direct actions are carried out to utilize it at its full capacity.
- **Power shifting capability [s]:** the duration during which a change in heating/cooling power can be maintained, given the dynamic boundary conditions and the current state of charge, before the comfort requirements are jeopardized.
- **Primary Energy:** energy from renewable and non-renewable sources which has not undergone any conversion or transformation process
- **RES Curtailment:** Temporary reduction of renewable energy generation due to a shortage of electricity demand or because the supplied power exceeds the grid capacity.
- **Smart Grid:** upgradable electricity network that is enabled for intelligent control and multi-directional communication between sources, loads and components in such a manner that allows for cooperative and economical energy utilization.
- **State of charge:** the fraction of the energy content of the storage medium at time t compared to the total storage capacity.
- **Storage efficiency:** the fraction of the heat that is stored during the ADR-event that can be used subsequently to reduce the heating/cooling power needed to maintain thermal comfort.
- **Structural thermal energy storage (STES):** TES using building materials as storage medium.
- **Thermal capacity:** Terminology used in the EPBD recast Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the performance of buildings. Regulation No

244/2012 supplementing this directive denotes 'thermal capacity per unit area' measured in units of $J/(m^2K)$ and to be evaluated according to EN ISO 13786⁷

- **Thermal energy storage (TES):** Any technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications.
- **Thermal inertia:** Commonly used for modelling thermal transfers properties of a material, defined as the square root of the product of the material's bulk thermal conductivity and volumetric heat capacity.
- **Thermal mass:** One or multiple elements in the building with a significant amount of 'thermal capacity' able to store thermal energy in a building.

⁷ ISO 13786:2007 - Thermal performance of building components -- Dynamic thermal characteristics -- Calculation methods.

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7.4 TWO PRACTICAL EXAMPLES

7.4.1 Example 1 – “Low tech” - Office building with cooling chiller

This example is an office building with a typical heavyweight building structure such as concrete providing a significant thermal energy storage capacity. The heating source is a gas boiler and the cooling occurs through chillers. Both heating and cooling distribution system are connected to local fan coil units. Because of those simple devices, this example is named “low tech” although a smart building controller has been installed in order to optimize the building control including possible pre-heating and pre-cooling strategies.

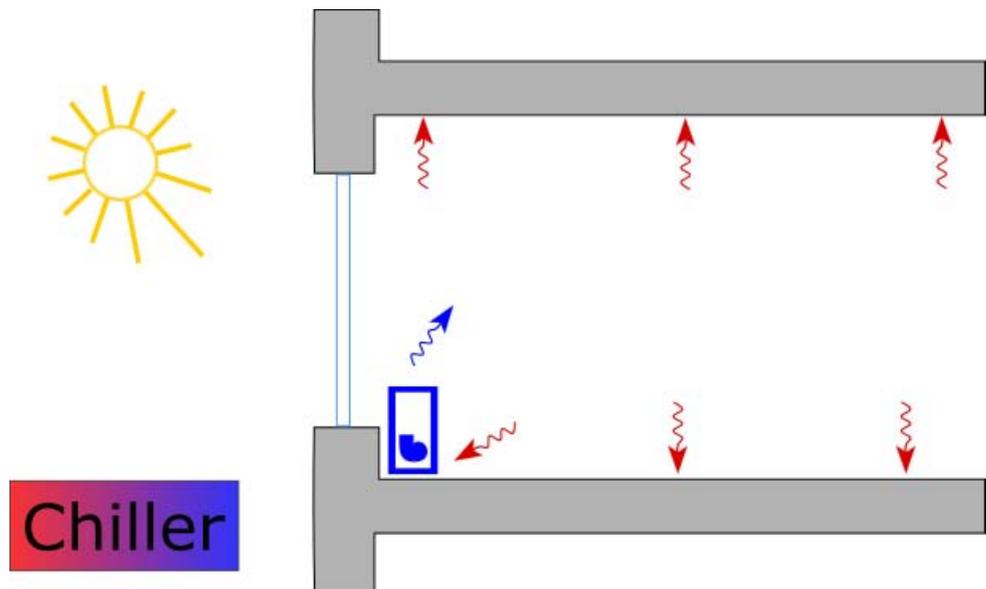


Figure 5: Schematic system description of Example 1

Because of large solar gains through wide windows and the significant internal thermal gains related to office spaces (mostly computers and users), the building requires cooling during the summer in order to avoid overheating. This cooling has a significant impact on the electricity bill when it is operated during the day. However, there is a price incentive to pre-cool the building during the night when electricity rates are lower than the day rates. At night, the electricity needed for circulators and the chiller can be purchased at lower tariffs. In the case of cooling, the air cooled in the fan coil circulates in the room and cools down the thermal mass of the building. By this means cooling is “stored” in the building structure.

During daytime, the thermal mass of the building absorbs internal and external heat gains. In many cases, the cooled down building structure is able to avoid active cooling until noon. The operative temperature raises, and when it reaches the upper boundary of the comfort range, the cooling system is activated. The sizing of the production units can be limited because of the peak-shaving effect the precooling enhances.

7.4.2 Example 2 – “High tech” – Office building with heat pump and TABS

This example is a modern office building with a concrete building structure providing a significant thermal energy storage capacity. The concrete slabs are including a Thermally Activated Building System (TABS) that acts as a heating and cooling distribution system. The heating and cooling source is a geothermal heat pump. The cooling can be passive (geothermal passive cooling with a circulator) or active (geothermal active cooling using the heat pump and the circulator). Because of those more advanced devices, this example is named “high tech”. A smart building controller has also been installed in order to optimize the building control including possible pre-heating and pre-cooling strategies.

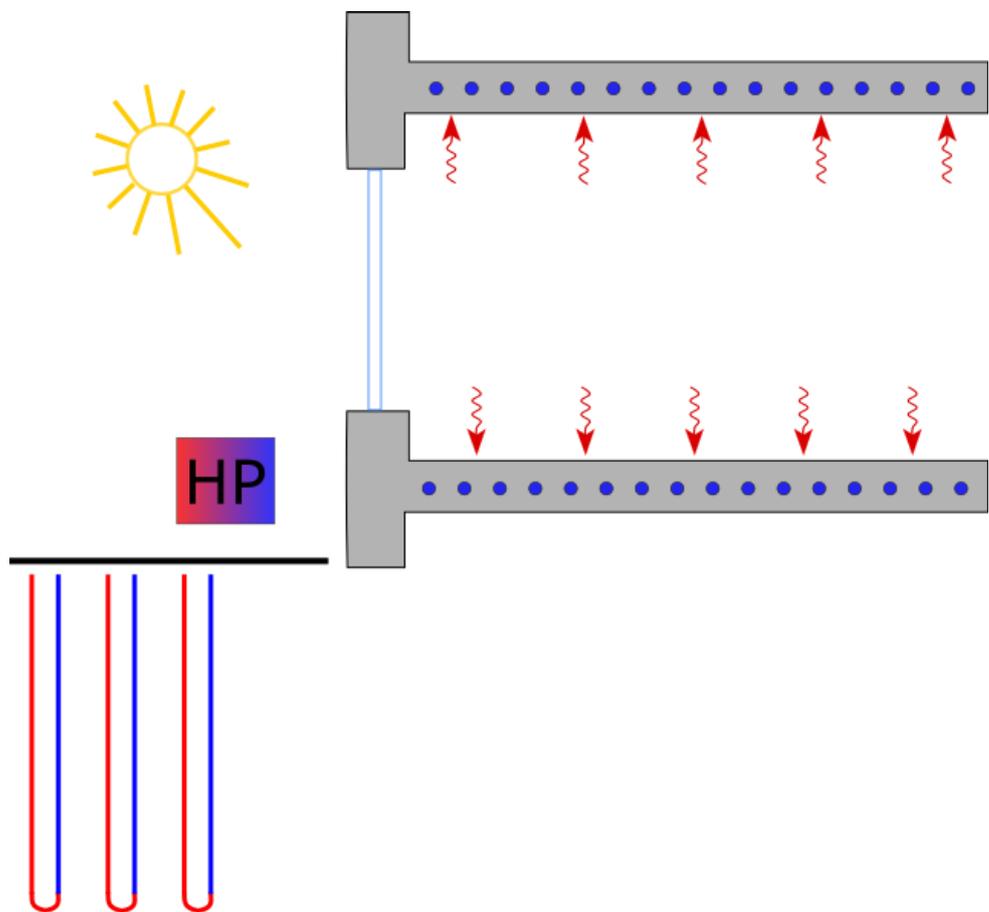


Figure 7: Schematic system description of Example 2

In this example, there is a large amount of electricity produced intermittently by wind turbines. During the periods with high wind production, there is an incentive to pre-cool the building in order to tap lower electricity tariffs. The cooling production system can follow the production of wind energy. During periods of high green electricity yield, the system will “charge” the TABS. In the case of cooling, it will drop the

surface temperature till +/- 22°C⁸. This means that the concrete slabs have a lower inside temperature and will be able to provide a lot of cooling the next day. During daytime, the thermal mass of the building absorbs internal and external heat gains. The heat pump is not active. Green electricity can be used for other purposes such as office equipment, ventilation, lighting, etc. The operative temperature raises, but does not exceed the upper part of the allowed temperature range.

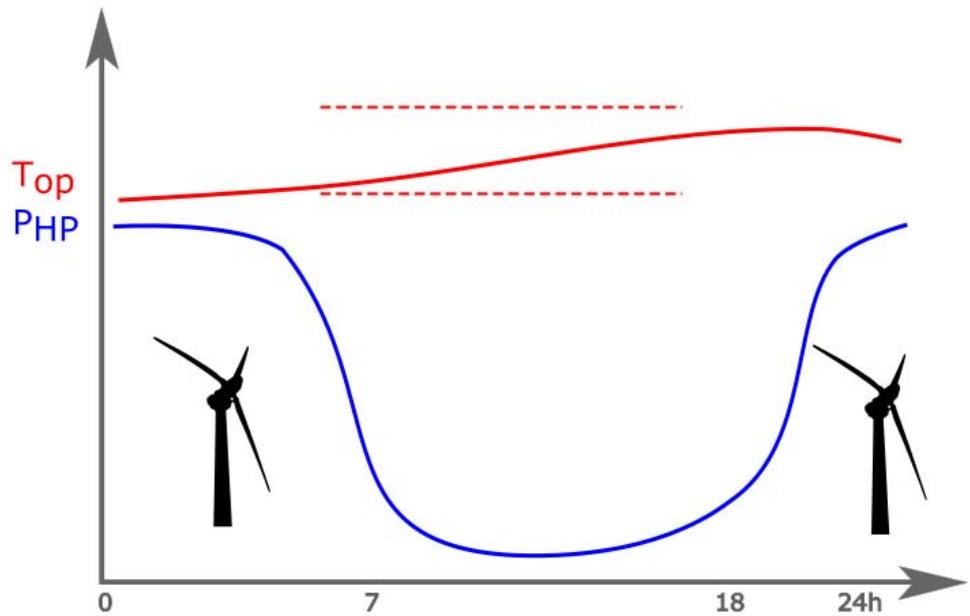


Figure 8: Conceptual daily power- and temperature profiles of Example 2. Here, T_{op} indicates the operative temperature with the comfort boundaries indicated with dashed lines, while P_{HP} denotes the power consumption of the chiller.

⁸ The surface temperature should always be higher than the dew point temperature. 20...22°C is a safe temperature in dry and moderate climates.

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