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Utilizing thermal building mass for storage in district heating systems: Combined building level simulations and system level optimization

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ABSTRACT

Higher shares of intermittent renewable energy in energy systems have raised the issue of the need for different energy storage solutions. The utilization of existing thermal building mass for storage is a cost-efficient solution. In order to investigate its potential, a detailed building simulation model was coupled with a linear optimization model of the energy system. Different building archetypes were modelled in detail, and their potential preheating and subsequent heat supply cut-off periods were assessed. Energy system optimization focused on the impact of thermal mass for storage on the energy supply of district heating. Results showed that longer preheating time increased the possible duration of cut-off events. System optimization showed that the thermal mass for storage was used as intra-day storage. Flexible load accounted for 5.5%–7.7% of the total district heating demand. Furthermore, thermal mass for storage enabled more solar thermal heating energy to be effectively utilized in the system. One of the sensitivity analyses showed that the large-scale pit thermal energy storage and thermal mass for storage are complimentary. The cut-off duration potential, which did not compromise thermal comfort, was longer in the newer, better insulated buildings, reaching 6 h among different building archetypes.

1. Introduction

District heating systems produce heat centrally and distribute it to the end consumers via transmission and distribution pipes. Heat storage can be used when a mismatch between the timing of production and demand for heat occurs. Other solutions include peak boilers that can quickly be dispatched. When comparing heat storage and peak boilers, the former usually has large capital costs and low operating costs, while the latter usually have larger operational costs and lower capital costs.

All buildings, which are connected to district heating systems, have certain thermal capacities for storing heat inside the structure of the buildings. Contrary to the usual heating storage types such as hot water tanks or water pits, the capital costs for the utilization of thermal mass for storage is close to zero, as the building structure does not have to be modified additionally. Thus, utilizing thermal mass for storage could be an efficient solution for load shifting and/or peak shaving in district heating grids. The objective of this paper is to analyse the potential of utilizing thermal mass for storage in district heating systems in order to reduce the operational costs of the district heating systems by optimally shifting the district heat load. District heating systems are dominated by the peak demand during a few morning hours [1], which results in higher operational costs of the district heating systems.

One of the main findings from a recent review of the district heating and cooling systems has indicated that district energy systems are more efficient than individual heating and cooling systems, based on many projects reviewed across the world [2]. Thermal energy storage was one of the emphasized technologies that has a potential to further increase efficiency into current district energy systems [2]. It has been anticipated that district heating should play an important role in future renewable energy systems [3]. Moreover, authors have concluded that the future smart thermal grids will involve more energy efficient buildings, as well as integration with electricity and gas grids [3]. For the case of future energy system of Denmark, the share of 55–57% of district heating

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in the total heat demand could be cost-effective from the energy system point of view, although significant heat savings in the building sector have been anticipated [4]. Another recent international review of district heating and cooling systems claimed that those systems have strong potentials to be feasible supply options in a future world [5]. An author has reported that large national district heating research projects are being supported in Denmark, Germany, Sweden and China [5]. It was further concluded that heat recovery and heat based on renewable energy sources is larger in the European Union than in the rest of the world [5]. Nevertheless, the future energy system will need to balance out the potential energy savings in the building sector with the renewable energy supply in a cost-effective way. One study showed that the energy demand of buildings could be cost effectively reduced by 12–17% by the year 2015 [6]. The same study has shown that larger savings are to be expected in individual heating areas than in district heating areas.

Thermal energy storage has proven to be a technology that can be beneficial towards the energy efficiency of a building by contributing to an increased share of renewable energy and/or reduction in energy demand or peak loads for both heating and cooling [7]. Thermal building mass for storage could serve as a supplement to already existing storage solutions, such as hot water tanks. The reason for the latter is the low capital costs in thermal building mass storage type, as no physical alterations to the buildings are needed. Many different thermal storage options have been researched and some are already implemented on a large scale. Thermal storage can be realized in several different ways. They can be central (closer to the supply side of the system) or decentral (close to the consumer side of the system). Another division considers the thermodynamic nature of the way heat is stored, i.e. whether it is latent, sensible or thermochemical storage. Seasonal thermal energy storage has been reviewed in Ref. [8] and it was concluded that although it is a promising technology, its cost does not make it applicable to all projects, even less for single family houses. Furthermore, a review of promising candidates for chemical heat storage has been reviewed in Ref. [9], highlighting its significant potential due to the high thermal storage density, but also its low efficiency, special consideration of safety and large initial investment that is required. Thermal energy storages using phase change materials (PCMs) have been reviewed in Ref. [10]. One of the main aspects of PCMs is their low thermal conductivity (usually between 0.2 and 0.7 W/mK), thus requiring the use of complex heat exchanger geometries to obtain required heat transfer rates from latent heat storage containers. Regarding thermal storage building integrated systems, one study reviews it extensively [11]. The authors have concluded that active storage systems in the building envelope could be used when constructing new buildings. The integration of active thermal storage in buildings should be planned during a design phase in order to overcome the problems of availability of space for installations. In the same study, it has been claimed that both commercial and public buildings have huge potential on implementing thermal energy storage in double skin façade as well as in ventilation systems.

The utilization of short term heat storage in the sensible thermal mass of the buildings has been investigated in a number of studies during the last years. The zero investment cost that is required for the utilization of the thermal mass along with the capacity that is available in the majority of buildings in northern climates makes it a promising storage solution. One study of combined thermal energy storage and buildings has also dealt with a potential of using thermal mass of buildings for sensible heat storage [7]. It was concluded that the thermal energy storage can result in increased energy efficiency in buildings, reduced emissions, increased efficiency of HVAC equipment and reduced peak loads in system [7]. It was further argued that it is important always to fulfil specific demands and conditions that differ from building to building [7]. In a Danish study [12], two residential buildings with different states of insulation and air tightness were examined in terms of heat storage and heat conservation. The findings showed that the potential of the thermal mass depends on many factors (level of insulation, heat emission system etc.) and varies significantly over the season. The poorly insulated building could offer short thermal autonomy or heat flexibility meaning the time where the building can perform without activating a heating system, while the energy efficient passive house had a much higher time constant. This means that large amounts of heat could be shifted for shorter periods of time in poorly insulated buildings. On the contrary, a complete switch-off of the heating system could be achieved in the passive house for more than 24 h without violating the thermal comfort of the occupants.

Demand side management (DSM) can be defined as a modified consumer energy demand through various methods. Usually, the balancing of intermittent generation and load shifting from peak demand hours to off-peak demand hours are the most important targets of the DSM. A study by Ref. [13] investigated the potential of structural thermal mass of a single family dwelling for demand-side management (DSM) equipped with an air-to-water heat pump coupled with low temperature heat emission system, as well as a photovoltaic system in South-eastern Europe. The findings showed that the structural storage capacity has strong potential for shifting peak electricity loads for heating to off-peak hours. The DSM potential was found to be higher for massive buildings than for light-weight buildings.

Furthermore, the interaction between the heating system and the available thermal mass is significant. The authors in Ref. [14] have addressed that even after very short overheating periods, the heating demand for the following hours can be reduced significantly (up to 20%) utilizing the thermal storage capacity of the examined building, which included a hydraulic radiator-based heating system. The main limiting factors to the discharging rate were the slow temperature increase within the thermal mass and the heat conduction into the deeper wall layers. Moreover, the influence of the ambient temperature to the storage performance of the thermal mass has been highlighted. The authors conclude that good DSM can be achieved with shorter overheating periods at cold weather conditions. In addition, a Swedish pilot study [15] investigated the storage potential of the thermal inertia of five multi-family residential buildings connected with a district heating (DH) system. Results showed that heavy-weight buildings, with a structural core of concrete, can tolerate large variations in heat deliveries while still maintaining an acceptable indoor climate. Thus, the control can be applied in many buildings in DH systems at a relatively low cost. The study also demonstrated that degree hours instead of a fixed time constant can be a more accurate metric to represent variations in indoor temperature caused by the utilization of the thermal mass of the buildings. Although many examples of the simulated uses of thermal mass for storage have been reviewed on a building scale, there is a lack of cases calculating the potential of thermal mass for storage on a system scale.

A few papers dealt with the analysis of the thermal mass for storage potential on a system scale. Authors in Ref. [16] have presented a framework for planning cost effective operation of HVAC systems utilizing multi-building thermal mass. They have used a business-economic optimization approach and optimized thermal mass for storage of commercial buildings [16]. However, in their approach, thermal mass for storage was used to impact only the power sector while their time frame was one day. A simulation platform and different control strategies for utilizing the thermal mass for storage has been presented in Ref. [17]. The authors have