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Thermal energy storage in district heating: Centralised storage *vs.* storage in thermal inertia of buildings

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ABSTRACT

Heat load variations in district heating systems lead to increased costs for heat generation and, in most cases, increased greenhouse gas emissions associated with the marginal use of fossil fuels. This work investigates the benefits of applying thermal energy storage in district heating systems to decrease heat load variations, comparing storage using a hot water tank and the thermal inertia of buildings (with similar storage capacity). A detailed techno-economic optimisation model is applied to the district heating system of Göteborg, Sweden. The results show that both the hot water tank and the thermal inertia of buildings benefit the operation of the district heating system and have similar dynamics of utilisation. However, compared to the thermal inertia of buildings, the hot water tank stores more than twice as much heat over the modelled year, owing to lower energy losses. For the same reason, only the hot water tank is used to store heat for periods longer than a few days. Furthermore, the hot water tank has its full capacity available for charging/discharging at all times, whereas the capacity of the thermal inertia of buildings depends on the heat transfer between the building core *and* its indoor air and internals. Finally, the total system yearly operating cost decreases by 1% when the thermal inertia of buildings and by 2% when the hot water tank is added to the district heating system, as compared to the scenario without any storage.

1. Introduction

More than a half of the total energy use by the Swedish residential and service sectors stems from space heating and hot water demands [1]. Around 55% of this energy is covered by District Heating (DH) systems [2]. One of the main challenges in the operation of DH systems is the significant variations in heat load, which result in part-load operation and frequent start-ups and stops for the heat generation units. Moreover, even though approximately 90% of the total heat generated in Swedish DH systems is derived from the burning of biofuels and waste incineration, the units used for load following are often fossil fuel-fired Heat Only Boilers (HOBs). Fossil fuel-fired HOBs cover the remaining 10% of the total Swedish heating load [3]. This corresponds to 2.75 MtCO_2 emissions annually [4]. One of the strategies employed to improve the imbalance between the heat load and supply, which can lead to a decreased need for high cost marginal generation, is to integrate energy storage into DH systems.

DH systems have some inherent Thermal Energy Storage (TES) in the district network itself, i.e., in the mass of circulating water, which can be used to buffer heat and, thereby, smoothen the supply so as to meet the varying heat load [5]. However, the buffering capacity of the DH network is limited [6], which means that the imbalance between the supply and heat load variations is still significant even after the volume in the piping network is used at maximum capacity. In the present work, two types of TES are investigated, which differ fundamentally in terms of their impacts on the heating system: TES *via* centralised Hot Water Tank (hereinafter referred to as HWT), which acts as a supply-side buffer and eases the need for achieving an instant balance between the load and supply; and TES that exploits the thermal inertia of buildings (hereinafter referred to as BITES, standing for Building Inertia Thermal Energy Storage), which alters the heat load itself by smoothing its variations. Furthermore, HWT and BITES differ from a stakeholder's perspective. The decisions related to the operation of HWT are made exclusively by the DH system operator (full control), whereas the utilisation of BITES requires the involvement of customers (limited control), such as that triggered in response to a change in energy price.

A number of studies that have modelled district energy systems, including such that incorporate TES, are discussed in a review paper of Sameti and Haghighat [7]. Most of these studies have focused on one type of TES used in district energy systems, i.e., either HWT or BITES. HWT represents an established technology that is used in applications

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Nomenclature

Abbreviations

BITES	building inertia thermal energy storage
CHP	combined heat and power
DH	district heating
HOB	heat only boiler
HP	heat pump
HWT	TES *via* hot water tank
TES	thermal energy storage
UC	unit commitment

Indices

deep	deep component of BITES
HWT	TES *via* hot water tank
N	total number of heat generation units in the DH system
n	set of heat generation units in the DH system
shallow	shallow component of BITES
t	set of time-steps (hours) in the modelling period

Parameters

A_{BITES}	total floor area of the buildings used as BITES (m^2)
A_{HWT}	total surface area of the tank that corresponds to HWT, excluding the surface of the bottom (m^2)
Cp_{air}	specific heat of air (J/kg·°C)
Cp_{water}	specific heat of water (J/kg·°C)
$\eta_{ch.}$	charge efficiency
$\eta_{disch.}$	discharge efficiency
K	heat transfer constant, which defines energy (heat) exchange between the shallow and deep components of BITES in a given time-step t (MWh/h)
K_{loss}	heat loss coefficient
$Load_{(t)}$	heat load in a given time-step (hour) t (MWh/h)
ρ_{air}	density of air (kg/m^3)
ρ_{water}	density of water (kg/m^3)
ΔT	temperature difference (°C)
TES_{cap}	capacity of TES (MWh)
$T_{out(t)}$	outside air temperature (°C)
τ	time constant (h)
U	heat transfer coefficient of the tank that corresponds to HWT (W/m^2·°C)
V	ventilation flow rate (m^3/m^2·s)
Vol	volume of the tank that corresponds to HWT (m^3)

Variables

$Flow_{(t)}$	energy (heat) exchange flow between the shallow and deep components of BITES in a given time-step t (MWh/h)
$Net.\ Load$	net heat load (MWh)
$Q_{(t,n)}$	heat output from a heat generation unit n in a given time-step t (MWh/h)
$T_{HWT(t)}$	universal water temperature in the tank that corresponds to HWT (°C)
	heat supplied to TES in a given time-step t (MWh/h)
$TES_{disch.(t)}$	heat withdrawn from TES in a given time-step t (MWh/h)
$TES_{loss(t)}$	losses from TES in a given time-step t (MWh/h)
$TES_{stored(t)}$	energy stored in TES in a given time-step t (MWh)

for heat load variation management in energy systems. It should be noted that other storage technologies such as seasonal thermal storage or power-to-heat, are not discussed here since their main purpose is not to moderate short-term heat load variations in DH systems but to store heat for long periods of time (e.g., between seasons) and to facilitate integration of variable electricity generation (e.g., from wind and solar), respectively. The studies with TES used for heat-load variation management differ in terms of the complexity of the thermodynamic representation of HWT in the modelling. Some studies apply a simplified TES representation, i.e., the representation of HWT in modelling is usually restricted to capacity limitations, ramp limits, and a single energy loss coefficient. In the study of Buoro et al. [8] such TES representation is used when identifying the optimal district energy system set-up and its optimal operation strategy for a set of users in an industrial area. The study of Oluleye et al. [9] presents a model developed to design district energy systems, which supply both heating and electric demands of domestic consumers, with TES used for supporting operation of CHP plants. Bachmaier et al. [10] performed a study on the spatial distribution of TES in DH networks. Caliano et al. [11] conducted a study that optimises design and operation strategy of a biomass-fired combined cooling, heating and power system coupled to TES with the objective to satisfy the energy demand of an Italian cluster of residential multi-apartment buildings. Other modelling studies as, e.g., the study of Steen et al. [12], provide representation of TES which estimates storage losses by considering the ambient temperature and static storage losses, which were not recognised in the previously mentioned studies. A linear model that describes the charging/discharging processes and the interior water temperature changes in a TES, stratified into three temperature layers, is presented by Chen et al. [13]. Using a mixed-integer linear optimisation model Schutz et al. [14] compare four approaches to model stratification in TES. Arabkoohsar and Andresen [15] represented TES in their modelling by including interior water temperature as well as water mass and mass flow rates to and from the TES. To study the operating conditions of a HWT as a subject to transient regimes, computational fluid dynamics models can be applied, as in the study of Verda and Colella [16].

The study of Heier et al. [17] provides a review of the TES technologies used in combination with buildings, including the option to use the thermal inertia of buildings as a TES, i.e., in the form of BITES, with a focus on the combination of storage technology and building type. The study of Gracia and Cabeza [18] reviews TES in buildings with a stronger focus on the phase change materials. The principle of BITES operation is based on the temporal over-heating or under-heating of buildings. Based on this principle, the potential of using BITES for smoothing the heat load variations in the DH of Göteborg (Sweden) was investigated theoretically in the study of Andersson and Werner [19]. Their results were experimentally proven in the study by Ingvarsson and Werner [20]. The conclusion from that study was that daily heat load variations in the DH system could be eliminated using BITES. In the later study of Kensby et al. [21], the principle of over-heating and under-heating was applied to multi-family sample residential buildings, which were equipped with hydronic radiator heating systems (common in multi-family residential buildings in Sweden) and connected to the DH system of Göteborg, with the objective of estimating their TES capacity. Kensby et al. [21] provided an empirical test of the response of indoor temperature and heat load to different over-heating or under-heating patterns. They found that multi-family residential buildings could be utilised as BITES with a capacity of 0.1 $kWh/m^2_{heated\ area}$ while limiting indoor temperature deviations, induced by the utilisation as TES, to ± 0.5 °C from the set-point temperature. In an attempt to describe the dynamics of the heat exchange that occurs between the building core and its indoor air and internals, as empirically investigated by Kensby et al. [21], Carlsson [22] developed an energy balance model that describes the building inertia as a TES with multiple