Seasonal large-scale thermal energy storage in an evolving district heating system – Long-term modeling of interconnected supply and demand

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Seasonal large-scale thermal energy storage in an evolving district heating system – Long-term modeling of interconnected supply and demand

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ABSTRACT

Given the strong seasonal nature of heating demands, peak heat is important during colder seasons. Instead of peak heat plants, seasonal large-scale thermal energy storage (TES) could be utilized. These can be charged during warmer seasons and discharged when required, decreasing the need for peak heat plants. Systems modelling studies on seasonal TES are lacking. Thus, a long-term local energy system model is applied under different scenarios to investigate the potential roles of seasonal TES in an evolving heating system. The results show that seasonal TES is economically viable for: all future electricity price cases for low TES construction costs, corresponding to repurposing of underground oil storages, and for most electricity price cases for mid- and high construction costs, corresponding to new underground excavations. Seasonal TES mainly decrease the investments in and usage of electric boilers or biogas boilers, while increase the utilization of heat pumps. Other technologies may be affected depending on the future trajectory of electricity price developments. The size of the TES is between 3 and 7% of the annual district heating heat demand, depending on construction cost and electricity price development. The expansion of district heating into new housing is mostly unaffected by the availability of TES.

1. Introduction

Large district heating (DH) systems are often, and increasingly, complex. They consist of many different types of heat generation plants and several subsystems interacting with each other. They are also, and increasingly, connected to various parts of the overall energy system and these connections in turn affect the heating systems' operation in several ways. Combined heat and power (CHP) plants and heat pumps (HPs) or electric boilers (EBs) are important linkages between the heating and electricity systems. An increasing share of intermittent electricity is likely to give incentives for an increasing importance of these linkages.

Increased intermittent renewable electricity generation may exacerbate electricity price fluctuations, and this is also affecting the heating sector; both its use and generation of electricity. Electricity storage, mainly in batteries, is currently being rapidly expanded but investment costs are still high, and subsidies are thus essential for these investments. The cost of storing energy in the form of heat rather than electricity can be much lower, in particular in large-scale storages, as heat storage units are associated with significantly lower investment costs [1] and do not require scarce and expensive materials (e.g., lithium) with high negative environmental impacts.

Generally, heat storages, hereafter Thermal Energy Storages (TES), in heating systems can be divided into short-term and long-term (seasonal). Short-term storages are designed to manage hourly or daily (up to a week) demand-supply variations, while seasonal heat storages are designed to manage storage from summer to winter. Due to the entirely different requirements of these two storage types, their designs also differ, but many of the advantages offered by the two storage types are similar, though differ in scale. Short-term TES may either be connected to any type of heating system while seasonal TES due to their scale only are to be connected to district heating systems.

The potential advantages of TES in DH systems include the following [2].

- Potential decrease of the size and number of other production units;
- Peak shaving and valley filling of heat demand;
- More extensive utilization of intermittent renewable energy sources; and
- Potential extension of DH networks.

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These advantages are linked to energy, economic and environmental benefits.

The short-term TES smoothening of the net heat load has been found to result in increasing HP heat production [3,4], while decreasing production of heat from bio- and gas-fired heat-only boilers (HOBs) [3]. The running system cost can be decreased through the use of a central TES [5,6], but these studies [3,5] did only consider operation costs and not the investment costs related to TES construction. TES can also lead to avoidance of over-investments in peak power capacity [4].

Utilization of TES in heating systems can affect the connected electricity system in several ways. Integration of intermittent renewable electricity sources is more efficient in a large system with interconnections between subsystems, since more options can be considered and utilized [7]. Combination of CHP plants with TES allows the CHP plants to increase their electricity production, while simultaneously decrease their heat production [8]. Thus, the economic feasibility of the CHP plant is improved, as the plant can increase electricity production when the price of electricity is high [9]. Simultaneously, TES can increase the performance levels and economics of HPs [4].

In the Nordic region, modifications to the current tariff systems could promote investments in HPs and TES, which could increase intermittent electricity generation [10] and even though DH systems could provide flexibility to the electricity system, initiatives to promote this flexibility are lacking in Sweden [11].

Investments in TES can be economically beneficial at the city level [12,12,13] concludes that integration of the electricity and heating sectors is a viable option compared to investments in new grid capacity in growing cities. Intermittent renewable electricity production can be utilized more easily in energy systems using the variation management provided by TES [2,14,15].

Finally, due to decreasing use of both peak heat and peak power plants and, thus, decreased emissions, TES investments are also leading to environmental benefits [2].

The main drawback of TES implementation is the high investment cost [2], even though it is much lower than the cost of batteries for electricity storage. Space requirements, especially for seasonal large-scale TES, are also a concern due to their large scale and since they mostly are part of urban area district heating systems.

On-going urbanization leads to potential extension of existing urban DH systems due to increasing demand. Since inclusion of TES will change both future DH supply side investments and its operation patterns, this will also affect their competitiveness versus other, individual heating options.

As the supply and demand sides are interconnected, the way in which one side evolves inevitably affects the other side as shown and discussed with a focus on electricity prices in Ref. [16]; on how cost-efficient heating option differs for different types of housing in Ref. [17]; on how the size of the existing DH networks affects the economics of connecting new buildings areas, as compared to individual solutions, to the DH network in Ref. [18]; and on effects of carbon emissions in Ref. [19]. Moreover, it has been shown that there is a difference in the cost-efficient heating solution depending on whether or not the mixing of technologies within the same housing area is allowed [20]. However, none of these studies has considered the effect of TES, which according to a previous study [2] can affect the viability of connecting new buildings to DH systems.

While a number of studies have addressed long-term heating solution development [16,17,20], to our knowledge only one study [4] have included the potential long-term impact of TES in their investigations on investments in and operation of new heating plants. TES units in energy systems have mostly been examined in dispatch studies of systems or single plants [3,5,6,8,9,14], or the studies have considered greenfield systems for one or a few years [12,13,15]. Thus, there is a lack of studies investigating how inclusion of seasonal large-scale TES in an existing DH system affects its future cost-efficient development and its competitiveness. Based upon the four above presented potential advantages of TES, from Ref. [2], therefore the following research questions are as addressed in this study.

- How does the potential to invest in seasonal large-scale TES affect the sizing and operation of other types of heat production units within an evolving urban energy system?
- How does seasonal large-scale TES affect the import/export of electricity from an urban heating system?
- Does investment in TES affect the competitiveness of DH in an evolving urban heating system?

The research questions are investigated by the development and application of a long-term cost-optimizing energy systems model. With this kind of model, the interaction of the different constituent components of the investigated system can be investigated.

2. Method

As heating systems are large, often consist of many components with long lifetimes and increasingly interact with other parts of the energy system, this study is based on a systems approach and uses long-term energy systems modeling to address the research questions. Energy systems models, in this case a cost-optimizing model, are used to investigate how technical and economic aspects interact. This section presents the layout of the investigated system, which evolves over time, and its components, with a focus on the TES.

Section 2.1 presents the system setup with its connections between the components of the system. As the focus of this study is on the role of TES in an evolving system, the details of the different types of TES are explained, as well as the rationale applied for choosing the type used in this study (Section 2.2). Section 2.3 provides details of the modeling and the modeling framework used.

Three different investment costs for TES are investigated in a sensitivity analysis. In addition, the sensitivity analysis covers four different electricity price cases and scenarios in which biogas is available or not (Section 2.4).

2.1. System setup

The developed heating system is summarized in Fig. 1. The heating system is adapted from Ref. [20] and consists of three pre-existing (*ab initio*) components: 1) DH supply plants of different types; 2) a DH grid; and 3) existing buildings that are already using DH as their source of heating. The heating system is also connected to an external electricity system. No fossil fuels are allowed to be used in the system from Year 2025 onwards, with the exception of the fossil municipal waste share used for waste incineration.

In this study, new housing of different types requiring heating is assumed to be built annually. The housing is aggregated into housing areas which consists of one specific housing type. Four types of new housing are investigated: two apartments of different sizes, and two single-family housing units of different sizes.

If DH is to be built within a specific area, three components are needed: internal DH piping; piping from the internal piping to each house; and a DH substation within each house. If DH is installed in the area, a DH connection is installed in all housing units.

As it is unusual to mix several kinds of heating technologies within the same house, all installations, except ventilation HPs, must have sufficient power capacity to meet the entire heating demand during all time periods. The exception for ventilation HPs is due to that these cannot cover the full heat demand of a house [21], and in this study they are assumed to only be able to cover the hot tap water demand.

2.2. Thermal energy storage units

Several types of TES are available. In Ref. [2], four types of sensible

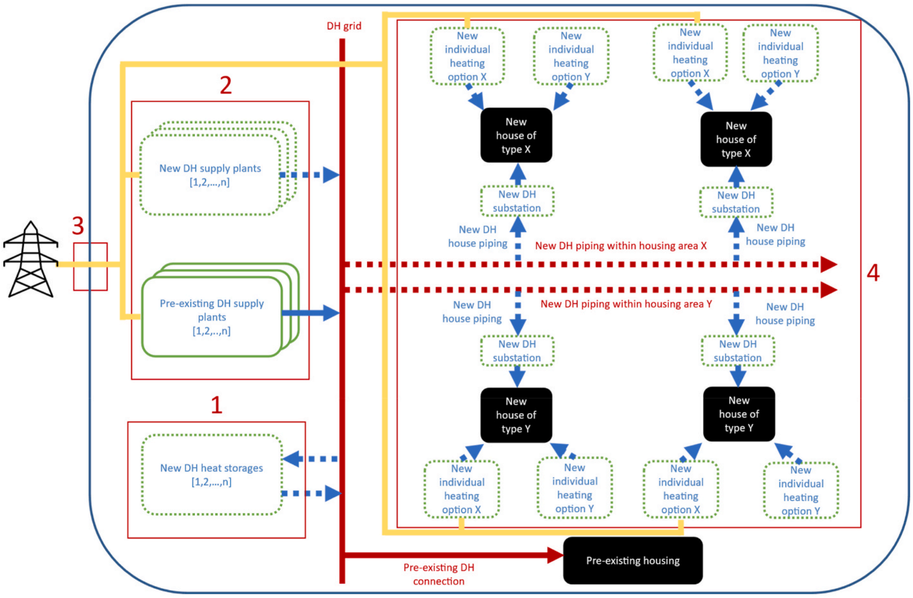

Fig. 1. Setup of the heating system showing the existing, starting system (solid lines) and the new, possible developments over time (dashed lines) to be chosen by the model. This study focuses on how new TES (1) affect: investments in and operation of DH supply plants (2); electricity imports and exports from the heating system (3); and the heating solution for new housing built annually (4).

(no phase transition of the storage medium) TES are outlined: tank (TTES); aquifer (ATES); borehole (BTES); and pit (PTES), while underground TES (UTES) is not included despite it is an available technology that has been built and utilized.

Sensible TES is the dominant TES type, and water is commonly used as the storage medium for several reasons, including its high thermal capacity, low cost, and lack of toxicity. BTES is also a sensible storage type, in that it uses the ground itself for heat storage and gravel is sometimes used in combination with water in PTES. Other types of TES include latent storage, in which the phase transition of the storage medium is utilized, and chemical storage, in which reversible chemical reactions or adsorption and absorption are utilized. Latent and chemical TES are not considered further in this paper. Other types of TES could also be utilized, such as the water in the DH grid itself or thermal inertia of buildings, but these types of TES can only store the heat for short periods of time, i.e., hours or a few days and are therefore not considered further in this study.

PTES and UTES are often used for seasonal storage and since the temperature of the stored water is sufficiently high, no HP is required, although it is possible to combine PTES and UTES with HPs. PTES are used for example in Denmark where the ground is well suited to this technology due to the sandy conditions while in Sweden most of the bedrock consists of granite, gneiss etc., in which UTES storage units can be built. In Sweden, there are examples of UTES that have been constructed by repurposing old underground oil storage facilities, in Västerås [22] and in Hudiksvall [23], both at sizes >10 GWh. Propositions for how new UTES can be built by excavations have also been formulated [24]. The largest PTES storage units in Denmark have capacities slightly above 5 GWh.

ATES are used in several countries, albeit mainly in non-DH applications [26]. In Ref. [27], it is stated that around 15 % of the area of Sweden has geologic conditions suitable for ATES, i.e., areas with eskers or porous sedimentary rock. The largest ATES in Sweden has a capacity of approximately 8.3 GWh [26], and is used to provide both heating and cooling for Arlanda airport in Stockholm.

BTES with capacities of a few GWh have been constructed in several locations. The largest BTES unit in Sweden is around 3.8 GWh [26], but it is not connected to a DH network. It is instead used by a production facility to decrease the amount of heat purchased from the DH network.

In general, ATES and BTES have lower output temperatures and higher storage losses compared to UTES and PTES [26]. In ATES and BTES, the storage medium is not heated to such high levels that the DH grids can utilize the heat directly, a HP is therefore required to increase the temperature to a level sufficient for the DH grid [28].

It has been pointed out [2] that ATES and BTES require specific ground characteristics to become viable options. ATES and BTES are also not as commonly connected to DH grids. For these reasons, ATES and BTES are not considered further in this study.

TTES are characterized by their high charging and discharging power capacities, while they have a relatively high investment cost per energy storage capacity unit. Thus, TTES is suitable for daily and weekly storage, as many cycles are needed to recover the investment cost. As TTES is primarily for short-term storage, this technology is not considered further in this study.

This study focuses on UTES and PTES because they are used for seasonal storage in DH grids and have discharge temperatures that are high enough to be used directly in DH networks. Although the construction parameters of UTES and PTES differ, the technical details of running and utilizing UTES and PTES are similar. For this reason, the TES used in this study is neither explicitly UTES nor PTES, but the technical data used are based on PTES data available from the Danish Energy Agency [25].

As the local conditions can have a strong impact on the investment costs of new TES, three different investment cost levels are investigated in this paper. The lowest cost relates to repurposing an existing underground oil storage unit. The medium cost level corresponds to the lower cost reported for the SKANSKA TES project [24], while the highest cost corresponds to the upper cost of the SKANSKA TES project.

Although the space requirements for TES can be substantial, no limits on the maximum amount of space available for TES are considered.

2.3. Modeling

This study uses a long-term, cost-optimizing dynamic systems model in which the supply and demand of heat are treated together and simultaneously, as previously developed in Ref. [20]. The TIMES framework, developed by the IEA-ETSAP, is used for development of the model. The TIMES framework, which has been used in various previous studies, enables long-term investigations of developing energy systems. The investigated modeling period is from Year 2023 up until Year 2050.

The investigated modelling period is divided into seven shorter periods where the first period consists only of the first modeled year. The second period consists of Years 2024–2027, while the remaining periods have lengths of five years. Each modeled period is divided into five time slices of different lengths representing different seasons with corresponding heat demands and electricity prices. As this study is focusing on seasonal storages, the lengths of the time slices are chosen to represent seasonal changes, in contrast to investigating e.g. on an hourly basis. The computational burden to solve this kind of model with a seasonal time resolution over many future years can be extensive [20], and the solution time for a model with a very high time resolution could potentially be vastly higher.

In TIMES, it is the total system cost over the whole modeling period that is minimized. The total system cost includes investment costs, O&M costs, and running costs, as well as the discounting applied in future years. Solving the model, many different outputs are acquired, among which are the investments in and the dispatch, from which the corresponding utilization factors can be calculated, of available technologies.

In the developed TIMES model, the storage capacity of a TES, in GWh, is directly linked to the charging/discharging capacity, in $\mathrm{MW_{heat}}$. This implies that a doubling in the investment in a TES in a specific year doubles both the storage capacity of a TES and the charging/discharging capacity. Further, since the focus of this paper is seasonal TES, the losses in the storages are implemented using a roundtrip efficiency calculated by charging the TES during summer and discharging during winter. The model can, however, charge and discharge a TES in whatever season which is optimal, but it is not possible to store heat between the modeled years.

2.4. Sensitivity analysis

Three parameters are investigated using a sensitivity analysis. Apart from the heat investment costs of TES presented in Section 2.2, the impacts of different electricity prices and the availability of biogas are investigated (see Table 1). Biogas consists mainly of methane, which can be used in heating systems in the same way as natural gas. Biogas HOBs are associated with low investment costs for new plants, but relatively high running costs. This makes biogas HOBs suitable for use as peak power plants.

The heating system and electricity systems are closely connected because the heating system is capable of being both a producer and consumer of electricity. The electricity price has historically varied in both the short term and long term for many reasons, such as increasing levels of intermittent electricity sources, bottlenecks in the electricity grid, and changes in fuel prices. The Russian invasion of Ukraine has had a major impact on European energy prices, both of electricity and other fuels. The starting point for this article is, therefore, that the electricity price starts at a high level. In one case, the price continues to be high, whereas in the three other price cases investigated, the price starts to decrease at different points in time and at different rates towards the approximate average electricity prices of Sweden in 2019–2020.

The availability of biogas is, however, still relatively low, although the production of biogas is steadily increasing. For this reason, two different biogas availability levels are investigated in this study: 1) no biogas is available for the heating sector; or 2) biogas is available to such an extent that the market price is similar to the cost of producing biogas through gasification of biomass [29]. In the case where biogas is available, it is assumed that there are no additional costs for e.g. new gas grids or storages.

Table 1
Summary of parameters used in the sensitivity analysis. All combinations of the parameters are tested, giving a total of 32 cases.

DH TES investment cost	Electricity price	Biogas available
TES not available	High	No
Low	High2030	Yes
Medium	Low	
High	Varying	

3. Data and assumptions

In this section, the data and assumptions used in this study are presented. First, the details of the new TES are outlined in Section 3.1. This is followed by the cost data for connecting new housing to the DH grid, as presented in Section 3.2. The electricity price cases investigated in this study are presented in Section 3.3. Lastly, the heat demand profiles are presented in Section 3.4.

In the Supplementary Materials, the cost and technical data for fuels (Table S.1), new investments for DH options (Tables S.2 and S.3), individual heating options (Tables S.4 and S.5), and policy data (Table S.6) are presented. Note that biogas boilers are not available as individual heating options, as this technology is uncommon in Sweden and few installations are made to new housing as there is a need for a gas grid.

The existing DH supply plants and pre-existing housing are based on the DH system of Gothenburg. The diverse supply plants include industrial excess heat, waste incineration, CHP plants, HPs and HOBs. Several of the supply plants reach their respective end of technical lifetime around Year 2030, and it is therefore necessary for the system to make investments in new supply plants within the modeled time horizon.

3.1. Thermal heat storage units

Three different TES investments costs are considered in this study based on different cost levels.

- *Low-cost TES* when there is already available unused underground space, which is refurbished into a UTES.
- *Medium-cost TES*, which corresponds to the lower investment cost of building a new UTES, which is double that of the low-cost TES.
- *High-cost TES, which* corresponds to the higher investment cost of building a new UTES, which is triple the cost of the low-cost TES.

The low-cost TES is based on the refurbishment cost of the UTES in Västerås, which is stated to be around 8 M€ [30] for a storage size of 13 GWh, which in turn is very close to the indicated investment cost for PTES from the Danish Energy Agency [25].

The investment costs for the medium and high cost TES, where there is no existing underground facility available, are based on the Skanska TES *Energilager* project [24], double and triple the cost of the UTES in Västerås, respectively.

For all cases, the technical lifetime is set to 25 years. The data used for the TES are listed in Table 2.

For the medium and high investment costs, a lifetime extension is

Table 2
Technical and economic data for new TES. Data based on [25].

	Investment cost 2023/2030/2040/2050, k€/$\mathrm{MW_{heat}}$	Roundtrip efficiency	Fixed O&M cost, k€/$\mathrm{MW_{heat}}$	Lifetime, years	Storage capacity per output capacity, MWh/$\mathrm{MW_{heat}}$
Low cost	87/81/76.5/70.5	0.7	0.45	25	150
Medium cost	174/162/153/141	0.7	0.45	25	150
High cost	261/243/229.5/211.5	0.7	0.45	25	150

probably cheaper after the first investment, as the first investment includes excavation of the underground bedrock, which is not required after the first investment. This aspect is not considered in this study.

The storage efficiency of TES can be lower in the first years when the TES is charged and is consequently still heating the surrounding rock. Neither this aspect, nor potential improvements in storage efficiency due to e.g. improved liners, are included in this study.

The commercial PTES projects outlined in Ref. [25] have roughly the same ratio between storage capacities and output capacities, while the UTES in Hudiksvall [23] has a somewhat lower ratio compared to these PTES projects. There is a however a large difference in the storage capacities of these storages. For this reason, a fixed ratio between the storage capacity and output capacity is used for new TES in this paper.

3.2. Internal DH piping length and cost for new housing

As pointed out previously [31], the investment cost for burying piping is heavily dependent upon the conditions of the ground and surroundings. Burying piping in already built areas is much more expensive than in an area that is planned for new exploitation. In this study, it is assumed that the new housing is built in new exploitation areas. The investment cost for burying the piping has been calculated using the cost tool from Ref. [32], in which the cost data have been collected from several companies.

The calculated investment costs can be compared to a previous report [33], in which it is stated that the total length of the Swedish DH grids is around 20,000 km, and that it would cost around 150 GSEK to renew the whole net. Thus, the renewal cost would be around 750 €/m. Given that the existing grids are buried in built areas, the renewal would cost more compared to establishing a grid in new areas, so the calculated costs in Table 3 are deemed to be reasonable.

3.3. Electricity price cases

How the electricity price will evolve in the future is highly uncertain. For this reason, four different electricity prices are considered in this paper (see Table 4). All the price cases start at the same level in Year 2023, which is based on the approximate prices for the period of 2021–2022 in southern Sweden. As the prices during 2021–2022 were historically high, three of the four investigated scenarios entail different decreases in the future electricity price towards the approximate average prices of 2019–2020 in Sweden. In addition, one scenario is investigated in which the electricity price remains high until Year 2050.

- *High*: The electricity price remains constant until Year 2050 for all seasons.
- *High2030*: The electricity price remains constant until Year 2030. After 2030, the price decreases by the same amount annually in all seasons until Year 2050
- *Low*: The electricity price decreases by the same amount annually in all seasons until Year 2050
- *Varying*: The electricity prices during the winter and peak seasons remain constant until Year 2050, while the prices for spring/fall and summer decrease annually.

Table 3
Calculated investment costs for piping for different housing areas and the required piping length within a new housing area.

	Investment cost, €/m	Length of internal DH grid, km	Housing units built annually
Apartment buildings, large	460	1.5	40
Apartment buildings, small	460	3	80
Single-family housing, large	320	1.5	200
Single-family housing, small	210	0.75	150

Table 4
Electricity price cases.

	Starting price (2023)	High (2050)	High2030 (2030/2050)	Low (2050)	Varying (2050)
Peak	100	100	100/30	30	100
Winter	100	100	100/30	30	100
Spring/Fall	100	100	100/30	30	30
Summer	100	100	100/30	30	30

3.4. Load duration curve for the heat demand

The applied load duration curve for the heat demand is shown in Fig. 2. Each profile is divided on a monthly level, except for the coldest month. The coldest month is divided into one period of approximately one week, *Peak_High*, which has an extra-high heat demand, and the remainder of the coldest month, *Peak_Low*, which has a lower heat demand than the highest peak. This setup allows the results of the model to reflect both the power and energy needs.

The heat profiles are based on real measurements obtained from a new housing area slightly south of Gothenburg [34]. It is assumed that decreases in the heat demand due to improved insulation in future housing only affect the space heating demand. For more details, see Ref. [20].

4. Results

Here, the results for the investigated cases are presented. Sections 4.1–4.4 address the first research question, Section 4.5 addresses the second question, and Section 4.6 addresses the third question.

First, in Section 4.1, the DH production mix and utilization factors for the different technologies are presented. This is followed by Section 4.2, in which the DH production during the coldest month is presented, which is the period during which the TES are discharged. The DH heat production capacity is presented in Section 4.3, and the size of the TES in the DH system is presented in Section 4.4.

In Section 4.5, the electricity import/export levels during the coldest week and month from the full heating system are presented.

Lastly, in Section 4.6, the differences in the heat demand supplied by DH for new housing between the cases where TES is or is not available are presented.

4.1. DH production mix and utilization factor

As shown in Figs. 3 and 4, the production of DH heat differs depending on whether or not TES are available. For all the electricity

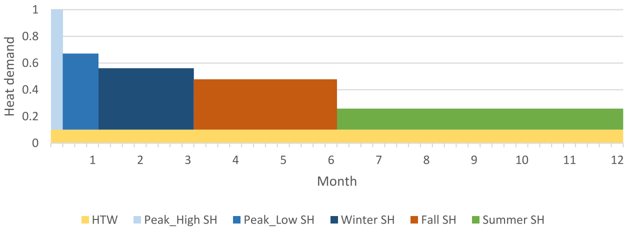

Fig. 2. Load duration curve for the heat demand during a year as shares of the demand of the coldest week. The duration curve in this figure is for a house with a specific heat demand of 60 kWh/m^2. For housing units with other specific heat demands, only the space heating (SH) demand is changed per m^2. The hot tap-water (HTW) demand remains unchanged per m^2.

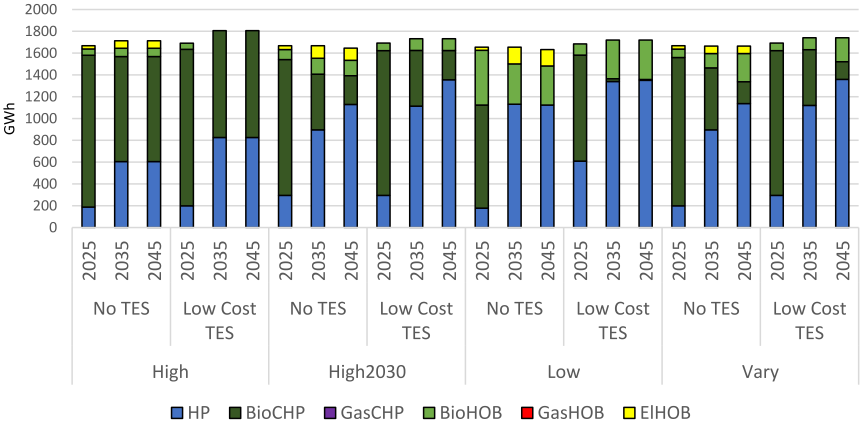

Fig. 3. Annual heat production levels at different electricity price profiles when no biogas is available. The waste incineration and industrial excess heat are omitted to improve readability.

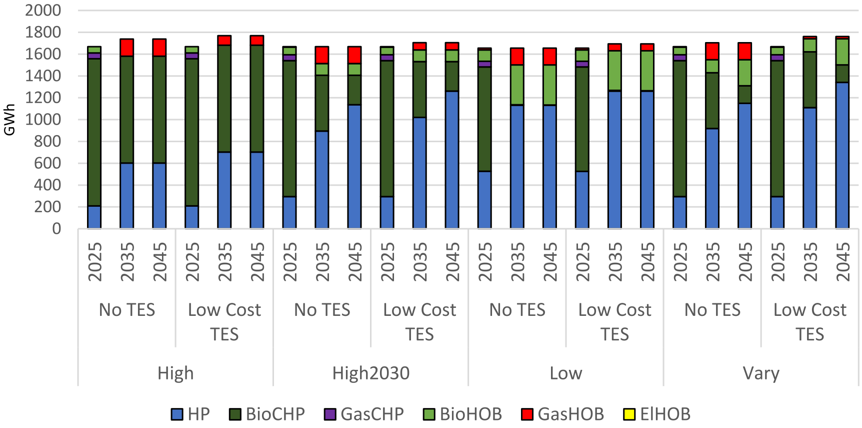

Fig. 4. Annual heat production levels at different electricity price profiles when biogas is available. The waste incineration and industrial excess heat are omitted to improve readability.

price cases and for cases with biogas availability, the amount of heat provided by DH HPs is increased if TES are available.

For the case without biogas, if TES units can be built, no new EBs are built. In the case of a high electricity price, no biomass HOBs are built. However, if biogas is available, the sizes of the gas HOBs are reduced if TES can be built.

The total level of DH production is increased if TES can be built due to two different mechanisms. For all the electricity price cases, there are energy losses in the TES, which requires that the total production level increases. In addition, some new housing units are connected to the DH grid, although the number of new houses connected depends on the electricity price (for more details, see Section 4.6).

The results show that TES primarily increase the utilization factor of DH HPs (see Table 5). The other DH technologies do not show any clear trend with respect to the utilization factor when TES are available. The utilization factor for HPs is increased since it is economical in all cases to install DH HPs to their maximum capacities and to run them at full capacity during the colder seasons (see Section 4.2), regardless of whether TES are available. However, if there are investments in TES, the HPs are utilized during summertime to charge the TES. In all cases, except for the High electricity case, all the HPs reach the maximum allowed utilization factor of 90 % in Year 2045, although the utilization factor is increased also for in the High electricity price cases. The same trend is seen in the higher TES investment cost scenarios.

4.2. DH production mix during coldest month

In Figs. 5 and 6, the DH heat outputs from the different technologies are shown during the coldest month, which also includes the coldest week. It is evident that if TES can be built, they provide around 25 % of the total heat from Year 2035 in the case where no biogas is available, for all the electricity price cases. The shares of the total heat are somewhat lower if biogas is available for the High, High2030 and Low electricity price cases at around 15 %, while in the Varying electricity price case, the share is 25 %.

4.3. DH heat production capacity

The installed heat output capacities are shown in Figs. 7 and 8. It is clear that the heat output capacities of the TES are large compared to the other technologies. In the cases with no biogas, the TES are around 150 % larger, in terms of output power, than the other technologies combined. In the cases in which biogas is available, TES output capacity is roughly the same or around 30 % above that of the other technologies combined for the High, High2030 and Low electricity price cases. In the Varying electricity price case, the TES output capacity is around double compared to the other technologies combined.

This result implies that the TES units are sized with respect to the total amount of energy that can be stored (in GWh), rather than the

Table 5

Utilization factors for DH HPs in the no TES scenario and low-cost TES scenario for the different electricity price cases. The numbers in parentheses indicate the changes in utilization factor compared to the no TES scenario. The results for all the DH technologies and TES investment costs are available in the Supplementary Materials.

No biogas available						
	No TES			Low-cost TES		
	2025	2035	2045	2025	2035	2045
High	13 %	43 %	43 %	14 % (5 %)	59 % (37 %)	59 % (37 %)
High2030	21 %	64 %	81 %	21 % (−1%)	79 % (24 %)	90 % (12 %)
Low	13 %	81 %	80 %	37 % (193 %)	90 % (11 %)	90 % (12 %)
Vary	14 %	64 %	81 %	21 % (49 %)	80 % (25 %)	90 % (11 %)
Biogas available						
	No TES			Low-cost TES		
	2025	2035	2045	2025	2035	2045
High	15 %	43 %	43 %	15 % (0 %)	50 % (17 %)	50 % (17 %)
High2030	21 %	64 %	81 %	21 % (0 %)	73 % (14 %)	90 % (11 %)
Low	37 %	81 %	81 %	37 % (0 %)	90 % (11 %)	90 % (11 %)
Vary	21 %	66 %	82 %	21 % (0 %)	79 % (21 %)	90 % (10 %)

output capacity (in MW).

The results further show that it is economical to make investments in TES on top of the existing system in the beginning of the modeled time horizon. Additional investments are also made into TES when old supply plants reach their respective end of technical lifetime around Year 2030. The sum of the capacities of the supply plants is consequently lower in the cases where investments in TES are allowed. No new investments are made into new TES or supply plants after Year 2035 as there is no expansion of the DH grid after Year 2035 (see subchapter 4.6.), and all plants which are available in Year 2035 are also available in Year 2045.

4.4. DH storage size

The TES sizes, in terms of GWh, for the different scenarios are presented in Table 6, as well in Figs. 7 and 8 for the low-cost TES. The results show that in the case of no availability of biogas, the TES size is decreased with an increasing investment cost. The size of the TES for the medium-cost investment case is decreased by around 20%–25 % compared to that for the low-cost investment cost. For the most-expensive case, TES are still built but they are smaller than for the medium-cost case for the High, High2030 and Low electricity price cases.

For the cases in which biogas is available, TES are being built, although in the High electricity price case, the TES size is very small in the medium- and high-cost investment cases. For the other three electricity price cases, the TES size is smaller in the more-expensive cases

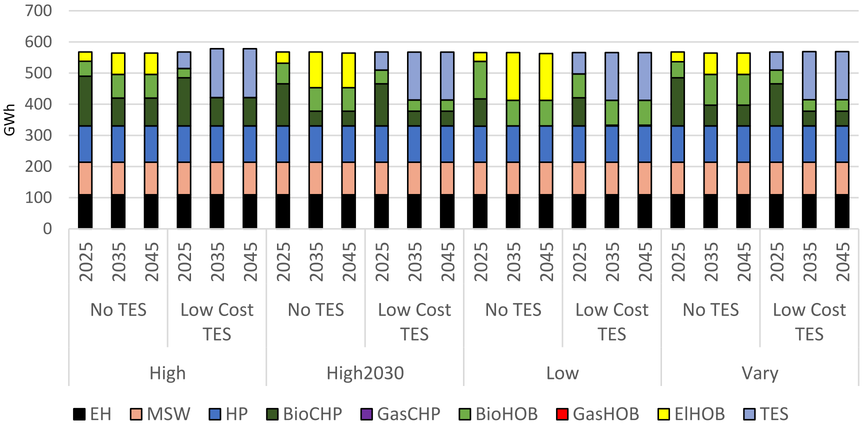

Fig. 5. Heat outputs during the coldest month from different heat technologies for different electricity price profiles when no biogas is available.

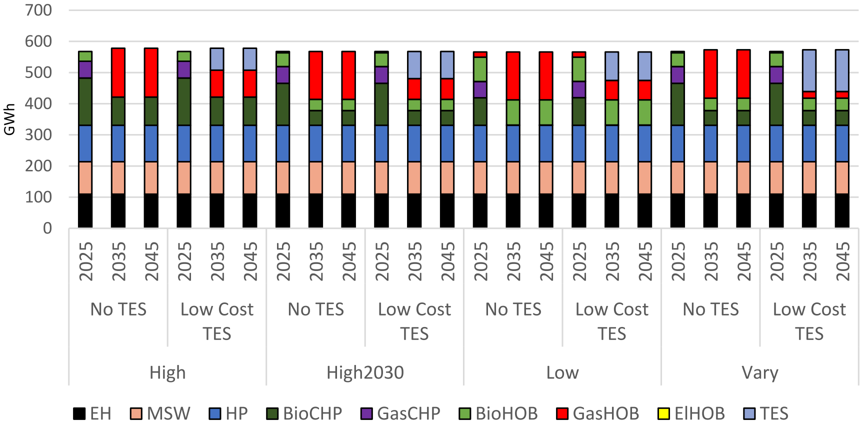

Fig. 6. Heat outputs during the coldest month from different heat technologies for different electricity price profiles when biogas is available.

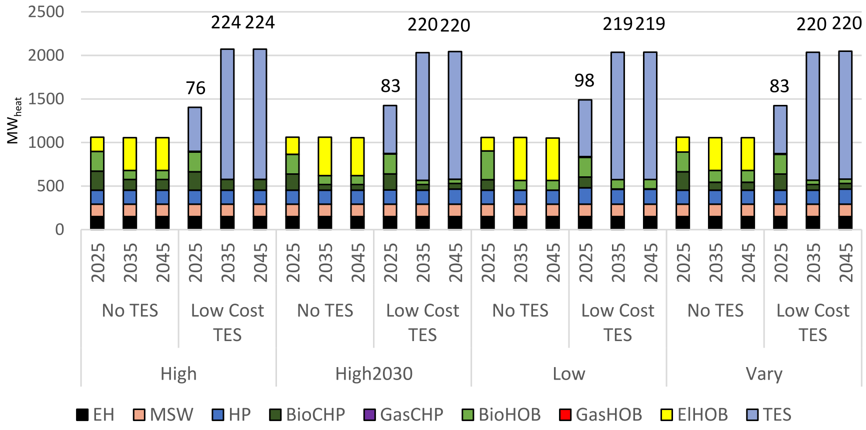

Fig. 7. Installed heat output capacities for the different electricity price profiles when no biogas is available. The numbers above the bars indicate the installed TES sizes, in GWh, if any TES is installed.

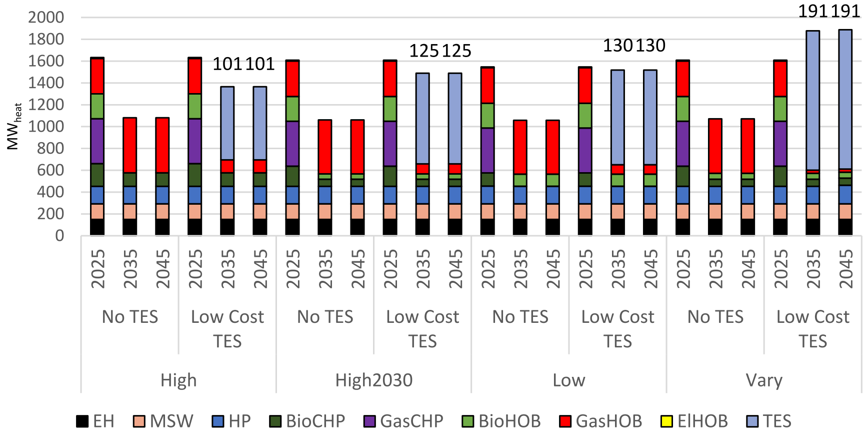

Fig. 8. Installed heat output capacities for the different electricity price profiles when biogas is available. The numbers above the bars indicate the installed TES sizes, in GWh, if any TES is installed.

Table 6
Installed TES sizes, in GWh, for different investment costs in the scenarios for the different electricity price cases. The numbers in parentheses indicate the sizes compared to the low-cost TES scenario.

No biogas available									
	Low-cost TES			Medium-cost TES			High-cost TES		
	2025	2035	2045	2025	2035	2045	2025	2035	2045
High	76	224	224	83 (9 %)	176 (−21 %)	176 (−21 %)	83 (9 %)	141 (−37 %)	141 (−37 %)
High2030	83	220	220	83 (0 %)	164 (−26 %)	164 (−26 %)	125 (51 %)	125 (−43 %)	125 (−43 %)
Low	98	219	219	83 (−16 %)	164 (−25 %)	164 (−25 %)	98 (1 %)	98 (−55 %)	98 (−55 %)
Vary	83	220	220	83 (0 %)	171 (−22 %)	171 (−22 %)	83 (0 %)	171 (−22 %)	171 (−22 %)
Biogas available									
	Low-cost TES			Medium-cost TES			High-cost TES		
High	0	101	101	4 (INF%)	4 (−96 %)	4 (−96 %)	4 (INF%)	4 (−96 %)	4 (−96 %)
High2030	0	125	125	1 (INF%)	99 (−21 %)	99 (−21 %)	83 (INF%)	83 (−34 %)	83 (−34 %)
Low	0	130	130	4 (0 %)	98 (−24 %)	98 (−24 %)	62 (INF%)	62 (−52 %)	62 (−52 %)
Vary	0	191	191	2 (INF%)	100 (−48 %)	100 (−48 %)	83 (INF%)	83 (−57 %)	83 (−57 %)

compared to the cheapest case.

4.5. Electricity imports during peak periods

The amounts of electricity imported in the coldest week and in the coldest month are shown in Table 7. The results show that in the case that there is no biogas available, TES decrease significantly the levels of imported electricity, as the TES units replace EBs. In some cases, there is even low-level export of electricity from the heating system when TES are available. If biogas is available, there is no difference in exports between the cases where TES are available or not from Year 2035 onwards. Although there is a decrease in exports in Year 2025 if TES are available.

Table 7
Electricity imports, in MW, during the coldest week and coldest month for the different electricity price cases. A negative value indicates export from the heating system. For the TES scenarios, the value indicates the maximum import (if the value is positive) or minimum export (if the value is negative) across the different investment costs for the TES.

	Coldest week						Coldest month					
No biogas available												
	No TES			With TES			No TES			With TES		
	2025	2035	2045	2025	2035	2045	2025	2035	2045	2025	2035	2045
High	154	374	399	−6	27	27	29	84	99	−7	−3	12
High2030	192	463	485	−6	55	81	43	164	177	−7	44	59
Low	176	541	563	16	160	185	57	243	255	15	148	163
Vary	162	383	408	−5	7	32	32	92	107	−7	1	16
Biogas available												
	No TES			With TES			No TES			With TES		
	2025	2035	2045	2025	2035	2045	2025	2035	2045	2025	2035	2045
High	−270	−7	18	−257	−7	18	−76	−12	3	−72	−12	−3
High2030	−267	18	43	−6	18	43	−72	6	21	−7	6	21
Low	−236	43	68	−27	43	68	−46	31	45	5	31	45
Vary	−267	5	30	−6	5	30	−72	−1	14	−7	−1	14

4.6. *Impact on DH to new housing of TES*

The results show that the amount of heat supplied to new housing by DH is not affected in any of the electricity price cases if biogas is available (see Table 8). However, if biogas is not available, small differences, in absolute terms, are seen in the high and varying electricity price cases. In the high electricity price case, the expansion of DH into new housing continues up until Year 2035, while the amount of heat supplied by DH is slightly higher if TES are available. For the varying price case, the DH expansion stops after Year 2025 without TES, and after Year 2030 with TES. It is mainly large apartment housing that sees an increase in DH use when there are any differences in the results. Air-to-water HPs represent the dominant heating solution for new housing of all types when DH is not used. It is important to highlight that the model used is an energy systems model which minimizes the total system cost and does not investigate individual consumer costs or preferences.

These results indicate that the possibility to invest in TES plays a relatively minor role in determining whether or not new DH grid expansion into newly constructed housing is economically feasible. Note that the results obtained for the case that has no biogas with TES are the same as when biogas is available, indicating that for new housing, TES and biogas HOBs seem to have the same effect.

5. Analysis and discussion

This study investigates the role of TES in an evolving DH system using long-term modelling, covering several decades, and including dynamic supply-demand interactions. In this way, the study is novel and contributes to our understanding of how the different components in an evolving DH system interact. From the results, it is clear that investments in TES are made in almost all the scenarios, showing that TES is an economically beneficial investment for the system under most conditions. The availability of biogas for peak heating loads has a large impact on the cost-efficiency of the TES, but it should be observed that a very low biogas cost, actually only the production cost, has been assumed.

Table 8
DH grid expansion into new housing.

	Maximum heat supplied to new housing without TES, GWh (Year with largest amount of heat supplied)	Maximum heat supplied to new housing with TES, GWh (Year with largest amount of heat supplied)
No biogas available		
High	61 (2035)	83 (2035)
High2030	27 (2025)	27 (2025)
Low	17 (2025)	27 (2025)
Vary	27 (2025)	55 (2030)
Biogas available		
High	83 (2035)	83 (2035)
High2030	27 (2025)	27 (2025)
Low	27 (2025)	27 (2025)
Vary	55 (2030)	55 (2030)

In all the electricity price cases, the TES investment results in increased utilization of HPs, since HPs are utilized more during summertime. In the model, there is a limit imposed on the heat source availability for the HPs, in this case stemming from the fact that sewage water is used as the heat source. The availability of other heat sources, such as low-grade excess heat from industries, is heavily dependent upon the local conditions. However, as seen in the results, HPs are an economically viable option, and utilizing local heat sources could prove to be valuable for future DH systems, especially in combination with seasonal TES. The industries that provide such heat for use in DH HPs may find business opportunities, although, as shown in Ref. [11], efficient use of excess heat from industries can be complicated to achieve. If it can be achieved, the need for primary energy can be decreased, thereby contributing to lower carbon emissions due to decreased usage of electricity and biomass [19].

The results show that seasonal TES are built for all three investment costs and electricity prices if no biogas is available. The size of the TES is around 7 % of the total annual DH production for the lowest investment cost, and around 3%–6% for the highest investment cost. This indicates that large seasonal TES can be economical even if the local conditions are not optimal. TES are built also in the biogas scenarios, albeit at smaller sizes compared to the scenarios with no biogas available. This further indicates that TES are economically viable. It should be noted, however, that the medium and high TES investment costs are based on new excavations of the underground bedrock. It is arguably cheaper to refit a medium-cost or expensive excavation after it has reached its initial end of technical lifetime. The investment cost after the first excavation is probably close to the cheaper TES option, which means that if an expensive TES is built it has a high likelihood of being utilized longer than its initial technical lifetime.

The results also show that the size of the TES is such that the potential power output is very high. For this reason, the potential for using short-term TES (the most-commonly applied TES today) to smoothen daily or hourly variations does not seem to have any role in this large seasonal TES. With a high temporal resolution, i.e. hours or days, the type of model used in this study could capture the behavior of fast charging and discharging of TES to cope with fast fluctuations in electricity prices due to a high amount of intermittent power. A high temporal resolution would therefore probably benefit the use of TES, possibly also TTES due to their fast charging and discharging potential, even more compared to the result shown in this study. However, whether or not TES built for seasonal use can be switched from charging to discharging in such a rapid manner is not investigated in this study and is of interest to investigate in further studies.

As argued previously [12], integrating heating systems with electricity systems can decrease the need for investments in new grid capacity for cities. This is supported by the results of the present study, as our results clearly show that the electric power capacity used by the heating sector during high-demand seasons is dramatically reduced when TES, but no biogas, is available. As the future availability of biogas is uncertain, investments in TES could play a significant role in future integrated energy systems by decreasing the need for new electric grid capacity. An otherwise low demand for grid capacity could enable more-opportunistic use of HPs for charging TES at times when the production level from intermittent electricity sources is high, thereby facilitating an increasing share of intermittent electricity.

The results of this study further show that whether it is economical to connect new housing to the DH grid is only weakly dependent upon whether TES are built or not (but then it should be stressed that the study implies a systems perspective and does not include individual electricity distribution grid costs). This contrasts with the previous statement [2] that one of the advantages of combining TES with DH is that this allows for additional buildings to connect to the DH network. However, it is arguably the cost for the customer (rather than the system cost) that will determine whether new housing will be connected to the DH grid. Whether or not DH is the most cost-competitive solution may therefore depend on which perspective is considered [35]. It has also been argued [11] that there is a lack of understanding between the actors in the energy system, as energy firms within the energy markets primarily prioritize their own business interests. In the absence of any modifications to business models and policies, barriers to TES adoption that are not primarily linked to the technical aspects of seasonal TES will remain.

Although the results of this study clearly indicate that seasonal TES are economically beneficial, there are several barriers that hinder the deployment of such TES. It has been noted [11] that the TES available and built into the DH systems currently in operation in Sweden are mostly used for short-term storage. It is a matter of concern that there is a lack of consensus among the various actors regarding the economic value of seasonal TES. In addition, the lack of incentives and high alternative risks are cited as risks for the deployment of flexibility measures. These barriers are not easily investigated in the type of modeling used in the present study.

6. Conclusions

While most current district heating systems do not include large-scale seasonal TES, the results of this study clearly indicate that significant economic and environmental benefits can be obtained through investments in seasonal TES. The study also concludes that the TES is sized according to the storage capacity (in GWh) rather than the charging/discharging capacity (in MW). As heating systems are local, context and site dependent and differ in terms of size, available plants and resources, there is hardly a 'one-fits-all' solution for every system. Therefore, detailed context-based investigations of how a TES investment would affect a particular heating system are important.

A TES investment in an existing heating system so as to avoid using electricity during the coldest periods is economically beneficial – unless biogas for peak heating loads is widely available. Nonetheless, large-scale TES are cost-efficient, regardless of the availability of biogas, at the time when existing DH supply plants reach their end of technical lifetime, thereby avoiding investments in heat production capacity that would only be used during peak periods. This finding underlines the need to investigate individual systems in detail regarding the need for and timing of investments in TES in relation to the characteristics of existing plants, as well as the plans for investments in new plants. The results of this study also show that investments in and utilization of new plants are affected by investments in TES. This further highlights the need to take TES into consideration when planning the future development of existing heating systems. The long lifetime of heating infrastructure further stresses this.

If investments are made in TES, it is mainly the production from HPs that is increased, as the TES are charged during the summertime. As HPs represent the technology within the heating system that benefits the most from investments in TES, this can have implications also for actors that operate primarily outside the heating system. Industries that have a need for cooling could identify business opportunities linked to providing low-grade excess heat for use in DH HPs.

The level of electricity import to the heating system during the coldest periods is significantly reduced if TES are built and no biogas is available. This indicates that TES is a viable option to increase the available electricity grid capacity when the availability of biogas is low and/or other sectors have a higher willingness to pay for available biogas. Although the level of heat production from HPs is increased if there are investments in TES, this occurs during warm periods when the electricity demand is also low. Therefore, utilizing the HPs in a more opportunistic fashion is probably not a cause for concern regarding the electricity grid capacity. Furthermore, the opportunistic production from HPs can increase the integration of intermittent renewable electricity production. Deciding to build a heating system with HPs and seasonal TES can, therefore, contribute to an emissions-free energy system at large scale, and not just to decarbonization of the heating sector.

Although TES are economically advantageous for the DH system, they do not seem to increase the cost-efficiency, in a systems perspective, of DH much as heating option for new housing. Thus, if there are societal or municipal goals to connect new housing to DH, seasonal TES investments are not sufficient and other policies are required.

CRediT authorship contribution statement

Karl Vilén: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Erik O. Ahlgren:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2024.100156.

References

[1] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. https://doi.org/10.1016/j.energy.2017.05.123.

[2] Guelpa E, Verda V. Thermal energy storage in district heating and cooling systems: a review. Appl Energy 2019;252:113474. https://doi.org/10.1016/j.apenergy.2019.113474.

[3] Romanchenko D, Kensby J, Odenberger M, Johnsson F. Thermal energy storage in district heating: centralised storage vs. storage in thermal inertia of buildings. Energy Convers Manag 2018;162:26–38. https://doi.org/10.1016/j.enconman.2018.01.068.

[4] Fazlollahi S, Becker G, Maréchal F. Multi-objectives, multi-period optimization of district energy systems: II-Daily thermal storage. Comput Chem Eng 2014;71:648–62. https://doi.org/10.1016/j.compchemeng.2013.10.016.

[5] Romanchenko D, Nyholm E, Odenberger M, Johnsson F. Impacts of demand response from buildings and centralized thermal energy storage on district heating systems. Sustain Cities Soc 2021;64:102510. https://doi.org/10.1016/j.scs.2020.102510.

[6] Sneum DM, Sandberg E. Economic incentives for flexible district heating in the nordic countries. Int J Sustain Energy Plan Manag 2018;16:27–44. https://doi.org/10.5278/ijsepm.2018.16.3.

[7] Lund H, Østergaard PA, Connolly D, Ridjan I, Mathiesen BV, Hvelplund F, et al. Energy storage and smart energy systems. Int J Sustain Energy Plan Manag 2016;11:3–14. https://doi.org/10.5278/ijsepm.2016.11.2.

[8] Nuytten T, Claessens B, Paredis K, Van Bael J, Six D. Flexibility of a combined heat and power system with thermal energy storage for district heating. Appl Energy 2013;104:583–91. https://doi.org/10.1016/j.apenergy.2012.11.029.

[9] Streckiene G, Martinaitis V, Andersen AN, Katz J. Feasibility of CHP-plants with thermal stores in the German spot market. Appl Energy 2009;86:2308–16. https://doi.org/10.1016/j.apenergy.2009.03.023.

[10] Bergaentzle C, Gunkel PA. Cross-sector flexibility, storage investment and the integration of renewables: capturing the impacts of grid tariffs. Energy Pol 2022;164:112937. https://doi.org/10.1016/j.enpol.2022.112937.

[11] Fernqvist N, Broberg S, Torén J, Svensson IL. District heating as a flexibility service: challenges in sector coupling for increased solar and wind power production in Sweden. Energy Pol 2023;172. https://doi.org/10.1016/j.enpol.2022.113332.

[12] Heinisch V, Göransson L, Odenberger M, Johnsson F. Interconnection of the electricity and heating sectors to support the energy transition in cities. Int J Sustain Energy Plan Manag 2019;24:57–66. https://doi.org/10.5278/ijsepm.3328.

[13] Heinisch V, Göransson L, Odenberger M, Johnsson F. The impact of limited electricity connection capacity on energy transitions in cities. Smart Energy 2021;3:100041. https://doi.org/10.1016/j.segy.2021.100041.

[14] Beiron J, Göransson L, Normann F, Johnsson F. Flexibility provision by combined heat and power plants – an evaluation of benefits from a plant and system perspective. Energy Convers Manag X 2022;16. https://doi.org/10.1016/j.ecmx.2022.100318.

[15] Holmér P, Ullmark J, Göransson L, Walter V, Johnsson F. Impacts of thermal energy storage on the management of variable demand and production in electricity and district heating systems: a Swedish case study. Int J Sustain Energy 2020;39:446–64. https://doi.org/10.1080/14786451.2020.1716757.

[16] Vilén K, Selvakkumaran S, Ahlgren EO. The impact of local climate policy on district heating development in a nordic city – a dynamic approach. Int J Sustain Energy Plan Manag 2021. https://doi.org/10.5278/ijsepm.6324.

[17] Vilén K, Selvakkumaran S, Ahlgren EO. Communal or individual – exploring cost-efficient heating of new city-level housing in a systems perspective. Smart Energy 2023;10:100097. https://doi.org/10.1016/j.segy.2023.100097.

[18] Sandvall AF, Ahlgren EO, Ekvall T. Cost-efficiency of urban heating strategies – modelling scale effects of low-energy building heat supply. Energy Strategy Rev 2017;18:212–23. https://doi.org/10.1016/j.esr.2017.10.003.

[19] Sandvall AF, Ahlgren EO, Ekvall T. Low-energy buildings heat supply–Modelling of energy systems and carbon emissions impacts. Energy Pol 2017;111:371–82. https://doi.org/10.1016/j.enpol.2017.09.007.

[20] Vilén K, Ahlgren EO. Linear or mixed integer programming in long-term energy systems modeling – a comparative analysis for a local expanding heating system. Energy 2023;283:129056. https://doi.org/10.1016/j.energy.2023.129056.

[21] Danish Energy Agency. Technology Data for Individual Heating Plants n.d. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-individual-heating-plants (accessed October 18, 2022).

[22] MälarEnergi. Energilager i bergrum n.d. https://www.malarenergi.se/om-malarenergi/framtidens-samhalle/vara-anlaggningar/energilager/. [Accessed 2 March 2023].

[23] Tidningen Energi. Här samlas fjärrvärme under berget n.d. https://www.energi.se/artiklar/har-samlas-fjarrvarme-under-berget/. [Accessed 2 March 2023].

[24] Andersson HE. Thermal Energy Storage - TES för att möte det hållbara samhället n.d. https://energiforskmedia.blob.core.windows.net/media/22615/hakan-eg-andersson-skanska.pdf. [Accessed 2 March 2023].

[25] Danish Energy Agency. Technology Data for Energy Storage n.d. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-energy-storage.(accessed October 18, 2022).

[26] Kuylenstierna J. Termisk energilagring i fjärrvärmenät. 2019.

[27] Fastigheter O. Guide för geoenergi. 2017.

[28] DEA. Technology Data. Energy storage, vol. 13. Danish Energy Agency; 2018. p. 104–16. https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-energy-storage. [Accessed 23 February 2023].

[29] Energi Göteborg. The GoBiGas project - demonstration of the production of biomethane from biomass via gasification. 2018.

[30] Tidningen Energi. Bergrummet som ska värma Västerås n.d. https://www.energi.se/artiklar/2021/mars/bergrummet-som-ska-varma-vasteras/(accessed March 2, 2023).

[31] Fjärrvärme Svensk. Kulvertkostnadskatalog 2007;1.

[32] Energiföretagen. Kostnadskatalog fjärrvärme distribution n.d. https://www.energiforetagen.se/forlag/fjarrvarme/Kostnadskatalog-fjarrvarme-distribution/(accessed October 18, 2022).

[33] Energiföretagen. Underhållshandboken för fjärrvärmedistribution. 2015.

[34] Fahlén E, Olsson H, Sandberg M, Löfås P, Kilersjö C, Christiensson N, et al. Vallda Heberg - sveriges största passivhusområde med förnybar energi. 2014.

[35] Grundahl L, Nielsen S, Lund H, Möller B. Comparison of district heating expansion potential based on consumer-economy or socio-economy. Energy 2016;115:1771–8. https://doi.org/10.1016/j.energy.2016.05.094.