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The impact of large-scale thermal energy storage in the energy system

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ABSTRACT

In the last decade, pit thermal energy storage (PTES) systems have been used as a large-scale heat storage solution in district heating systems due to their low specific investment cost and high storage efficiency. Despite the existing knowledge on thermal energy storage (TES) technologies, their economic and environmental impacts have not been quantified in the literature, and very few studies have studied PTES as part of the energy system. For this reason, the energy system model Balmorel was used to quantify the impact of TES on the energy system, particularly PTES, and compare it to the tank thermal energy storage (TTES) alternative. The investigation was focused on Denmark and its neighboring countries. It was found that it was only the energy systems using TES that could achieve carbon neutrality by 2050. The main reason was the added flexibility due to the energy storage that allowed the system to have a 35% higher PV capacity, 10% higher wind capacity, and lower levels of curtailment. Additionally, systems with TES had 2.4 €/MWh lower average heat price (with 24% lower peak price). When comparing PTES with TTES, it was found that PTES systems were more advantageous, achieving a 1.5 €/MWh lower average price of heat.

1. Introduction

Storage as a concept can be defined according to physical and financial optimization. In physical terms, storage can decouple production and consumption within a feasible timeframe. In financial terms, arbitrage through storage allows for buying low and selling high. In the case of heating, the physical abundance of, e.g., excess heat from an electrolyzer may not be matched by an equivalently high heat demand in a given hour. Here, storage can decouple heat sources and sinks, potentially within hours, days, or even months [1]. Financially, such decoupling can enable the utilization of the least-cost heat sources. For instance, low-cost electricity at nighttime can be used to produce heat with a heat pump, which can then be stored in a thermal energy storage (TES) system and used during the day when electricity prices are high.

Large-scale TES used for heating are generally characterized as sensible heat storage, i.e., the storage energy content is raised by increasing the temperature of the storage material [2]. Still, large-scale TES systems merit a further definition since the term can be applied to at least three different technologies: High-temperature storages for electricity production through liquid salt, thermal oils, or similar, typically based on concentrated solar power [3]; high-temperature storages for electricity and heat production in a low-cost medium like rocks [4]; and lower temperature thermal storage in a low-cost medium like water, with heat supply as the sole purpose [5]. Our study applies the latter definition of the term TES.

The simulation of energy systems with TES is highly affected by the selection of the system's boundaries and the trade-off between computational requirements and accurate system representation. Single systems are usually simulated with a high level of detail, e.g., modeling of the TES temperature, stratification, and detailed heat losses, as in [6]. Usually, these simulations use software like TRNSYS [7], Modelica [8], etc. On the contrary, if the energy system boundary is at the city or country level, simplified modeling of TES needs to be done using only techno-economic characteristics (e.g., cost, lifetime, and efficiency, as in [9]). For these analyses, energy system models like Balmorel, EnergyPLAN, GENESYS, PyPSA, etc., can be used [10,11]. Multiple iterations are required (and usually high computational time) to determine the optimal system configuration. Such analyses typically require further system simplifications; thus, temporal and spatial aggregation is applied in the modeling. In temporal aggregations, models use a selection of representative hours/periods (e.g., four weeks using every third hour, as in [12]). In contrast, for spatial aggregation, models use a selection of consumption/production characteristics (e.g., 30

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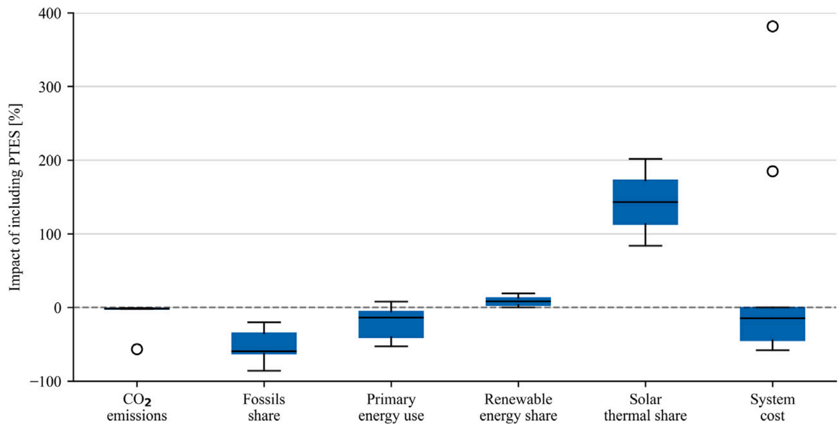

Fig. 1. Comparison of the impact of utilizing PTES on a local energy system. Values denote the percentage increase of systems with PTES compared to systems without PTES (e.g., 150% solar thermal share means that systems with PTES feature 2.5 times higher solar thermal generation compared to systems without TES). Based on the screening of 307 papers, data was reduced to six relevant studies [5,13–17] containing 16 analyses in total. The white circles denote outliers.

nodes, each representing demand and supply from a single European country, as in [9]). Consequently, there are many ways of simulating TES systems based on the modeling approach, boundaries of the energy system, and assumptions.

The two main TES technologies in the Danish district heating sector are water tank thermal energy storage (TTES) systems and water pit thermal energy storage (PTES) systems. While TTES is a well-known technology, PTES is a relatively new technology, with the first large-scale system starting operation in 2012. A PTES is constructed by excavating a pit in the ground, which is lined with a watertight polymer liner and is then filled with water and covered with an insulated floating lid. PTES have become popular in recent years due to their low cost compared to other TES technologies [18]. Since PTES is not yet a mature technology, the efficiencies of the existing pilot PTES systems for long-term storage range from 60% to 70%, being affected by the ground conditions, insulation lid performance, etc. [19]. However, storage efficiencies greater than 90% have been achieved in the PTES in Dronninglund, creating a paradigm for future PTES systems [19].

Often, TES is characterized according to the storage duration: short-term (hours-week) and long-term (months) [20]. Short-term TES are generally used for peak shaving, while long-term TES are used for transferring energy across seasons. In Denmark, TTES systems are typically used for short-term storage, while PTES systems have primarily been used for long-term storage. However, for PTES, this distinction in terms of time may no longer be appropriate. This is due to the possible utilization of a PTES as a very large but short-term storage system (e.g., like the short-term PTES currently under construction in Høje Taastrup, Denmark [21]).

TES for heating is well-described in literature as a part of large-scale energy system analyses (e.g., [22]), in combination with solar heating [23] and in terms of optimizing the production of district heating plants [24]. The usefulness of TTES has been demonstrated in several studies of district heating (DH) systems [25] (storages resulted in lower levelized cost of heat) and in the daily production optimization in the many commercially operating, real-world deployments. The sector coupling relevance of both PTES and TTES has been demonstrated by the large, modeled deployment in energy system studies of Europe by Sneum et al. [22] (229 GWh intraseasonal heat storage by 2035 in Denmark) and Gea-Bermúdez et al. [26] (20 TWh long-term heat storage in Northern-Central Europe by 2035). For comparison, the deployment of Danish TES in 2017 was 50 GWh [27].

Several studies [13,28–30] have reviewed the general traits of PTES and TTES. We extended this work with a meta-review of small and large energy systems with and without PTES. This review shows a slightly mixed picture (see Fig. 1). Literature directly analyzing the impacts of PTES is limited. With a caveat for the small sample size (see Appendix B), we see that PTES generally results in lower system costs, although with a large spread. CO_2 emissions decrease by only 1%–2%, while reductions in fossil use and primary energy use are more pronounced. Conversely, renewables shares are increased. The increase in solar thermal is noteworthy and aligns well with the general practice of co-locating solar thermal plants with PTES. Common for the screened studies is that they investigate single plants, not large-scale energy systems on a national or international level (except [14] that investigates the German energy system).

Recently, there has been a high interest in PTES systems, and many studies have been published. For example, numerical PTES simulations were conducted, assessing the storage performance [31]. Additionally, phenomena related to the operation of PTES (e.g., natural convection) have been numerically investigated [32]. Last, various control strategies regarding the seasonal operation of PTES have been numerically investigated [33]. Nevertheless, all these studies focus on individual plants, not their integration with the energy system.

In summary, PTES systems have been analyzed in theory, demonstrated, and deployed in practice. Despite this, a research gap remains as few studies on PTES' specific impact exist. Borri et al. [34] have reviewed the scientific literature on TES and similarly identified a lack of economic and environmental aspects concerning TES. Finally, neither of the studies analyzed the particular impact of PTES in large-scale energy system analyses.

Thus, the aim of this study was to answer the following research questions:

1. What is the impact of TES in an energy system on a national and international level?
2. What is the impact of PTES in an energy system compared to the TTES alternative?
3. Which PTES characteristics have the largest effect on future deployment and development?

In line with similar large-scale energy system studies on other technological options (e.g., low specific power wind turbines [35] or energy efficiency [36]), we explore the potential deployment and use of PTES in the current and future energy systems. PTES, like other technologies under development, have faced technological challenges (e.g., lid and liner durability). To illustrate the potential of PTES, we assume these teething troubles are solved in the analysis. And in the same vein as the studies mentioned above, we do so not to advocate for the technology but to explore PTES' potential impact.

In the present study, we applied the comprehensive energy system model, Balmorel [37], to answer the research questions. Balmorel has been applied to assess different energy transition scenarios and was developed to enable holistic energy system analyses. Additionally,

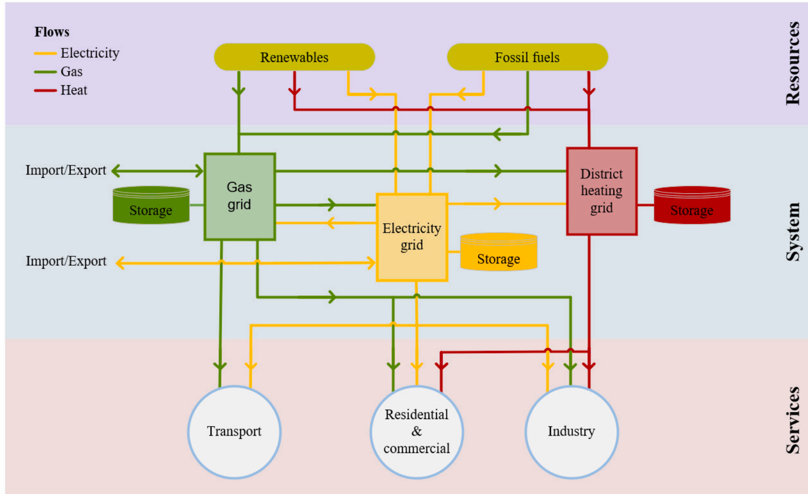

Fig. 2. Schematic of energy sector modeling in Balmorel (adapted from [44]).

it has been used to conduct deep-dive analyses of specific parts of the energy system at different geographical scales and with different scopes. It has, for example, been applied for analyzing the decarbonization of the Northern European integrated power and district heating system [38,39], the role of district heating in a national context [40], and the transition of local heating systems [41]. It has also been used for analyzing the integrated energy system with sector coupling [26] and focusing on producing renewable transport fuels, including Power-to-X (PtX) and sector coupling opportunities [42,43], as well as many other studies.

An overview of the Balmorel model and the applied modeling approach is provided in Section 2. The simulated scenarios, along with the data assumptions, are presented in Section 3, followed by the results of the study in Section 4, and conclusions in Section 5.

2. Method: Energy system model, balmorel

2.1. General description of balmorel

Balmorel [45] is an open-source, deterministic, partial equilibrium model for optimizing energy systems assuming perfect markets and economic rationality [37]. Similar to other energy system models, it builds upon a bottom-up approach and computes the least-cost solution for the energy system (minimizing the investment and operation costs)to satisfy the energy demands. The mathematical formulation and results have recently been compared against four other well-known open-source energy system models [11,46], with conclusions emphasizing the model's validity.

Furthermore, Balmorel is a technology-rich energy system model with a comprehensive representation of energy technologies and infrastructures. The model converts the energy sources to energy vectors, which can then be transmitted to demands or conversion technologies in different energy sectors. In parallel, it optimizes both investment and operational dispatch.

2.2. Spatial and temporal dimensions

The spatial representation in Balmorel consists of countries, regions, and areas. Each country can have multiple regions, and each region can have multiple areas. The division of each country into regions and areas can be facilitated using different measures, for example, geography, market bidding zones, or the size of energy demand. The regions are used to define a country's electricity demand and maintain the electricity balance, while the areas specify the characteristics inside a region (e.g., wind and solar potential) and define heat demands. The areas can also be used for any other categorization of the heat sector, for example, the split between the industrial and residential sectors, temperature levels, etc.

The temporal resolution in Balmorel consists of three levels: years, seasons, and terms. Years are divided into seasons, and seasons are divided into terms. In this way, the temporal resolution in Balmorel is flexible and can be designed to capture the main features depending on the research question and required accuracy while potentially reducing the computation time. For example, instead of simulating all hours of the year, it is possible to select some periods that are representative of the entire simulation period. It is also possible to simulate all time steps at high resolution considering all hours. Overall, the choice is a trade-off between computation time and temporal resolution.

2.3. Energy system coupling and coverage in balmorel

Balmorel covers the main energy sectors (i.e., power, heat, gas, and transport) and vectors (i.e., electricity, gas, and heat transfer fluids), thereby allowing for holistic analysis of the current and future sector-coupled energy system. Balmorel is built upon a modular structure, which enables the user to include energy sectors in the modeling scope and more detailed features within each sector. Fig. 2 illustrates the representation of energy sectors and interactions between energy vectors in the Balmorel model.

2.3.1. Coupling between the heat, power, and transport sectors

In most countries, energy sectors are already coupled to some extent and are expected to become even more interlinked in the future [47]. One way of facilitating the linkage across energy sectors is by employing energy conversion technologies. Examples of conversion technologies that couple the heating sector with the power sector are heat pumps, boilers, and combined heat and power (CHP) plants. Furthermore, linkages between electricity, heating, and fuel production for the hard-to-abate transport and industrial sector are expected to be more widespread in the future. For example, Power-to-X (PtX) fuels could supply the heavy long-haul transport sector and also decarbonize the industrial sector.

Electricity is supplied to cover the demand of the power sector, while the transport sector demand is supplied either through electrification or the production of liquid fuels, e.g., PtX. Last, the heating sector is supplied with electricity, district heating, or fuels. This way, Balmorel can optimize the system, including different conversion pathways and efficient utilization of sources.

Furthermore, as the future power system is expected to be dominated by high penetrations of variable renewable energy sources, system flexibility becomes prominent and urgently needed. The flexibility can be provided through four main options, i.e., flexible generation, increased transmission capacity, demand side management, and storage (electricity, heat, and hydrogen). Consequently, internal competition across the flexibility providers appears, even with cross-sectoral benefits. These cross-sectoral effects are assessed in the present study, where Power-to-Heat technologies combined with district heating and TES might be the least-cost opportunity to provide the needed flexibility to the power system, compared to, e.g., batteries.

2.3.2. Heating sector

The simulation of the non-industrial heat consumption in Balmorel is done without accounting for temperature levels. For example, while the district heating supply temperature differs in each country, in Balmorel, only the heating demand is considered (details for each country are presented in Appendix C). Additionally, the utilization of excess heat (e.g., from electrolyzers) is included in the model, and it is assumed that it can be supplied directly to the district heating grid (without the need for heat pumps to increase its temperature).

District heating networks transfer heat from large-scale production technologies (e.g., boilers, CHP plants, heat pumps, electrolyzers, solar heating, and storage technologies) to consumers. The DH demands were included in the modeling framework, and conversion from individual heating solutions to DH was allowed for different heating sectors, e.g., residential, tertiary, and industry. District heating areas were aggregated to reduce the simulations' computation time. Aggregation was done according to the size of the demands to account for the effects of economies of scale of some technologies (e.g., heat storage), land availability, costs, etc. Since the aggregation was according to demand size and not geography (as in [42,43,48]), heat transfer was not allowed between the DH areas. The resulting scales for the DH areas were: small, medium, and large.

The heat demand of the industry sector was modeled based on the temperature level required by each industry type. This way, the industry sector was divided into high-temperature (HT), requiring temperatures higher than 500 °C; medium-temperature (MT), requiring temperatures between 100 - 500 °C; and low-temperature (LT), requiring temperatures lower than 100 °C. A more detailed explanation of the temperature split is described in [26,49].

Apart from the temperature division, the heat consumption of the industrial consumers was further divided into whether or not they were connected to the DH grid and, if so, which DH grid scale they belonged to. The industry not connected to DH could be connected to the large DH areas as long as the model found it economical to invest in heat transmission capacity. Additionally, it was also possible for the LT industry to supply excess heat to the DH grid if they were connected. Similarly, the MT industry could supply excess heat to the LT industry.

Similar to the industry sector, the remaining heat load (encompassing the residential and tertiary sectors) was divided into two categories for each region: already connected to the DH network and not connected. This load was implemented by assigning an inflexible demand for domestic hot water and space heating to the population of each country. The heat load not connected to the DH network was called "individual users" and corresponded to a different percentage of the total demand depending on the country (see [50]). The reader is referred to [39] for more details on this.

Furthermore, the individual users connected to the DH grid were divided into groups depending on which scale of DH they belonged and were not allowed to use other technologies to cover their heat demand. On the contrary, individual users not connected to the DH grid had to cover their heat demand using technologies such as solar heating, heat pumps, boilers, and small-scale heat storage. In case it was considered profitable by the model, these users had the option to be connected to DH-large areas.

It should be noted that this study focused only on the optimization of the supply side. Thus, the effect of flexible demand and small-scale storage in individual buildings was not investigated. The reader is referred to [51,52] if more information is desired on this topic.

2.3.3. Modeling heat storage

Balmorel only simulates energy flows; thus, aspects like thermal stratification, efficiency based on storage duration, etc., are not accounted for. These simplifications reduce the computation time, which is essential when doing country-level simulations.

Two types of heat storage can be used, namely short-term and seasonal heat storage. Short-term heat storage (intra-seasonal) is defined as having a storage duration of less or equal to one week. In comparison, seasonal heat storage (inter-seasonal) is defined as having a storage duration longer than one week and up to one year. The modeling of TES in Balmorel is facilitated using five equations that account for different aspects of the storage operation, namely the system heat balance (1), storage dynamics (2), storage charge and discharge limit (3)–(4), and storage capacity (5). The mathematical formulations in Eqs. (1)–(5) are generalized to represent both inter- and intra-seasonal heat storages. More information on the modeling of TES in Balmorel can be found in Appendix D.

The heat balance (Eq. (1)) ensures that heat demand, $d^{heat}_{y,a,s,t}$, is satisfied in all areas a, at all timesteps s,t, and for every year y. The heat generated by the various generation technologies, $p^{gen\_heat}_{y,a,g,s,t}$ can be stored by charging the TES $p^{TES,charge}_{y,a,g,s,t}$, and discharged at a later timestep $p^{TES,discharge}_{y,a,g,s,t}$.

Eq. (2) represents the dynamic equation for heat storage modeling, i.e., the heat storage content at the next time step, $v^{TES}_{y,a,g,((s,t)+1)}$, is equal to the heat storage content at the beginning of the time segment, $v^{TES}_{y,a,g,s,t}$, plus the difference between charging the TES, $p^{TES,charge}_{y,a,g,s,t}$, and discharging, $p^{TES,discharge}_{y,a,g,s,t}$, while also considering the storage efficiency, $\epsilon^{TES,eff}_{g}$. The difference is multiplied by the length of the time segment, $\gamma_{s,t}$, in order to account for time aggregation. Note that heat losses from the storage are accounted for during discharging.

Eq. (3) sets the upper limit for the charging rate of the heat storage, $\lambda^{TES,charge}_{g\in\mathcal{G}^{TES}}$. Similarly, Eq. (4) defines the upper limit for the discharging rate of the TES, $\omega^{TES,discharge}_{g\in\mathcal{G}^{TES}}$.

Finally, in Eq. (5), the capacity of the TES, $v^{TES}_{y,a,g,s,t}$, should be less or equal to the sum of the existing capacity, $k^{TES,ex\_CAP}_{y,a,g}$, and new investment $k^{TES,new\_CAP}_{y,a,g}$, also considering decommissioning of capacity, $k^{TES,decom\_CAP}_{y,a,g}$.

System heat balance equation (heat supply equals demand):

$$\sum_{g\in\mathcal{G}^{heat}} p^{gen\_heat}_{y,a,g,s,t} - \sum_{g\in\mathcal{G}^{TES}} p^{TES,charge}_{y,a,g,s,t} + \sum_{g\in\mathcal{G}^{TES}} p^{TES,discharge}_{y,a,g,s,t} = d^{heat}_{y,a,s,t} \quad \forall y\in\mathcal{Y},\ a\in\mathcal{A},\ g\in\mathcal{G}, s\in\mathcal{S}, t\in\mathcal{T} \tag{1}$$

See Eqs. (2)–(5) given in Box I.

3. Data assumptions and scenarios

3.1. Geographical and temporal scope

The present study assesses the impact of large-scale thermal storage in energy systems focusing on Denmark as a part of the Northern European energy system. As elucidated in the methods section, energy systems are becoming increasingly interconnected in terms of energy sectors and across countries. Therefore, as the Danish power system is connected to surrounding countries, a larger geographical scope is needed to capture system effects on the power system and, thereby, power prices. Therefore, this study's geographical scope includes Denmark, Norway, Sweden, and Germany, whose power systems are connected through transmission lines. The electricity system is divided into market bidding zones, as defined by Nord Pool power market [53] and illustrated in Fig. 3A.

Unlike electricity distribution, heat distribution can only happen locally, i.e., through district heating. As described in Section 2.3.2, district heating networks can supply part of each country's heat demand. All simulated countries can have all grid scales (i.e., large,

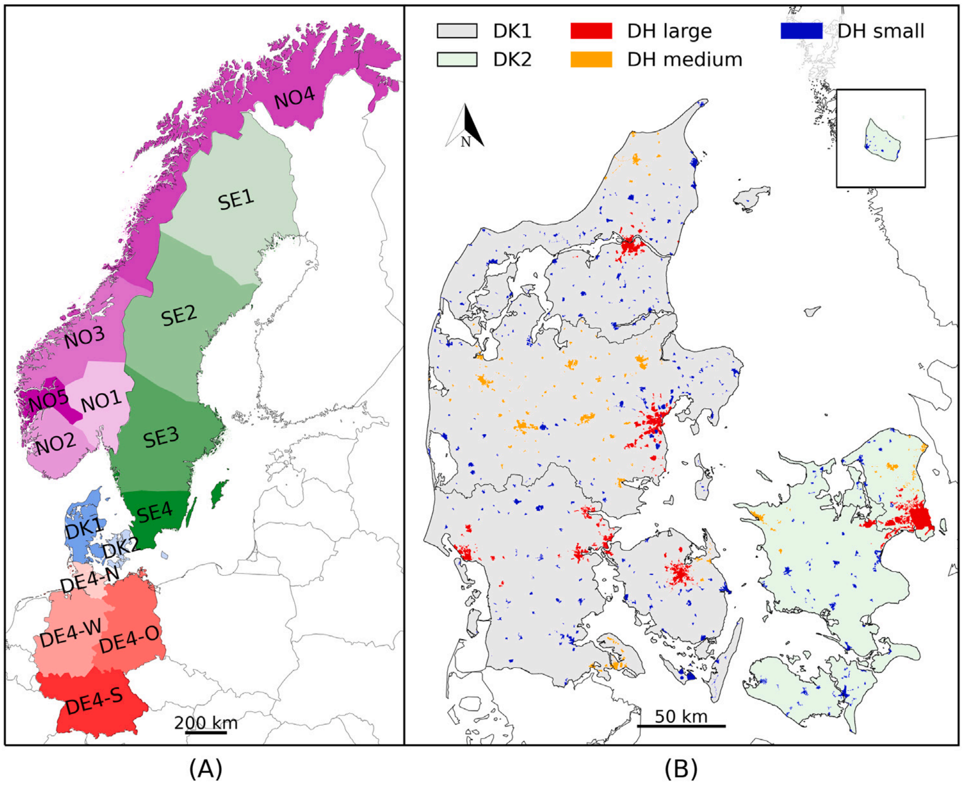

Fig. 3. Map of countries and regions (colored) (A), and aggregation of district heating areas in Denmark in Balmorel (B).

TES dynamic equation:

$$v^{TES}_{y,a,g,s+1,t+1} = v^{TES}_{y,a,g,s,t} + \gamma_{s,t}\left[p^{TES,charge}_{y,a,g,s,t} - \frac{p^{TES,discharge}_{y,a,g,s,t}}{\epsilon^{TES,eff}_{g}}\right] \quad (2)$$

TES charge capacity limit:

$$p^{TES,charge}_{y,a,g,s,t} \leq \frac{k^{TES,ex\_CAP}_{y,a,g} - k^{TES,decom\_CAP}_{y,a,g} + k^{TES,new\_CAP}_{y,a,g}}{\lambda^{TES,charge}_{g}} \quad (3)$$

TES discharge capacity limit:

$$p^{TES,discharge}_{y,a,g,s,t} \leq \frac{k^{TES,ex\_CAP}_{y,a,g} - k^{TES,decom\_CAP}_{y,a,g} + k^{TES,new\_CAP}_{y,a,g}}{\omega^{TES,discharge}_{g}} \quad (4)$$

TES capacity:

$$v^{TES}_{y,a,g,s,t} \leq k^{TES,ex\_CAP}_{y,a,g} - k^{TES,decom\_CAP}_{y,a,g} + k^{TES,new\_CAP}_{y,a,g} \quad (5)$$

$\forall y \in \mathcal{Y},\ a \in \mathcal{A},\ g \in \mathcal{G}^{TES},\ s \in \mathcal{S},\ t \in \mathcal{T}$

Box I.

medium, small) in every region; however, this is not always the case (e.g., Norway only has medium-sized DH areas, while Germany only has large ones).

Specifically, Denmark has six large central district heating networks and around 400 small- and medium-sized district heating networks [54]. Five of the large DH areas are located in DK1 (Aarhus, Aalborg, Odense, TVIS [55], Esbjerg), and the sixth is in DK2 (Greater Copenhagen area). The DH areas are aggregated into three main categories, i.e., DH-large, DH-medium, and DH-small, for each of the DK1 and DK2 regions. For example, all small DH areas of one region are modeled as one area, having a demand equal to the sum of the individual areas. Thus, the heating networks are not modeled individually. The criterion by which the DH grids were divided into the three categories was their size/demand. With this division, it could also be ensured that different technologies could be built in different areas (e.g., a large CHP plant was not allowed to be installed in a DH-small area to consider economy-of-scale effects). More details on the division of DH grids by size can be found in [56]. An example of the Danish DH areas in Balmorel is illustrated in Fig. 3B.

In this study, Balmorel is computing the least-cost solution for the energy transition toward 2050, with 10-year intermediate steps. Each year of the simulation is represented by 8 seasons and 12 terms. Each season corresponds to one week of the year, i.e., weeks 1, 8, 15, 22, 29, 36, 43, and 50. Furthermore, each of these weeks is represented by 12 hourly time steps selected from one day. Each timestep is repeated until the next modeled timestep arrives, thus, simulating an entire year. Although the temporal resolution is rather coarse, the simulation still accounts for seasonal trends (e.g., ambient temperature, energy demand, prices, seasonal storage charge level). It should be noted that, despite the time aggregation, the computational time of the model was 2.5 days. Therefore, it was not considered feasible to investigate the effect of higher temporal resolutions on the results.

3.2. Techno-economic parameters for heat storage systems

In general, Balmorel uses TTES for short-term heat storage (storage duration of less than a week) and PTES for seasonal heat storage (storage duration of more than a week and up to one year). Although it is common practice to use the term seasonal storage when heat is transferred across seasons (i.e., from summer to winter), seasonal storage does not have a fixed storage duration in Balmorel. Therefore, the efficiency for the PTES (80%) was taken as an average between 70%, which is expected for PTES seasonal storage without a heat pump [57], and 90%, which is expected for PTES used for short-term storage (Table 1). It should be noted that this is a simplistic modeling approach since, in reality, the storage efficiency depends on the cycle duration.

It should also be noted that the existing seasonal TES systems have primarily utilized solar thermal as the heat source. However, PTES can be coupled to any heating source and is thus considered flexible in Balmorel. This is for example the recent PTES in Høje Taastrup (Denmark), which is charged from various heating sources including waste incineration, biomass combustion, and heat pumps.

Regarding the charge/discharge capacity, PTES and TTES were assumed to have the same limits since they were connected to the same network. Similarly, since all the investigated thermal energy storage systems were directly connected to the district heating network, the storage capacities were calculated assuming that TES operated with an upper temperature of 90 °C (forward temperature) and a lower temperature of 40 °C (return temperature). These temperatures are typical for PTES in Danish district heating networks when a heat pump is not used to cool down the storage [58]. Nonetheless, Balmorel does not simulate temperatures but energy flows. The temperature difference is used for calculating the specific storage cost, i.e., determining the relationship between m^3 and MWh. Thus, the effect of different operating temperatures can be elucidated from the sensitivity analysis graphs of the investment costs (see Section 4.3). For example, half the temperature difference corresponds to twice the investment cost.

The economy data for TTES are based on tank installations in Danish DH plants and were taken from Sveinbjørnsson [27]. Fig. 4 illustrates the specific investment cost for PTES and TTES with respect to their storage volumes. Each dot represents the data for one heat storage system. It may be observed that PTES and TTES are technologies of scale since their specific cost decreases significantly with an increase in volume. Despite the similar trend of the investment cost for the two technologies, it must be noted that the specific cost for PTES is much lower than TTES (the y-axes differ by a factor of 4). The main reasons are the differences in materials and construction approaches. The individual data points from actual systems were fitted to a power function, which was later used to calculate the cost of storage systems of various sizes.

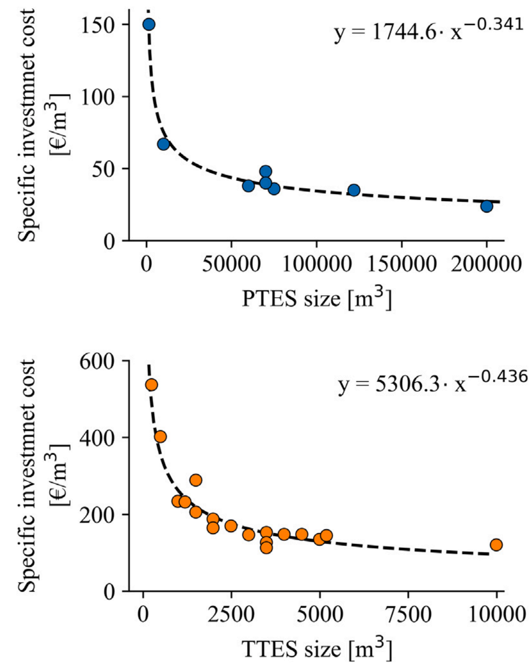

Fig. 4. Specific investment cost for PTES and TTES as a function of their size in m^3. Each dot corresponds to an actual system. The dashed curve is the corresponding trend line.

As it may be seen in Fig. 4, most TTES systems have volumes of 500 - 5 000 m^3, with an average size of approximately 3 000 m^3. TTES systems are generally considered more cost-effective than PTES for small volumes (i.e., smaller than 10 000 m^3) [57]. For this reason, for the simulated TTES systems, a volume of 3 000 m^3, which is common in Denmark, was selected (Table 1).

Regarding the Danish PTES, the volumes of the operational storage systems range from 60 000 - 200 000 m^3. However, at the moment of writing, two serially connected PTES systems with volumes of 750 000 m^3 and 250 000 m^3 are planned to be constructed in the town of Odense, Denmark. Thus, it is evident that the sizes of the future constructed PTES might be much larger than the existing ones.

It has to be noted that, in Balmorel, due to the aggregation of DH areas, the installed TES capacity does not correspond to one storage system but to many smaller ones (depending on the number of aggregated areas). For this reason, the chosen sizes for the simulated PTES were not selected as the largest possible, but sizes were chosen based on the installed storage capacity during the simulation. PTES of 250 000 m^3 were only allowed to be installed in large DH areas, 100 000 m^3 in medium DH areas, and 50 000 m^3 in small DH areas (Table 1). Choosing larger storage volumes would lead to a lower specific investment cost that would give a financial advantage to the technology; however, suitable land availability is often an obstacle, especially in large cities, and consequently, large storage systems may not be practically feasible. Thus, choosing smaller PTES sizes was an attempt to have more realistic scenarios and representative costs for the actual systems.

The land cost was also included in the investment cost for PTES. For the TTES, due to their smaller size and construction style, the cost of land was not found to affect the final price significantly. The land price used was based on data for Denmark (2015 - 2019) and was taken equal to 1.8 €/m^2 [59]. Last, it should be noted that all investment costs were discounted using a 4% annual discount rate, as recommended by the Danish Energy Agency [57]. The techno-economic parameters used for simulating PTES and TTES are summarized in Table 1. The characteristics of the remaining generation and storage technologies included in the simulations were based on data from the Danish Energy Agency's Technology Catalogs [60].

Table 1
Data used for PTES and TTES simulation in Balmorel. The investment cost for PTES is assumed to decrease in the future as the technology matures, and there is a linear decrease from 2020 to 2050.

Type	Size [m^3]	Investment year	Investment cost [k€/MWh]	Efficiency [%]	Charge/Discharge capacity rate [MW]	Lifetime [years]
PTES large	250 000	2020 2050	0.35 0.28	80	40	20 25
PTES medium	100 000	2020 2050	0.49 0.40	80	40	20 25
PTES small	50 000	2020 2050	0.64 0.52	80	40	20 25
TTES	3 000	–	2.90	98	40	40

Table 2
Fuel prices [€/GJ] and CO_2 costs [€/tCO_2] in Balmorel for simulated years.

Fuel [€/GJ]	2020	2030	2040	2050
Coal	2.31	2.67	2.74	2.81
Lignite	0.75	1.00	1.00	1.00
Municipality waste	−3.26	−3.26	−3.26	−3.26
Natural gas	5.64	8.32	9.29	10.26
Nuclear	0.76	0.76	0.76	0.76
Wood chips	6.20	6.20	6.20	6.20
CO_2 costs [€/tCO_2]	5.93	75.16	105.22	127.77

Table 3
Renewable potential by region.

Region	Solar PV [GW]	Onshore wind [GW]	Offshore wind [GW]
DK1	15.6	6.1	70.2
DK2	9.4	1.9	15.2
DE4-O	119.5	32.7	16.6
DE4-N	39.8	4.8	–
DE4-S	119.5	29.1	–
DE4-W	119.5	32.1	58.8
NO1	4.7	3.5	–
NO2	4.7	2.5	18.4
NO3	4.7	1.9	34.1
NO4	4.7	5.6	30.7
NO5	4.7	0.5	7.0
SE1	14.7	8.9	10.8
SE2	14.7	11.0	10.8
SE3	14.7	11.0	10.8
SE4	14.7	4.0	10.8

3.3. Fuel and carbon emission costs and renewable potential

Fuel and carbon emission costs are presented in Table 2. The fuel price projections are adopted from [61]. The municipality waste has a negative fuel price to represent the value that the waste incineration plant receives. From a modeling perspective, it also ensures that this fuel is used for baseload production.

It may be observed that, apart from nuclear, there is an increase in fuel prices toward 2050. The increase in fossil-fuel prices is in line with future plans for carbon neutrality. Furthermore, the decarbonization pathway of the entire energy system is driven by a carbon emission cost, which is also taken from [61], to ensure a coherent transition.

The potentials of onshore wind and solar PV are often constraining the solution space for the optimal energy system configuration. Therefore, Table 3 presents the implemented availability potentials for wind and solar PV in the two Danish electricity market regions. The onshore wind and solar PV potentials are further divided into different resource grades to account for differences in full load hours (capacity factor) inside a region and to illustrate that the most prominent locations are explored first.

3.4. Simulated scenarios

Various scenarios were simulated to elucidate the effect of TES on the complete energy system. First, the No TES scenario was compared to the TES scenario to shed light on the value of thermal storage for the energy system. Afterward, scenarios with either PTES or TTES were compared to reveal the benefit of installing one heat storage technology over the other. The simulated scenarios were:

– No TES: A No TES scenario was created in which Balmorel was not allowed to install thermal energy storage systems.
– TES: The TES scenario allowed investments in both TTES and PTES heat storage systems.
– PTES: In the PTES scenario, Balmorel was allowed to invest only in PTES systems as a heat storage technology (for both short-term and seasonal storage).
– TTES: In the TTES scenario, Balmorel was allowed to invest only in TTES systems as a heat storage technology (for both short-term and seasonal storage).

4. Results

First, the effect of heat storage systems on the energy system is investigated in Section 4.1. Later, a system using PTES as a heat storage technology is compared to a system using TTES in Section 4.2. The PTES characteristics were investigated with an aim to quantify their effect on the utilization of this technology in Section 4.3. Last, the influence of the electricity transmission capacity on the energy system (in particular the TES systems) is presented in Section 4.4.

4.1. Comparison between the No TES and TES scenario

The No TES and the TES scenarios were compared to identify the effect of heat storage systems on a country level (Section 4.1.1) and on all the simulated countries (Section 4.1.2).

4.1.1. Effect on a country level (Denmark)

From Fig. 5A, it may be seen that the TES scenario enables wider utilization of renewable energy sources like solar and wind. Although both TES and No TES install the maximum capacity for onshore wind in Denmark, the TES scenario installs over the entire simulated period 35% more PV capacity and 10% more offshore wind capacity than the No TES scenario. On the contrary, the No TES scenario features a larger capacity of dispatchable technologies like boilers (electric and biomass), CHP, and heat pump units to cover the electricity and heat demand.

It should be noted that the No TES scenario has a larger share of technologies with high-capacity factors (e.g., CHP and heat pumps). In contrast, the TES scenario features a larger share of low-capacity factor technologies (e.g., PV and wind). This means that the TES scenario has to install higher generation capacities, as a higher capacity would be required in order to generate the same amount of energy.

Due to the mismatch between electricity production from renewables and electricity demand, generation technologies can be curtailed. Renewables can be shut down (curtailed) in high-production and low-demand periods. Curtailment is calculated as the difference between the unconstrained generation and the actual supplied power. Balmorel can curtail generation if it is more profitable than expanding the energy infrastructure (e.g., electricity transmission grid, Power-to-Heat technologies, storage). Due to the lack of thermal storage in the No TES scenario (and thus flexibility), the curtailment levels are much higher than in the TES scenario. In Fig. 5B, curtailment is compared between the two scenarios as an absolute value (in TWh). It may be observed that the TES scenario has, on average, 53% lower curtailment than the No TES scenario.

The higher curtailment level of the No TES scenario can also be depicted in the hourly cost of heat (Fig. 5C). In periods when the electricity price reaches zero, it was observed that the heating price was negative when there was an absence of heat storage (No TES scenario). From late Spring to early Autumn, hours of negative heat prices were present in the No TES scenario (mainly during daytime), while in the summer, there were entire days of negative heat prices.

Two steps explain the negative prices: firstly, negative prices derive from the choice of modeling method, and second, they derive from the simulation scenario conditions (see list below). As mentioned, Balmorel is a partial equilibrium model optimizing toward a societal optimum across different markets — electricity and heat. Prices can be high, low, or even negative in these markets. Negative prices arise when non-storable supply exceeds demand (e.g., when profits from electricity generation from a CHP plant exceed losses from heat generation). This reflects the real world, where we also see negative prices in the electricity and heat markets. The scenario-specific reasons for the negative prices were a combination of the following:

1. Low heat demand in the summer period.
2. Forced operation of CHP back-pressure plants producing both heat and electricity from burning municipality waste.
3. High renewable energy production (especially PV).
4. Insufficient heat storage capacity.

The presence of TES also affects the peak price of heat. Discharging the storage in periods of high heat demand instead of using more costly alternatives (e.g., natural gas boilers) ensures lower peak heat prices. Consequently, on average, the TES scenario had a 24% lower peak price for heat compared to the No-TES scenario. For all the simulated years, the No TES scenario had an average price for heat 2.4 €/MWh higher than the TES scenario.

It has to be mentioned that during the timesteps when the model invests in new technologies, high price spikes occur for heat and/or electricity (depending on whether the technology produces heat or electricity). For this reason, outliers are not shown in the box plots in Fig. 5C, and 99% of the data is presented.

The corresponding electricity cost for Denmark for the TES and No TES scenarios are presented in Appendix E. It was found that the weighted mean electricity price is almost the same for the TES and No TES scenarios (on average, the No TES scenario had an approximately 1% higher mean electricity price).

In order to get a better understanding of the energy flows in the heat sector, a Sankey diagram for the Denmark 2050 TES scenario is presented in Fig. 6. It may be observed that heat pumps produce most of the required heat. Moreover, the heat storage systems supplied 20% of the total demand (19% and 1% for long-term and short-term, respectively).

It should be noted that Balmorel produces each commodity (e.g., hydrogen) in the country that has the lowest cost and then transports it to neighboring countries. For this reason, in the situation where only Denmark, Norway, Sweden, and Germany are investigated, Denmark is chosen to produce the majority of PtG and export electricity instead of just covering its own energy needs due to its good offshore wind conditions (see Table 3). Consequently, since the excess heat is primarily produced by hydrogen production, the high PtG production in Denmark increases the installation of TES systems for utilizing the excess heat. However, this would not necessarily be the case if other

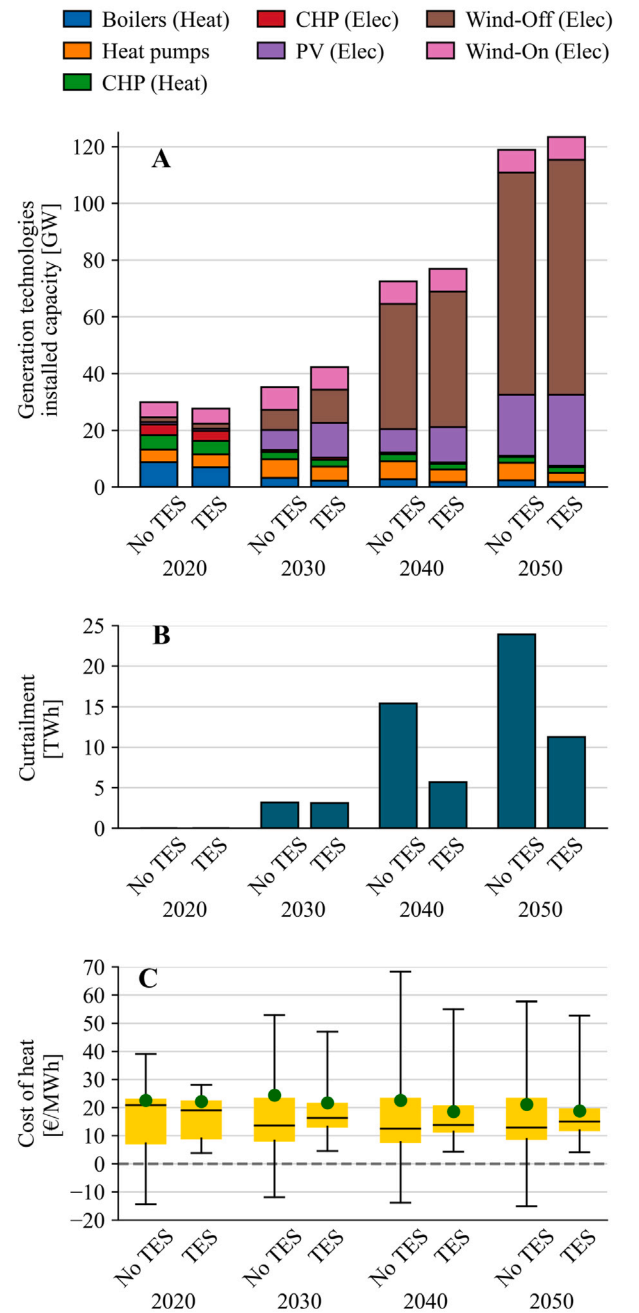

Fig. 5. Comparison between the No TES and TES scenarios for Denmark regarding the installed capacities (A), curtailment (B), and cost of heat (C). The weighted mean yearly heat prices are indicated with a green circle.

countries were included in the simulation (e.g., Southern European countries with higher solar energy potential).

It should be noted that hydrogen is used in the model to cover the energy demand in the transport and industrial sectors. However, it could also be used for peak production through fuel cells, but this was not considered profitable by the model for most countries.

Regarding heat storage, it should be mentioned that the actual installed TES capacity in Denmark in 2017 was 50 GWh, mainly consisting of TTES systems [27]. However, in Balmorel, in the TES scenario, the TES capacity for Denmark in 2050 was 3 858 GWh (66 GWh of TTES and 3 792 GWh of PTES). To put this into perspective, it corresponds to approximately 390 TTES systems, each having a volume of 3 000 m^3,

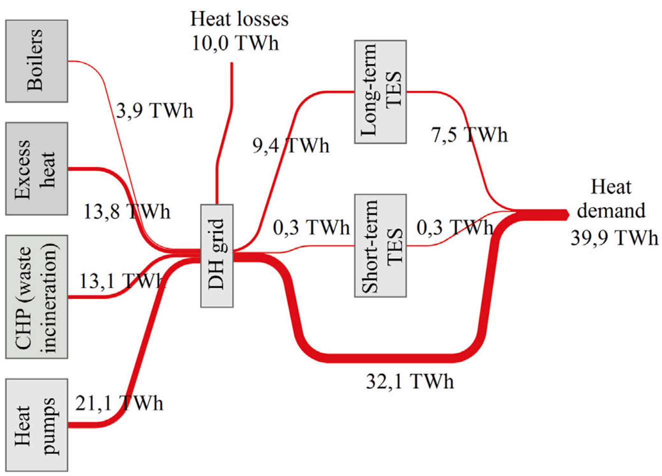

Fig. 6. Sankey diagram showing the energy flows for Denmark's heat sector in the 2050 TES scenario. Excess heat is produced primarily from hydrogen production.

and 240 PTES systems, each having a volume of 250 000 m^3, with a charge/discharge capacity of 40 MW.

However, the aggregation of district heating networks in Balmorel is inflating the use of TES, so the actual optimal values are expected to be somewhat lower. Nonetheless, it is clear that the number of installed TES in Denmark has to increase dramatically in the near future to reach cost-optimal carbon neutrality by 2050.

Last, for Denmark, the costs of TES (capital, operation, and maintenance (O&M)) corresponded to approximately 6% of the total costs of the energy system for the entire simulation period.

4.1.2. Effect on the entire simulated area (multiple countries)

It should be mentioned that the main reason for including Denmark's neighboring countries is to obtain realistic energy trading (electricity and fuels). Since electricity and fuel trading is permitted among neighboring countries, the model can find it more beneficial to have higher emissions, costs, or fuel use in one specific area. Thus, by including the entire simulation area, it was possible to have a more holistic view of the results. Consequently, in order to assess the effect of heat storage on the primary fuel consumption, CO_2 emissions, and total annual costs, it was considered necessary to include the results for all simulated countries.

Fig. 7A presents the primary fuel consumption for all the simulated countries. It may be observed that the No TES scenario uses coal and lignite in 2020 and 2030, while the TES scenario only uses them in 2020. Similarly, the No TES scenario uses natural gas as fuel until 2040, while the TES scenario has a lower usage and only utilizes them until 2030. As expected, the TES scenario uses more solar and wind power as fuel, while the No TES scenario compensates for that by using more wood chips (biomass). Both scenarios use similar amounts of hydropower, municipal waste (for waste incineration), and nuclear.

Based on the primary fuel used, it is evident that the TES scenario limits the use of fossil fuels after 2030 and goes entirely carbon-free by 2050. This may also be seen in Fig. 7B, where the CO_2 emissions for the two scenarios are presented. Notice that the No TES scenario still has CO_2 emissions in 2050 (around 10 kt). When looking at the total emissions over the entire simulation period, the quicker decarbonization of the TES scenario led to 5% lower CO_2 emissions, corresponding to approximately 26 Mt, thus providing also a more environmentally friendly solution.

Regarding the total costs, the TES scenario had, on average, 4% lower costs than the No TES scenario, corresponding to approximately 10 billion €. As it may be observed in Fig. 7C, the No TES scenario had higher capital, fixed, and fuel costs due to the different technologies,

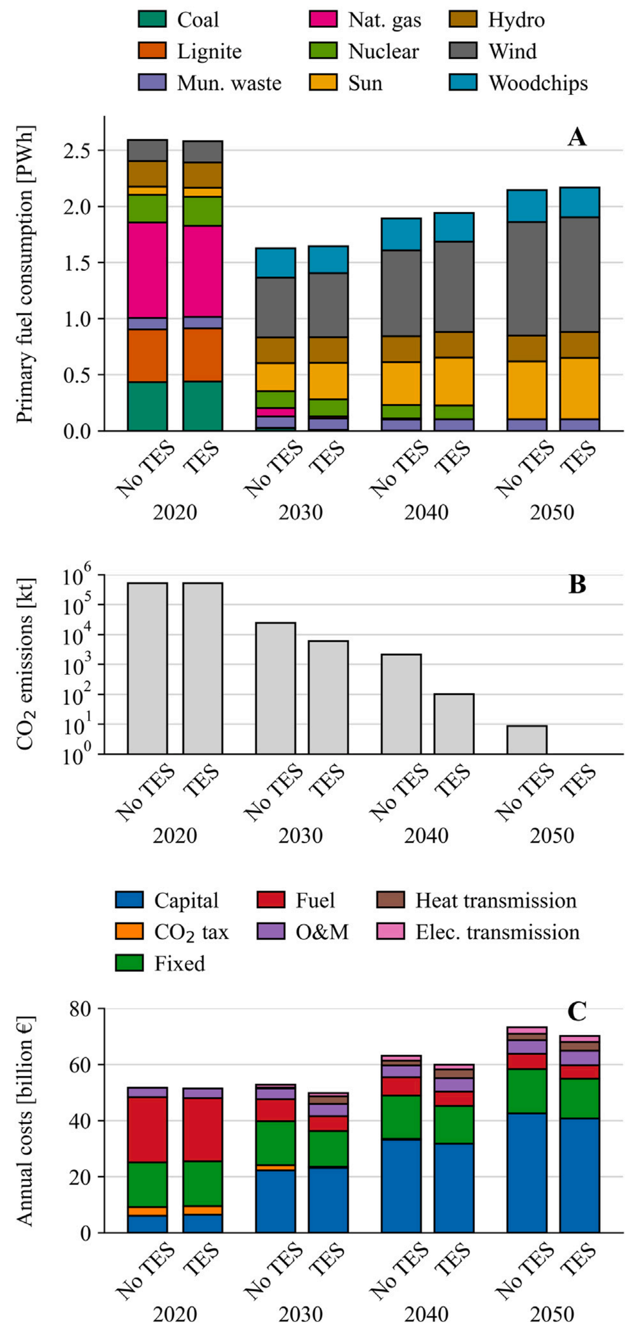

Fig. 7. Comparison between the No TES and TES scenarios for all investigated countries regarding the primary fuel consumption (A), CO_2 emissions (B), and annual costs (C).

fuels, and amount of energy trading, as well as a higher CO_2 tax burden than the TES scenario. The higher capital costs were due to the greater installed capacity of the more expensive technologies (e.g., heat pumps, boilers, and CHP). On the contrary, the TES scenario had higher O&M and transmission costs.

It should be noted that although the study focused on Denmark and its neighboring countries, the obtained results could potentially be applied to other countries with district heating grids. The main difference in the Danish district heating network compared to other countries is the low supply/return temperatures. However, this study investigated future scenarios, and future generations of district heating feature low supply/return temperatures [62]. Overall, this study presents a possible

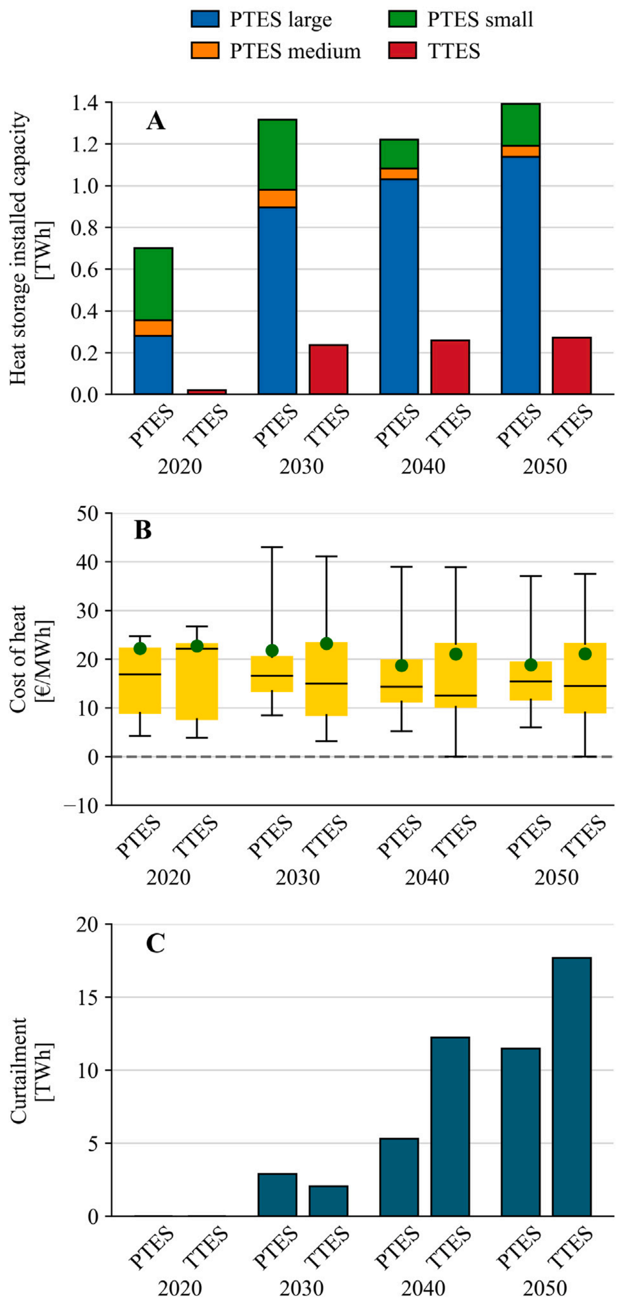

Fig. 8. Comparison between the PTES and TTES scenarios for Denmark regarding the installed heat storage capacity (A), the hourly cost of heat (B), and curtailment (C). The weighted mean yearly heat prices are indicated with a green circle.

future alternative to conventional heating technologies (e.g., natural gas boilers) with the implementation of sector coupling.

4.2. Comparison between PTES and TTES

In this section, the impact of PTES and TTES technologies was investigated on a country level (Denmark) in order to identify differences between the use of the two TES technologies. Information about the installed capacities in Denmark's neighboring countries can be found in Appendix F.

In Fig. 8A, it may be observed that the installed capacity for PTES is, on average, approximately five times higher than TTES. The main reason is the much lower cost of PTES compared to TTES (the specific cost for PTES is approximately 24 €/m^3 while for TTES, it is 121 €/m^3). This results in a much larger heat storage capacity for the PTES scenario, enabling higher use of renewables. In the PTES scenario, the optimal system has 6% higher PV capacity and 6% higher wind capacity than the TTES scenario. On the contrary, in the TTES scenario, investments favor dispatchable technologies, with 8% higher boiler capacity, 6% higher CHP capacity, and 19% higher heat pump capacity. As a result, the PTES scenario features more sun and wind as primary fuel, while the TTES scenario utilizes more wood chips. The higher share of renewables in the PTES scenario enables a larger production and export of hydrogen and electricity.

It should be noted that the installed TES capacity depends on many factors (including the heat demand and the characteristics of each technology), but also on whether the model finds more profitable alternative flexibility options (e.g., electricity transmission), as described in Section 2.3.1. Thus, very different results can be obtained for each TES technology.

The effect of cheaper storage leads to an increase in heat storage capacity, resulting in a lower heat price as illustrated in Fig. 8B. Although the peak heat prices for each year are similar for the two scenarios, the TTES scenario has a higher mean price for heat (22.1 vs. 20.6 €/MWh). The high heat storage capacity in the PTES scenario enables large amounts of heat to be transferred from summer to winter but also enables arbitrage, i.e., charging with cheap energy when there is an energy surplus. This leads to a lower average price of heat and a lower level of curtailment, as seen in Fig. 8C. In general, PTES seems more favorable to TTES regarding costs and performance at a system level, especially considering that it is not yet a mature technology and there is still a margin for improving the technology.

The validity of the obtained results from Sections 4.1 and 4.2 was compared with results from existing studies in the literature, where it was found that they were in good agreement. Details of this comparison can be found in Appendix G.

As it may be seen in Fig. 8A, most of the installed PTES are "large", meaning that they are built in large DH areas (i.e., large cities) where large plots of land might not be available. The construction of PTES on the outskirts of cities could be a solution; however, this often requires costly extensions of the existing network. For this reason, research is ongoing to find ways of exploiting the PTES surface for other uses, e.g., like the ones described in [63].

Unlike TTES, which can be built on the ground and has a small footprint, PTES is an underground storage technology; thus, stable ground conditions are required for its construction. Additionally, sites with shallow groundwater tables should be avoided since this could increase heat losses from the storage and complicate its construction.

Last, due to the usage of steel and concrete, TTES can store temperatures up to 100 °C (even a bit higher if pressurized), while PTES is limited up to 90 °C due to the polymer liner. Thus, PTES might not be a viable option in countries with high DH supply temperatures. However, this is considered a minor issue since lower DH supply temperatures are expected to be adopted in the future (supply temperatures lower than 70 °C [23]).

Overall, with adequate planning, PTES systems can be considered a highly effective solution for most future heat storage projects since they outperform TTES systems in terms of increasing renewables' utilization, minimizing heat price, etc.

4.3. Effect of PTES characteristics

A sensitivity analysis was conducted to investigate the PTES characteristics' effect on implementing this technology in the energy system. The four main parameters of PTES were investigated: charge/discharge capacity, lifetime, investment cost, and efficiency. It has to be mentioned that although these parameters can be interconnected (e.g., cost and lifetime), this has not been quantified in the literature for PTES. Additionally, there are situations where this might not be applicable

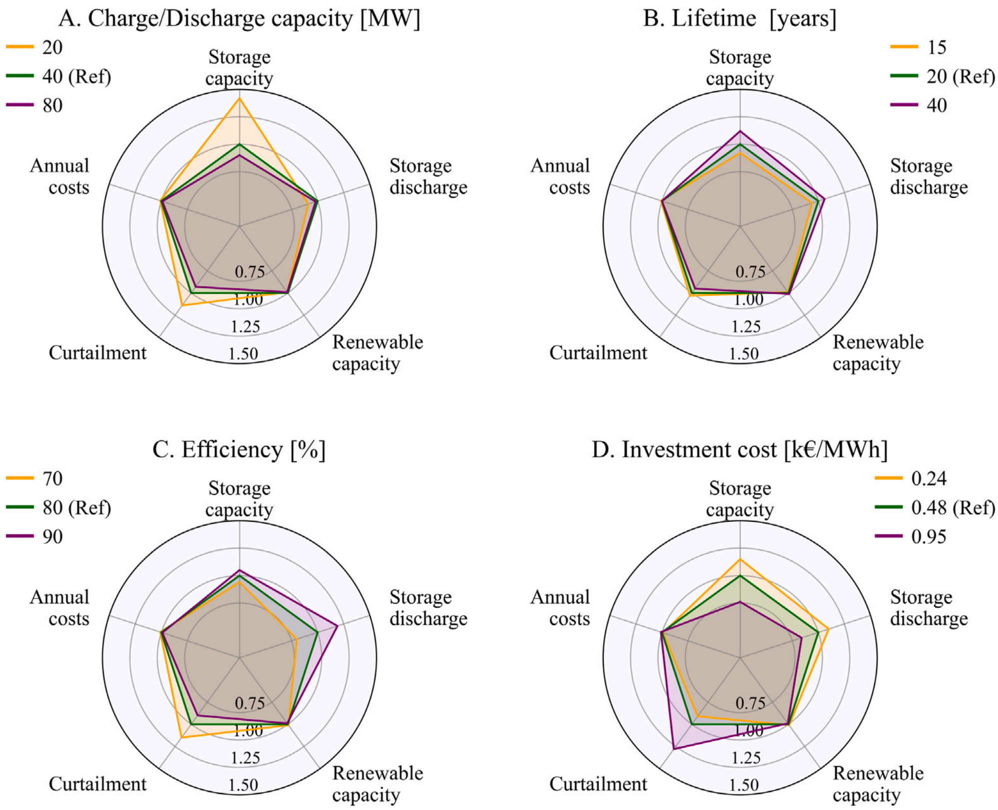

Fig. 9. Sensitivity analysis on the main technical PTES parameters. Values denote the increase of each parameter compared to the reference scenario (e.g., 1.5 storage capacity means that this scenario features a 1.5 increase in the storage capacity compared to the reference scenario).

Table 4
PTES parameter values used in the sensitivity analysis.

Parameter	Low extreme	Reference	High extreme
Charge/discharge capacity [MW]	20	40	80
Lifetime [years]	15	20	40
Investment cost [k€/MWh]	0.24	0.48	0.96
Efficiency [%]	70	80	90

(e.g., additional expenses due to non-ideal ground conditions). For this reason, these parameters were investigated individually.

Three scenarios were simulated for each parameter: a reference scenario (i.e., the PTES scenario from Section 4.2) and two extreme scenarios. The average parameter values used in the sensitivity analysis are presented in Table 4.

Five system parameters were assessed to identify the sensitivity of the investigated parameters on the energy system: optimal installed heat storage capacity, heat storage discharged energy, installed renewable capacity, curtailed energy, and annual costs. Storage discharged energy refers to the amount of energy discharged by the short- and long-term TES to the district heating grid. Renewable capacity refers to the installed capacity of PV and wind installed in the energy system. The sensitivity analysis results are presented as four spider charts in Fig. 9.

It has to be noted that since the reference system already had a high implementation of renewable technologies, only marginal differences were observed regarding the installed renewable energy capacity and annual costs among the different scenarios. This observation was true for all the investigated parameters.

Fig. 9A illustrates that a lower charge/discharge capacity would increase the installed storage capacity but simultaneously reduce the energy discharge from the storage and increase curtailment. This indicates the importance of this parameter, as it dictates how fast the storage can respond to either a surplus of energy or a peak in demand. A high charge capacity enables the PTES to store a large amount of excess energy in a short time, thus limiting the need for curtailment. Similarly, heat storage systems with a high discharge capacity can supply heat in a short time to cover a demand peak, thus reducing the peak load. Balmorel tried to offset this limitation by installing a 40% higher PTES capacity for the case with low charge/discharge capacity, but even so, the heat discharged by the PTES was marginally lower compared to the reference scenario. However, it must be noted that little benefit was observed from increasing the charge/discharge capacity of the Reference case.

The lifetime of the PTES affects the implementation of the technology through the Levelized Cost Of Energy (LCOE). A shorter lifetime leads to higher LCOE, thus making the technology less financially attractive. This can be seen in Fig. 9B, where a longer life led to a higher installed capacity for PTES and, as a result, lower curtailment; however, the differences from the reference case were small compared to other parameters tested.

The effect of storage efficiency may be observed in Fig. 9C. Compared to the reference case, a PTES efficiency of 70% would reduce the installed storage capacity by 6% and the storage discharge by 20% (due to higher heat losses), also leading to 15% higher curtailment. As expected, a higher PTES efficiency positively affects the storage and overall system operation.

Last, for the investment cost, by reducing the price of the PTES by 50%, there was a 15% increase in the installed heat storage capacity, 10% higher storage discharge, and a 10% reduction in curtailment.

It is evident that improving all the investigated PTES parameters would improve both the PTES and the overall energy system performance, increasing the technology's implementation at the same time. However, this investigation identified the investment cost and the efficiency of the PTES as the two parameters having the largest impact on the future utilization of the technology. Perhaps most importantly, the sensitivity analysis confirms the robustness of the study in terms of deployment of PTES: This deployment remains large, even under less favorable conditions.

4.4. Flexibility options

As was mentioned in Section 2.3.1, flexibility in an energy system can be achieved through generation, transmission, demand side management, and storage (electrical, heat, and hydrogen). These four options are utilized in order to cover the electricity and heat demand in the least-cost way.

Since storage is the main focus of this study, it was decided to investigate another flexibility option to identify its effect on the energy system (and possibly on storage). It was decided to investigate electricity transmission since a lot of countries could be facing transmission bottlenecks and might have the aim to become more self-sufficient. Additionally, planning transmission capacity between countries is time-consuming and could be subject to political decisions. It has to be noted that this is only one of many flexibility options that could be investigated. Other relevant options include load shifting, smart charging of electric vehicles, etc.

The electricity transmission scenarios that were investigated were, apart from the reference scenario (PTES scenario also used in Section 4.3), Denmark in island mode (i.e., not being able to trade energy with any of its neighboring countries) and Denmark without being allowed to install new transmission capacity (i.e., only using the existing transmission capacity in 2020 and able to trade fuels).

In order to investigate the effect of electricity transmission capacity on the energy system, the total installed heat storage, PV, wind, hydrogen storage, and dispatch capacities, along with the average electricity and heat price, were plotted for the entire simulation period (2020–2050), as presented in Fig. 10.

In island mode, the model invested 25% less in PV and 70% less in wind capacity and tried to cover the heat and electricity demand by investing 50% more in dispatchable capacity and 25% more in heat storage capacity. The use of conventional generation technologies had a major impact on the average electricity price, which was 20% higher. However, the increase in heat storage capacity was able to maintain the average heating price at approximately the same level. In parallel, since electricity and hydrogen exports were impossible, there was 80% lower hydrogen storage capacity.

Using the existing transmission capacity in 2020, it may be observed that the heat storage, dispatchable, and PV capacity, as well as the average heat and electricity prices, remain approximately constant. However, since there are limitations in electricity exports, there is 25% less wind capacity installed, which in turn equally reduces the hydrogen storage capacity due to fewer periods of cheap electricity for hydrogen production.

Last, it should be noted that although Balmorel could invest in different flexibility providers (e.g., storage, flexible generation, transmission interconnectors) in all scenarios, batteries were not used in Denmark. This indicates the high relevance of sector coupling as an alternative to installing battery storage. It should be noted that the cost of batteries was based on [64].

Overall it is obvious that additional electricity transmission capacity adds a high degree of flexibility to the energy system. Nonetheless, it was also revealed that heat storage could offset the absence of transmission capacity in order to maintain a similar average price of heat.

5. Conclusions

This paper investigated the effect of thermal energy storage (TES), particularly pit thermal energy storage (PTES), on an energy system. The study focused on Denmark and its neighboring countries and quantified the impacts of PTES on their future energy systems. The

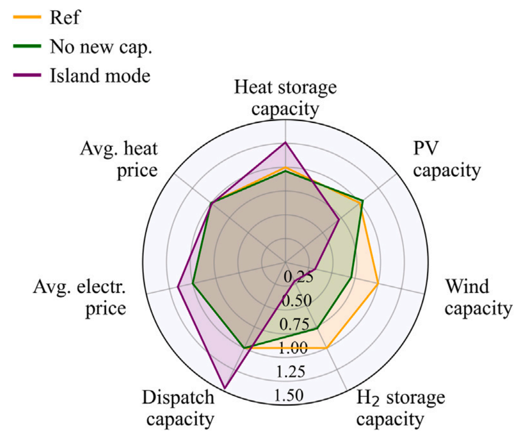

Fig. 10. Investigation on transmission capacity flexibility for Denmark.

analysis was done using the energy system model Balmorel, which was used to calculate the least-cost solution for the energy transition toward 2050. As PTES is not a mature technology, sensitivity analyses were also performed on its technical and economic characteristics. The main findings from this investigation were the following:

- Energy systems using TES could achieve carbon neutrality by 2050, unlike systems without TES, where CO_2 emissions existed even in 2050. TES systems accelerate decarbonization through increased cost efficiency.
- TES systems utilized 35% higher PV capacity and 10% higher wind capacity. In parallel, TES systems had a 53% lower level of curtailment and ultimately 2.4 €/MWh lower average heat price (with 24% lower peak price).
- In the absence of electricity transmission capacity with neighboring countries, a larger deployment of TES capacity could ensure an almost constant average heat price.
- PTES systems were found to reduce system costs, enabling higher utilization of renewables (both wind and solar) compared to TTES due to the lower cost of PTES systems and, thus, greater deployment (approximately five times).
- PTES systems led to a 1.5 €/MWh lower average heat price than TTES.
- The combination of PV, wind, heat pumps, and new energy infrastructure will have an important role in future energy systems. Particularly in Denmark, they are expected to cover approximately half of the heat demand. When large volumes of TES are available (e.g., PTES), the installed PV and wind capacity is increased, while for smaller TES volumes (e.g., TTES), greater heat pump capacities are used to cover the demand.

It has to be mentioned that since Balmorel simulates only energy flows, similar results can be expected when substituting PTES with other heat storage systems that have similar characteristics, i.e., high efficiency and low cost.

CRediT authorship contribution statement

Ioannis Sifnaios: Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Daniel Møller Sneum:** Writing – original draft, Conceptualization. **Adam R. Jensen:** Writing – review & editing, Visualization. **Jianhua Fan:** Writing – review & editing, Supervision, Funding acquisition. **Rasmus Bramstoft:** Writing – original draft, Methodology, 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

No data was used for the research described in the article.

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Appendix A. Nomenclature

Nomenclature

Sets

$\mathcal{A}$	Areas
$\mathcal{G}$	Technologies
$\mathcal{G}^{TES}$	Subset of storage technologies
$\mathcal{S}$	Seasons
$\mathcal{T}$	Time periods in a season
$\mathcal{Y}$	Years

Variables

$k^{TES,new\_CAP}_{y,a,g}$	new installed capacity of heat storage technology $g \in \mathcal{G}^{TES}$, in year, y, and area a
$p^{gen\_heat}_{y,a,g,s,t}$	heat generation in year, y, area a of technology g in the time period s,t
$p^{TES,charge}_{y,a,g,s,t}$	heat for charging the heat storage technology $g \in \mathcal{G}^{TES}$ in year, y, area a, and time period s,t
$p^{TES,discharge}_{y,a,g,s,t}$	heat from discharging of heat storage technology $g \in \mathcal{G}^{TES}$ in year, y, area a, and time period s,t
$v^{TES}_{y,a,g,s,t}$	heat storage content of the heat storage $g \in \mathcal{G}^{TES}$ in year, y, area a, and time period s,t

Parameters

$\epsilon^{TES,eff}_{g}$	efficiency of heat storage technology $g \in \mathcal{G}^{TES}$
$\gamma_{s,t}$	length of chronological time segment s,t
$\lambda^{TES,charge}_{g}$	charging time for heat storage technology $g \in \mathcal{G}^{TES}$
$\omega^{TES,discharge}_{g}$	discharging time for heat storage technology $g \in \mathcal{G}^{TES}$
$d^{heat}_{y,a,s,t}$	heat demand in year, y, for area a in the time period s,t
$k^{TES,decom\_CAP}_{y,a,g}$	decommissioning capacity of heat storage technology $g \in \mathcal{G}^{TES}$, in year, y, and area a
$k^{TES,ex\_CAP}_{y,a,g}$	existing capacity of heat storage technology $g \in \mathcal{G}^{TES}$, in year, y, and area a

Table 5
Electricity and heat demand for investigated countries from 2020–2050.

Country	Year	Heat [TWh]		Electricity [TWh]	
		Total	Peak	Total	Peak
DK	2020	74	1.5	30	0.5
	2030	50	1	36	0.5
	2040	50	1	42	0.6
	2050	50	1	43	0.6
DE	2020	1304	29.1	446	6.5
	2030	880	19.6	449	6.5
	2040	880	19.6	473	6.9
	2050	880	19.6	497	7.2
NO	2020	58	1.2	97	1.4
	2030	39	0.8	98	1.4
	2040	39	0.8	99	1.4
	2050	39	0.8	100	1.5
SE	2020	171	3.4	101	1.5
	2030	115	2.3	102	1.5
	2040	115	2.3	106	1.5
	2050	115	2.3	111	1.6

Appendix B. Methodology – literature review

The query (interseasonal OR inter-seasonal OR large-scale OR "large scale" OR seasonal OR long-term OR long-duration) AND ("heat storage" OR "thermal storage" OR "thermal energy storage") AND ("district heating" OR "district energy") brought 307 results, whereof 121 was found relevant in the initial screening. A large portion (68) of these primarily dealt with solar thermal. Borri et al. [34] have similarly noted the large body of research linking TES and solar. Along with irrelevant studies, the solar studies were sorted out since the scope of the present study is PTES in energy systems with a diversity of sectors and producers. Solar thermal is still represented in the remaining studies but as one source among others. This left the review with a final set of 92 relevant references. Numbers on 15 scenarios were extracted out of five studies to perform the analysis in and around Fig. 1.

Appendix C. Electricity and heat demand for investigated countries

The heat and electricity consumption for the investigated countries is presented in Table 5. It may be observed that from 2030 onward, there is a reduction in the heat demand for all countries. This reduction is based on the European Union regulation regarding energy efficiency targets for 2030, which states that consumption should be decreased by 32.5% compared to 2020 [65]. The increase in energy efficiency is not obvious in the electricity demand, as there is added demand due to electrification. Thus, overall there is a small increase in electricity demand for all countries. The peak demand for heat and electricity is also presented in Table 5 for each country and year.

It should be noted that the magnitude of the heat demand is proportional to the population of each country, while the electricity demand also depends on other factors (e.g., industry, degree of electrification in transport and heating sectors). The allocation of the heat demand to the different regions of each country was based on the electricity demand of each region.

The data for the heat demand were taken from [37,49,66,67]. Electricity demand and distribution losses were obtained by Eurostat [67]. Since Balmorel is open-source, all data can be accessed and downloaded freely from [45].

The seasonal variation of the electricity and heat demand for Denmark in 2050 is presented in Fig. 11. It should be noted that only the 8 simulated weeks and 12 h (every other hour for one day) for each week are presented in the figure. The profile of the heat demand was based on the methodology presented in [49]. For obtaining the final yearly results, temporal aggregation of the values was performed. Similar profiles were used for all simulated countries and all simulated years.

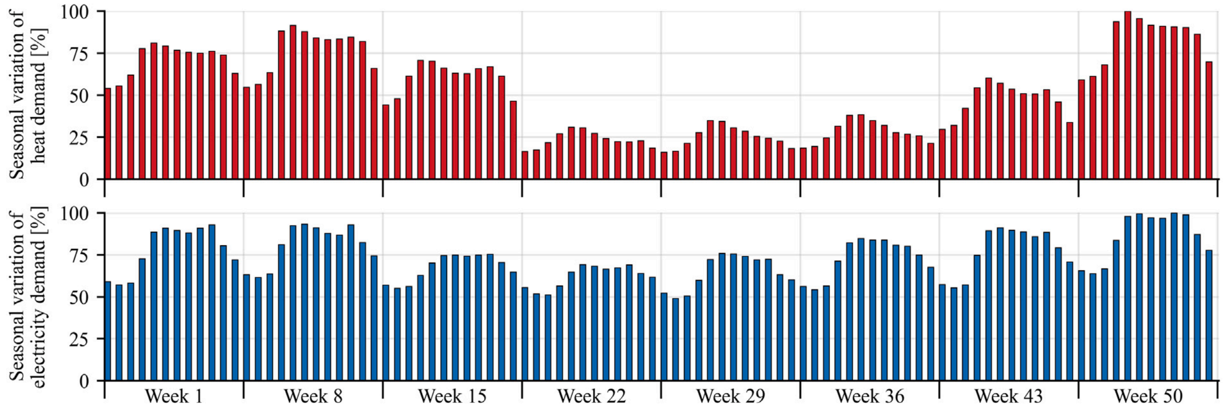

Fig. 11. Seasonal heat and electricity demand variation for Denmark in 2050. The simulated hours and weeks were repeated in order to represent one full year. A similar trend was followed in all simulated countries for all simulated years.

Table 6
Total installed generation and storage capacities for simulated countries.

		Dispatch [GW]	Wind [GW]	PV [GW]	Hydro [GW]	Fuel cells [GW]	Short-term TES [GWh]	Long-term TES [GWh]	Batteries [GWh]	H_2 storage [GWh]
DK	PTES	46	174	50	0	0	305	4626	0	114
	TTES	50	166	48	0	0	72	715	0	101
DE	PTES	1039	458	1007	36	17	4227	75874	34	693
	TTES	1044	460	949	36	21	786	21493	20	682
NO	PTES	35	36	30	128	0	0.6	2950	0	17
	TTES	39	36	25	124	0	36	749	0	15
SE	PTES	125	58	70	65	0	170	8706	0	57
	TTES	134	56	60	65	0	122	1830	0	51

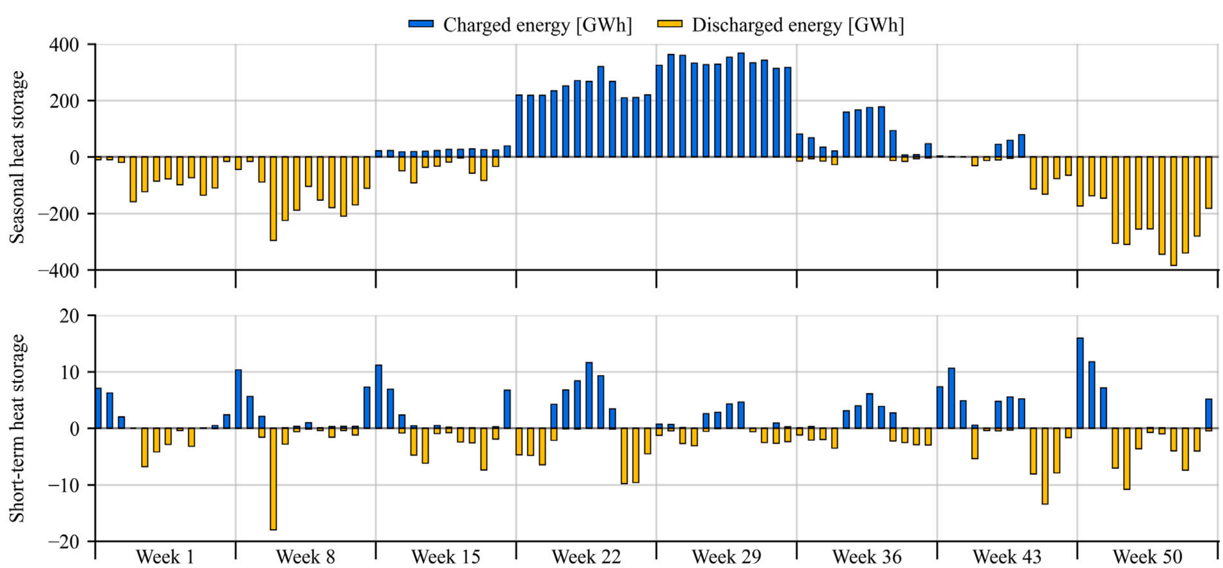

Fig. 12. Seasonal and short-term TES operation for Denmark in 2030.

Appendix D. Heat storage operation

The modeling of TES in Balmorel is done using the following assumptions.

- The short-term TES needs to have the same energy content at the start and end of each season. However, its energy content can vary from time step to time step.
- The seasonal TES needs to have the same energy content at the beginning and end of each year. However, its energy content can vary across seasons and time steps.
- An aggregation factor representing the length of the time segment (denoted with $\gamma_{s,t}$ in Eq. (2)) should be used to calculate the yearly charged and discharged energy from TES.
- Balmorel is free to decide the charge level of the storage at the start of the simulation (both for seasonal and short-term TES).

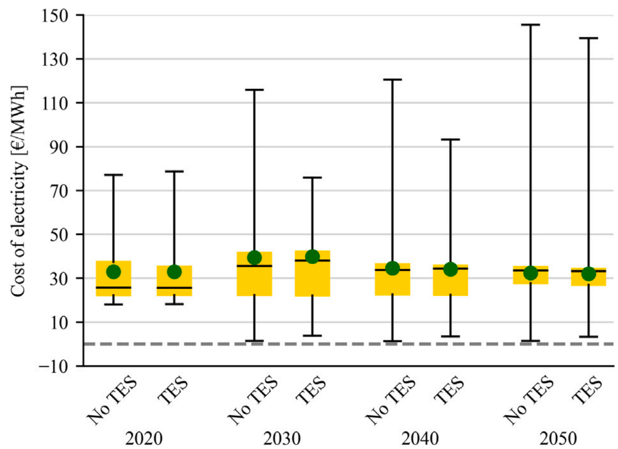

Fig. 13. Comparison between the No TES and TES scenarios for Denmark regarding the electricity cost. The weighted mean yearly electricity prices are indicated with a green circle. The grey dashed line denotes an electricity price of zero.

A visualization of the seasonal and short-term operation is presented in Fig. 12. It can be observed that the seasonal storage is charged primarily during the summer and discharged during winter. On the other hand, the short-term TES performs one storage cycle per week. In the winter, the short-term TES is primarily charged during nighttime and discharged during the day, whereas, in the summer, it is charged during daytime and discharged at night.

Appendix E. Electricity cost in Denmark

The electricity cost in Denmark for the simulated years is presented in Fig. 13. It may be observed that the TES scenario has, in general, lower peak electricity prices compared to the No TES. The main reason is that the TES scenario can use the stored heat to cover the heat demand when the electricity price is high (instead of operating, e.g., a heat pump using expensive electricity). However, the weighted mean electricity price is almost the same for the TES and No TES scenarios (on average, the No TES scenario had an approximately 1% higher mean electricity price).

Appendix F. Installed capacities

The total generation and storage capacities installed in the simulated countries are presented in Table 6. The term "dispatch generation capacity" denotes the sum of heat pumps, boilers, and CHP plants installed in a country. In general, in all simulated countries, it may be observed that the PTES scenario installs more PV, TES, and H_2 storage, while the TTES scenario installs more dispatchable generation technologies. Of course, some countries do not follow the same trend due to their different energy systems. For example, in Norway, a very small capacity of short-term TES is installed in the PTES scenario, and the model invests more in hydropower compared to TTES.

Last, as mentioned in Section 4.4, batteries were not used in Denmark, although they have the potential to be used. In Table 6, it can be observed that batteries and fuel cells are only installed in Germany.

Appendix G. Comparison of the literature with the results of this study

As mentioned in the introduction of the present paper, the existing studies concerning the impact of PTES are few in number and varied in assumptions. Only one study found in the literature is based on analyses of a whole country (Germany) [14], while the remaining studies are analyses of single district heating systems [5,13,15–17]. In terms of the time period studied, the range is 1 to 30 years.

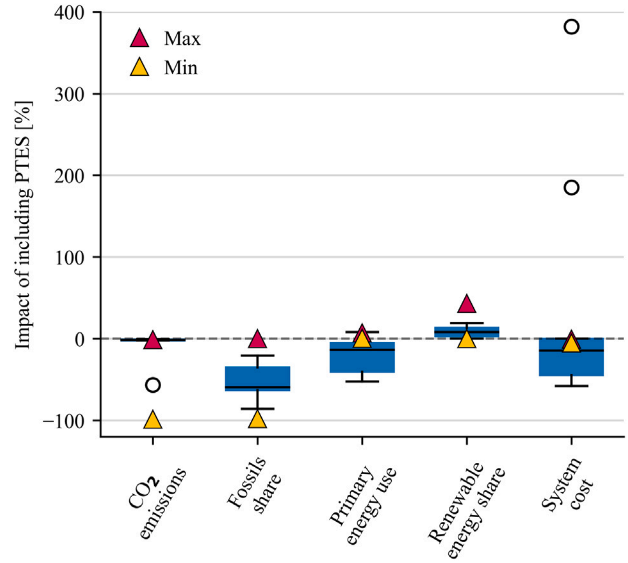

Fig. 14. Comparison between the obtained results from this study (triangles) with the results of similar studies from the literature (boxplots). The two triangles indicate the maximum and minimum obtained values.

Keeping this in mind, we carried out a meta-study comparing results from the literature against the difference between the present study's No TES and PTES scenarios. The study included all the simulated countries (DK, DE, NO, SE) and the entire simulated period (2020–2050). Fig. 14 presents this comparison, and it may be observed that, in general, the results of this study are comparable to the literature results. The biggest difference was found for the CO_2 emissions and the fossil share since, in the present study, decarbonization was achieved by 2050 for the PTES scenario.

As a summary of the figure, when including PTES in the energy system, the present study reported on average 5% lower CO_2 emissions, 8% less use of fossil fuels, 4% higher primary energy use, 13% higher renewable energy share, and 4% lower system costs, compared to systems without having TES.

Appendix H. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.apenergy.2023.121663.

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