Experiences from the first short-term pit thermal energy storage

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Abstract

Pit thermal energy storage (PTES) is a promising low-cost storage technology used in connection with district heating. PTES systems have historically been coupled with solar district heating systems and used as seasonal heat storage. However, in January 2023, the first PTES operating as short-term heat storage started operating in Høje Taastrup, Denmark. Unlike existing PTES, this storage is not connected to a solar heating system but directly to the district heating grid and has a storage cycle of around two weeks. This paper presents lessons learned and the first results from the construction and operation of the Høje Taastrup PTES.

Keywords: heat storage, large-scale energy storage, district heating, PTES

1. Introduction

The pit thermal energy storage (PTES) technology has been developed and demonstrated in combination with large solar collector fields in Denmark (Soerensen and From, 2011). In principle, a PTES is a large water reservoir lined with a watertight polymer liner (to prevent water from leaking to the ground) and covered with a floating insulating lid (to reduce heat losses). The PTES technology's main benefit is its simplicity and low material usage, which has enabled construction costs below 27 €/m^3 (Schmidt et al., 2018). However, since PTES is not yet a mature technology, the storage efficiencies of the existing systems range from 60% to 90% (Sifnaios et al., 2023a). So far, PTES systems have only been used for seasonal heat storage, enabling district heating networks to achieve solar fractions higher than 40% (Sveinbjörnsson et al., 2017).

In 2023, the first PTES used for short-term heat storage started operation in Høje Taastrup, Denmark. The pre-feasibility study showed that the optimal operation of the PTES was as a short-term heat storage (storage duration 1-2 weeks) and not as a traditional seasonal storage. Unlike the existing PTES systems, the PTES in Høje Taastrup is charged directly from the district heating network and is not connected to a solar thermal collector field. This way, various heat sources can be used to charge the storage, adding a large degree of flexibility to the district heating system. For example, in times of surplus renewable electricity, heat pumps or electric boilers can be used to charge the storage, and the heat can then be discharged at a later point. The storage also enables more optimal operation of combined heat and power (CHP) plants and utilization of larger amounts of waste heat.

Due to the short-term storage operation, the top water layer of the PTES will, in practice, have an almost constant temperature of 90 °C. However, the polymer liners used in the existing storages could not be guaranteed for such conditions. For this reason, a new liner was developed and installed, which can withstand temperatures of 95 °C for 50 years. This paper presents experiences from the construction stages and initial results from the operation of the PTES in Høje Taastrup.

2. The storage construction

The construction of the PTES in Høje Taastrup started in April 2020 and was completed in December 2022. Typically, the construction period is approximately one year; however, a crack in the liner in February 2021, believed to be caused by the freezing ambient conditions, delayed the construction.

The storage volume is 70,000 m^3, and the operating temperatures are approximately 45 – 90 °C. Fig. 1 shows photos from the start of the excavation and the liner installation. It should be noted that in the image showing the liner installation, the geotextile can also be identified (bright, white-colored liner), which is placed under the bottom liner and provides drainage and cushioning to the liner. Fig. 2 shows the installation of the diffusers and the final lid installation. Note that the black liner in Fig. 2 covering the PTES is a protective liner placed

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on the PTES during the water-filling phase to prevent dirt from entering the PTES and minimize corrosion. It should also be mentioned that this is the first PTES where the diffusers were placed close to the edge of the storage. Traditionally, the diffusers were located in the middle of the PTES. However, placing them at one end of the storage makes the installation easier and cheaper since less piping is required.

Fig. 1: Excavation (left) and liner installation (right).

Fig. 2: Diffuser installation (left) and completed lid (right).

2.1. Liner

The liner is an essential part of the PTES since it prevents water from leaking into the ground. Additionally, a liner is installed between the top water surface and the floating insulation lid to prevent water from entering the lid. Commercial PTES have so far all used polymer liners. Specifically in Denmark, all existing PTES have been constructed with a welded high-density polyethylene (HDPE) liner to ensure water tightness. The main reason for choosing polymer liners is their low cost and easy installation (Sifnaios, 2023).

The main drawback of polymer liners is that they degrade when exposed to high temperatures, thus limiting the storage's lifetime. Additionally, polymer liners are not completely water-tight; therefore, some water diffuses into the ground and lid construction.

For the PTES in Høje Taastrup, a new 2.5 mm thick polypropylene (PP) liner was used, which is expected to last 50 years at a temperature of 95 °C. Apart from the longer lifetime, the PP liner was approximately 120,000 € cheaper compared to HDPE alternatives and equally easy to install and weld. The PP liner was found to have approximately four times higher water permeability compared to the HDPE alternatives; however, this was not considered a problem (at least for the sides and bottom of the storage).

Unfortunately, the installed PP liner cracked in February 2021 during the water-filling of the PTES. This incident was a result of the following reasons:

- there was low ambient temperature (below freezing), which made the PP liner brittle
- wooden rods were used to hold the protective liner in place, and in some cases, they had pierced through the PP liner on the embankment
- the weight of the water created extra tension on the PP liner

After inspection, it was decided that the liner was irreparable. Thus, the PTES was emptied of water, and the PP liner was replaced with an improved version, which included additives to withstand temperatures below freezing. In the past, liner manufacturers focused on developing materials that could withstand high temperatures; however, this incident revealed the need for liners to withstand low temperatures.

2.2. Lid construction

The floating insulating lid is the only component that minimizes heat losses to the ambient and is the most expensive component of the PTES. Flexible insulation materials are usually used in lid constructions for the lid to be able to bend due to the thermal expansion of the water.

So far, two different insulation materials have been used, namely Nomalén (NMC Termonova, 2011) and Light Expanded Clay Aggregate (LECA). Nomalén insulation is sold as mats made of cross-linked polyethylene foam, while LECA is small, expanded clay pebbles. Nomalén has been used in the PTES in Marstal and Dronninglund, whereas LECA has been used in Gram, Vojens, and Toftlund (Sifnaios et al., 2021).

Although seasonal PTES connected to solar thermal plants are considered to have a technology readiness level (TRL) of 8, there are still issues related to the lid that have a significant impact on their performance and lifetime, such as:

- degradation of the insulation performance due to exposure to high temperatures and moisture for long periods
- difficulty in removing rainwater from the lid's surface

To overcome these challenges, the company Aalborg CSP has developed a new modular lid (see Fig. 3), with an expected lifetime of a minimum of 25 years (Aalborg CSP, 2020). This lid has been installed in the Høje Taastrup PTES and in Marstal and Dronninglund. Different types of insulation with varying insulating properties and temperature resistance were used to ensure the lid's durability at high temperatures. A high-temperature resistant version of Nomalén was placed close to the storage water surface, and an extruded polystyrene insulation (XPS) was placed on top. Additionally, the lid was divided into multiple modules for more efficient rainwater handling (see Fig. 2). A slope was created towards the center of each module using varying levels of pebbles, and a pump was located at the center to remove the rainwater.

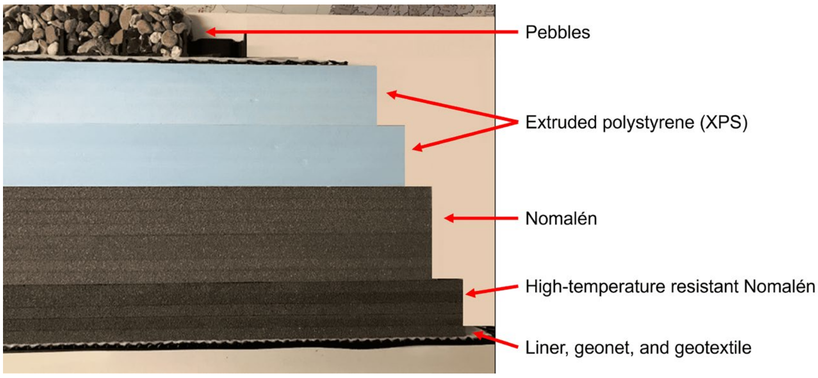

Fig. 3: The new version of the Nomalén lid used in Dronninglund, Marstal, and Høje Taastrup, constructed by the company Aalborg CSP (Sifnaios, 2023).

3. Monitoring program

In order to monitor the operation and performance of the PTES in Høje Taastrup, a number of sensors were installed (see Fig. 4). The monitoring program included the following parameters:

- The storage temperature is measured using four temperature strings, each having 14 PT100 sensors. Two strings are placed at the east end of the PTES and two at the west end.
- Several sensors have been placed between the insulation layers in the lid measuring temperature, humidity, and heat flux.
- The ground temperature is measured using a temperature string having 10 PT100 sensors. The

temperature is measured until a depth of 15 m from the top of the embankment.

- The moisture and thermal conductivity of the ground is measured at a depth of 1 m from the top of the embankment.
- A weather station is used to measure the ambient air temperature, humidity, and wind speed.
- The storage water level is measured in a small well adjacent to the PTES using a guided radar and a hydrostatic sensor.

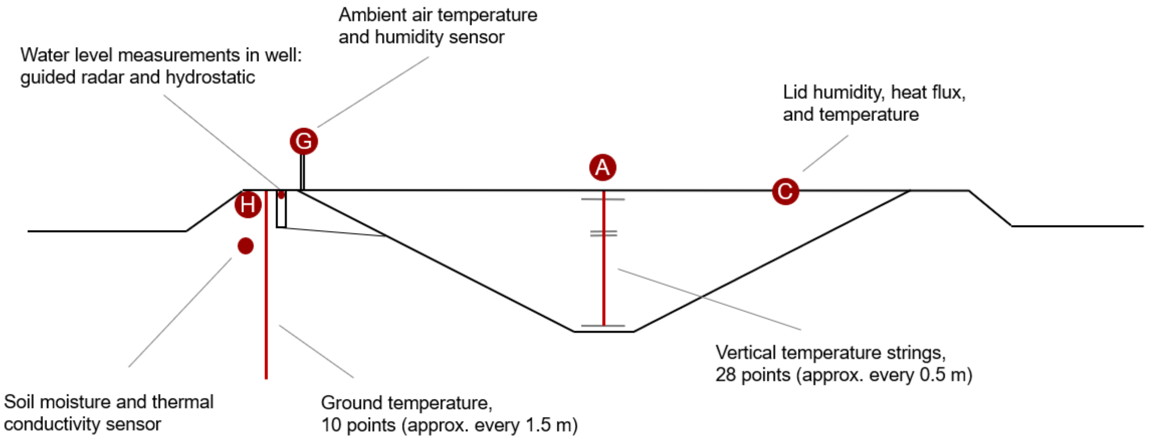

Fig. 4: Schematic of the storage monitoring equipment and measurement points.

4. Storage operation and performance

The temperature of the water layers in the PTES since the start of its operation is presented in Fig. 5. It can be observed that the storage did not operate much during June and July due to the low heat demand during this period. Apart from the summer and a few periods of deep discharge, the water temperature at the top of the PTES was close to 90 °C. However, it should be noted that although the PTES is operational, its operation is still not completely automized, and a number of tests are run frequently. Thus, the presented results should be considered preliminary and may not be indicative of long-term performance.

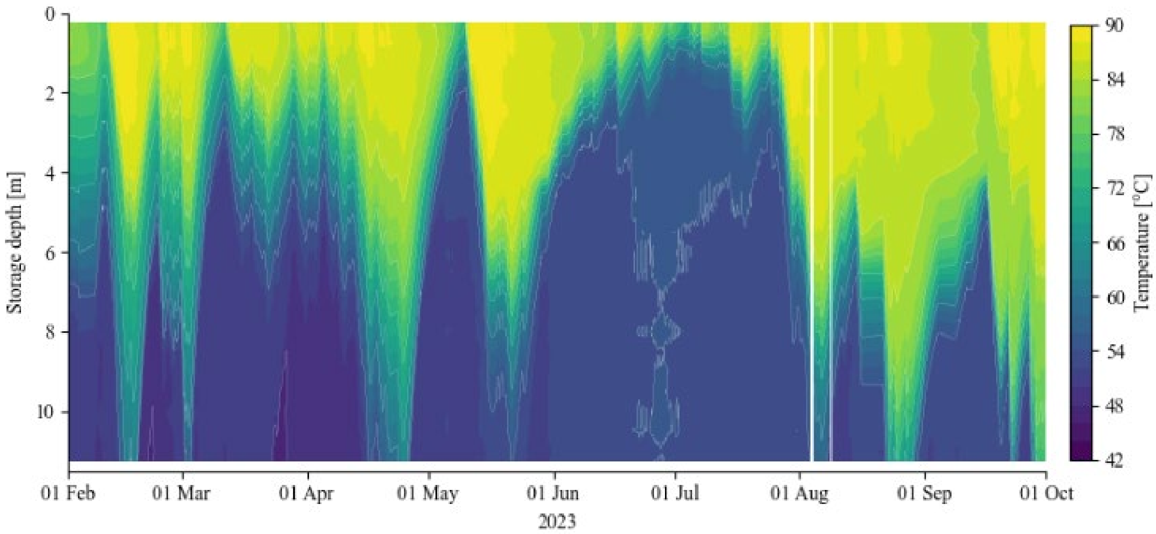

Fig. 5: Water temperature in the PTES.

The weekly charged and discharged heat from the PTES is illustrated in Fig. 6, along with the storage energy content. It should be noted that the PTES maximum capacity was estimated at 3600 MWh (assuming a temperature operating range of 45-90 °C, a constant water density of 980 kg/m^3, and a constant specific heat of 4.18 kJ/kg K). Consequently, it may be observed that the storage was fully charged for the first time in April 2023, while approximately 1000 MWh were charged or discharged most weeks, demonstrating the short-term operation of the storage. Fig. 6 verifies the minimal operation of the PTES in June and July 2023.

The mean monthly efficiency of the PTES during the entire operation period was 84%. However, this value is expected to increase as the heat losses toward the ground become less and less with time. A recent study by Sifnaios et al. showed that the heat losses for a short-term PTES stabilize after approximately eight years (Sifnaios et al., 2023b). Again, it should be emphasized that these results are preliminary, and a more extended monitoring period is required to obtain more representative results of the storage operation during its lifetime.

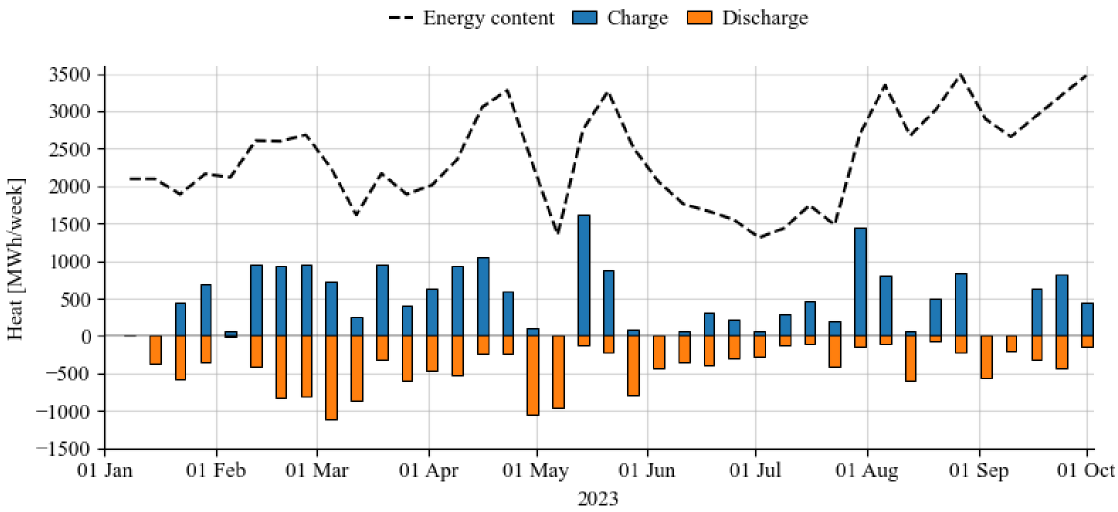

Fig. 6: Weekly charged and discharged energy and storage energy content.

Since the PTES in Høje Taastrup was the first to have the diffusers installed at one end of the storage (instead of the middle), the investigation of stratification was of significant interest. Fig. 7 illustrates the temperature difference between the storage temperature measured at the east and west ends of the PTES. It may be observed that there was a deviation smaller than 1 K between the two ends of the storage, indicating a horizontal uniformity of temperatures. Thus, this design choice can be recommended for future storages.

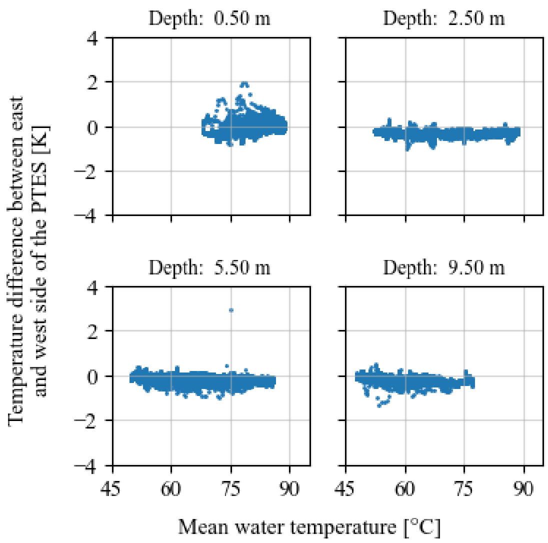

Fig. 7: Temperature difference between the east and west sides of the PTES.

In order to further investigate the stratification in the PTES, the stratification coefficient (*St*) was calculated, as introduced by Wu and Bannerot (1987). In order to calculate this indicator, the storage is divided into discrete layers corresponding to the position of the installed temperature sensors. It is also assumed that each layer has a uniform temperature. This coefficient gives information about the stratification of a storage by comparing the temperature of each water layer with the weighted average storage temperature. A high value indicates a good degree of stratification, whereas a value of zero indicates that the storage has a uniform temperature. However, it should be noted that this coefficient has no physical meaning, but it can be used to compare two different storage systems or different storage operations. The expression developed by Wu and Bannerot (1987), is presented below:

$$St = \sum_{n=1}^{N} \frac{m_i \cdot (T_i - T_{avg})^2}{m_{total}} \qquad \text{(eq. 1)}$$

where T_i is the temperature and m_i is the mass of the i'th layer, T_{avg} is the average storage temperature, and m_{total} is the total mass of the storage system.

The *St* for the PTES in Høje Taastrup is presented in Fig. 8. The range of *St* was 0-260 K^2, with a mean value of 160 K^2. For comparison, the range of the stratification coefficient in Dronninglund was 0-500 K^2 with an average value of 154 K^2. For more details on the stratification in the PTES in Dronninglund, the reader is referred to (Sifnaios et al., 2022).

Since the PTES in Høje Taastrup is used as a short-term (i.e., it is charged and discharged several times throughout the year), it is expected to have a higher degree of mixing and, thus, a lower degree of stratification. This is verified by the lower maximum value of *St* for Høje Taastrup compared to Dronninglund. Nevertheless, the mean value of *St* for the PTES in Høje Taastrup is slightly higher, indicating that despite the short-term operation that induced higher mixing, the placement of diffusers in one end of the storage seems to perform well.

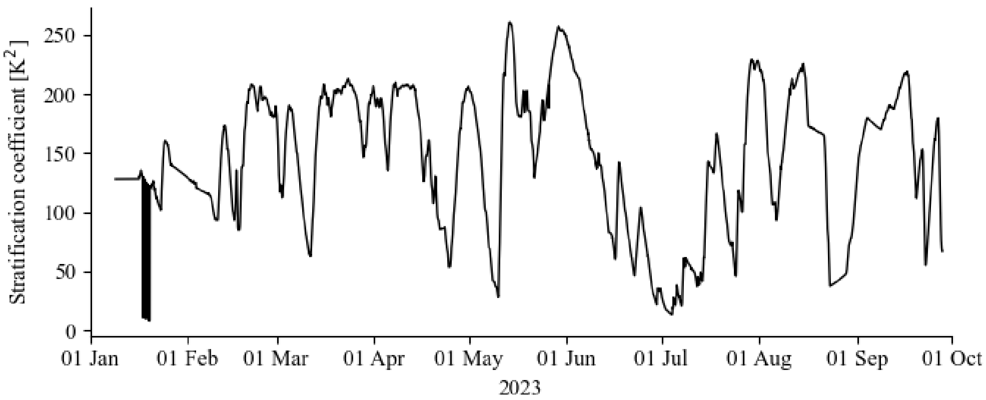

Fig. 8: Stratification coefficient.

Fig. 9 illustrates the ground temperature around the PTES. It should be noted that the ground temperature sensors were installed at the end of July, so a shorter monitoring period is available. However, it is still evident that the ground temperature slowly increases due to the storage operation, particularly close to the surface, where the highest storage temperatures occur.

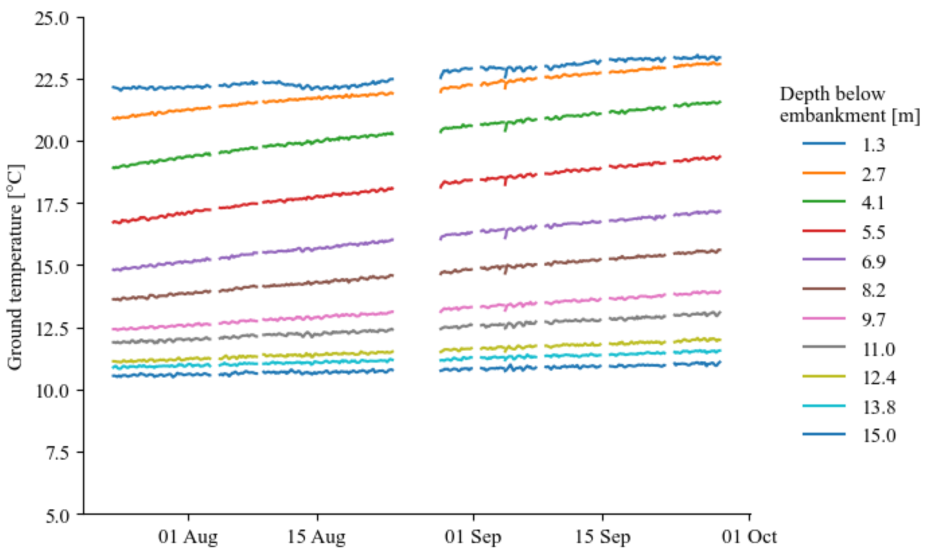

Fig. 9: Ground temperatures around the PTES.

Last, Fig. 10 presents the lid heat fluxes as measured by heat flux sensors installed between the insulation layers in the lid. Similar to the ground temperature, the lid heat flux sensors were installed at the end of July 2023. Although the heat flux is measured in two different locations in the lid, there seemed to be good agreement between the two measurements. Overall, the measured heat flux is in accordance with the theoretical estimation of heat flux based on the thermal characteristics of insulation. This indicates that the lid performs well.

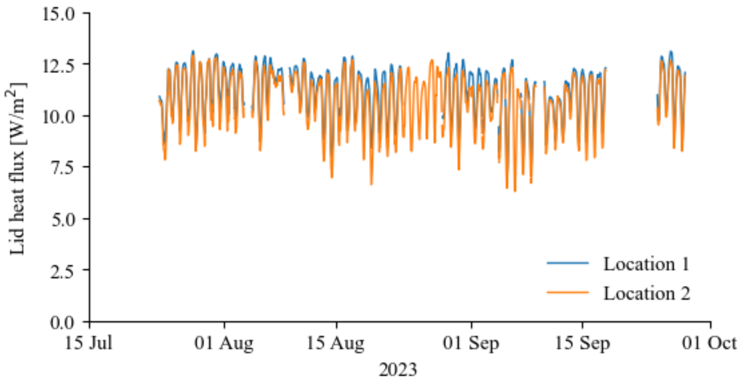

Fig. 10: Lid heat flux measured at two locations on the lid.

5. Conclusions

This study presented experiences from the construction stages and preliminary results from the operation of the PTES in Høje Taastrup, which is the first PTES operated as a short-term heat storage. In general, not many conclusions can be drawn since the storage operates for less than a year. However, the results indicate that installing the diffusers close to the edge of the PTES seems possible without compromising stratification. Overall, the PTES operates as expected, indicating that PTES can be used not only as seasonal storage systems but also as short-term.

6. Acknowledgements

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