Effect of Design Characteristics on Pit Thermal Energy Storage Performance

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Abstract

Pit thermal energy storage (PTES) systems have been developed as a low-cost, water-based storage technology for district heating networks. While annual efficiencies greater than 90% have been realized, many existing storages have suffered from high heat losses and poor stratification. Thus, research is still necessary for identifying and optimizing the parameters that affect the operation and performance of PTES. This study investigated the effect of design characteristics and ambient temperature on PTES heat loss and efficiency. More specifically, the influence of aspect ratio and slope of the storage sides were investigated for three locations (Denmark, Finland, and Greece) using the software ANSYS Fluent. It was found that the slope of the PTES sides had a larger impact on the storage efficiency than the aspect ratio. The investigated PTES with steeper side-wall slopes had a 12% higher efficiency than one with a gradual slope, while the PTES with a rectangular shape had a 3% lower efficiency than a square one. Regarding different locations, a PTES in Greece would have 5% higher efficiency than one in Finland due to higher ambient temperatures that reduce heat losses.

Keywords: Heat storage, design optimization, heat loss, heat transfer, PTES

1. Introduction

Many different heat sources can be utilized in the district heating (DH) networks, such as waste incineration, biomass, wind, solar, geothermal energy, natural gas, oil, coal, and surplus heat from industry (Danish District Heating Association, 2021). In Denmark, where DH covers 64% of the country's residential heat demand, there is an effort to increase the share of renewables in the DH sector in order to be carbon neutral by 2050 (Ministry of Foreign Affairs of Denmark, 2020). To achieve this, energy storage has to be utilized due to the intermittent nature of renewable energy sources like solar and wind. For example, typical DH networks can achieve a solar fraction of 20%, whereas DH networks with seasonal energy storage systems can achieve solar fractions higher than 40% (Sveinbjörnsson et al., 2017).

One of the most promising storage technologies in the district heating sector is pit thermal energy storage (PTES), which is a low-cost technology that utilizes water as the storage medium. Several PTES systems have been demonstrated in Denmark and connected to large-scale solar collector fields (Soerensen and From, 2011). The current state-of-the-art PTES has an efficiency greater than 90% (Winterscheid and Schmidt, 2017), demonstrating that PTES can be a cost-effective heat storage technology with a large potential.

At the time of writing, there are five storages in operation in Denmark, namely in Dronninglund (60,000 m^3) (Schmidt and Sørensen, 2018), Marstal (75,000 m^3) (Jensen, 2014) , Vojens (200,000 m^3) (Rambøll, 2015), Toftlund (70,000 m^3) (Rambøll, 2016), and Gram (122,000 m^3) (PlanEnergi, 2015). Additionally, there is one PTES under construction in Høje Taastrup (70,000 m^3) (Aalborg CSP, 2020) and one in the planning stage in Odense (1,000,000 m^3). Outside of Denmark there is only one operational PTES, which is in Lagkazi, Tibet (15,000 m^3) (Aalborg CSP, 2019).

All the existing PTES systems were constructed after 2012, and the technology has mainly been developed by making minor changes to existing designs based on previous practical experience. For this reason, research is necessary on topics of major importance to their operation and performance, e.g., their design.

This paper investigated the effect of two key design characteristics of PTES; the slope of the storage sides and the

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aspect ratio (AR). Steeper side walls reduce the surface area of a storage, thus reducing heat losses. Similarly, an aspect ratio equal to one is desired from a heat loss perspective as it reduces the surface area of the storage. The effect of these parameters on heat loss and energy efficiency was investigated using a numerical simulation model in the software ANSYS Fluent. Last, the effect of ambient temperature on heat loss and efficiency was investigated using the same method.

2. Methods

The heat loss from a PTES can be divided into heat loss from the water through the insulated lid and the uninsulated side walls. The heat loss through the lid can be estimated as one-dimensional with high accuracy if the insulation properties are known. However, the heat loss to the soil is complex as it has to be modeled in 3D, and the soil's thermal capacity must be considered.

In order to investigate the effect of the design characteristics on the PTES performance, a model of the soil domain around the PTES was developed in ANSYS Fluent. Fluent is a computational fluid dynamics (CFD) software that uses the Green-Gauss Finite Volume Method (FVM) to discretize the conservation form of the partial differential equations.

The heat loss from the water to the soil was simulated by applying the water temperature (varying with height) to the soil boundary. This simplification is valid under the assumption that the convection coefficient between the water-soil interface is negligible relative to the conduction in the soil. By not including the PTES water in the model, only heat conduction in the soil had to be simulated instead of a fluid dynamics study; thus, the computation time was dramatically reduced.

2.1 Simulated PTES designs

The annual heat loss to the ground was calculated for five different storage configurations. The geometry of the reference case was modeled after the PTES in Marstal, and the water-soil interface was simulated using 16 vertical layers, each having a height of 1 m and a constant temperature for each time step.

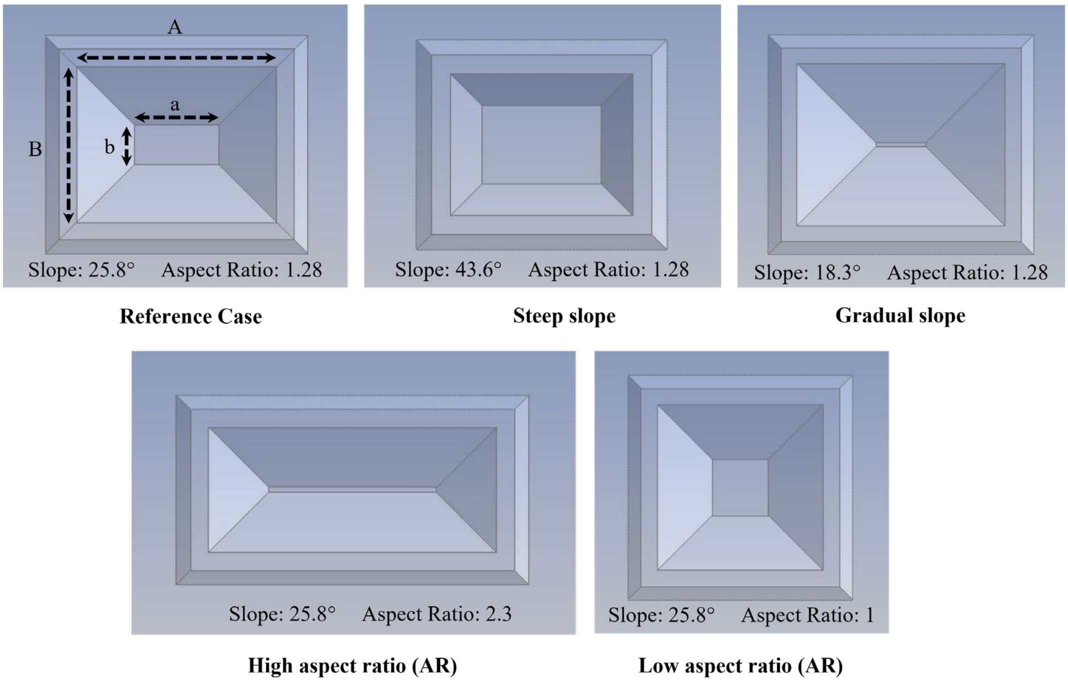

Fig. 1: Investigated PTES configurations.

The slope of the storage sides and the storage aspect ratio (AR) were investigated. The aspect ratio is the ratio of the long edge of the storage relative to the short edge, i.e., a square storage has an aspect ratio of 1, and a rectangular storage has an aspect ratio greater than 1. The five storage configurations are illustrated in Fig. 1, and their key characteristics are listed in Tab. 1. All the investigated storage configurations had the same storage volume, height, number of vertical layers, and volume per layer across PTES. Consequently, the area of the lid, side walls, and bottom walls varied greatly for the different designs. Also, it should be noted that the layers in each storage had different heights for them to have the same water volume.

Tab. 1: Dimensions of the investigated scenarios.

Parameter	Reference case	Different slope tilt		Different aspect ratio		Units
		Steep slope	Gradual slope	High AR	Low AR	
Side slope	25.8	43.6	18.3	25.8	25.8	°
Lid aspect ratio	1.28	1.28	1.28	2.3	1	-
Bottom side length (a)	47.6	63.4	30.3	92	34.1	m
Bottom side width (b)	22.6	42	2	3.2	34.1	m
Top side length (A)	113.1	97	127.9	157.2	99.3	m
Top side width (B)	88.1	75.6	99.6	68.4	99.3	m
Sides and bottom area	11,022	9,110	13,396	11,971	10,886	m^2
Lid area	9,972	7,331	12,732	10,745	9,868	m^2
Storage height			16			m
Storage volume			76,929			m^3

From Tab. 1, it can be observed that the different slope tilts have a larger effect on the surface area of the storage. For example, the Steep slope case has 22% less surface area overall than the reference case, whereas the Gradual slope case has a 24% larger surface area compared to the reference case. On the other hand, the High AR case has an overall 8% larger area than the reference case, and the Low AR case has only a 1% smaller surface area than the reference case. These differences in the surface area are expected to impact the heat losses and efficiency of the PTES significantly.

2.2 Thermal properties of the ground and lid

It must be noted that the selected ground thermal properties are not necessarily exact for the PTES in Marstal. Instead, the selected values are indicative of the general soil conditions in eastern and central Denmark, which have moraine landforms with loamy soils rich in silt, clay, and sand (Adhikari et al., 2014). Typical values for moraine soil were taken from (Ditlefsen et al., 2012):

- Density: 2200 kg m^{-3}
- Specific heat: 1700 J kg^{-1} K^{-1}
- Thermal conductivity: 2 W m^{-1} K^{-1}

These values were used for the entire soil domain, which was initialized having a uniform temperature of 8 °C. The bottom of the soil domain (50 m below the bottom of the PTES) was simulated to have a fixed boundary temperature of 8 °C. The side walls of the soil domain were modeled using adiabatic boundary conditions. The top of the soil domain (which was in contact with the ambient air) was simulated to have a forced convection coefficient of 30 W m^{-2} K^{-1}, indicative of an average airflow velocity of 5 m/s according to Laloui and Rotta Loria (2020).

Regarding the lid, the thermal properties used in the calculations were chosen based on values of the original Nomalén (NMC Termonova, 2011) lid, which was initially installed in Marstal and Dronninglund. For calculating the heat loss through the lid, the following equation was used:

$$E_{lid\ loss} = A_{lid} \cdot k_{lid} \cdot h_{lid} \cdot (T_{top\ layer} - T_{amb}) \qquad \text{(eq. 1)}$$

where A_{lid} is the surface area of the lid, k_{lid} is the effective thermal conductivity of the lid structure (0.06 W m^{-1} K^{-1}), h_{lid} is the thickness of the lid (0.24 m), $T_{top\ layer}$ is the temperature of the storage's top layer, and T_{amb} is the ambient air temperature.

2.3 PTES and ambient temperature

The water temperatures from the Marstal PTES were used to simulate a seasonal heat storage operation from January 2013 to December 2015. The reference case (located in Denmark) was used for comparison, and with the same water-temperature profile, the storage was simulated for two additional locations, namely Finland and Greece. Regarding the ambient temperatures, Typical Meteorological Year (TMY) temperatures were used for Copenhagen (Denmark), Helsinki (Finland), and Athens (Greece). The data used in the simulations are presented in Fig. 2.

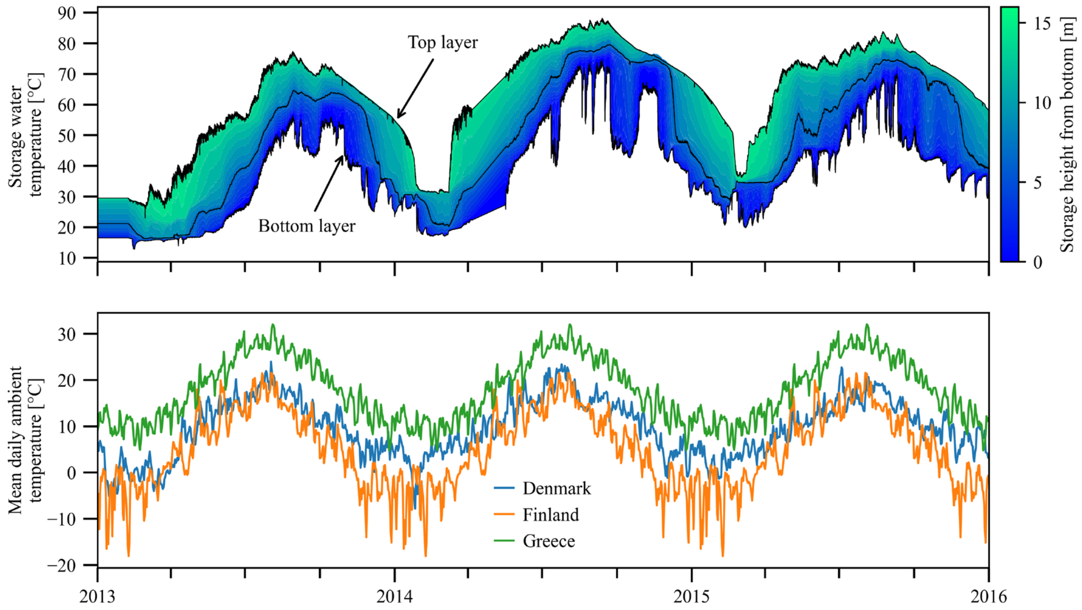

Fig. 2: PTES and ambient temperatures used in the simulations.

2.4 Efficiency calculation

The energy balance of a thermal storage system can be expressed as follows:

$$E_{out} = E_{in} - E_{loss} - \Delta E \qquad \text{(eq. 2)}$$

where E_{out} is the energy discharged from the storage, E_{in} is the charged energy, and E_{loss} is the energy lost due to heat losses. ΔE is the internal energy change of the storage, i.e., the difference between the internal energy at the start and end of the period of consideration.

Since all simulated PTES have the same volume and temperature per storage layer, they all have the same internal energy change. Assuming that they all have the same charged energy (E_{in}) and that the heat loss is calculated by the heat transfer CFD simulation, the discharged energy (E_{out}) can be calculated using Equation 2. Then the PTES energy efficiency can be calculated using Equation 3, as explained in (Sifnaios et al., 2022).

$$\eta_E = \frac{E_{out}}{E_{in} - \Delta E} = \frac{E_{out}}{E_{out} + E_{loss}} \qquad \text{(eq. 3)}$$

3. Results

So far, in all the constructed PTES, only the lid area has been insulated, whereas the sides and bottom have had no insulation. This decision was made for two main reasons:

1. It was difficult and expensive to find an insulation material that could withstand the weight of the water without collapsing.
2. It was not considered important due to most heat loss occurring through the lid's surface.

This last statement can be observed in Fig. 3, where the annual heat loss for the investigated PTES is presented. After three years of operation, for all cases, approximately 55% of the heat loss comes from the lid, while 42% from the sides and 3% from the bottom. However, it must be noted that the heat loss from the sides and bottom of the PTES decreases with time as the ground temperature stabilizes and that three years of operation are insufficient for a seasonal storage to stabilize the ground temperature.

In Fig. 3, it can be observed that the storage sides' slope considerably impacts the annual heat loss toward the ground. The main reason is that a steeper slope leads to a smaller surface area, thus leading to lower heat losses. The Steep slope case had 21% lower total heat loss overall and 16% lower heat loss toward the ground compared to the reference case. On the other hand, in the Gradual slope case, where the slope of the sides was less steep than in the reference case, the total heat loss was 22% higher, and the heat loss toward the ground was 17% higher. The Gradual slope case had lower bottom heat losses than the Steep slope case, but overall, the Steep slope had 35% lower heat losses.

Comparing the cases with the same slope (i.e., High AR and Low AR cases), it was found that a square PTES shape (aspect ratio=1) can decrease the lid heat loss by 9% and the loss toward the ground by also 9%.

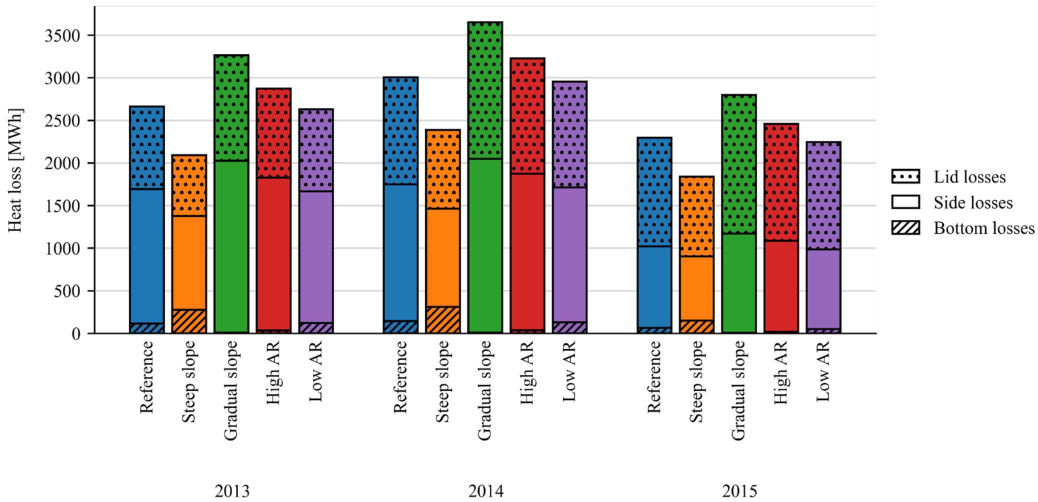

Fig. 3: Annual heat loss for the investigated PTES configurations.

The heat loss values for the last year of the simulation (2015) are reported in Tab. 2. The reason for showing only the values for 2015 is that, since there was preheating of the ground during the previous two years, the values for 2015 are considered more representative of the long-term operation of the PTES. The PTES energy efficiency was also calculated for 2015 for the different PTES configurations. It may be observed that the Steep slope had 6% higher efficiency than the reference case, while there was a 12% difference between the Steep and Gradual slope cases. Last, the square-shaped PTES of the Low AR case had 3% higher efficiency than the rectangular one of the High AR case. Although it is evident that the PTES design has a big impact on its performance, it has to be noted that, in many cases, its aspect ratio is dictated by the shape of the available plot of land. In addition, the side-wall slope is dictated by ground stability and, thus, the soil properties.

Tab. 2: Heat loss and efficiency for 2015 for the investigated PTES configurations.

Case	Bottom heat loss [MWh]	Side heat loss [MWh]	Lid heat loss [MWh]	Efficiency [%]
Reference case	63	957	1274	72
Steep slope	150	751	936	78
Gradual slope	4	1167	1626	66
High AR	17	1068	1373	70
Low AR	50	933	1261	73

The annual PTES heat loss for the different simulated countries is presented in Fig. 4. As expected, the storage in Finland had the highest heat loss as Finland had the lowest ambient temperature of the investigated countries. On the contrary, the lowest heat loss occurred in Greece, which had the highest ambient temperature. The PTES in Finland had, on average, 5% higher total heat losses compared to Denmark, while the one in Greece had 8% lower.

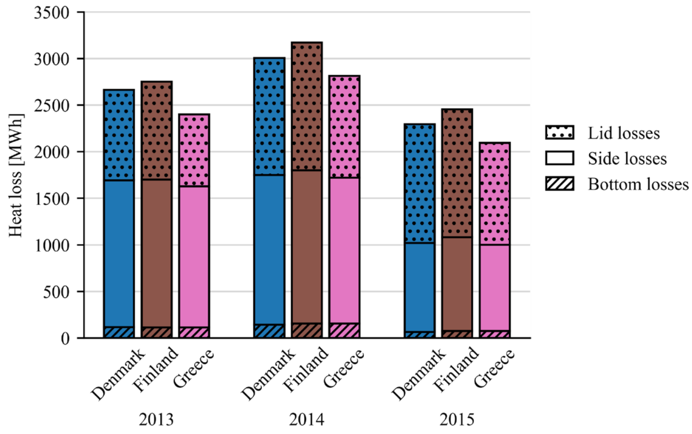

Fig. 4: Annual heat losses for Denmark, Finland, and Greece.

Table 3 presents the heat losses and efficiency for 2015 for the reference case for the three locations. The results show that the bottom heat loss is primarily affected by the storage temperature since all locations had the same bottom heat loss each year. The side heat losses were also comparable for the three locations, having a variation of approximately 9%. In contrast, the variation was much larger for the lid heat losses, namely 22%. Thus, the different ambient temperatures primarily affect the heat loss from the lid and, to a lesser extent, the heat loss from the sides. Last, a 5% variation in efficiency was calculated for the same storage water temperatures.

Tab. 3: Heat losses and efficiency for 2015 for Denmark, Finland, and Greece.

Country	Bottom heat loss [MWh]	Side heat loss [MWh]	Lid heat loss [MWh]	Efficiency [%]
Denmark	63	957	1274	72
Finland	63	1007	1373	70
Greece	63	923	1095	75

4. Conclusions

This study investigated the effect of two key design characteristics of pit thermal energy storage systems (the slope of the storage sides and the aspect ratio) and the effect of ambient temperature on storage heat loss and efficiency. A numerical simulation model was created in ANSYS Fluent that considered the soil domain around the PTES for investigating the heat loss from the water to the soil. Temperature data from the Marstal PTES were used to simulate the water domain from 2013 to 2015, and the design of the Marstal storage was used as the reference case. It was found that, due to a smaller surface area, a PTES with a steeper side slope had 21% lower total heat loss and 16% lower heat loss toward the ground compared to the reference one. Additionally, the square PTES design (aspect ratio=1) was shown to have a 9% lower total heat loss than the rectangular one. Furthermore, the slope of the PTES sides had a larger impact on the storage's efficiency than the aspect ratio; the variation in efficiency due to different side slopes was 12%, while the efficiency only varied by 3% due to different aspect ratios. Regarding different locations, a PTES in Greece was found to have 5% higher efficiency than one in Finland due to the higher ambient temperature that decreases the lid and side heat losses. Last, the heat losses through the bottom of a PTES were primarily affected by the storage temperature and not the ambient temperature since all simulated locations had the same bottom heat loss for each year.

5. Acknowledgments

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6. References

Aalborg CSP, 2020. Aalborg CSP receives order for lid solution for Integrated Pit Thermal Energy Storage (PTES) System [WWW Document]. URL https://web.archive.org/web/20210417200554/https://www.aalborgcsp.cn/index.php?id=321&tx_news_pi1%5Bnews%5D=775&tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&cHash=6

d7aff98a878e1d08d5ecd7f38e4fdbb (accessed 5.4.22).

Aalborg CSP, 2019. 15,000 M3 PTES for district heating, Tibet [WWW Document]. URL https://web.archive.org/web/20210418202632/https://www.aalborgcsp.com/projects/15000-m3-ptes-for-district-heating-tibet/ (accessed 5.4.22).

Adhikari, K., Minasny, B., Greve, M.B., Greve, M.H., 2014. Constructing a soil class map of Denmark based on the FAO legend using digital techniques. Geoderma 214–215, 101–113. https://doi.org/10.1016/j.geoderma.2013.09.023

Danish District Heating Association, 2021. Facts about district heating in Denmark [WWW Document]. URL https://web.archive.org/web/20220331213035/https://www.danskfjernvarme.dk/sitetools/english/about-us (accessed 5.4.22).

Ditlefsen, C., Vangkilde-Pedersen, T., Højberg, A.L., 2012. Geologi og jordvarmeboringer. Oversigt over geologiske forhold af betydning ved etablering af jordvarmeboringer i Danmark [WWW Document]. Natl. Geol. Undersøgelser Danmark og Grønl. URL https://geoenergi.org/xpdf/jordvarme-og-geologi-d3_2.pdf (accessed 9.5.22).

Jensen, M.V., 2014. Seasonal pit heat storages - Guidelines for materials & construction IEA-SHC Tech Sheet 45.B.3.2.

Laloui, L., Rotta Loria, A.F., 2020. Heat and mass transfers in the context of energy geostructures, Analysis and Design of Energy Geostructures. https://doi.org/10.1016/b978-0-12-816223-1.00003-5

Ministry of Foreign Affairs of Denmark, 2020. Global Climate Action Strategy [WWW Document]. URL https://web.archive.org/web/20220331213212/https://um.dk/en/foreign-policy/new-climate-action-strategy (accessed 5.4.22).

NMC Termonova, 2011. Nomalen 28N [WWW Document]. URL https://web.archive.org/web/20220426161150/https://azupcs365certviewer.azurewebsites.net/api/GetSDB?env=se&articleNr=550984 (accessed 4.20.22).

PlanEnergi, 2015. Long term storage and solar district heating [WWW Document]. URL https://web.archive.org/web/20220306155726/https://planenergi.dk/wp-content/uploads/2017/06/sol_til_fjernvarme_brochure_endelig.pdf (accessed 5.4.22).

Rambøll, 2016. Damvarmelagre [WWW Document]. URL https://web.archive.org/web/20220504080511/https://dk.ramboll.com/-/media/3fc11649e25942c195fa90e63ea41e11.pdf (accessed 5.4.22).

Rambøll, 2015. South-Jutland stores the sun's heat in the world's largest pit heat storage [WWW Document]. URL https://web.archive.org/web/20210827074933/https://ramboll.com/projects/re/south-jutland-stores-the-suns-heat-in-the-worlds-largest-pit-heat-storage?utm_source=alias&utm_campaign=sun-storage (accessed 5.4.22).

Schmidt, T., Sørensen, P.A., 2018. Monitoring Results from Large Scale Heat storages for District Heating in Denmark.

Sifnaios, I., Jensen, A.R., Furbo, S., Fan, J., 2022. Performance comparison of two water pit thermal energy storage (PTES) systems using energy, exergy, and stratification indicators. J. Energy Storage 52, 104947. https://doi.org/10.1016/j.est.2022.104947

Soerensen, P.A., From, N., 2011. High solar fraction with pit heat storages, in: 30th ISES Biennial Solar World Congress 2011, SWC 2011. pp. 3020–3030. https://doi.org/10.18086/swc.2011.21.07

Sveinbjörnsson, D., Laurberg Jensen, L., Trier, D., Ben Hassine, I., Jobard, X., 2017. Large Storage Systems for DHC Networks.

Winterscheid, C., Schmidt, T., 2017. Dronninglund District Heating Monitoring Data Evaluation for the Years 2015-2017.