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Design and Construction of Large Scale Heat Storages for District Heating in Denmark

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Abstract

District energy is one of the main technologies in transition of existing buildings in cities to be heated and cooled without using fossil fuels. But many heat sources as solar thermal, heat from waste-to-energy plants, geothermal energy and excess heat are available only during summer or constantly during the year. Large scale thermal storages make it possible to utilize these sources, replace peak fossil based production and integrate fluctuating electricity from PV and wind. This makes thermal storages a key element in future Smart Energy Systems, with integration of heating, cooling, electricity, gas and transport systems.

Since the 80ties large scale thermal storages have been developed and tested in the Danish energy system. From 2011 five full scale pit heat water storages and one pilot borehole storage have been built. Design and experiences during construction of the first 3 pit heat storages (Marstal 75,000 m^3, Dronninglund 60,000 m^3, Gram 122,000 m^3) and the pilot borehole storage (Brædstrup 19,000 m^3 soil) are now basis for a new generation of large storages integrated in DH systems.

The paper includes discussion of choice of design, experiences from the implementation and operation phase from Marstal, Dronninglund and Brædstrup and results from test of liner and insulation materials. Monitoring results are presented in a separate paper (Schmidt and Sørensen 2018).

Keywords:

Sensible storage; pit heat storage; borehole storage; district heating; district cooling; integrated district energy production.

1. Introduction

1.2 Seasonal thermal energy storage

Excess heat from power production is enough to cover the total heat demand for buildings in EU (Persson, Möller and Werner 2014). In addition to this comes excess heat from waste incineration and industrial processes. These resources can be utilized in transition of cities to 100 % CO_2 neutral heating and cooling systems. The roles of storages can be:

- Buffer storage: short term storage and / or peak load shifting
- Long-term / seasonal storage of e.g. solar thermal or surplus heat
- Energy management of multiple heat producers like e.g. CHP, solar thermal, heat pumps, industrial excess heat etc.

This publication focuses on sensible seasonal heat storages, especially borehole thermal energy storages (BTES) and pit thermal energy storages (PTES) in applications with solar thermal systems.

1.3 Storage Concepts

Four storage concepts are in focus for the ongoing engineering research on sensible large-scale TES (see Fig. 1). Each storage concept has different capabilities with respect to storage capacity, storage efficiency, possible capacity rates for charging and discharging, requirements on local ground conditions and on system boundary conditions (e.g. temperature levels), building costs, etc. The best solution for a specific project must always be found by a technical-economical assessment of the possible storage concepts.

For the construction of buried thermal energy storages there are no standard procedures regarding wall construction, charging device, etc. available. Aquifer thermal energy storages (ATES) and borehole thermal energy storages (BTES) normally require permissions from water authorities for heat storage application. For tank thermal energy storages (TTES) and pit thermal energy storages (PTES) a clarification with authorities is recommended.

Due to the size and geometry and due to the requirements in terms of leakage detection and lifetime, many techniques and materials have their origin in landfill construction. However, with respect to high operation temperatures, materials and techniques cannot be simply transferred. Dimensions of pilot and research large-scale TES that have been realized within the last 25 years for solar assisted district heating system range from several 100 m^3 up to more than 200,000 m^3.

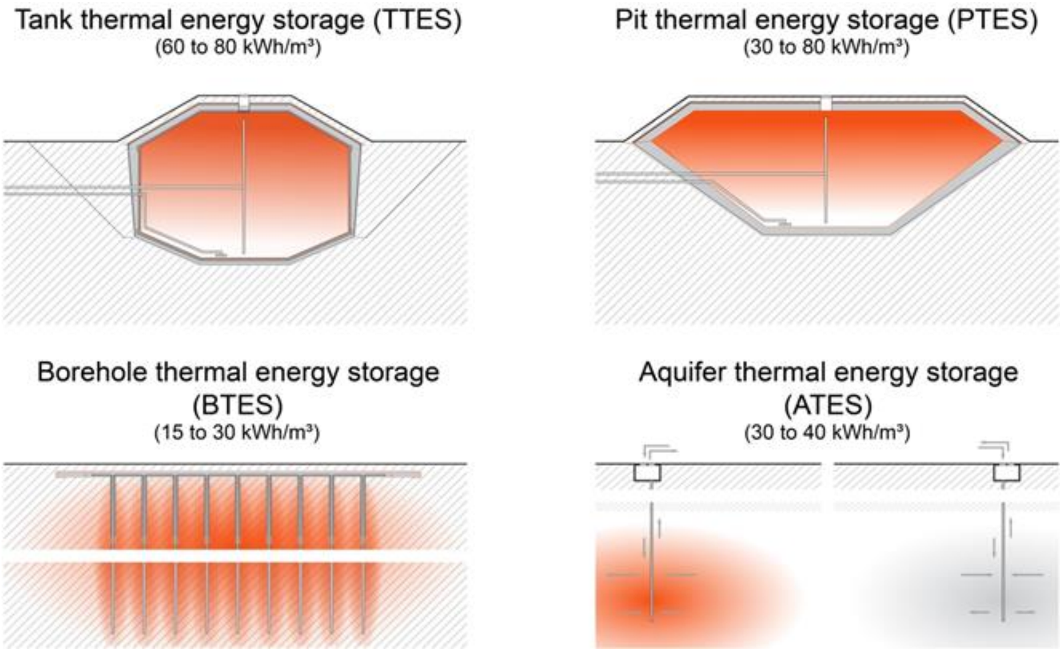

Fig. 1: *Main concepts for seasonal thermal energy storage (source: Solites)*

2. Borehole thermal energy storages (BTES) in Brædstrup

The district heating plant in Brædstrup consists of the following main components:

18,600 m² solar collectors
19,000 m³ BTES
5,500 m³ + 2,000 m³ steel tanks
1.3 MW_{th} electrical heat pump
10 MW electrical boiler
Natural gas fired CHP

The BTES, the 5,500 m³ steel tank, the electrical boiler, the heat pump and the 10,600 m² of solar collectors were put in operation in May 2012 as part of the project "Boreholes in Brædstrup". The BTES is meant as pilot storage to give experience for an eventual extension of the BTES and the solar collector area to aim for higher solar fraction in the district heating system

2.1 Design of BTES in Brædstrup

The BTES consists of 48 boreholes with a distance of 3 m and a layout as shown in Fig. 2. The distance of 3 m was the minimum safety distance for drilling. The optimum distance between the boreholes for a triangular pattern was found from an economical optimization to be 2.99 m.

In Brædstrup from an economical and heat loss point of view the boreholes should be as deep as possible without entering the level of potential flowing ground water. The ground water level at the storage location is more than 50 m below the surface, and the depths of the boreholes are 45 m to keep a safe distance to the expected ground water level.

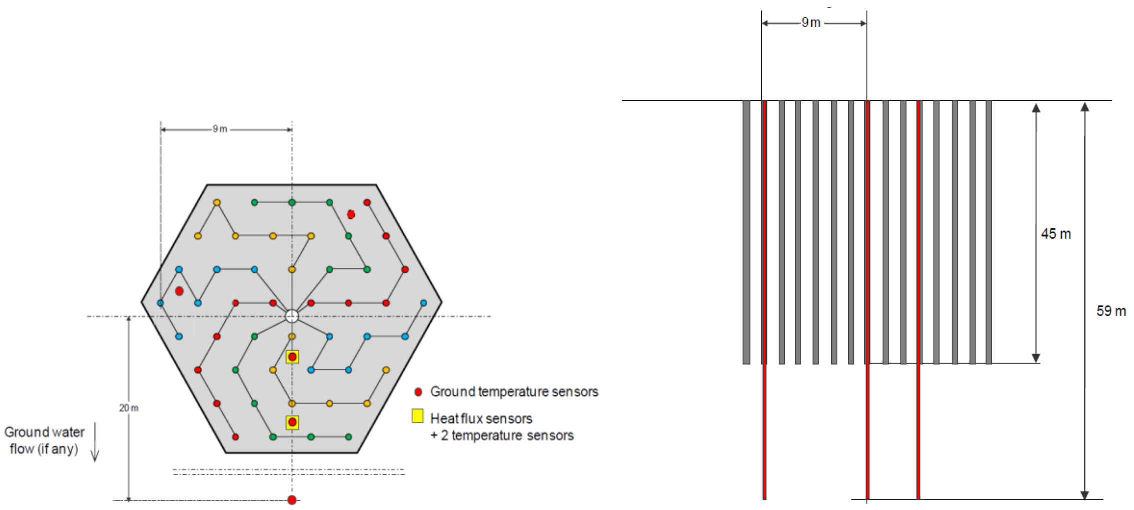

Fig. 2: *Layout of the BTES in Brædstrup, top view and cross sectional view (Sørensen et. al 2013)*

Each borehole is equipped with a double U-pipe, 6 boreholes are connected in series in a string from the centre of the storage towards the periphery resulting in a total of 16 parallel flow strings. The U-pipes consist of DN32 PEX pipes with built in oxygen barrier to prevent corrosion in the transmission pipe. The pressure drop in the storage is calculated to app. 2.0 bar at a dimensioning flow of 25 m^3/h. A pressure drop of 2 bar is preferred to obtain a uniform flow distribution.

When charging the storage hot water is circulated through the strings from the centre towards the periphery to give some level of temperature stratification of the storage with the hottest part in the centre. At discharging cold water is circulated in the opposite direction through the strings from the periphery towards the centre. To reduce the heat loss from the storage the top of the storage is designed as an insulated cover. The cover will be exposed to high temperature (80°C) and humidity, which has to be taken into account in the choice of insulation material and the cover design (see Fig. 3).

Seashells are chosen for insulation of the cover after a number of tests. The thickness of the insulation was found by an economical optimization, and to avoid excessive convection in the insulation it was calculated and tested that a separating layer is needed.

TRNSYS DST-model type 557a was used for design calculations and GenOpt for economical optimization of the energy system including BTES, heat pumps and existing system.

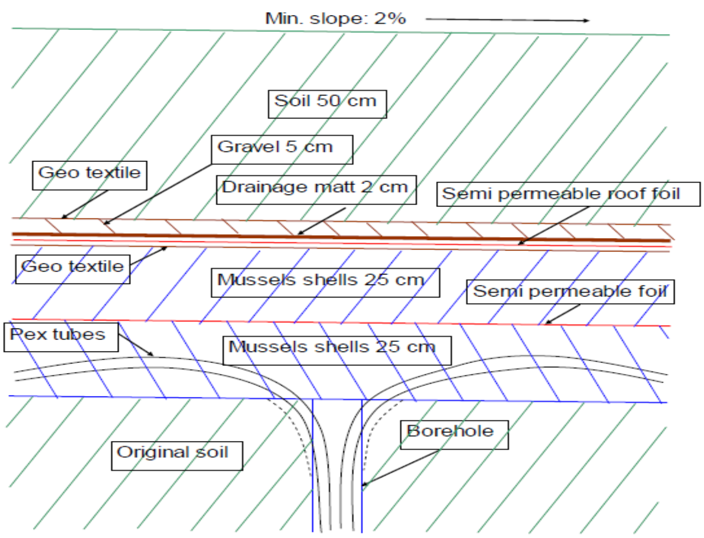

Fig. 3: *Section view of the cover indicating the layers of the construction (Sørensen et. al 2013).*

2.2 Construction of BTES in Brædstrup

After some tests and geotechnical investigations the construction work was started in early June 2011 by preparing the surface for drilling by scraping off the upper 50 cm of soil and marking up the location of each borehole. After preparation of the surface the boreholes were established during a period of 14 weeks. This was 9 weeks more than planned. The delay was mainly caused by an unexpected hard layer of soil that was reached in approximately one quarter of the storage.

Placement of the probes and back-filling with grouting was done immediately after drilling off each hole as an integrated process.

After completing the drilling the connection well was placed in the middle of the storage. The individual pipes were connected to each string of 6 boreholes and each string tested for leaks by pressurized water and connected to the manifolds in the connection well. After the pipe connection and connection of the temperature probes to a control panel in the connection well the insulated cover of the storage was build up layer by layer. The pipe connection and the construction of the cover were done in a period of 7 weeks from beginning of October 2011.

2.3 Investment cost of BTES in Brædstrup

The BTES in Brædstrup was implemented for a total cost of 260,000 € which equals 14 €/m3 storage. The costs in € (the buffer tank is not included in the price) can be divided into:

Drillings incl. grouting	148,000 €
Lid incl. pipes and fittings in cover and connection well	112,000 €

2.4 Operation experiences

The storage in Brædstrup has been in operation in 4 years. A monitoring program has been ongoing all 4 years. The results will be presented in an Enerstock 2018 paper from Solites (Schmidt and Sørensen, 2018).

Furthermore, PlanEnergi and Brædstrup Fjernvarme has supervised the moisture % in the lid and other operational issues. The results from this part are that the moisture % in the lid is 100 in the upper insulation layer and around 80 in the lower insulation layer. This has not changed the last two years.

PlanEnergi has also set up curves showing measurement results, see Fig. 4.

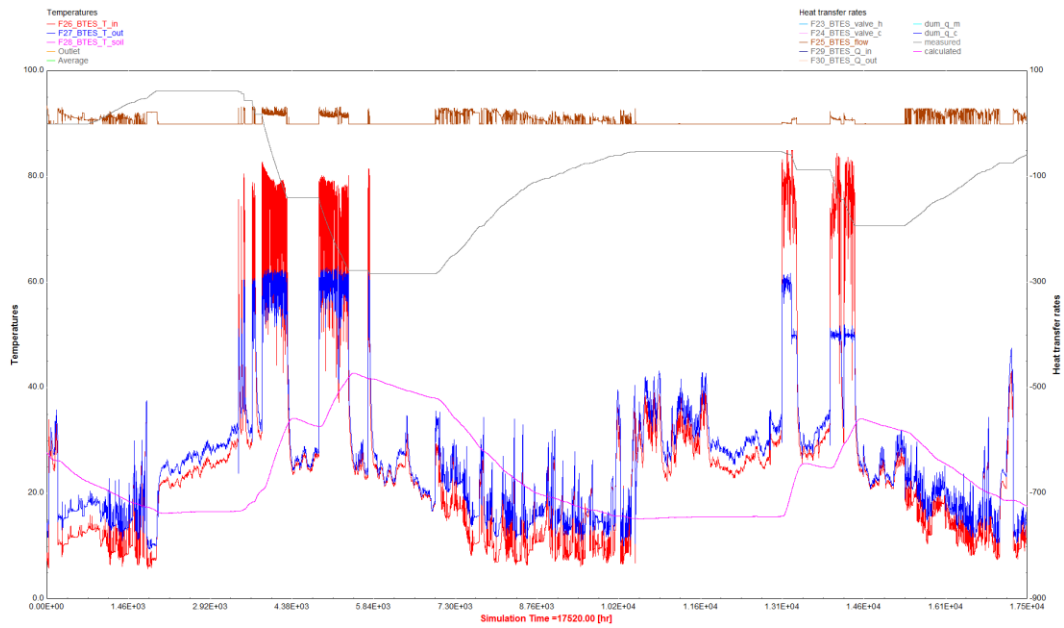

Fig. 4: *Measurements from the pilot borehole storage from 2014 and 2015. Brown = flow [m³/h], red and blue = inlet and outlet temperatures [° C], pink = average soil temperature in the storage [° C] and grey = calculated charging and discharging [MWh].*

Figure 4 shows some measurements from the pilot borehole storage from 2014 and 2015. The charging and discharging are calculated from the flow and the inlet and outlet temperatures.

The flow and the inlet temperatures are used as input to verify the borehole storage model in TRNSYS. Then the heat capacity and the heat conduction of the borehole storage is optimized to resp. 2,100kJ/(m³·K). The result, which is shown in Fig. 5 shows that there is a good compliance between the measurements at the pilot borehole storage and the borehole storage model in TRNSYS.

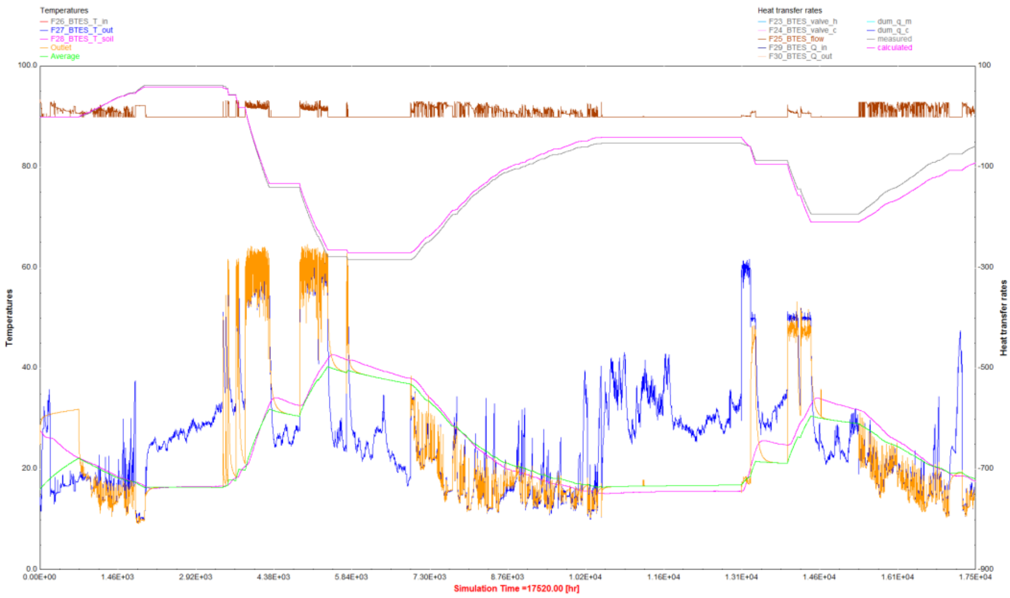

Fig. 5: *Comparison of measured and simulated values for 2014 and 2015. Brown = measured flow [m³/h] and orange = simulated outlet temperatures [° C], lower pink = measured and green = simulated storage temperatures [° C], and grey = measured and upper pink = simulated accumulated charging and discharging [MWh]. The first month is used for preheating the model, and is therefore not a part of the comparison.*

As can be seen from Fig. 4 and 5 the storage has not been fully utilized in 2015. The reason is that Brædstrup only charge with excess solar thermal heat and this was limited in 2015.

2.5 Conslusion BTES in Brædstrup

Performance and operation of the storage is as expected and thus the technology is reliable. Some of the Key Performance Indicators (KPI's) for the pilot storage are:

Volume: 19,000 m³ soil

Capacity: 400 MWh (T_{max} 50° C, T_{min} 12° C)

Efficiency: 63 % (2014-2016)

Investment/capacity: 0.65 €/kWh
Max charge/discharge capacity: 600 kW
Investment/max charge capacity: 433 €/kW

For a full-scale storage of same type efficiency is calculated to 81,5 %. Preliminary price calculations for the full-scale plant show similar price level as for the pilot plant.

3 Pit heat storages (PTES)

3.1 PTES in Marstal

The district heating production plant in Marstal consists of the following main components:

33,365 m^2 solar collectors
10,000 m^2 pilot pit heat storage
75,000 m^3 pit heat storage
2,100 m^3 steel tank
4 MW biomass boiler with 750 kW ORC unit
1.5 MW_{th} electrical heat pump
Bio oil boilers

15,000 m^2 solar collectors, the PTES, the biomass boiler with ORC and the heat pump were put into operation in June 2012 as a part of the project "SUNSTORE 4", which is supported by EC 7th framework. The project enables Marstal district heating to deliver heating to the consumers from 100 % renewable energy sources wherefrom app. 50 % is solar heat.

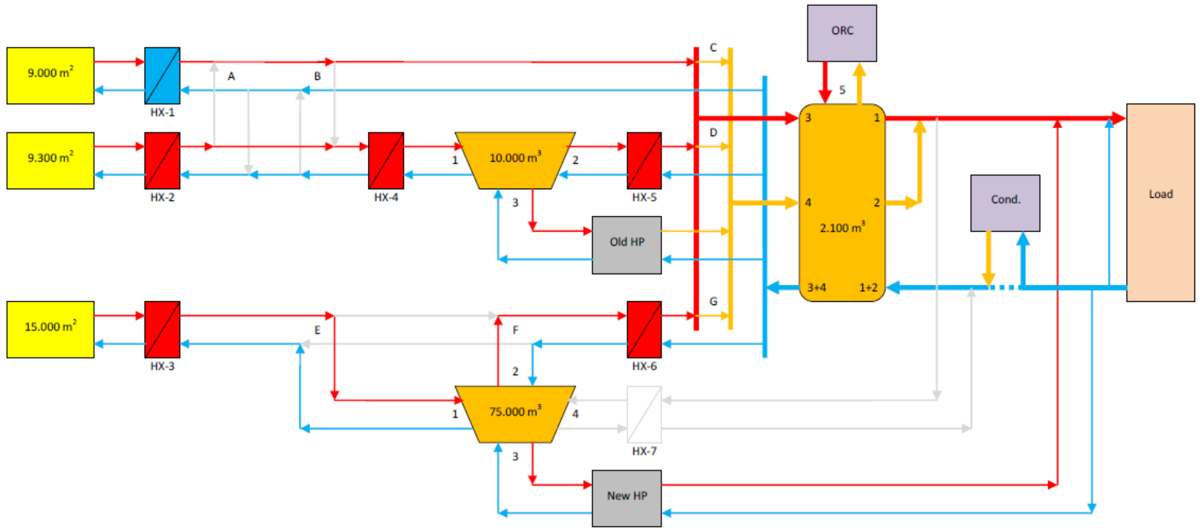

Fig. 6: Function diagram for the TRNSYS model of the production plant in Marstal (PlanEnergi Deliverable 2.1, March 2013)

3.1.1 Design of the Marstal pit heat storage

The necessary size of the storage is calculated from TRNSYS Type 342 integrated in the overall system and economically optimized. The geometry of the storage is defined as a truncated pyramid upside down. The excavated soil from the lower part of the storage is used as an embankment around the storage. To ensure stability of the storage during excavation and long-term stability, geotechnical investigations of the local conditions were made. The geotechnical investigations pointed out that the inclination of the internal sides of the storage should not be steeper than 1 on 2 (27°).

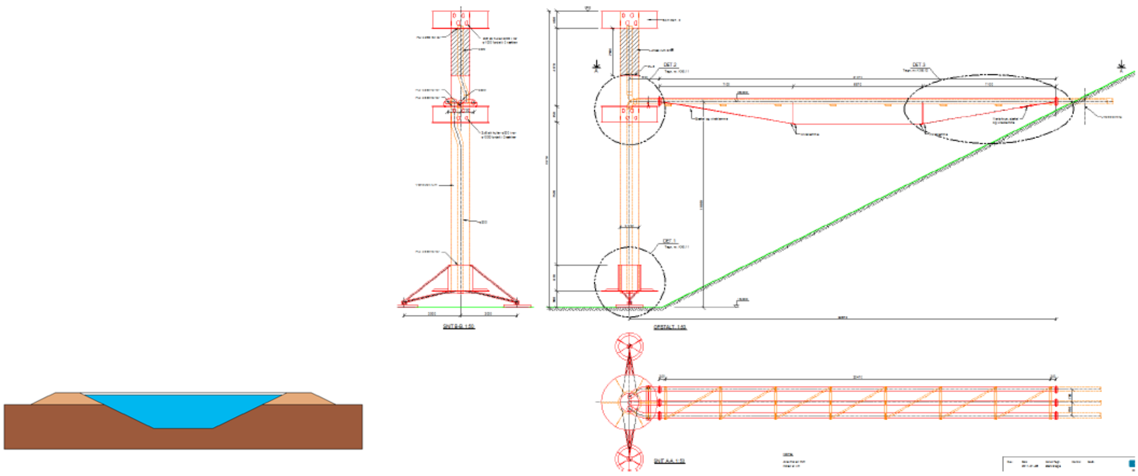

Fig. 7: *Left: Section view of the geometry of the pit heat storage. Right: The in- and outlet arrangement. (PlanEnergi Deliverable 2.2, March 2013).*

The storage is covered by an onsite welded HDPE liner to create a watertight lining of the storage. The liner is fastened by anchor trenches around the storage. The chosen liner has been tested for long term stability and from the test it is concluded that the lifetime will be at least 20 years when exposed to the conditions planned for the Marstal storage.

On top of the storage the water is covered by a floating insulating cover. The surface covered is app. 10 000 m². Different designs of the cover have been investigated as a part of the project "SUNSTORE 4" and the final design consists of (from bottom to top): 2 mm HDPE liner on top of the water, drainage net, 240 mm insulation (Nomalén), drainage net and 1 mm HDPE liner as top liner (see Fig. 8)

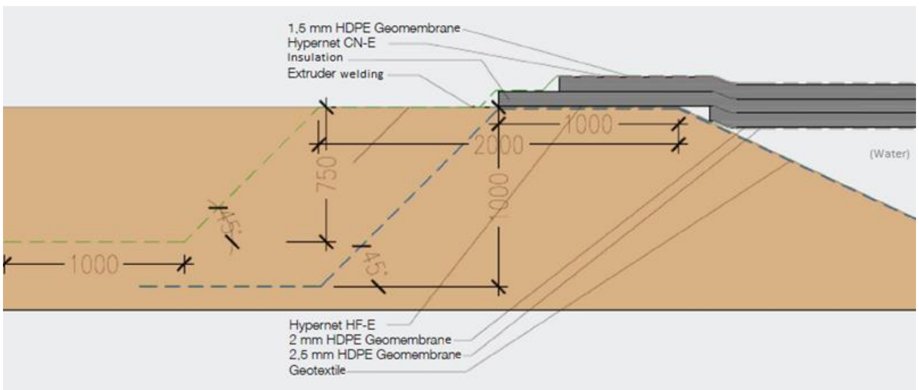

Fig. 8: Cross section of the edge of the floating cover (Vang Jensen 2014)

The intention of the drainage net is to allow ventilation between the insulation and the liner. This is necessary because of vapor diffusion through the liners. If the vapor is not removed there is a potential risk of condensate in the insulation that could damage the insulation over time. The base ventilation is handled by 30 roof vacuum valves mounted along the edges of the cover and if necessary a blower can be installed to force a higher ventilation rate through the cover.

The insulation is based on a cross bonded PE foam insulation. As for the liner the properties of the insulation regarding temperature and moisture stability is very critical.

The surface of the cover is exposed to a large amount of water during heavy rainfalls. Different solutions to ensure an efficient way to handle the water have been investigated. There are two main principles: To let the rainwater float across the edges of the storage or to collect it in the middle. The final design is based on collecting the rain water in the middle of the cover. This means that the rain water has to be pumped away, but the advantage is that it is easier to avoid puddles of water on the cover and air traps below the cover. To help guide the water in the right direction and to create tension in the liner several weight pipes are placed on top of the storage. The weight pipes consist of HDPE pipes filled with concrete.

3.1.2 Implementation of the Marstal pit heat storage

The implementation of the storage was complicated because of bad weather conditions.

Fig. 9: *Pictures of the excavation process. In the first picture the excavators are preparing the slides for liner implementation. The second picture is a few days after a cloud burst. In the last picture a cable excavator is digging up mud from the bottom while the liner implementation has begun (Source: PlanEnergi)*

The excavation, liner work, water filling and lid construction were supposed to be implemented in the period from spring to autumn 2011 but were delayed because of rain. The liner work was finished end of November 2011 and water had to be filled in during winter. The lid was constructed in spring 2012. The floating liner was welded section by section on shore and continuously pulled out on the water surface until the entire surface was covered. The insulation and the top liner were installed at the same time in a continuous process.

3.1.3 Investment costs of the PTES in Marstal

The total price of the PTES was 2.63 mio. € or 35 €/m^3. This is 5 € more than expected mainly because of difficult excavation conditions.

3.1.4 Operation experiences

The overall experience in the operation period from 2012 until 2017 is that the storage functions well, but some minor problems have turned up:

After one year corrosion was found by a diver inspection of the storage. The problem was that galvanized metal was mixed with iron and that organic material in the water gave possibilities for bacterial corrosion. PH has now been changed from 7.4 to 9.8 and galvanized metal replaced.

The heat exchanger between storage and energy system was very ineffective. The reason was sludge from the storage water. The heat exchanger was cleaned and a filter had to be implemented in the heat exchanger inlet.

Two holes in the liner have been located in the yearly diver inspection. The holes have been patched by a diver.

3.1.5 Conclusion PTES Marstal

Performance and operation of the storage is nearly as expected. The technology seems to be reliable, but lifetime for liner and insulation has to be further investigated.
Some of the KPI's for the storage are:
Volume: 75,000 m^3 water
Max capacity: 6,000 MWh (T_{max} 88^o C and T_{min} 17^o C monitored in 2014)
Thermal losses/capacity 48 % (Thermal losses 2,908 MWh in 2014, capacity 6,000 MWh))
Investment/capacity: 0.44 €/kWh
Max charge/discharge capacity: 10 MW
Investment/max charge capacity: 263 €/kW

3.2 PTES in Dronninglund, DK

The district heating production plant in Dronninglund consists of the following main components:

37,573 m^2 solar collectors
60,000 m^3 pit heat storage
2.1 $MW_{cooling}$ absorption heat pump
Bio oil boilers
Gas engines

The pit heat storage, the solar collectors and the absorption heat pump were in operation from March 2014 as part of the project "Sunstore 3", supported by the national Danish

EUDP-program. The project enables Dronninglund district heating to deliver heating to the consumers from 70 % renewable energy sources where app. 40 % is solar heat.

3.2.1 Design of the storage

The storage, the solar collectors and the absorption heat pump were recalculated in TRNSYS to find the most feasible combination covering 50 % of the heat production

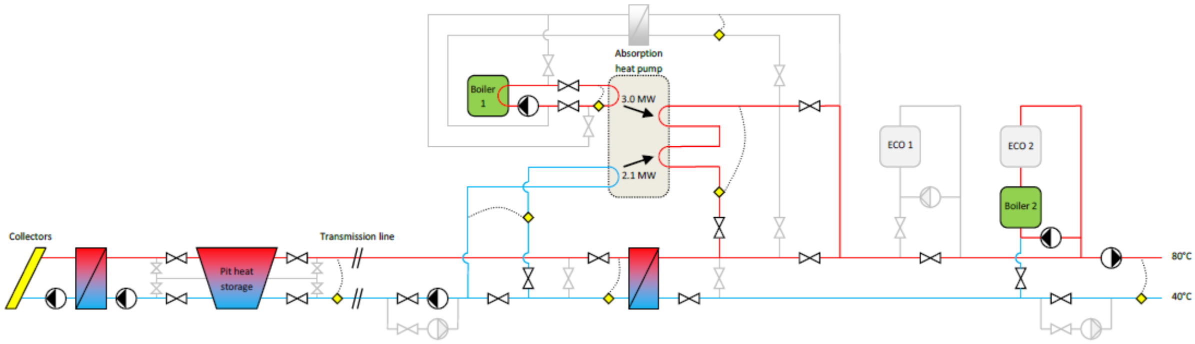

Fig. 10: Principle diagram from Dronninglund (Sørensen March 2015).

The design of the storage is similar to the Marstal design, but the excavation was easier because the storage is situated in an old gravel pit. Furthermore, a new HDPE liner was used. The supplier has given Dronninglund a 20-year performance guarantee if liner temperature does not exceed 90 °C.

Further differences to Marstal are that stainless steel is used in in- and outlet pipes instead of normal steel, water for filling has been treated with reversal osmosis and pH is 9.8 as for water in district heating pipes to prevent corrosion. Additionally, less dirt was entering the storage during construction because the lid was implemented before winter. Filters were implemented at the storage side of the solar heat exchangers to prevent dirt from coming into the heat exchangers, and heavier weight pipes implemented to be sure, that air under the lid would be transported to the edges of the storage.

3.2.2 Implementation of the Dronninglund PTES

Fig. 11: *Pictures from implementation of the pit heat storage in Dronninglund (source Dronninglund DH)*

The excavation, liner work, water filling and lid construction took place in the period from March 15th 2013 to October 2013.

There were no major challenges during the construction period.

3.2.3 Investment costs

The total price of the PTES was 2,3 mio. € or 38 €/m^3.

3.2.4 Operation experiences

During the operation period from 2014 no major problems have turned up. Water ponds are regularly removed from the lid and water can occur in the insulation maybe because water from water puddles on the lid comes through the ventilation valves. A yearly diver inspection shows no corrosion signs and clear water.

3.2.5 Conclusion PTES Dronninglund

Performance and operation of the storage is as expected. The technology seems to be reliable but life time for liner and insulation has to be further investigated. Some of the KPI's for the storage are:

Volume: 60,000 m^3 water
Capacity: 5,400 MWh (T_{max} 89° C and T_{min} 12° C)
Thermal losses/capacity 19 % (Thermal losses 1020 MWh in 2016, capacity 5,400 MWh)
Investment/capacity: 0.43 €/kWh
Max charge/discharge capacity: 27 MW
Investment/max charge capacity: 85 €/kW

4 Test of liner and insulation material

4.1 Liner tests

As mentioned life time for liner and insulation in PTES have to be further investigated.

Polymer liners are relatively cheap and easy to install with well documented welding and testing techniques. A test methodology has been developed by Danish Technological Institute where samples can be tested with up to 120° C water on one side and air on the other side in "test cells" (Pedersen and Nielsen 2000). The durability of the material is defined to when the physical property elongation at break is below 50 %.

Two HDPE-liners were tested from 2003 to 2004. The test temperatures were 100, 107 and 115° C.

For calculation of the duration period at lower temperatures Arrhenius equation is used and for calculation of expected service life in a pit heat storage, where the temperature varies during a year, the formula for calculation of service life for pre insulated district heating pipes in EN253 is used.

The result for the two HDPE-liners can be seen in Table 1. The temperatures mentioned in the table are constant temperatures.

	Service life (years)	
Temperature (°C)	Liner 1	Liner 2
90	2.5	3.2
80	6.1	7.2
70	15.9	17.0
60	43.7	42.4

Table 1: *Service life for HDPE liner 1 and 2*

For both liners the service life for at pit heat storage calculated for storage temperatures if the storage was placed at Marstal Fjernvarme was more than 20 years.

In 2008 the SUNSTORE 3 project in Dronninglund started. In that project the intention was to extend the temperature range and thus the storage capacity up to 90° C and down to 10° C. Liner 1 and 2 could still be used but would give limitations in use of the storage. During the design phase two new HDPE-liners were tested in 2010-11 and 2012-13. The test temperature was 110° C. The results can be seen in Table 2.

	Service life (years)	
Temperature (°C)	Liner 3	Liner 4
90	2.9	4.3
80	6.8	10.0
70	15.6	23.0
60	35.9	52.9

Table 2: *Service life for HDPE-liners 3 and 4*

A liner with same conditions as liner 2 was implemented in the SUNSTORE 4 project in Marstal in the 75,000 m^3 pit heat storage. At that time liner 4 was not tested.

In the SUNSTORE 3 project a newly developed HDPE-liner was implemented in 2013, because the supplier promised 20 years performance guarantee at 90^o C constantly.

A test of the new liner implemented in the SUNSTORE 3 pit heat storage at 60,000 m^3 has been carried out by Danish Technological Institute from December 2014. The expectation was that the duration of the test at 110^o C should be 4-5 years, but already after less than 1½ year the test showed physical property elongation at break below 50 %.

This is surprising and a new test was made from September 2016. The theory is, that de-ionized test water with pH 9.6 can break down the antioxidants in the liner material and oxygen can then differ trough the liner from outside and oxidate the liner.

The only difference between this test of liner 5 and the former liner tests is, that the first 4 liners were tested with tap water on the water side. In the test from September 2016 is used tap water to be able to compare to former results.

Additionally, a test of the insulation material is ongoing. The material is tested at 90^o C and 95% RH. The test is still ongoing.

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