

Danish Case on Large-scale Thermal Storage to enable a Flexible Energy System

Use of storage and lessons learnt



22 October 2025

Frontpage picture: Aerial photo of the PTES in Høje Taastrup. Photo: Ioannis Sifnaios, DTU

Report title: Danish Case on Large-scale Thermal Storage to enable a Flexible Energy System

Subject: Use of storage and lessons learnt

Release date: 22 October 2025

Project No.: 25-027

Prepared by: PAS, NF, HW

Quality-assured by: NF

Document no.: 01

Version: 1.3

Prepared for: Danish Energy Agency and LEA Hessen

Table of Contents

Table of Contents.....	3
List of Figures	4
List of Tables.....	5
List of Abbreviations	6
Executive Summary.....	7
1. Introduction	8
2. Tank Thermal Energy Storages (TTES)	10
3. Pit Thermal Energy Storages (PTES)	13
4. Borehole Thermal Energy Storages (BTES)	18
5. Heat planning and preparation when starting a PTES project.....	20
5.1 Case Dronninglund	22
5.2 Case Høje Taastrup	24
6. Screening of economically feasibility.....	26
6.1 Case Dronninglund	34
6.2 Case Høje Taastrup	35
7. How to find a site for PTES	36
7.1 Case Dronninglund	36
7.2 Case Høje Taastrup	38
8. Authorities' permissions	40
8.1 Case Dronninglund	41
8.2 Case Høje Taastrup	44
9. Design and tender	45
9.1 Case Dronninglund	49
9.2 Case Høje Taastrup	50
10. Implementation and supervision	51
10.1 Case Dronninglund	56
10.2 Case Høje Taastrup	58
References	60

List of Figures

FIGURE 1: OVERVIEW OVER AVAILABLE LARGE-SCALE THERMAL ENERGY STORAGE CONCEPTS [1].	8
FIGURE 2: EXAMPLE OF PRINCIPLE DIAGRAM FOR A SOLAR THERMAL PLANT COMBINED WITH NATURAL GAS FIRED CHP [2].	10
FIGURE 3: DISTRIBUTION OF SIZES OF THE TANKS [3].	11
FIGURE 4: LEFT: TOP DIFFUSER IN A 5,500 M ³ TTES UNDER CONSTRUCTION IN BRÆDSTRUP, DK. RIGHT: 5,500 M ³ TTES UNDER CONSTRUCTION. THE TANK IS LIFTED AND WELDED FROM BENEATH. PHOTO: BRÆDSTRUP FJERNVARME.	12
FIGURE 5: LEFT: 5,500 M ³ TTES FINALIZED WITHOUT INSULATION. RIGHT: INSULATION AND COVERING FINALIZED.	12
FIGURE 6: GENERAL COMPARISON OF SPECIFIC COSTS BASED ON A REFERENCE VOLUME [4].	13
FIGURE 7: UPPER LEFT THE ABANDONED GRAVEL PIT. UPPER RIGHT EXCAVATION IS FINALIZED, AND THE IN- AND OUTLET IS IMPLEMENTED. BOTTOM LEFT HDPE MEMBRANE IS MOUNTED. BOTTOM RIGHT WATER HAS BEEN FILLED IN. PHOTOS: DRONNINGLUND FJERNVARME.	14
FIGURE 8: SYSTEM DIAGRAM FOR DRONNINGLUND. SOURCE: PLANENERGI.	15
FIGURE 9: ENERGY FLOW IN THE DRONNINGLUND PTES 2014-17. STORAGE EFFICIENCY WAS 90%, NUMBER OF CYCLES 2/YEAR, $T_{MAX} = 89^{\circ}\text{C}$ AND $T_{MIN} = 10^{\circ}\text{C}$ [5].	15
FIGURE 10: FUNCTION OF THE PTES IN HØJE TAASTRUP. SOURCE: VEKS AND HTF.	16
FIGURE 11: BTES IN BRÆDSTRUP, DENMARK. THE DEPTH OF THE PIPES (GREY LINES) IS 45 M, THE DEPTH OF THE GROUND TEMPERATURE SENSORS (RED LINES) IS 59 M. THE HORIZONTAL DISTANCE BETWEEN THE SENSORS IS 9 M [6].	18
FIGURE 12: GEOMETRY USED FOR THE THREE PTES COMPONENTS IN TRNSYS: TYPE 342 (LEFT), TYPE 1300 + TYPE 1301 (MIDDLE) AND TYPE 1322 (RIGHT).	23
FIGURE 13: DIAGRAM SHOWING THE GOOD AGREEMENT BETWEEN MEASUREMENTS AND MODELLING IN DRONNINGLUND. LEFT AXIS: TEMPERATURE DISTRIBUTION INSIDE THE PTES (TOP, MIDDLE AND BOTTOM TEMPERATURES) AS MODELLED IN TRNSYS (USING TYPE 1300 + TYPE 1301, SEE RED, BLUE AND PINK CURVES) AND AS MEASURED (ORANGE, GREEN AND LIGHT BLUE CURVES). RIGHT AXIS: ENERGY CONTENT EVOLUTION AS MODELLED IN TRNSYS (BROWN CURVE) AND AS MEASURED (LIGHT PINK CURVE). MEASURED DATA IS FROM 2017.	23
FIGURE 14: WEEKLY CHARGED, DISCHARGED ENERGY AND ENERGY CONTENT [9].	25
FIGURE 15: SPECIFIC INVESTMENT IN [€/MWh/Y] AS A FUNCTION OF ROW DISTANCE AND PANEL SLOPE IN A FLAT PLATE SOLAR COLLECTOR FIELD.	27
FIGURE 16: SPECIFIC INVESTMENT IN [€/MWh/Y] AS A FUNCTION OF A FLAT PLATE SOLAR COLLECTOR APERTURE AREA AND ABSORPTION HP CAPACITY.	28
FIGURE 17: EXAMPLE OF AN OPTIMIZATION PROGRESS IN BRÆDSTRUP, DK [6].	28
FIGURE 18: OPTIMIZATION RESULTS FROM A PLANNED ENERGY SYSTEM IN LØGUMKLOSTER, DK.	29
FIGURE 19: PROJECT COSTS DEPENDING ON VOLUME (DANISH ENERGY AGENCY, 2025).	30
FIGURE 20: SPECIFIC COSTS DEPENDING ON VOLUME (DANISH ENERGY AGENCY, 2025 [7]).	30
FIGURE 21: VISUALIZATION OF A SQUARED 100,000 M ³ PTES IN EVEN TERRAIN IN FAVORABLE / DANISH? GROUND CONDITIONS, NOTE – NO DIFFUSER OR PIPING IS VISUALIZED.	31
FIGURE 22: SPECIFIC FOOTPRINT OF A PTES AS FUNCTION OF THE WATER VOLUME, BASED ON THE SAME GEOMETRICAL ASSUMPTIONS AS DESCRIBED ABOVE (WITHOUT ADDITIONAL AREA NEEDED FOR ACCESS ROAD, TECHNICAL BUILDING ETC.). THE ERROR OF THE EQUATION IS LESS THAN 2% FOR STORAGES > 100 000 M ³ .	32
FIGURE 23: SANKEY DIAGRAM WITH DESIGN FIGURES FOR THE SUNSTORE 3-SYSTEM IN DRONNINGLUND [12].	34
FIGURE 24: POTENTIAL NEW SITES FOR PTES. SOURCE: GEO.	37

FIGURE 25: MAP OF THE PTES SITE IN HØJE TAASTRUP WITH DISTANCES IN [M]. PURPLE: PTES AND PUMP STATION. RED: NEW PIPE LINE BETWEEN PTES AND HEAT EXCHANGER BUILDING. GREEN: NEW TRANSMISSION PIPES. BLUE: NEW DISTRIBUTION PIPES.	39
FIGURE 26: PICTURE OF SOLAR FIELD AND PTES IN DRONNINGLUND AFTER IMPLEMENTATION (AERIAL VIEW FROM SOUTH).	41
FIGURE 27: VISUALIZATION OF STORAGE EMBANKMENTS WITH (BOTTOM) AND WITHOUT (TOP) PLANTS.....	42
FIGURE 28: ILLUSTRATION OF DISTANCE FROM BARROW MOUNDS (THE PURPLE CIRCLES) IN DRONNINGLUND.....	43
FIGURE 29: VISUALIZATION OF THE PTES IN HØJE TAASTRUP (GREY COLOR) IN THE SCREENING REPORT (VIEW FROM NORTHEAST).....	44
FIGURE 30: TEST OVEN AT THE UNIVERSITY OF LINZ.	47
FIGURE 31: THE PTES IN MARSTAL AFTER A CLOUDBURST.....	51
FIGURE 32: ARC TEST PRINCIPLE (FIGURE TAKEN FROM ASTM7953 STANDARD PRACTICE FOR ELECTRICAL LEAK LOCATION ON EXPOSED GEOMEMBRANES USING THE ARC TESTING METHOD).....	53
FIGURE 33: LOCATION OF LEAK DETECTION SENSORS IN HØJE TAASTRUP (SOURCE: SENSOR DKS GMBH).	54
FIGURE 34: DRONNINGLUND, MID-MAY 2013. PHOTO: NIRAS.	56
FIGURE 35: DRONNINGLUND, OCTOBER 2013. PHOTO: NIRAS.	57
FIGURE 36: HØJE TAASTRUP, JUNE 2020. PHOTO: HTF.	58
FIGURE 37: HØJE TAASTRUP WITH NEW PP-MEMBRANE AND SACRIFICIAL HDPE MEMBRANE ON TOP OF IT, OCTOBER 2021. THE 3 DIFFUSERS OF THE IN- AND OUTLET SYSTEM CAN BE SEEN AT THE FAR END. PHOTO: HTF.	59

List of Tables

TABLE 1: COMPARISON OF STORAGE CONCEPTS REGARDING HEAT CAPACITY AND GEOLOGICAL REQUIREMENTS. TTES CAN ALSO BE ABOVE GROUND [1].	9
TABLE 2: LIST OF PTES IMPLEMENTED BY DANISH DH SUPPLIERS [7]. PRICES ARE THE REAL IMPLEMENTATION COSTS IN THE IMPLEMENTATION YEAR (CURRENT PRICES) INCLUDING STORAGE EXCEPT WATER FILLING, IN-AND OUTLET PIPES AND DIFFUSORS AND BUILDING, PUMPS AND HEAT EXCHANGERS AT THE STORAGE SIDE.	17

List of Abbreviations

- ATES Aquifer Thermal Energy Storages
- BTES Borehole Thermal Energy Storages
- CHP Combined Heat and Power
- CO₂ Carbon Dioxide
- DH District Heating
- DK Denmark
- DTI Danish Technological Institute¹
- DTU Danish Technical University²
- EIA Environmental Impact Assessment
- GIS Geographic Information System
- HDPE High Density PolyEthylene
- HP Heat Pump
- HTF Høje Taastrup Fjernvarme³ (Høje Taastrup District heating utility)
- LTES Large Thermal Energy Storages
- PI Piping and Instrumentation
- PP PolyPropylene
- PTES Pit Thermal Energy Storages
- RO Reverse Osmosis
- TES Thermal Energy Storages
- TTES Tank Thermal Energy Storages
- VAT Value Added Tax
- VEKS Vestegns Kraftvarmeselskab⁴

¹ <https://www.dti.dk/>

² <https://www.dtu.dk/english/>

³ <https://htf.dk/>

⁴ <https://www.veks.dk/en>

Executive Summary

This report is made for planners and policy makers to facilitate implementation of large thermal water storages in district heating systems. The report includes Danish experiences focused mainly on Pit Thermal Energy Storages (PTES) and partly also on Tank Thermal Energy Storages (TTES).

Large scale thermal storages will be an important element in future efficient district heating systems because they can provide the electricity sector with flexibility services and at the same time store excess heat from industries and waste incineration and reduce consumption of fossil fuels in peak hours. For storages of more than 50,000 m³ PTES are of special interest because the investment costs for TTES are 2-4 times higher than for PTES with the same storage capacity.

Chapters 1-4 in the report describes the historical reasons for development and use of TTES and PTES in Denmark. Nearly all district heating utilities have installed TTES originally connected to CHP plants, but later also in connection with solar thermal plants, biomass plants, large scale heat pumps and electric boilers.

PTES has been developed connected with large scale solar thermal plants, but recently also used as flexibility provider in large district heating systems.

PTES in Dronninglund (stores heat from solar thermal) and Høje Taastrup (stores heat from waste heat incineration, CHP production and heat pump production) are used as cases in the report.

The following chapters (5-10) present Danish experiences and lessons learned in the planning and implementation phases of PTES:

- Heat planning and preparation (chapter 5)
- Screening of economically feasibility (chapter 6)
- How to find a site for PTES (chapter 7)
- Authorities' permissions (chapter 8)
- Design and tender (chapter 9)
- Implementation and supervision (chapter 10)

In each of these chapters there is a general introduction to the topic explaining methodologies and tools used in Danish projects and what to be aware of in the different project steps. Experiences are in each chapter included from the cases in Dronninglund and Høje Taastrup.

1. Introduction

Large-scale thermal energy storages (for district heating purposes) are normally based on water as the storage medium, but other storage media (soil and gravel) can be used. Storages are normally unpressurised, and operating temperatures are below the boiling point of water (100°C). Large-scale thermal storages are commonly defined as storages with a storage capacity of at least 1 GWh. They can be utilized as short-term storages or long term/seasonal storages depending on their storage cycle duration.

There are four different types of large-scale thermal storages for district heating systems:

- Tank Thermal Energy Storages (TTES), which normally are steel tanks above ground,
- Pit Thermal Energy Storages (PTES), which normally are underground storages where excavated soil is used as surrounding embankments,
- Borehole Thermal Energy Storages (BTES), which consist of boreholes with closed loops of underground water pipes, and
- Aquifer Thermal Energy Storages (ATES), where an underground water reservoir is used as storage (open system).

The four types are illustrated in Figure 1.

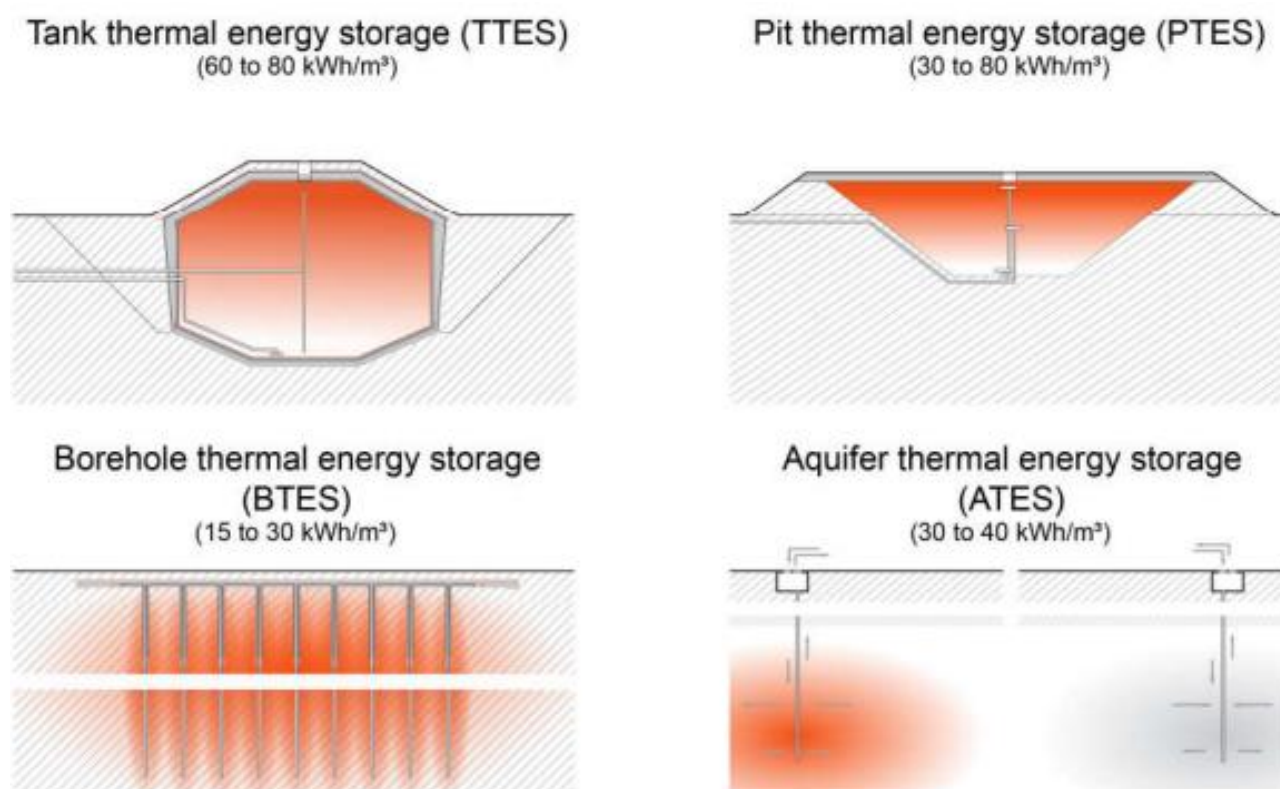


Figure 1: Overview over available large-scale thermal energy storage concepts [1].

In this report we will primarily present Danish experiences with PTES, but also explain the use of TTES in Danish district heating systems. One case of BTES will be presented, but since realized ATES plants in Denmark are only small-scale, ATES will not be presented.

Table 1: Comparison of storage concepts regarding heat capacity and geological requirements. TTES can also be above ground [1].

TTES	PTES	BTES	ATES
Storage Medium			
water	water*	gravel-water*	sand-water rock-water
Heat Capacity in kWh/m³			
60 - 80	60 - 80	30 - 50	15 - 30
Storage Volume for 1 m³ water equivalent			
1 m ³	1 m ³	1.3 – 2 m ³	3 – 5 m ³
Geological Requirements			
- stable ground conditions - preferably no groundwater - 5 – 15 m deep	- stable ground conditions - preferably no groundwater - 5 – 15 m deep	- drillable ground - high heat capacity - high thermal conductivity - low hydraulic conductivity ($k_f < 10^{-10}$ m/s) - natural ground-water flow < 1 m/a - 30 – 100 m deep	- natural aquifer layer with high hydraulic conductivity ($k_f > 10^{-5}$ m/s) - confining layer on top - no or low natural groundwater flow - suitable water chemistry at high temperatures - aquifer thickness of 20 – 100 m
Storage Temperature Range			
5 - 95 °C	5 - 95 °C	-5 - 90 °C	2 - 20 °C for shallow and 2 - 80 °C for deep systems

* Water is more favorable from the thermodynamic point of view. Gravel-water is often used if the storage surface is to be designed for further usage (e.g. for streets, parking lots etc.)

2. Tank Thermal Energy Storages (TTES)

Up through the 1980s and 1990s, the Danish energy system was greatly expanded with decentralized combined heat and power (CHP) plants. Both in the form of new greenfield CHP plants, but also because older plants converted production from other fuels to natural gas-based CHP. Steel tanks are a widely used form of heat storage in connection with a decentralized CHP plant, as the heat produced together with the electricity production is often not related to the current heat demand in the district heating system. Steel tanks make it possible to have heat production and heat consumption at different times. This means that CHP plants can produce during the most favorable hours in relation to the electricity prices.

Typically, the steel tanks installed in the 1980s and in the first half of the 1990s are dimensioned for the plants' production of electricity according to the 3-tier tariff. In the 3-tier tariff the lowest electricity price was in summer weekends and therefore typical storage capacities were able to cover the district heating demand for 2-3 days in the summer period.

From around 2005 it was more feasible for the natural gas fired CHP plants to use new variable tariffs introduced on the electricity market (spot market). This made it possible for the natural gas fired CHP plants to integrate solar thermal plants in the heat production system. The solar thermal plant covered most of the heat consumption in the summer period and used the same steel tank implemented for the CHP plant. See Figure 2.

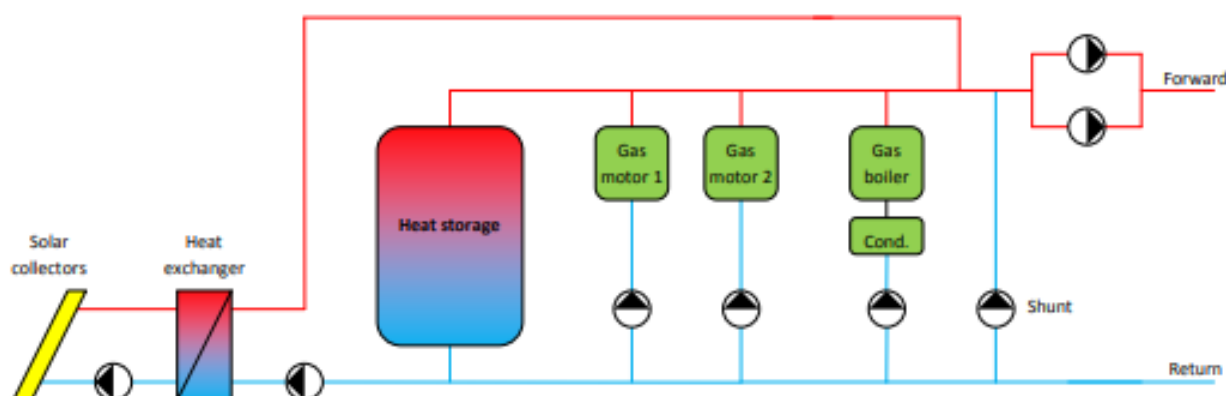


Figure 2: Example of principle diagram for a solar thermal plant combined with natural gas fired CHP [2].

The steel tanks also served as peak shaving in winter and as reserve in periods where other units were repaired or fell out. For the managing people this was attractive also for biomass only plants, and often the size of their accumulation tanks was determined by the number of hours the storage could cover in winter.

From 2018 economical conditions for electrical heat pumps were gradually improved in Denmark. This made heat produced from new established heat pumps more economically feasible than heat produced from new established solar thermal plants, and implementation of new solar thermal plants was replaced by implementation of large-scale heat pumps.

In 2025 more than 180 Danish district heating utilities have installed heat pumps. The total thermal capacity is around 600 MW. In addition, around 1,500 MW of electrical boiler capacity has been installed. Both heat pumps and electric boilers are selling regulation services to the electricity sector, and the steel tanks are now flexibility providers in power to heat.

The Danish District Heating Association made in 2013 a survey among its 450 members. 368 plants responded and 294 had a storage tank (80%). The average storage volume was 3,000 m³ and the total energy capacity was 50 GWh. See Figure 3.

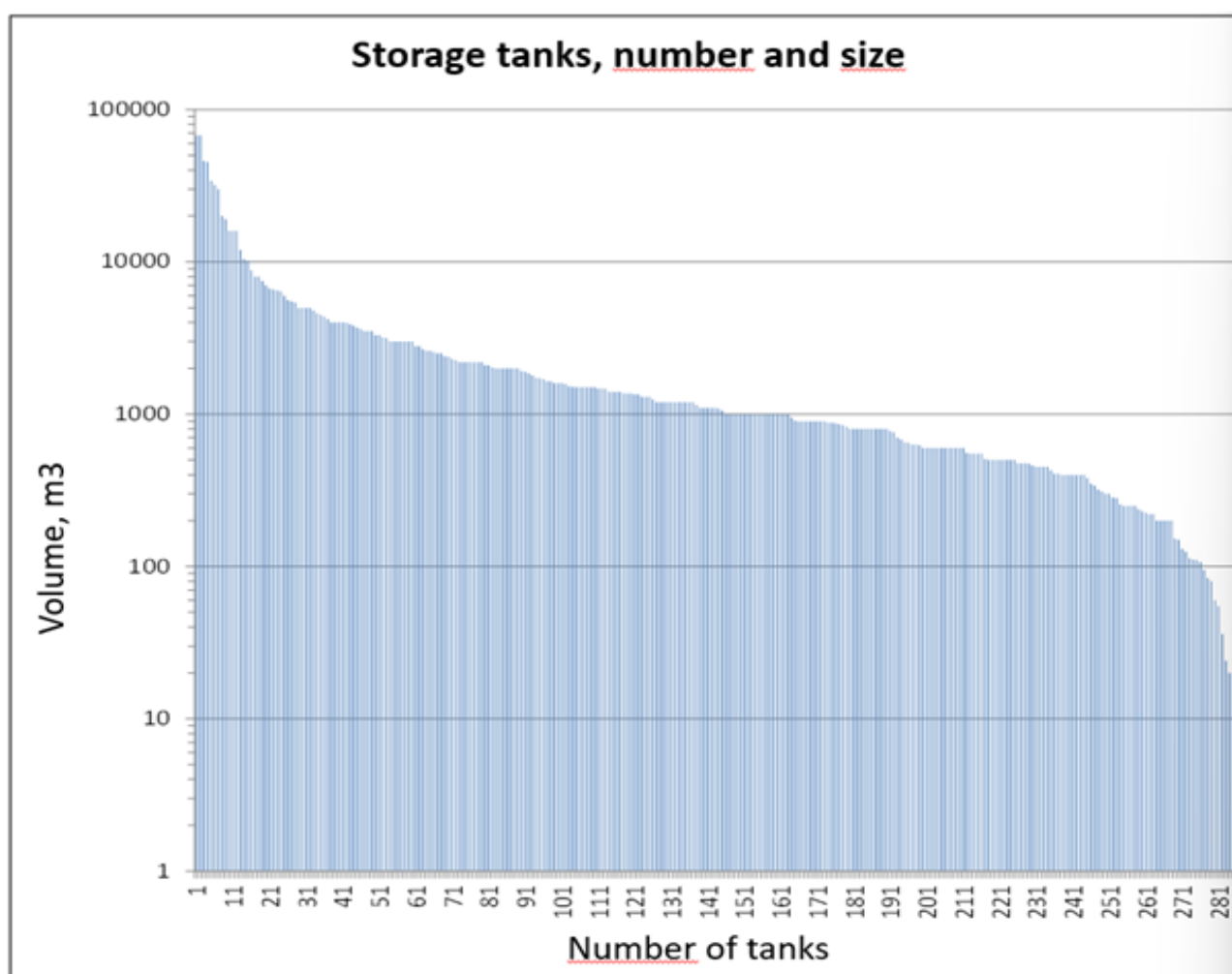


Figure 3: Distribution of sizes of the tanks [3].

Today the capacity is even higher since new steel tanks are continuously being implemented, driven by incomes from the electricity market.

Danish TTES are commonly steel tanks with (at least) two diffusers. One at the top and one at the bottom. In- and outlet capacity is typically similar to the district heat consumption in peak hours. TTES are normally directly connected to the city's district heating network, and oxygen in the storage water is avoided by adding nitrogen between the water surface and the tank top. Nitrogen is generated next to the tank. If possible TTES are also used as pressurizer in the district heating network. Normal insulation standard is 300 mm of mineral wool on the sides and top.



Figure 4: Left: Top diffuser in a 5,500 m³ TTES under construction in Brædstrup, DK. Right: 5,500 m³ TTES under construction. The tank is lifted and welded from beneath. Photo: Brædstrup Fjernvarme.



Figure 5: Left: 5,500 m³ TTES finalized without insulation. Right: Insulation and covering finalized.

Under this link you can find a movie from implementation of a 4,600 m³ steel tank in Hadsund, DK:

<https://steeltank.dk/products/heat-accumulation/?lang=en>.

3. Pit Thermal Energy Storages (PTES)

From June 1979 to June 1988 Task7, Central Solar Heating Plants with Seasonal Storage, was carried out in IEA SHC and lead by Sweden. The purpose was to find suitable long term storage facilities for hot water produced by large scale solar thermal plants. Different technical solutions were developed and compared. See Figure 6.

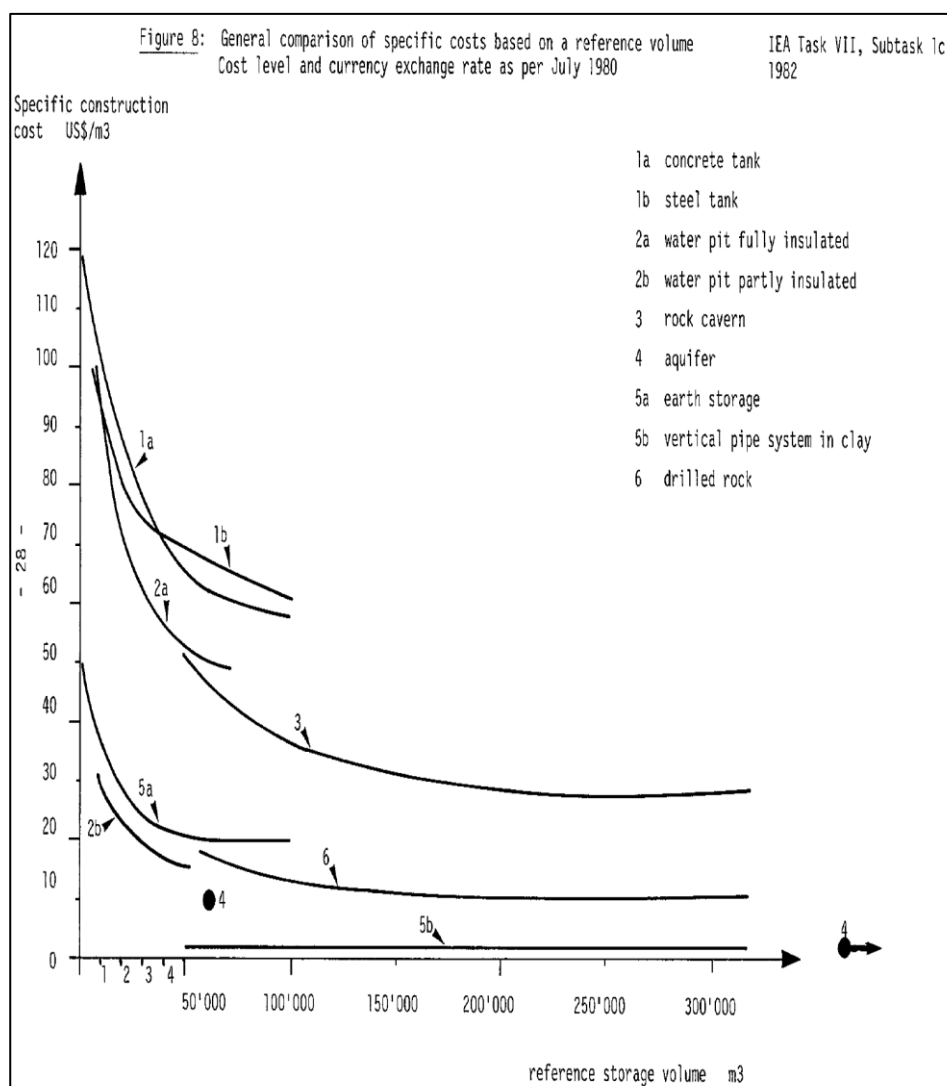


Figure 6: General comparison of specific costs based on a reference volume [4].

For Danish conditions, solution 2b seemed to be the most promising solution since solution 5b requires a special soft clay which cannot be found in Denmark and solution 6 requires rock which we only have at the island of Bornholm. Also for solution 4, aquifer, suitable geological conditions cannot be found unless it is accepted to use ground water in shallow solutions where maximum temperature is 20°C. Development of the concept was carried out at Danish Technical University (DTU) during the 1980ties, resulting in a pit storage concept where excavated soil is used for embankments (with soil balance), the storage is tightened, water filled in, and the storage is finalized with an insulated lid. The concept was

supposed to be used for storing hot water from solar thermal plants, waste heat and CHP plants and utilized for district heating.

Large-scale (aperture area > 1,000 m²) solar thermal plants for district heating were in Denmark implemented from 1988. The solar fraction was typically 20-25% of the total district heat production, but already in the 90ties there was a wish among some of the Danish District heating utilities for larger solar fractions by combining solar thermal plants with seasonal storages. The first pilot storage outside universities was implemented in 1995, and finally in 2013 and 2014 the first full scale plants were implemented in Marstal and Dronninglund. The target was to reach solar fractions of 40-50%.

Marstal and Dronninglund are typical representatives of pit heat storage charged by solar thermal in the summer period and discharged to the district heating system in late autumn/winter. In both cases a heat pump is connected to the PTES. In such a system the PTES will have 1-2 yearly cycles, where one cycle is defined as the PTES being charged and discharged one time with its full capacity. Since the PTES will be both charged and discharged in spring and autumn more than one cycle can be reached.

The PTES in Dronninglund was implemented in an abandoned gravel pit. See Figure 7.



Figure 7: Upper left the abandoned gravel pit. Upper right excavation is finalized, and the in- and outlet is implemented. Bottom left HDPE membrane is mounted. Bottom right water has been filled in. Photos: Dronninglund Fjernvarme.

The PTES in Dronninglund is 60,000 m³, and the in- and outlet capacity is 27 MW. It is connected to 37,500 m² of flat plate solar thermal collectors and an absorption heat pump. See Figure 8.

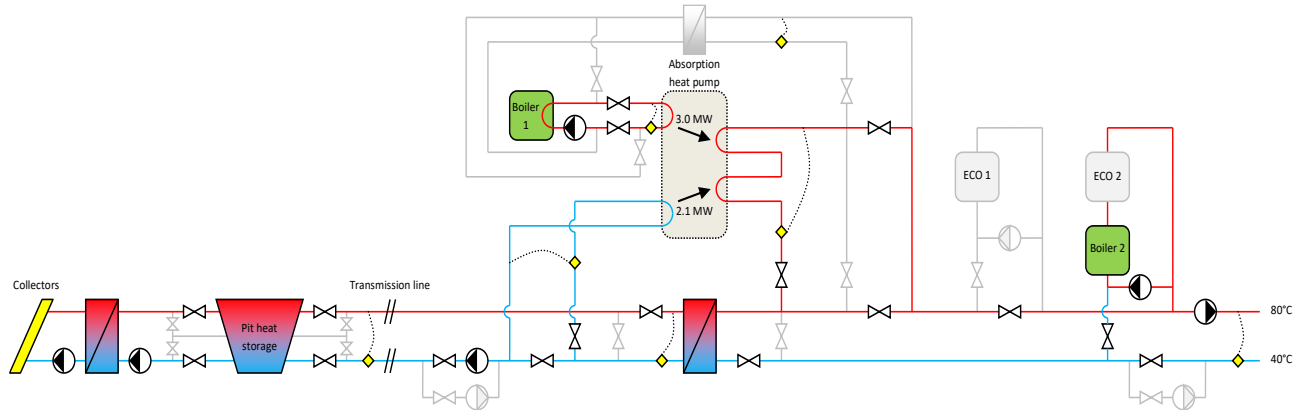


Figure 8: System diagram for Dronninglund. Source: PlanEnergi.

The systems in Marstal and Dronninglund was evaluated in a monitoring program managed by the company Solites from Stuttgart. The main results for Dronninglund can be seen in Figure 9.

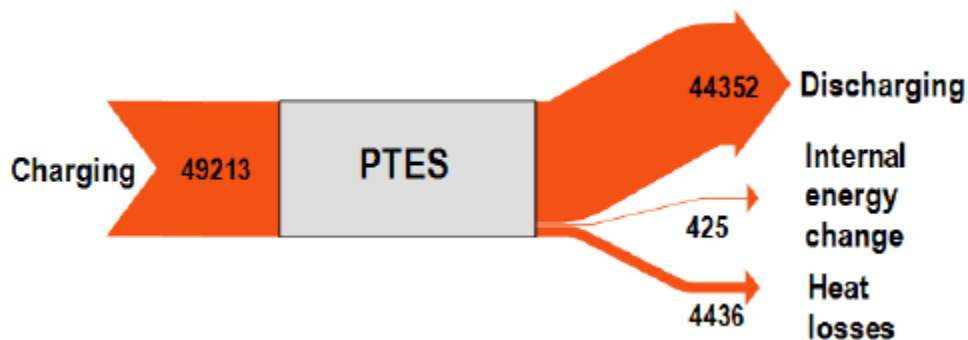


Figure 9: Energy flow in the Dronninglund PTES 2014-17. Storage efficiency was 90%, number of cycles 2/year, $T_{max} = 89^{\circ}\text{C}$ and $T_{min} = 10^{\circ}\text{C}$ [5].

In the Danish electricity system, the amount of fluctuating electricity production from wind and solar has passed 50% in average and 100% in periods. The consequence has been that large scale heat pumps have been introduced in the district heating systems utilizing low electricity prices. This has decreased the solar thermal implementation. On the other hand, it has increased the economically feasibility of introducing flexibility and sector coupling in the Danish energy system. Flexibility in an energy system where fluctuating electricity production has a large role is very much dependent on storage facilities. Electrical storages (batteries, pumped hydro...) are of course a possible solution, but the price of storing capacity of one kWh is 100 € or more compared to 0.5 – 2 € for storing one kWh in a PTES. Thus, a new market for PTES has come up. The first project of this type is a PTES project in Høje Taastrup providing flexibility to CHP plants in Copenhagen. See Figure 10.

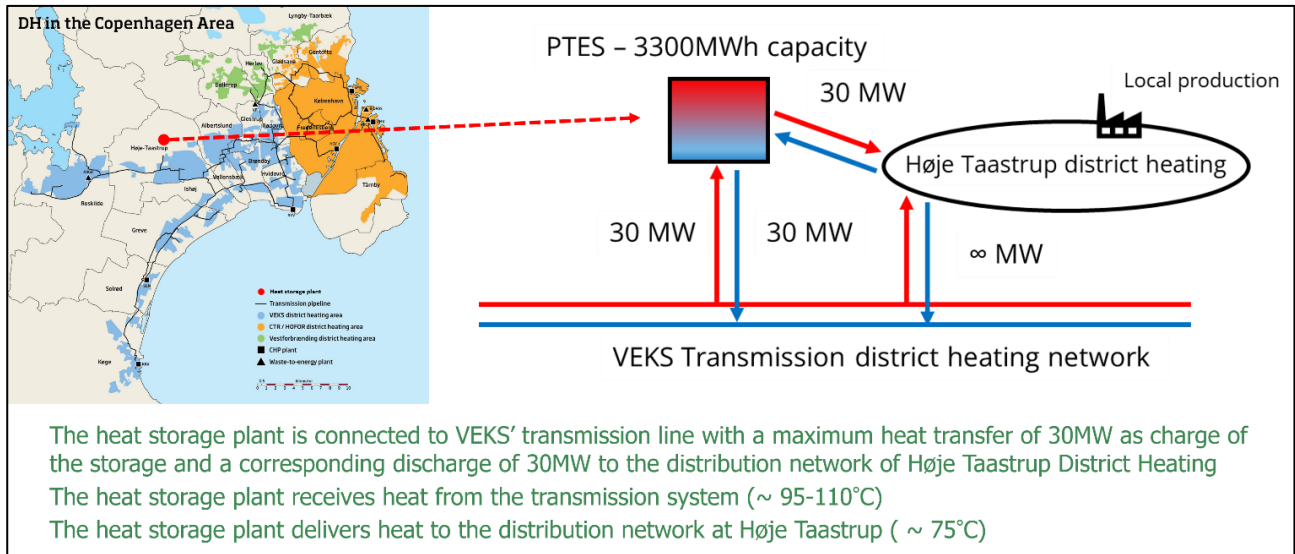


Figure 10: Function of the PTES in Høje Taastrup. Source: VEKS and HTF.

The roles of the storage in Høje Taastrup are:

- Storage for waste heat from e.g. waste incineration.
- Storage for cogeneration (adds flexibility to the electricity market).
- Storage for heat from heat pumps and electric boilers (adds flexibility to the electricity market).
- Peak shaving. Saves natural gas in peak hours.

This means more storage cycles pr. year and better economically feasibility, but also higher temperatures the whole year in the PTES. How these challenges are met is described in the implementation report [8].

The list of PTES established in Denmark can be seen in Table 2.

Table 2: List of PTES implemented by Danish DH suppliers [7]. Prices are the real implementation costs in the implementation year (current prices) including storage except water filling, in-and outlet pipes and diffusers and building, pumps and heat exchangers at the storage side.

PTES	Ottrup-gård	SUN-STORE 2 Marstal	SUN-STORE 3 Dronninglund	SUN-STORE 4 Marstal	Vojens	Gram	Toftlund	Høje Taastrup
Year of construction	1993-95	2003	2013	2011-12	2014-15	2014-15	2016-17	2020-22
Size, m ³ (water volume)	1,500	10,000	60,000	75,000	210,000	125,000	85,000	70,000
Investment, million €	0.23	0.67	2.3	2.7	5.0	4.3	4.1	6.0
Investment, €/m ³	150	67	38	36	24	34.5	48	86
Investment, €/kWh	5.2	1.0	0.43	0.45	0.41	0.36	0.59	1.83
Temperature range, °C	35-60	35-90	10-89	17-88	40-90	20-90	20-90	45-90
Capacity, MWh	43.5	638	5,400	6,000	12,180	12,125	6,885	3,300
Charging and discharging cap., MW	0.39	6.51	26.1	10.5	38.5	30.0	22.0	30.0
Calc. heat loss, total, MWh/y	85	402	1,602	2,475	5,500	4,024	1,900	1,577
Measured heat loss, MWh/y [#]	70		1,175	2,927				

#Measured data for 1998-2001 (Pilot storage in Ottrupgård), 2013 (Marstal) and 2014 (Dronninglund).

Next in the pipeline is a 700,000 m³ PTES for Fjernvarme Fyn.

The future Danish PTES will also have a role in storing waste heat from PtX plants (production of hydrogen, methane, methanol, ammonia...) and storing of deep geothermal heat.

4. Borehole Thermal Energy Storages (BTES)

BTES, a system consisting of tubes in boreholes (duct storage), normally operated in combination with heat pumps, are implemented in several countries. A typical BTES operates at low temperatures (0 to 30°C). The storage efficiency can reach 90 to 100% when the BTES is operated around the average natural temperature of the ground, and there is no strong natural groundwater flow. Furthermore, BTES are characterized by requiring a relatively small area of land, as the surface area may be used for other purposes, depending on plant design. BTES can also be used for storing higher temperatures (up to 90°C). A pilot BTES (19,000 m³ of soil) has been implemented in connection to solar thermal at Brædstrup Fjernvarme in Denmark.

Figure 11 illustrates the system in Brædstrup with 2 U-pipes in each of the 48 boreholes. The BTES is charged by pumping hot water from the center of the BTES down and up from the boreholes (6 in series) and back to the center. That will heat up the soil in the summer period. In the winter period the BTES is discharged by pumping cold water in the opposite direction. The BTES is connected to a 5,500 m³ TTES and a 1.2 MW_{heat} heat pump.

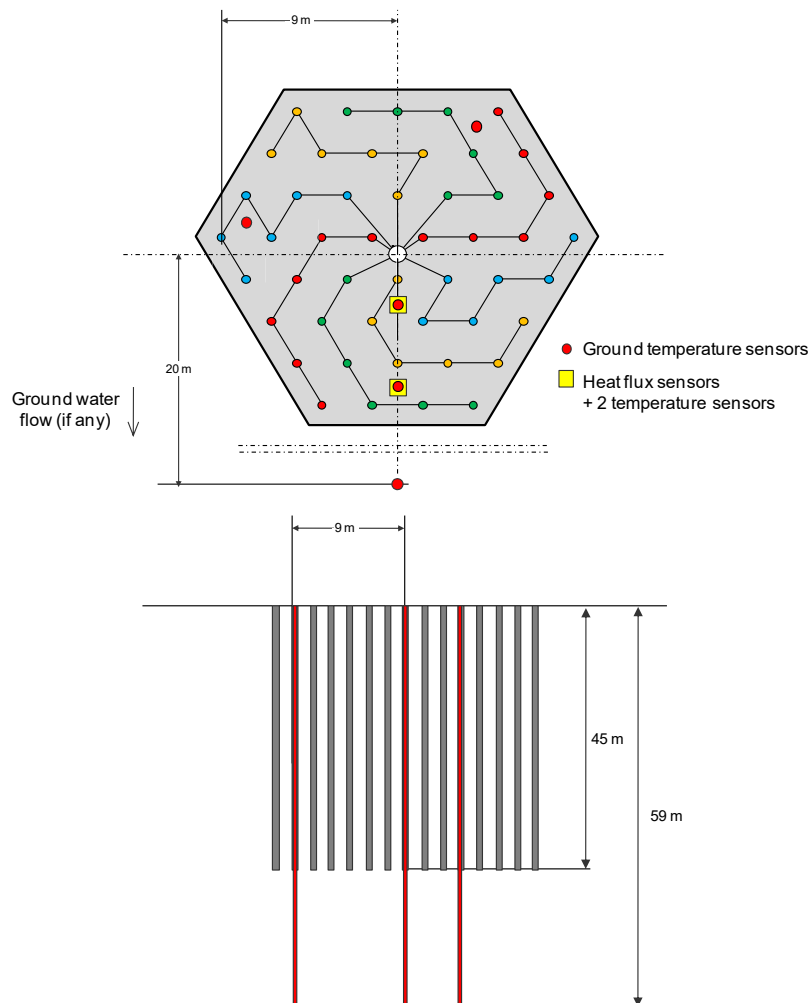


Figure 11: BTES in Brædstrup, Denmark. The depth of the pipes (grey lines) is 45 m, the depth of the ground temperature sensors (red lines) is 59 m. The horizontal distance between the sensors is 9 m [6].

The BTES in Brødstrup was a pilot plant which was heated up to 60°C. The design was inspired by the BTES in Crailsheim, Germany. The function of the BTES was as calculated, but a full-scale plant has not been implemented since Brødstrup Fjernvarme finds the in- and outlet capacity too small. For the pilot plant it is 300-600 kW. For a full-scale plant of 210,000 m³ soil it would have been 3-6 MW.

5. Heat planning and preparation when starting a PTES project

The following chapters (5-10) present Danish experiences and lessons learned in the planning and implementation phases of PTES:

- Heat planning and preparation (chapter 5)
- Screening of economical feasibility (chapter 6)
- How to find a site for PTES (chapter 7)
- Authorities' permissions (chapter 8)
- Design and tender (chapter 9)
- Implementation and supervision (chapter 10)

In each of these chapters, experiences are included from the cases in Dronninglund and Høje Taastrup.

Before starting a PTES project, it can be useful to make some rough estimates of the heat sources, that can be stored in the PTES, the number of cycles and the heat sources that can be replaced when discharging the storage.

Prices for stored heat and the advantage of more than one storage cycle per year

The price for storing heat can vary from more than 100 €/MWh to less than 10 €/MWh depending on investment cost, financing, operation costs and number of storage cycles. Storage cycles are defined as:

$$CN = \frac{Q_{DC}}{Q_{CAP}}$$

Q_{DC} = heat discharged from the storage pr. year;

Q_{CAP} = heat capacity of the storage

Storage cycles in a PTES are normally not full cycles where the storage is fully charged and discharged but composed by partly charging and discharging during a year.

Example with few cycles

In **Dronninglund** the price of the storage is 2.3 mio. €, heat capacity is 5,400 MWh and heat loss is calculated to 1,602 MWh/y (See Table 2). Besides that, operation costs were estimated to 21,100 €/y and financing costs were estimated to 135% of the investment.

Yearly costs are then $2,300,000 \text{ €} \times 1.35 / 20 \text{ y} + 21,100 \text{ €/y} = 176,350 \text{ €/y}$.

With one cycle/y $5,400 \text{ MWh} - 1,602 \text{ MWh} = 3,798 \text{ MWh}$ can be discharged and the price for stored heat is then $176,350 \text{ €} / 3,798 \text{ MWh} = 46.4 \text{ €/MWh}$.

With two cycles/y the price for stored heat will be $176,350 \text{ €} / (2 \times 5,400 - 1,602) \text{ MWh} = 19.2 \text{ €/MWh}$.

The PTES in Dronninglund stores heat from a solar thermal plant from summer to winter. It has two cycles pr. year which as can be seen is important for the economy. The production price for solar thermal heat is app. 30 €/MWh, so in Dronninglund the price for replaced heat had as a rule of thumb to be more than 50 €/MWh.

Example with several cycles

In **Høje Taastrup** the price of the storage is 6.0 mio. €, heat capacity is 3,300 MWh and heat loss is calculated to 1,577 MWh/y (See Table 2). Besides that, operation costs are estimated to 160,000 €/y and financing costs to 135% of the investment.

Yearly costs are then $6,000,000 \text{ €} \times 1.35 / 20 \text{ y} + 160,000 \text{ €/y} = 565,000 \text{ €/y}$.

With one cycle the price for stored heat is $565,000 \text{ €} / (1 \times 3,300 - 1,577) \text{ MWh} = 328 \text{ €/MWh}$.

With 10 cycles/y the price for stored heat is $565,000 \text{ €} / (10 \times 3,300 - 1,577) \text{ MWh} = 18 \text{ €/MWh}$.

Høje Taastrup stores heat from combined heat and power plants when heat is cheap and replace expensive heat from peak load boilers (mainly natural gas) and from CHP plants in periods with low electricity prices and is supposed to have up to 25 cycles/y corresponding to 7 €/MWh.

In this case 7 €/MWh is the price for heat if 25 cycles are reached and production costs are 0 €/MWh.

What to be aware of according to different heat sources that could be stored

Waste heat from **waste incineration** is often constant during the whole year. If the production capacity is lower than the summer load, PTES is not needed. Same if the production capacity is higher than the winter peak load. In between PTES can store the surplus production in the summer period and cover downtime periods and replace fuels in the winter period. The most optimal situation occurs if the production capacity is high enough to also charge the storage in mild periods during winter.

Waste heat from industries can have the same conditions as heat from waste incineration, but normally it is necessary to get knowledge about flow, forward and return temperatures, if possible, on an hourly basis to be able to make a correct economical calculation. Many industries do not have waste heat in nighttime or during the weekends, so here storage makes even more sense, as they will get more yearly cycles.

In Denmark **CHP plants and heat pumps** can use the electricity marked:

- As day ahead market (hourly based) where for instance heat pumps run in periods with the lowest electricity prices (and CHP plants run in periods with the highest electricity prices).
- As balancing market where for instance heat pumps offer up-regulation (by reducing electricity consumption) within 15 minutes.

Since heat demand must be covered also outside these periods and balancing sometimes has to last in longer periods, storage capacity is needed to maximize the income from the electricity market.

Electric boilers can offer frequency regulation within 30 seconds and will also need connection to storage capacity. Electric boilers often have high power capacity and therefore need high storage capacity for longer running periods. For instance, a 100 MW boiler will need nearly 3,000 m³ storage per hour at full load if the temperature difference between in- and outlet is 30°C and heat consumption is 0.

Heat from **deep geothermal drillings** will have the same constant capacity as heat from waste incineration, but often with lower temperatures. Also, **hydrogen production plants and other PtX plants** are expected to have a nearly constant capacity because of high investments and therefore many running hours.

When looking at heat sources for PTES the price of the heat source is of course important, but charging during winter, utilization of electricity market and replacement of expensive peak fuels can be needed to gain economically feasibility.

Heat planning

Mapping of resources for district heating is part of the heat planning process for municipalities. If there are relevant sources for long term storing of heat in or near the municipality, it is relevant to include PTES in future scenario calculations.

5.1 Case Dronninglund

Dronninglund District Heating is a consumer owned utility producing app. 40 GWh of heat per year. Every year there is a general assembly where major decisions are discussed. Dronninglund was the first Danish utility to install gas engines for CHP production (in 1989).

The general assemblance in autumn 2006 decided gradually to change to 100% renewable energy production without use of biomass, and the board therefore investigated the possibilities. Among these solar thermal and PTES was calculated and showed unchanged heat production prices with a solar fraction up to 50% provided 20% subsidies from the Danish state. Subsidies were granted first for pre-feasibility studies and later also for design and implementation.

Operation experiences, Dronninglund

The plant in Dronninglund is described in chapter 3. It has been in operation since spring 2014. Peak production from the solar collectors is 700 W/m² or app. 26 MW. Variable flow in the solar collectors makes it possible to decide the charging temperature in the PTES. It is normally 85°C. Heating up the PTES starts in February and in a normal summer the PTES is full mid August. In good summers, it can be necessary to cool the storage bottom running the solar thermal system in nights (heat blow off). The flow temperature in the DH grid is 70 – 75°C, return temperature around 40°C. The storage is discharged with the flow temperature until November. When the top temperature in the storage is lower than 70 – 75°C an absorption heat pump will increase the flow temperature and cool the bottom of the PTES. In February the temperature in most of the storage is app. 10°C. Monitoring results can be seen in [5]. The absorption HP has later been replaced by an electrical HP, which is also able to cool down ambient air (air source HP).

In the Heatstore project [10] PlanEnergi made TRNSYS calculations for Dronninglund and compared these with monitoring results. Three different PTES components (types) were tested against measurement data from 2017 and showed good overall agreement. The best agreement was found when using the component simulating an inverted truncated cone geometry (see Figure 12 and Figure 13).

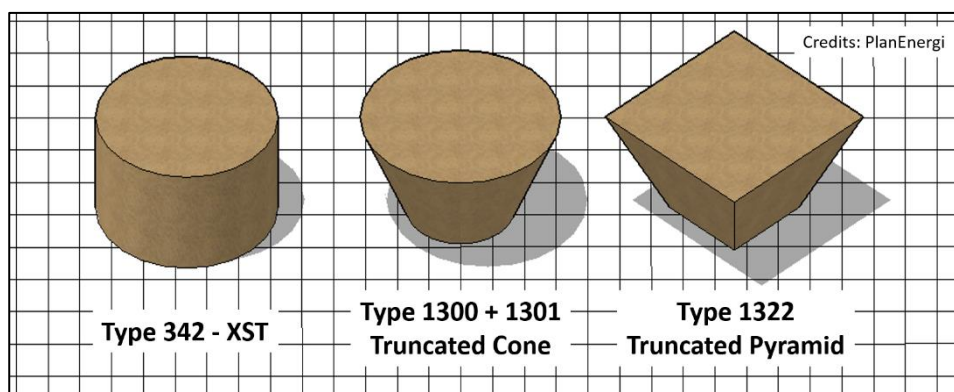


Figure 12: Geometry used for the three PTES components in TRNSYS: Type 342 (left), Type 1300 + Type 1301 (middle) and Type 1322 (right).

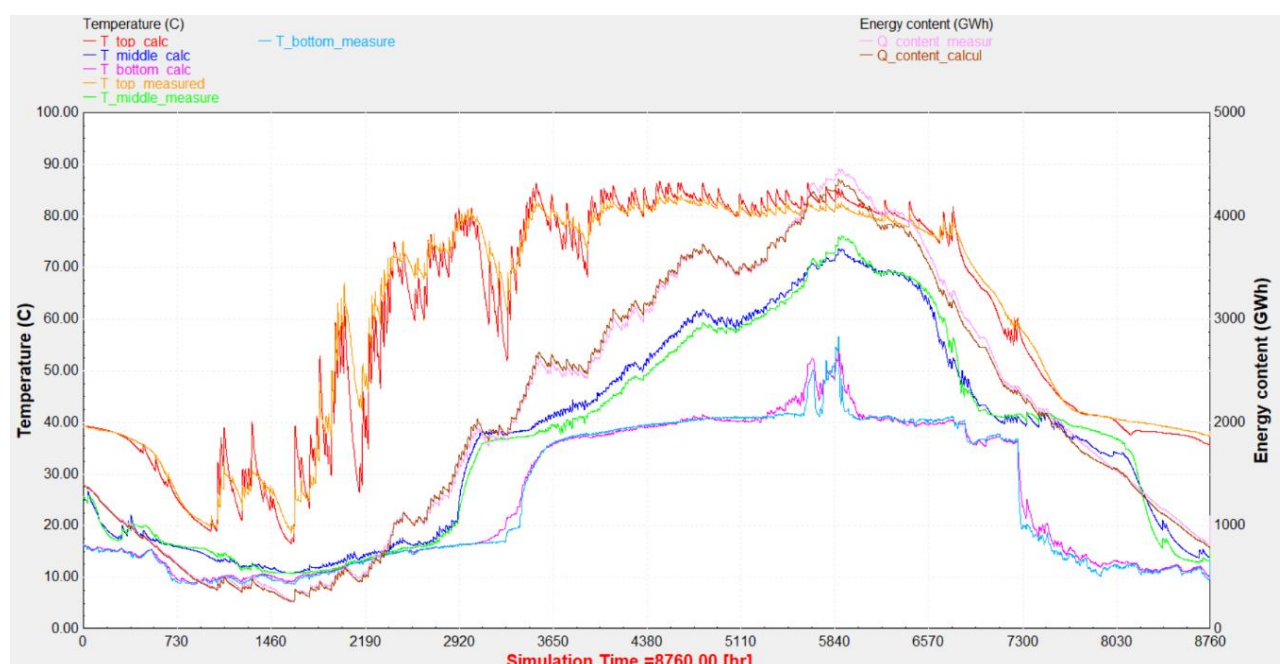


Figure 13: Diagram showing the good agreement between measurements and modelling in Dronninglund. Left axis: temperature distribution inside the PTES (top, middle and bottom temperatures) as modelled in TRNSYS (using Type 1300 + Type 1301, see red, blue and pink curves) and as measured (orange, green and light blue curves). Right axis: energy content evolution as modelled in TRNSYS (brown curve) and as measured (light pink curve). Measured data is from 2017.

Type 1322 is even more precise than Type 1300 + 1301, but calculation time can be very long. Thus Type 342 is normally used in pre-design stages and Type 1300 + 1301 and Type 1322 are used for detailed design.

In- and outlet capacity of heat exchangers is 27 MW, and the system can regulate from 0 to 27 MW within a few minutes.

The storage lid was changed three years ago because the insulation material in the old lid shrank because the insulation could not stand temperatures and moisture. The new lid is implemented by Aalborg CSP and of same type as the lid in Høje Taastrup.

5.2 Case Høje Taastrup

Scenario analyses in the “Heating plan greater Copenhagen” developed by the transmission companies CTR, HOFOR and VEKS in 2014 pointed out that if CO₂ neutrality in district heating in Copenhagen was to be obtained, large scale thermal storages would have environmental and economic benefits in an energy system with a huge fraction of electricity from wind power. The reason for this being the ability of thermal storages to store district heating when it is cheap to produce and hence optimize the total electricity and heating production system in Copenhagen.

Høje Taastrup Fjernvarme (HTF) is a consumer owned distribution company serving Høje Taastrup municipality with district heating, found a site and promised to implement a PTES in cooperation with VEKS. Calculations showed that a PTES of 70,000 m³ with in- and outlet capacity of 30 MW (maximum take-off from the distribution system in Høje Taastrup) and a storage capacity of 3,300 MWh could be economical feasible. Heat sources for the PTES are heat produced at seven CHP plants (three waste-to-energy facilities with a total of 400 MW_{heat} and four biomass CHP plants with a total of 2,050 MW_{heat}). 56% of the calculated income is from saved peak load (mainly natural gas) and 44% is from higher income to CHP plants.

The PTES was built in 2019 – 2022.

Operation experiences

The storage is charged when heat is cheap to produce and discharged when heat is expensive to produce. Change between charge and discharge is decided by Varmelast. Varmelast is a company owned by the three transmission companies in Copenhagen. It is established to optimize electricity and heat production in Copenhagen. Varmelast makes a 7-days optimization based on electricity prices and makes intraday plans for charging and discharging (and for running CHP plants). It is a challenge to plan for seven days and often conditions are changed (fall out, change in weather) so that the 7-days plan is overruled by the intraday plans.

In Høje Taastrup the charge and discharge capacity can be changed with only 0.2-0.5 MW/min or 1-2% of the in- and outlet capacity/min. because of regulation of the systems outside the storage. For the storage itself the charging and discharging can go from 0 to max within a few minutes.

Danish Technical University produce yearly monitoring reports. The report for 2024 is public [9]. Figure 14 shows weekly charged and discharged energy for 2024.

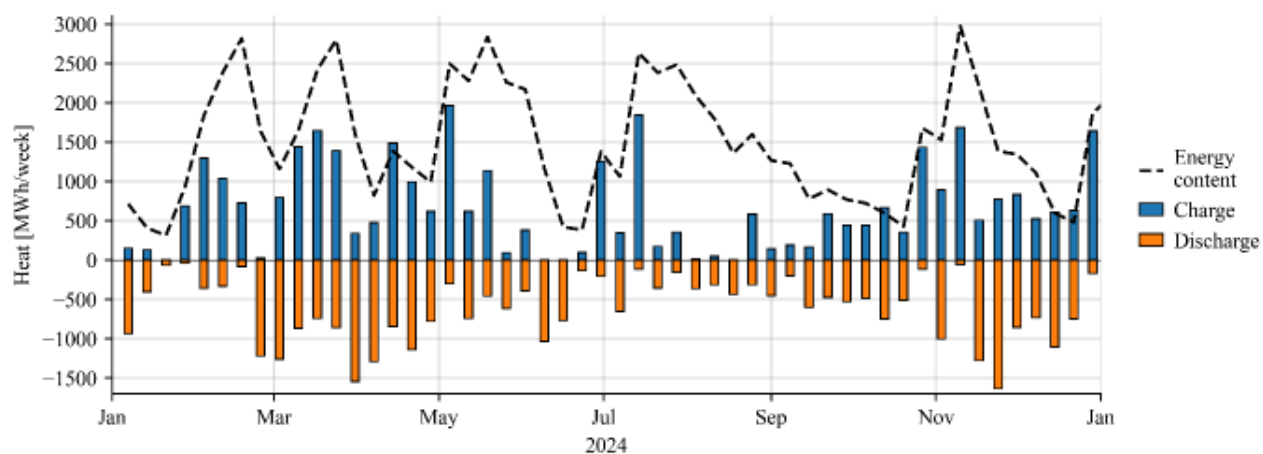


Figure 14: Weekly charged, discharged energy and energy content [9].

6. Screening of economically feasibility

Screening tools for system calculations

A thermal energy storage (TES) has no value in itself. The value of the TES comes from the interaction between the TES and the energy system the TES is connected to. To calculate the feasibility of a TES it is therefore necessary to perform a techno-economic simulation of the energy system with and without the TES. The difference between the operating costs for the two simulations can then be compared to the investment of the TES. A DH system consists of the DH heat load, the energy conversion units and energy storages. The recommended simulation period is one year with a timestep of one hour.

As software tools for techno-economic simulations of energy systems with TES, energyPRO, TRNSYS and Balmorel will be briefly described below.

energyPRO

energyPRO⁵ is a user-friendly software which is relatively easy to learn and use. It was originally designed to simulate DH systems with alternating electricity prices, but over the years it has been developed to simulate other systems as well. The simulations are based on energy (e.g. in MWh) and thermal power (e.g. in MW). A weak point of energyPRO is that the simulation cannot be based on temperature developments during the simulation, so all temperatures must be predefined, which works very well for many energy systems, but is not suited for energy systems where the performance of one unit depends on a temperature from another unit (e.g. solar thermal and long term TES, or a heat pump and TES).

TRNSYS

TRNSYS⁶ is a generic Transient System Simulation Tool, originally developed to simulate energy systems with solar thermal. The simulations are based on flows (e.g. in kg/h) and temperatures (e.g. in °C), from which energy and thermal power easily can be calculated. The software comes with a library of components (called types), and more types can be purchased. The user can also modify the types or develop own types, or build new components based on equations.

PlanEnergi⁷ has used TRNSYS to simulate many systems with PTES, e.g. Dronninglund and Marstal.

Balmorel

The Balmorel open source energy system model⁸ was released in 2001. It was developed with the purpose of getting an overview of the energy system – mainly with respect to electricity and district heating – in the light of the energy system liberalization trend in the European Union.

⁵ <https://www.emd-international.com/software/energypro>

⁶ <https://www.trnsys.com/>

⁷ <https://planenergi.eu/>

⁸ <https://www.man.dtu.dk/english/about-us/departments-organisation/divisions/climate-and-energy-policy-division/energy-economics-and-modelling/balmorel-model>

The modeling was done in GAMS (General Algebraic Modelling System) and coding was fairly general, allowing the model to be extended and applied with respect to energy system details as well as geography.

A description of the model may be found in “The Balmore open source energy system model”, Energy Strategy Reviews, Volume 20, April 2018, Pages 26-34.

EA Energy Analyses⁹ has made a Balmore model of the DH system in Greater Copenhagen, and this model has been used to simulate the operation and the savings of the PTES in Høje Taastrup.

Parametric studies and numerical optimization

When a simulation model has been developed, it can be used to perform parametric studies. In this way e.g. the sizes of the components can be varied to find the economical most feasible component sizes.

Figure 15 shows an example of a parametric study in TRNSYS, where the specific investment in a flat plate solar collector field is calculated as a function of the row distance and the panel slope. It can be seen that the higher the row distance the lower the specific investment, and that at a row distance of e.g. 4.5 m, the panel slope should be 25°–30°.

	3.0 m	3.5 m	4.0 m	4.5 m	5.0 m	5.5 m	6.0 m
10°	695	689	688	687	687	687	687
15°	688	673	668	667	666	666	666
20°	689	669	658	653	652	651	651
25°	696	670	656	647	644	643	642
30°	708	678	659	648	642	640	639
35°	724	690	668	654	646	643	641
40°	743	706	681	665	655	650	648
45°	765	726	698	680	668	661	658
50°	790	748	719	698	684	676	672
55°	823	776	743	720	705	696	691
60°	866	815	779	753	734	724	718

Figure 15: Specific investment in [€/MWh/y] as a function of row distance and panel slope in a flat plate solar collector field.

Figure 16 shows another example of a parametric study in TRNSYS, where the specific investment in a flat plate solar collector field combined with a PTES of 116,000 m³ and an absorption HP is calculated. Here the lowest specific investment is 647 €/MWh/y is obtained with a collector area of 27,500 m² and a HP capacity of 10 MW.

⁹ <https://www.ea-energianalyse.dk/en/>

	7300 m ²	10000 m ²	12500 m ²	15000 m ²	17500 m ²	20000 m ²	22500 m ²	25000 m ²	27500 m ²	30000 m ²	32500 m ²	35000 m ²	37500 m ²	40000 m ²	42500 m ²	45000 m ²	47500 m ²	50000 m ²
0 MW					1 298	1 195	1 160	1 147	1 141	1 135	1 130	1 127	1 128	1 130	1 132	1 136	1 141	1 148
2.5 MW	1 099	942	1 001	1 071	1 047	955	915	905	914	938	958	974	989	1 003	1 017	1 032	1 048	1 064
5 MW	1 083	895	800	742	723	755	739	733	736	744	764	788	812	838	861	883	904	921
7.5 MW	1 106	910	802	749	709	685	666	660	662	668	678	700	723	745	767	790	813	833
10 MW	1 129	926	815	761	719	694	669	651	647	649	657	675	698	720	741	762	785	806
12.5 MW	1 150	942	828	772	729	703	677	659	653	654	661	678	701	723	744	765	787	809
15 MW	1 169	957	840	783	738	711	685	666	659	660	667	684	707	729	750	771	793	815
17.5 MW	1 186	970	851	792	747	719	692	673	666	666	673	690	713	735	755	777	799	820
20 MW	1 202	982	861	801	754	726	699	679	671	672	679	695	718	740	761	782	804	825

Figure 16: Specific investment in [€/MWh/y] as a function of a flat plate solar collector aperture area and absorption HP capacity.

Parametric studies works well for varying only a few parameters at the same time (1 or 2, 3 becomes more complicated).

Numerical optimization, which is a very powerful concept, can be used to vary any number of parameters simultaneously. Numerical optimizations in TRNSYS can be performed by using the free general optimization tool GenOpt¹⁰.

As an example, 8 parameters were varied simultaneously when the BTES energy system in Brædstrup was optimized using GenOpt & TRNSYS. Figure 17 shows an example of the optimization progress where the heat price is reduced from a starting point at 61.87 €/MWh to an optimized value of 59.33 €/MWh.

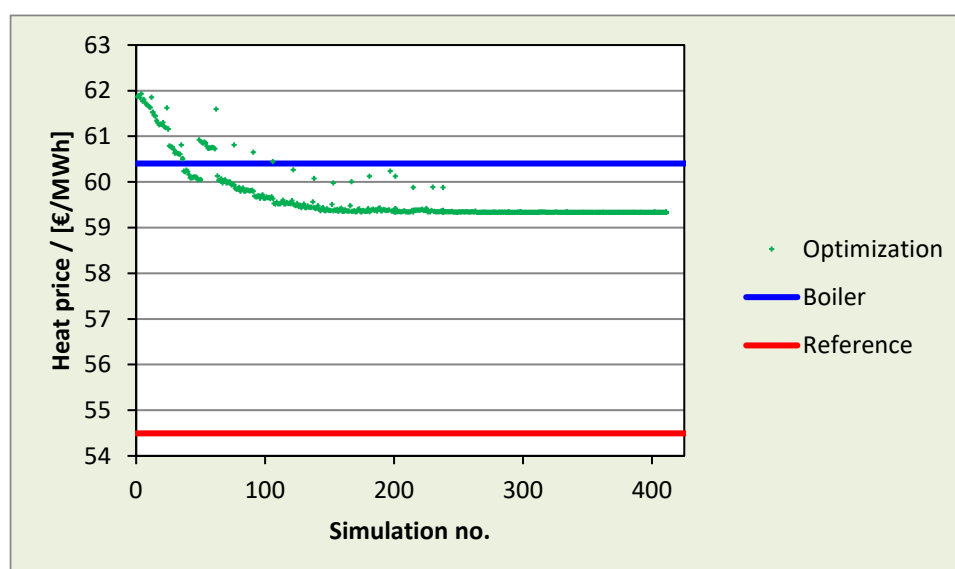


Figure 17: Example of an optimization progress in Brædstrup, DK [6].

In another example, the sizes of the solar thermal, the PTES and the HP were varied simultaneously when a planned energy system in Løgumkloster, DK, was optimized using GenOpt & TRNSYS. Figure 18 shows the results before and after the optimizations of 5 different scenarios. The optimizations reduces the heat prices by 5 to 12 €/MWh, while the solar fractions at the same time are increased from [35% – 43%] to [56% – 64%].

¹⁰ <https://simulationresearch.lbl.gov/projects/genopt>

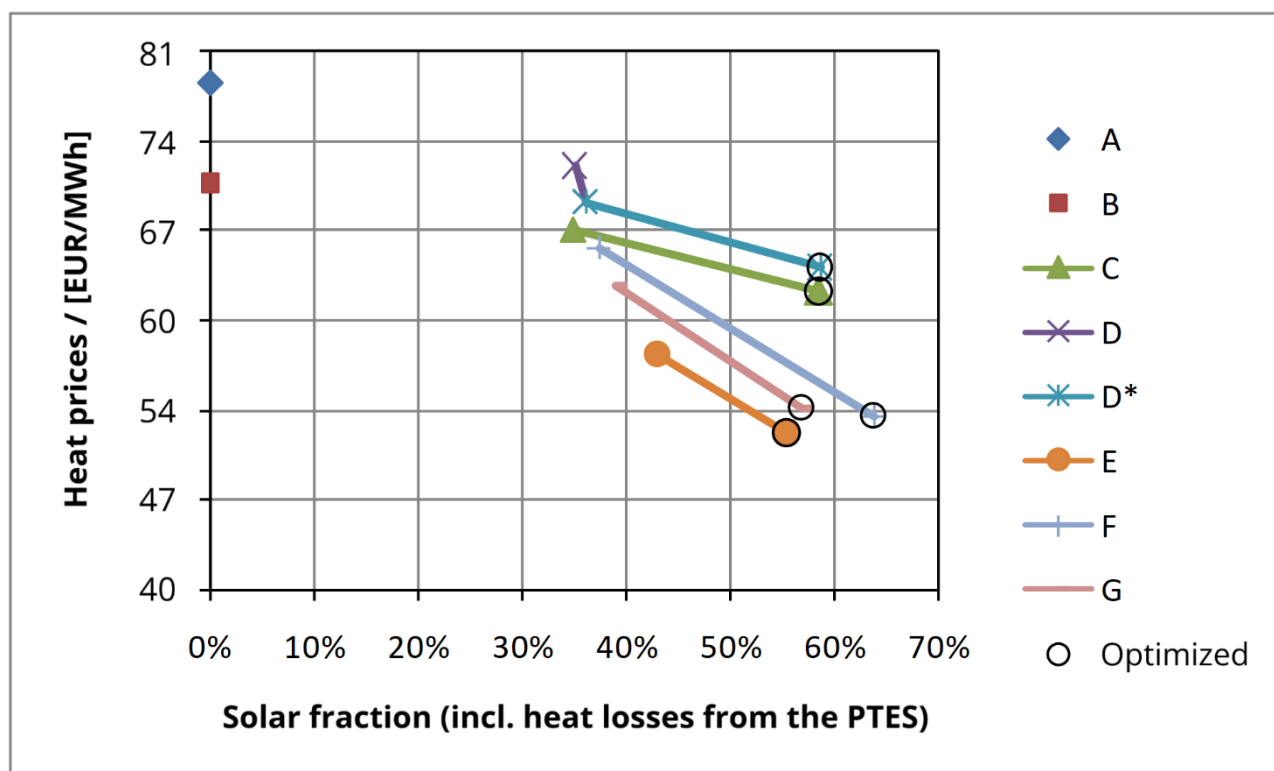


Figure 18: Optimization results from a planned energy system in Løgumkloster, DK.

Investment costs for TTES and PTES

The Danish Energy Agency publishes technology catalogues with the aim of creating a uniform, generally accepted, and up-to-date basis for energy planning activities. These include future forecasts, assessments of supply security and environmental impacts, climate change assessments, and technical and economic analyses, e.g. on the framework conditions for the development and use of certain technology classes. This includes, among other things, a catalog with data on energy storage technologies [7], which is regularly updated as technologies evolve, data changes significantly, or errors are found.

In order to enable comparative analyses between different technologies, it is essential that data is actually comparable. The information in the tables of the energy catalog refers to the state of development of the technology at the time of the final investment decision in the respective year. Among other things, the data for 2025, 2030, 2035, 2040, and 2050 were updated in the version published in February 2025 for LTES (Large Thermal Energy Storage). The financial data provided in euros (€) corresponds to real prices, deflated to the 2020 level, and does not include value added tax (VAT) or other taxes or subsidies (see Figure 19).

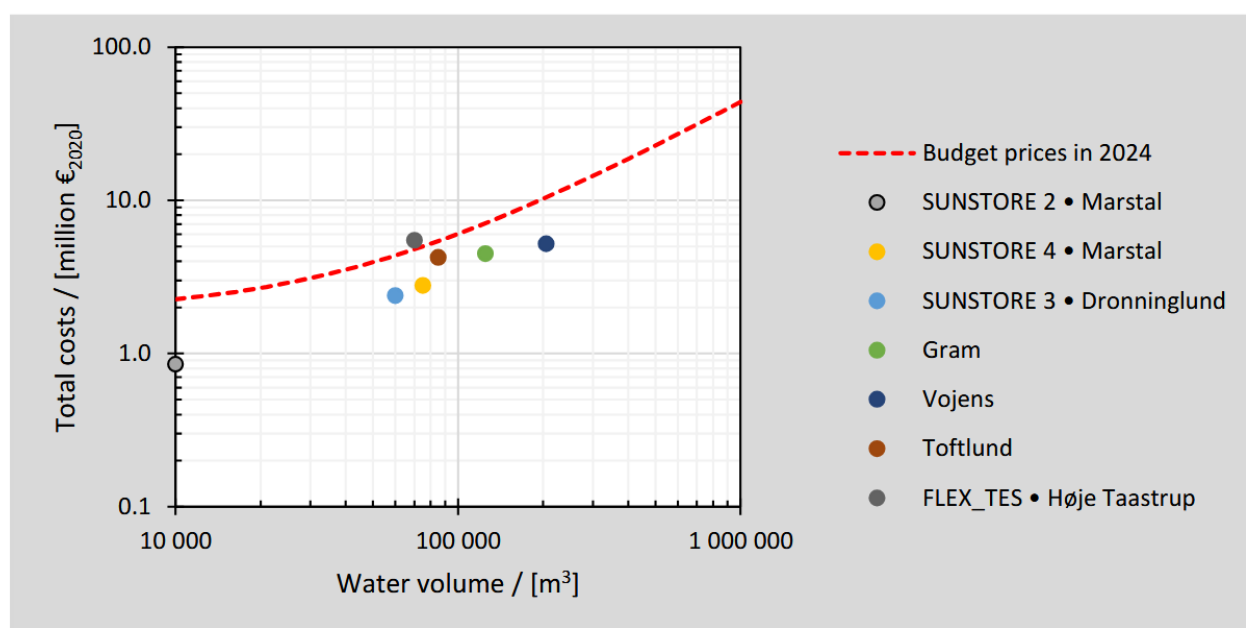


Figure 19: Project costs depending on volume (Danish Energy Agency, 2025).

Using the dashed red approximation function, project costs of approximately € 6 million for a 100,000 m³ storage facility and approximately € 2.2 million for a 10,000 m³ storage facility are shown.

Looking at the specific costs, i.e. the project costs allocated to PTES in relation to one cubic meter of water, the strong cost degression of PTES in the range of 10,000 – 100,000 m³ becomes apparent (see Figure 20). The points in the figure represent actual costs for PTES in Denmark. The red dotted line shows the budget prices for 2024 using the net price index for 2020.

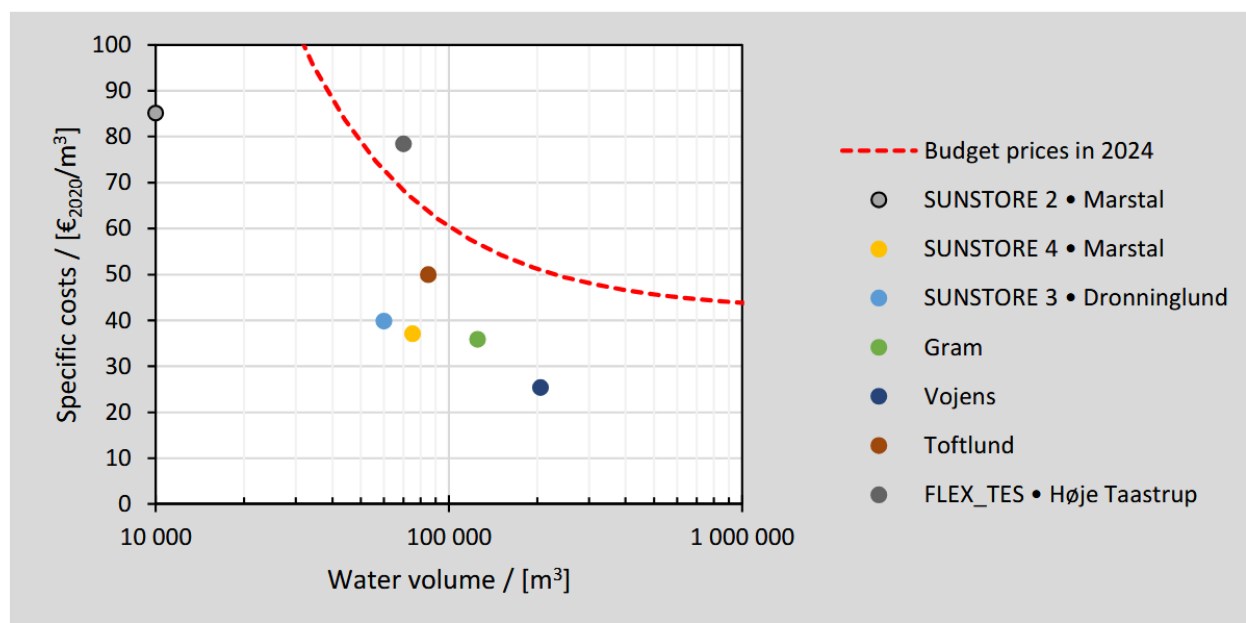


Figure 20: Specific costs depending on volume (Danish Energy Agency, 2025 [7]).

Costs shown refer to pre-coronavirus cost levels and are based primarily on empirical values from Denmark. Furthermore, the costs only take into account the costs of the storage facility itself, i.e. they do not include costs for plant technology and/or post heating.

For a cost calculation of a squared PTES with 100,000 m³ with inside and outside slopes of 1:2 placed on an even terrain and no interference with ground water 60 €/m³ can be derived from Figure 20 (pre-coronavirus cost levels!), but according to the latest Danish experiences unit costs from 72 to 78 €/m³ are realistic applicable CAPEX.

Such example design for 100,000 m³ would lead to a footprint area of approx. 23,100 m² as visualized in Figure 21.

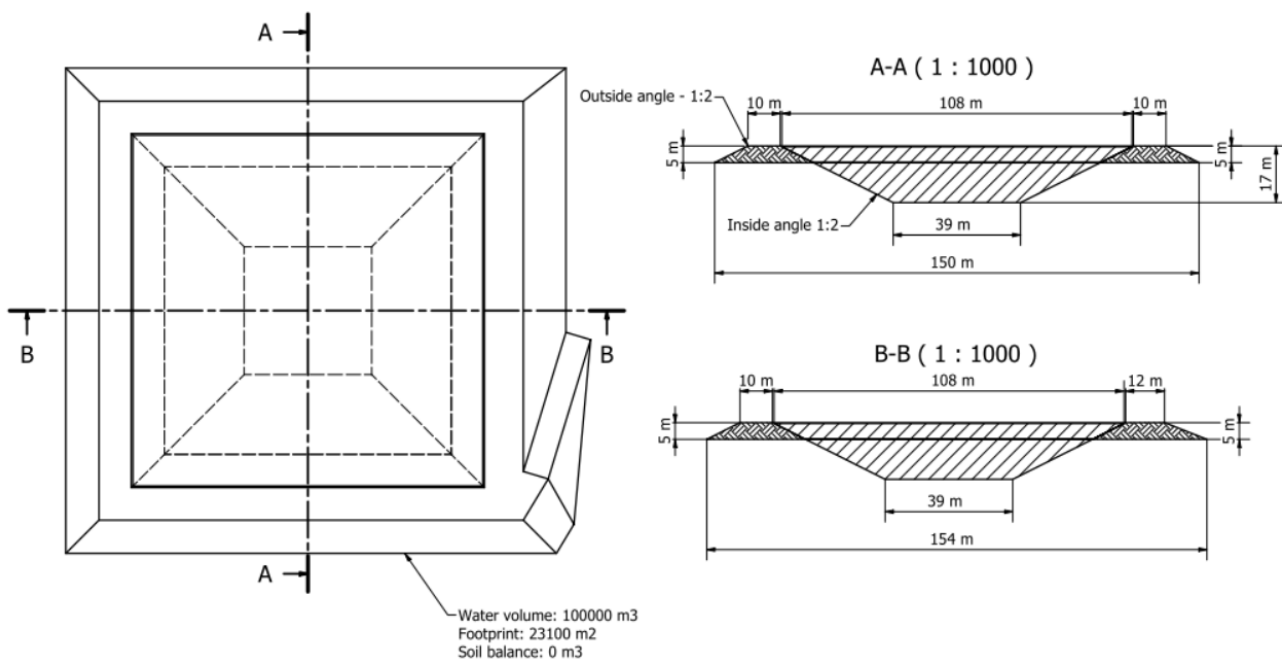


Figure 21: Visualization of a squared 100,000 m³ PTES in even terrain in favorable / Danish? ground conditions, note – no diffuser or piping is visualized.

In addition to this area demand approx. 2,400 m² of additional area will become required for a minimum of side installations, such as access and roads, a building for pumps and heat exchangers, some kind of solution to handle / drain rainwater, fences etc. In total a land space of ca. 26,000 m² can be seen as a realistic area demand in an optimal case in a case with a slope of 1:2. A land price of 4 €/m² would then increase the investment costs by 104,000 €, while a land price of 200 €/m² would increase the investment costs by 5,200,000 €. This will result in 73 – 79 €/m³ with 4 €/m² land and 124 – 130 €/m³ with 200 €/m² land, but still the price for a steeltank (TTES) of similar capacity would be 2-3 times higher than for a PTES with 200 €/m³.

The area needed for a PTES will be relatively smaller, the larger the PTES is. See Figure 22.

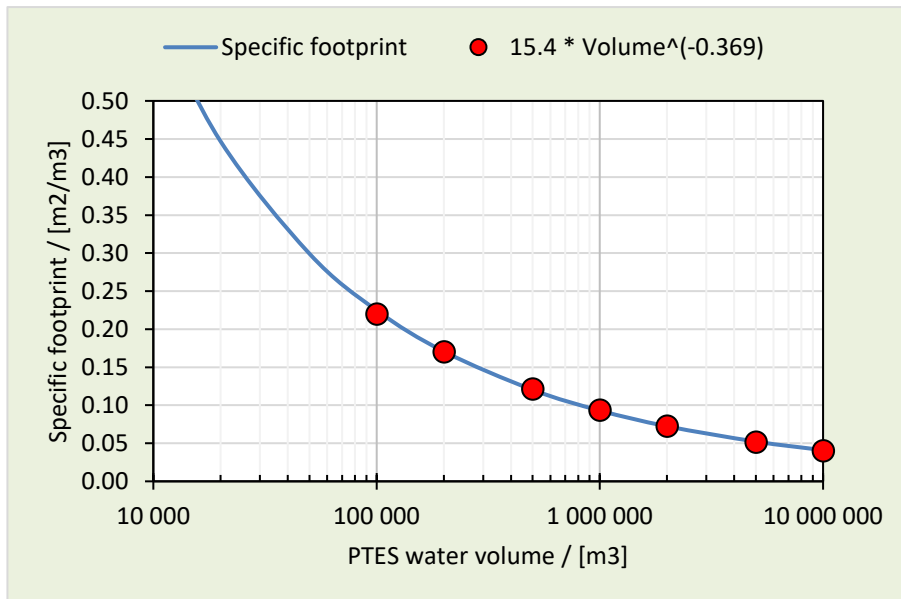


Figure 22: Specific footprint of a PTES as function of the water volume, based on the same geometrical assumptions as described above (without additional area needed for access road, technical building etc.). The error of the equation is less than 2% for storages > 100 000 m³.

TTES and/or PTES. Heat pump or no heat pump

Even though the construction of TTES and PTES are different, the operation of the two kinds of storage is quite similar.

The main construction difference is that DH water can be used directly in TTES but not in PTES. TTES can therefore be used without heat exchangers between the storage and the DH network, which is not the case for PTES. The reason for the latter is that oxygen diffuses into the water in the PTES, and oxygen is unwanted in the rest of the DH system. TTES can therefore also be used as pressurizers in the DH system, as well as handling thermal expansion of the water in the DH system. PTES, on the other hand, need to be separated from the DH system by heat exchangers. The water pressure on the PTES side of the heat exchangers is given by the atmospheric pressure on the water surface in the PTES. The pumps on the PTES side of the heat exchangers should therefore be placed so low under the water surface in the PTES that cavitation is avoided.

From a functional perspective, the most relevant parameters both TTES and PTES are the storage volume (in m³) and the charge and discharge capacity (in m³/h). Combined with a temperature difference (ΔT) the energy capacity (e.g. in MWh) and the charge and discharge capacity (e.g. in MW) can easily be calculated.

For PTES, the temperature drop over the PTES heat exchangers are also an important parameter, as the discharged heat will be colder than the charged heat.

Both TTES and PTES are charged by pumping heated water into the top of the storage while at the same time taking colder water out of the bottom of the storage. The storages are discharged by

pumping cold water into the bottom of the storages while at the same time taking warmer water out of the top of the storages.

Both types of storages rely on thermal stratification, which means that colder water stays below warmer water because the colder has a higher density than the warmer water.

At least two diffusers are needed (one at the top and one at the bottom of the storage), but more diffusers are also possible.

The main reason for choosing a PTES over a TTES is that PTES are cheaper than TTES for high capacities (e.g. > 100,000 m³).

In many situations, a system with a PTES will benefit from also adding a smaller TTES. The TTES could then handle short-term variations in both heat production and heat demand, as well as deliver a higher temperature to the DH network than the PTES.

TES combined with a heat pump

A TES could be combined with a heat pump (HP). The HP can be used for:

- Increasing the temperature from the storage in case the temperature in the top of the storage is lower than the demand.
- Decreasing the temperature in the bottom of the storage. This can be used to increase the energy capacity of storage as well as reducing the heat losses from the storage.

These two functions can also be combined with heat production units, which efficiencies depend on operating temperatures, e.g. solar thermal.

However, here we need to distinguish between the HP-COP¹¹ and the system-COP. The HP-COP can be used with external heat sources, e.g. ambient air, and is defined as:

$$COP_{HP} = \frac{(\text{Delivered heat})}{(\text{Consumed electricity})}$$

DH water on the other hand is considered as an internal heat source, so when a HP is cooling DH water, we need to use the system-COP instead. The system-COP is defined as the difference between the system with the HP in operation and the HP not in operation as:

$$COP_{System} = \frac{(\text{Delivered heat with the HP}) - (\text{Delivered heat without the HP})}{(\text{Consumed electricity with the HP}) - (\text{Consumed electricity without the HP})}$$

The HP-COP can easily be measured, but system-COP cannot be measured. Instead, it is necessary to simulate the energy system with and without the HP, and then use the equation above.

In case of no external heat sources, the system-COP of the HP will be 1.0 (as for an electric boiler), meaning that the only energy added to the system will be the electricity consumed by the HP.

¹¹ COP = Coefficient of Performance, and for a HP this is defined as the ratio between the delivered heat and the consumed electricity (either in MW/MW or in MWh/MWh).

6.1 Case Dronninglund

The energy system in Dronninglund, including the PTES, was calculated in TRNSYS.

3 scenarios were simulated:

1. A system without a HP.
2. A system including an electrical driven HP.
3. A system including an absorption HP.

Scenario # 1 was simulated to get a baseline to be compared with the other scenarios.

Scenario # 2 turned out to be not feasible, mainly because of too high electricity prices (including taxes).

Scenario # 3 was based on an absorption HP driven by hot water (160°C) produced by a biooil fueled boiler (See Figure 8).

Scenario # 3 turned out to be the most feasible scenario of the investigated solutions.

Design numbers for scenario # 3 can be seen in Figure 23.

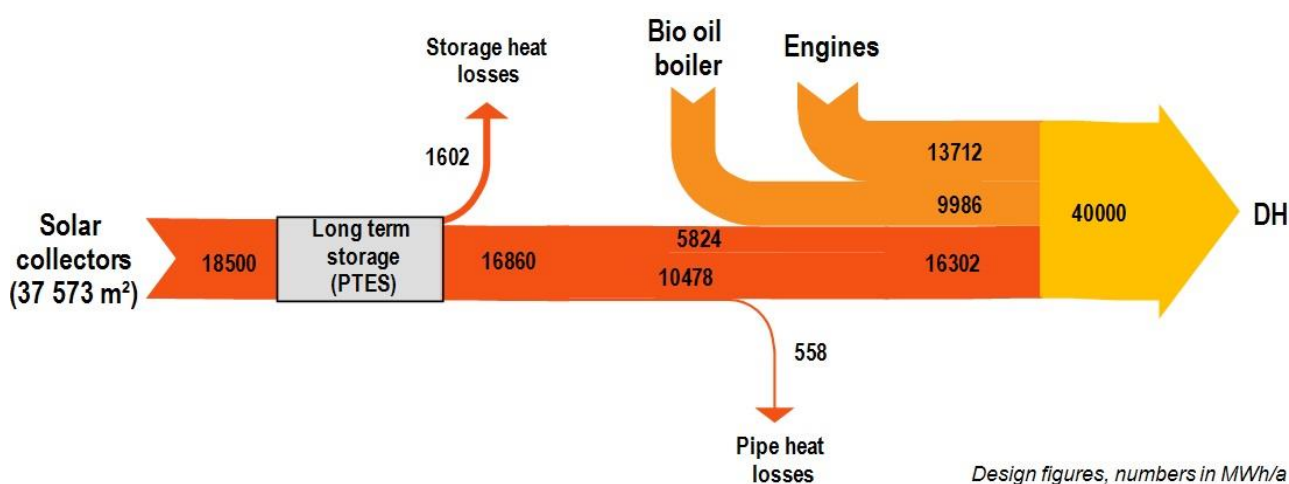


Figure 23: Sankey diagram with design figures for the SUNSTORE 3-system in Dronninglund [12].

6.2 Case Høje Taastrup

The PTES in Høje Taastrup is calculated in the Balmorel software. The calculation is for 2025 and shows the following changes in fuel consumption, when the PTES is operated compared to not operated:

- Natural gas -14,200 MWh
- Oil -1,700 MWh
- Straw -1,900 MWh
- Wood pellets 560 MWh
- Woodchips 10,300 MWh
- Waste 13,600 MWh

The total investment amount is 10.7 Mio. €. incl. subsidies. See calculation below:

Activity	Investment, Mio. €
Preparation expenses	0.55
Design and supervision	1.14
Storage and pumping station	6.05
Heat exchanger building	2.42
District heating pipeline	0.94
Electricity etc.	0.44
Water	0.51
Total	12.04
EUDP subsidies	-1.34
Total incl. subsidies	10.70

Income/year is calculated to 1.05 Mio € and operation costs are estimated to 0.16 Mio €/year. This results in a simple payback period of 12 years and an IRR of 7.5% calculated for 20 years. The lifetime for the PTES is expected to be more than 20 years.

7. How to find a site for PTES

The ideal PTES site is next to a feed-in point in the district heating system, and near to heat sources to be stored, PTES bottom above the ground water level in a not too hilly area with soil that can be reused for building embankments and:

- Without environmental restrictions such as Natura 2000 or drinking water area.
- Without infrastructural obstacles as reservation for future housing or roads.

In the first screening areas are searched near to feed-in points or a transmission pipe and outside existing or planned housing areas (to avoid high prices for land). GIS-maps from the municipal planning department can exclude protected nature and protected drinking water areas and areas with planning reservations.

In this first step the district heating utility in cooperation with the municipal planning department normally will be able to find alternative PTES sites.

In Denmark we have a database of drillings (Jupiter¹²) where ground water level and sometimes also soil conditions can be found for drillings already carried out, and that can be used to further qualify alternatives. A similar database can be found for each Federal State in Germany.

For the possible site next step is then to make 1-3 test drillings. During drillings soil samples are extracted and tested in laboratory to give information about:

- Ground water levels (secondary and primary).
- Excavation (feasibility and evaluation of soil).
- Possibility of re-use of excavated soil in embankments (soil balance).
- Slope stability of built-up embankments during implementation and operation.
- Ground water handling.

The site investigations will typically be gathered in a report describing each site, result of geotechnical investigations, possible size of storage, possible environmental obstacles, connection to district heating and electricity system and summarizing the costs to compare the alternatives.

7.1 Case Dronninglund

Dronninglund is a village with 3,700 inhabitants in the northern part of Jutland. It is surrounded by farmland. A site for PTES should also include a site for what was estimated to be 40,000 m² of solar thermal, so altogether the site was estimated to 16 hectares.

In cooperation with the municipal planning department suitable areas were found southeast of the village, but geotechnical investigations showed unfortunately that the ground water level was only 1.8 m below the surface, and that the soil conditions were sand with silt, which was difficult to compress and thus to reuse the excavated material to embankments.

The utility got an estimate of the extra costs of app. 400,000 € for ground water lowering. Taken into account also the risk according to soil conditions, they decided to look for alternative locations and

¹² <https://www.geus.dk/produkter-ydelser-og-faciliteter/data-og-kort/national-boringsdatabase-jupiter>

found a new site north of the village. Unfortunately, geotechnical investigations showed even worse soil conditions and extra costs of app. 600,000 €. Again, the utility decided to give up the location and look for possibilities with larger distances to the feed-in points.

West of the village is an area with an abandoned gravel pit. See A and B in Figure 24.

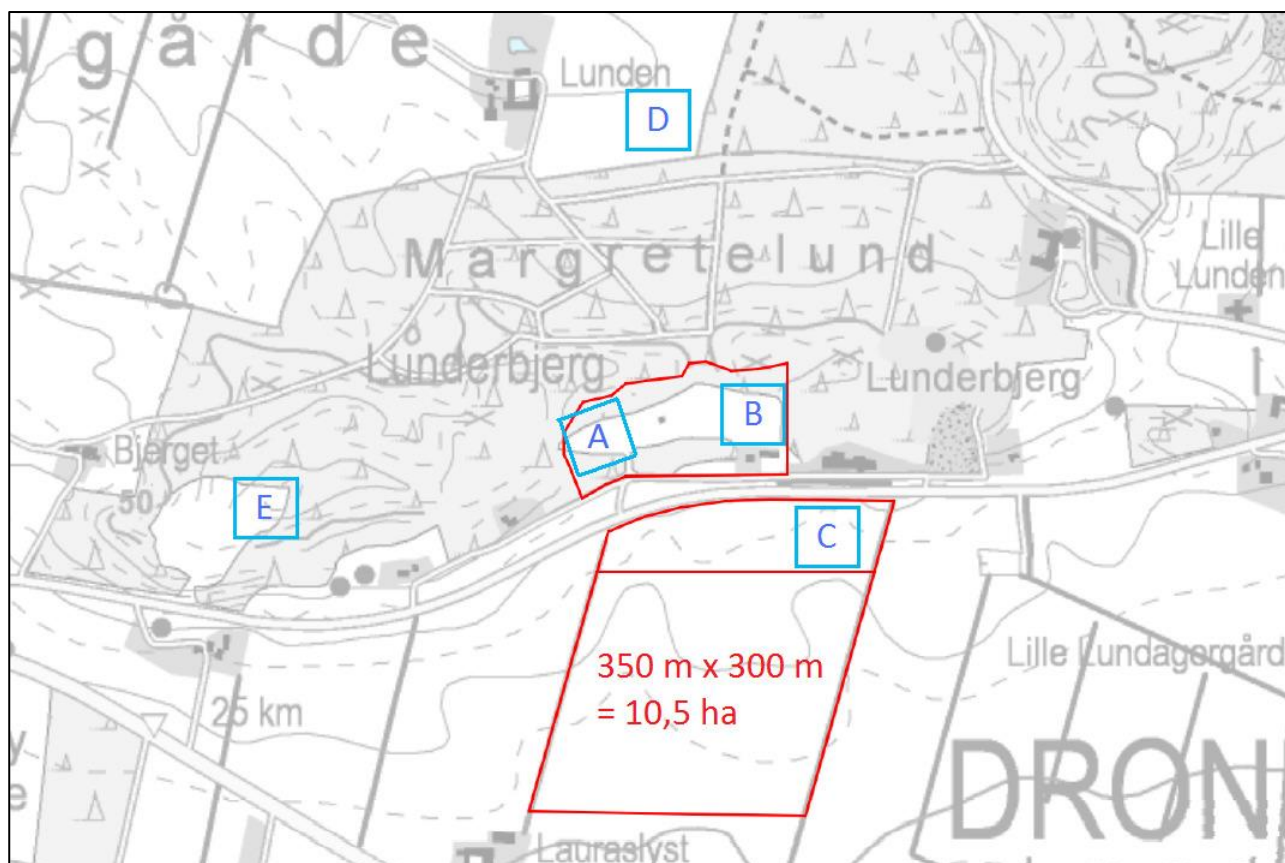


Figure 24: Potential new sites for PTES. Source: Geo.

A geotechnical report (No. 4!) evaluated the sites and site A and B in the abandoned gravel pit was estimated as promising solutions where excavated material (sand) can be utilized as embankments, and the distance between the storage bottom and the ground water level would be more than three meters.

The utility did not dare to buy the gravel pit and the area for solar collectors, but made negotiations where the owners offered to sell the areas to a certain price within a time limit long enough to get the authorities approval and for the utility to take the final implementation decision.

One of the landowners did not want to make this kind of negotiation, and the municipality accepted therefore that the land could be expropriated. This is possible if there is an approved local plan and alternative sites are not possible to find.

7.2 Case Høje Taastrup

Høje Taastrup is a suburb to Copenhagen with 59,000 inhabitants. The local district heating utility is consumer owned and produces 15% of heat themselves primarily by use of heat pumps (using ground water, excess heat from data centers and hot side of district cooling heat pumps) as heat sources.

The district heating utility is one of the largest consumer owned utilities in Denmark and has been frontrunner with new DH solutions.

As mentioned earlier, the heating plan for greater Copenhagen from 2014 pointed out that if CO₂ neutrality in district heating in Copenhagen was to be obtained, large scale thermal storages would have environmental and economical benefits. Sites in Copenhagen are expensive, so the best option would be to find a site near the transmission system (the storage should serve seven CHP plants in Copenhagen) and on farmland which was not included in plans for the city. HTF found such an area north of the highway from Copenhagen to Roskilde. See Figure 25.

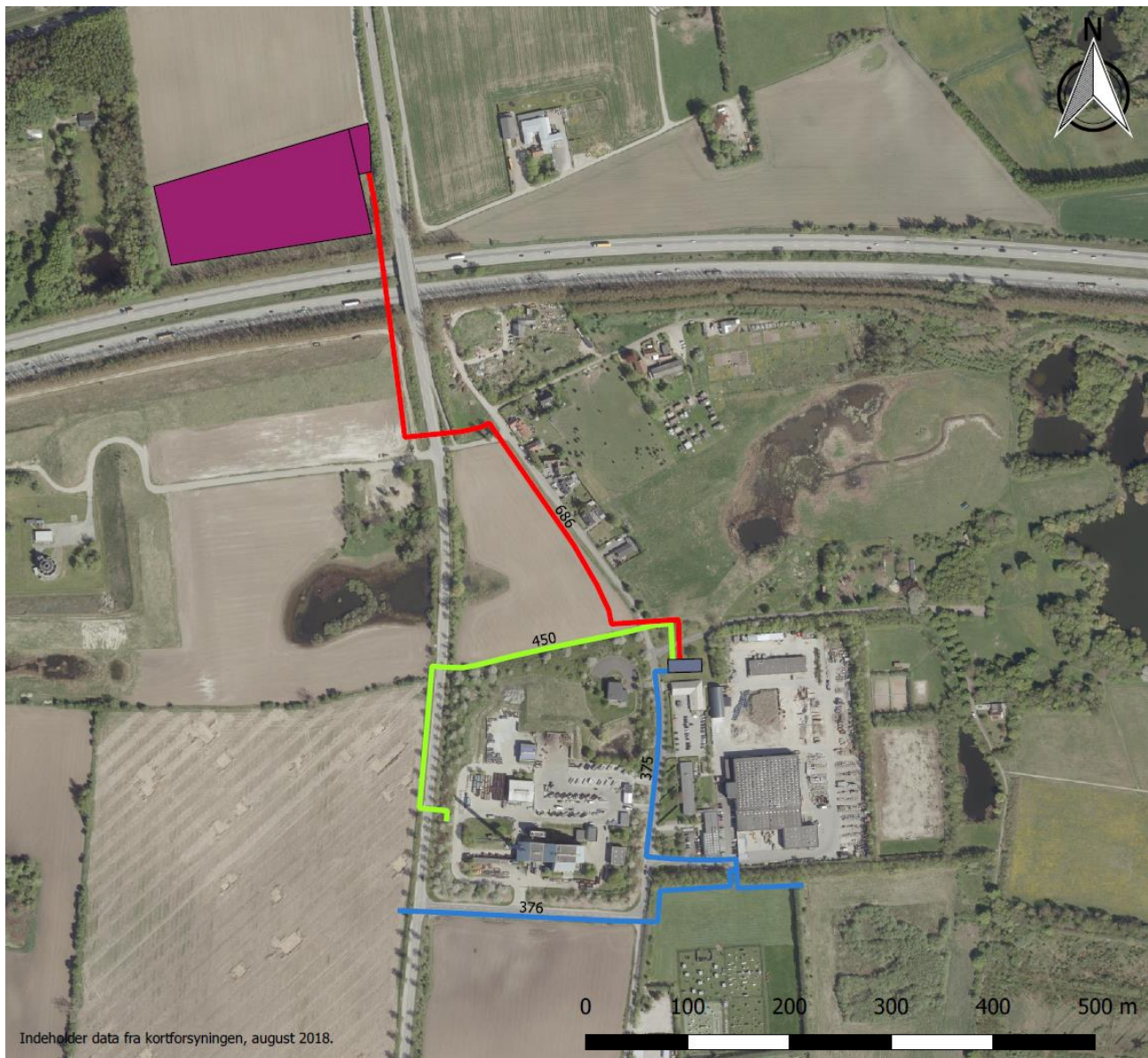


Figure 25: Map of the PTES site in Høje Taastrup with distances in [m]. Purple: PTES and pump station. Red: New pipe line between PTES and heat exchanger building. Green: New transmission pipes. Blue: New distribution pipes.

HTF required geotechnical investigations of the site. Geo made 15 drillings between 1 and 17 meters deep, and estimated that the area was suitable for a PTES since the ground water level was below 17 meters from surface and estimated that soil was mainly clay. Only to get rid of rainwater might be a problem because of tight underground.

8. Authorities' permissions

It is important from the beginning of a PTES project to be in close contact with the permitting authorities because PTES permission normally is a new topic for them and thus information and close cooperation is needed.

The most important permission in DK is the planning permission. Normally a Local Plan is elaborated according to Law of Planning. In the local plan the new energy plant is visualized and all consequences for landscape and environment are described. A public phase of 8 weeks is part of the process.

As part of the local plan a screening of environmental consequences must be elaborated. Screening of the environmental consequences has in a summarized way to describe changes compared to the present situation according to:

- Landscape (visualization of PTES is needed).
- Biodiversity (protected flora and fauna).
- Climatic conditions (CO₂ emissions and savings).
- Ground water (heating up and consequences for drinking water).
- Surface water and wastewater handling.
- Human health (noise, vibrations...).
- Cultural heritage (buildings, archaeology).
- Risk of accidents (dam breach, overflow).
- Traffic impact.

Both in the implementation phase and in the operation phase.

If the environmental impact is estimated as significant an Environmental Impact Assessment (EIA) report is needed. Significant impact can for instance occur if considerable ground water lowering is needed, because it can affect protected flora and fauna (and buildings) in the surroundings.

After the planning acceptance other permissions (building permission etc.) are needed.

For authorities permissions in Germany presentations from the Treasure project [13] will be available in deliverable D2.2 in the beginning of 2026.

8.1 Case Dronninglund

In Dronninglund the municipality answered that screening of environmental consequences did not show significant impact on the environment and thus an EIA report was not needed.

Neighbors south of the solar plant were against the project and appealed the decision.

In the screening report it was written that ground water might be used filling the storage and consequences of that were not described. The board of appeal therefore decided to discard the screening and ordered an EIA report to be elaborated. Some of the most important topics in the local plan/EIA report were:

- It is normally not allowed to have buildings within 300 meters from a forest, but since the buildings will not be visible the municipality granted an exception. See Figure 26.



Figure 26: Picture of solar field and PTES in Dronninglund after implementation (aerial view from south).

- Plants must be placed at the storage banks to integrate the storage in the landscape. See Figure 27.



Figure 27: Visualization of storage embankments with (bottom) and without (top) plants.

- It is normally not allowed to have buildings within 100 meters from barrow mounds, but since there will be no changes in the insight to the barrow mounds and no changes in insight from the barrow mounds the municipality granted an exception. See Figure 28.



Figure 28: Illustration of distance from barrow mounds (the purple circles) in Dronninglund.

- A calculation of the expected development in ground water temperature and a drilling where ground water temperature south of the storage can be monitored was required to be sure that drinking water temperatures will not exceed 20°C.

The EIA report and the local plan was accepted by the municipality, and the project implementation could start in spring 2013.

8.2 Case Høje Taastrup



Figure 29: Visualization of the PTES in Høje Taastrup (grey color) in the screening report (view from northeast).

In Høje Taastrup the municipality answered that the screening of environmental consequences did not show significant impact on the environment. The reasons were:

- The area is not protected.
- There is no protected fauna (farm area).
- No historical or cultural landscape.
- No influence on ground water since the storage water will be district heating water.
- No significant change in traffic.
- No people affected.
- The area is not environmentally vulnerable.

9. Design and tender

Geotechnical design is carried out according to EN 1997 Eurocode 7: Geotechnical design. It means that the geotechnical investigations carried out under Chapter 7 (How to find a site for PTES) will be further detailed **and a data report and design report must be elaborated and be part of the documents prepared by the utility before design and tendering**, because detailed design of the storage geometry requires knowledge of soil conditions and groundwater conditions.

Design and tendering of PTES has in Denmark until now been prepared for a tender on the basis of functional requirements (functional specifications). It means that suppliers must take the responsibility for meeting the functional requirements as a total contractor and include all costs in the quotation unless the quantity of the service is changed. The project is fully described in the tender documents, incl. drawings of all important details and diagrams with proposed dimensions and components. The reasons for functional tendering are to give contractors freedom to use own solutions still fulfilling the functional requirements. This can be an advantage at least in a stage where the technology is still developing.

Tools for optimization of storage and system

Tools for optimization of storage and system (and other components) are described in chapter 6.

These tools have an important role in the early stages of the project, but they can also play a significant role in detailed design which is needed in the tendering process. A PI diagram shows how the components are connected to each other, and if the simulation model is based on the PI diagram it can be used to dimension the pipes and other components. This requires that the model is based on flow and temperatures, like in TRNSYS. The TRNSYS model in Dronninglund was used in this way.

Important issues in the design phase

In the design phase it must be decided how the project will be divided in construction works. A single construction contract for the total project is of course convenient for the owner, but since only a few suppliers are able to handle everything, subcontracting will be needed and make the project more expensive. If the construction works for instance are divided into:

- Pipe work (incl. in- and outlet system).
- Soil excavation and embankments (incl. concrete work).
- Membrane work.
- Lid.

more suppliers can give their bids without subcontracting. The negative side of this is that interfaces between contractors must be described precisely by the owner.

For each of the construction works demands are specified.

Vulnerable components and details

Some components and details in PTES are vulnerable. Primarily because of the high temperatures and the corrosion risk.

Membranes

As water is used as the energy storage medium, polymer membranes are used as sealing barrier. In other sectors such as mining or landfills these materials are commonly used – often as HDPE (high density polyethylene). The storage of liquids at high temperatures is associated with increased requirements due to the faster aging process of materials caused by elevated temperatures of the storage water. For this reason, advanced material formulations for high-temperature resistance are applied in a PTES sealing.

Polyethylene of raised temperature resistance (PE-RT) liners

Five different HDPE liners have been tested by the Danish Technological Institute (DTI) in the period 2000-2018, of which the younger tests have been undergone with PE-RT material, a further development of HDPE. The results have been technical lifetimes of up to 6 years at constant 90°C. A PE-RT liner has also been tested by RISE (Swedish accredited testing institution), where the result is a 25-year lifetime. The test conditions are different to DTI, so the supplier of this liner estimates that the lifetime of the liner is at least 12 years under the conditions in Høje Taastrup (90°C constantly). Polymer liners have the advantage that they are available in wide rolls (5–7.5 m) and are easy to weld. Moreover, the price is low. Polyethylen liners have therefore been used in Danish pit thermal energy storages with seasonal operation profile (PTES facilities in Marstal, Dronninglund, Gram, Vojens and Toftlund).

High-temperature-resistant polypropylene (PP-HTR) liners

The Institute of Polymeric Materials and Testing, University of Linz, Austria, developed a PP (polypropylene) liner with superior ability to withstand high surrounding temperatures (PP-HTR). The reason for working with PP rather than HDPE is that PP degrades more slowly in water than PE-RT. The development process involves lifetime assessment based on the extrapolation of aging data from elevated to service-relevant temperatures, and from 100 µm specimens to 2 mm thick liners [11]. Since polymers degrade faster the thinner they are, results can be obtained relatively quickly. Many tests are performed simultaneously. Figure 30 shows one of the test ovens.



Figure 30: Test oven at the University of Linz.

The test results show that the service life of PP-HTR is, with approx. 30 years at permanent 95°C, significantly longer than those of PE-RT with 5 years in comparison (see Dresden case in [11]).

Suitability and Safety in the Installation Phase

HDPE and PP liners are weldable. Machine welds are tested with air pressure (double seam) and extrusion welds with vacuum testing. Subsequent testing of the sealed area can be done with an arc test (see Figure 32).

There is good experience with the tightness of established liners.

In Marstal, a welding defect of the HDPE liner was repaired under water at a later stage, but Marstal was not arc tested. In Høje Taastrup Arc-Testing has been carried out leading to small repairs before water filling was started. In other storages, no leaks have been found in the bottom and sides during operation. HDPE and PP are installed in 2.5 mm thickness with a roll width of, for example, 7.50 m. Sharp stones must be removed, and a protective layer between the soil and the liner, a geotextile or geocomposite is used. Installation should follow international standards and guidelines, such as German DVS standard.

In comparison to polyethylene, for a polypropylene liner it must be taken into account that this material is more prone to low temperatures (it becomes brittle around the freezing point of water), which may require additional efforts during the implementation.

Penetrations

Penetrations are points in the sealed surface where the sealing must be penetrated on the slopes, in the bottom, or in the floating liner of the insulating cover (e.g., for pipes, connections, etc.). Most of

these locations are normally made of polymeric material as well and it is recommended to use the same material formulation for the sealing liner material and the penetration material. High care must be taken for on-site sealing works and it is **not** recommended to use copper wire in combination with extrusion seams. Any site tests for seam tightness of seams facilitated on site shall be carried out as vacuum tests. In addition, penetration parts should be prefabricated off-site whenever possible to reduce the sealing works on site to a minimum.

Insulation materials

The purpose of the insulation materials is to reduce heat losses from the floating PTES lid.

So far it has not been found feasible to install insulation at the sides and/or the bottom of the PTES. One of the reasons for this is that the soil itself acts as insulation, with a moderate thermal conductivity ($0.25 - 2.20 \text{ W/m}\cdot\text{K}$) combined with a large thickness (in the order of 10 m). However, insulation of the transition zone between the lid and the top of the PTES can be considered.

The ideal insulation material for the lid should be cheap, not too heavy and have a long lifetime (not less than 20 years) under the expected working conditions, e.g. high temperatures (up to 90°C) and high humidity. Also, the insulation must be able to withstand liquid water (cold and warm), e.g. during the installation, or in the case of leakages. The lid should be constructed in a way that makes it possible to dry out the insulation if it becomes wet.

The design of the lid should be done in a way that minimizes cold bridges, e.g. between insulation mats. When using granulated insulation materials in the lid (e.g. expanded clay nuts) it is very important to implement a design that avoids thermal convection, because the thermal gradient is in the opposite direction of gravity. Thermal convection has been observed in the lid in Gram, where the measured heat loss through the lid in 2018-19 was 5.3 times higher than the design value. Afterwards, the insulation of the lid in Gram was improved significantly.

In the newest lid construction in Danish PTES projects are used crosslinked PE mats in combination with XPS plates as insulation materials.

Heat exchangers and pumps

Water can be pumped into the PTES, but the pumps cannot suck water out of the storage. On the suction side of the PTES pumps the water must “flow by itself”, i.e. the flow from inside the PTES to the suction side of the PTES pumps rely on the atmospheric pressure and the water column from the water surface to the suction side of the PTES pumps. To avoid cavitation the suction side of the PTES pumps must therefore be located at an adequate low point, which fulfills the NPSH requirement of the pumps. Worst case is with the highest water temperature.

The most important design parameter for the heat exchangers is the temperature drop from DH water to PTES water and back again. Fouling should be avoided by the water quality on both sides of the heat exchangers.

Water quality

Raw water can be treated by removing unwanted substances, and/or by adding other substances.

The water for a PTES should always be softened, i.e. calcium should be removed to avoid calcium deposits in the heat exchangers. The water should also be treated to avoid bio film in the heat exchangers.

All other treatment of the water is done to ensure a long lifetime of the materials in contact with the water. The main materials in contact with the water are the liners (for water tightening) and steel (for the inlet and outlet system). The liner materials are normally very chemical resistant, so no additional water treatment is necessary here.

On the other hand, steel is prone to corrosion. Black steel can be used with high pH value (by adding NaOH) and a low oxygen content, but as oxygen will diffuse through the liners black steel is not the best choice. In order to use stainless steel (e.g. 304 and 316), all salts must be removed (using RO).

Development is being made to find corrosion-free materials (e.g. PP) for the inlet and outlet system. The main motivation for this is that the water treatment can be quite expensive (5–10 €/m³).

The PTES water should also be as environmentally friendly as possible to minimize the environmental impact during construction, operation and eol. Often unwanted substances should be avoided in the ground water.

If the owner is a public utility or a utility providing public services (as district heating) the Directive 2014/25/EU of the European Parliament on procurement by entities operating in the water, energy, transport and postal service sectors must be followed.

PTES is a new technology for many suppliers. This can mean very low prices and very high prices if the supplier is unexperienced. Therefore, prequalification of suppliers is needed and also it is preferable that quality has a higher weight than price in the evaluation.

If the tender is based on functional requirements, the supplier will be responsible for the final design, but still the owner needs to follow the project and to be informed about solutions. Therefore, when contracts are made, a time schedule sharing a.o. when vulnerable parts will be solved, and when final design and drawings are sent from the supplier to the owner must be carefully discussed before signing.

9.1 Case Dronninglund

In Dronninglund the utility bought the membranes and the insulation materials. The enterprises were:

- a) Soil excavation.
- b) In- and outlet in stainless steel, internal pipes and all components (heat exchangers, pumps, valves, absorption heat pump and control system).
- c) Membrane work and lid implementation.
- d) Technical building.
- e) Transmission pipe.
- f) Solar thermal plant.
- g) Detailed geotechnical investigations.

Enterprises b, c, d and f were defined by functional requirements.

9.2 Case Høje Taastrup

Also in Høje Taastrup the owner had the intention to buy the membranes and the insulation materials, but during the design process it went obvious that to use the same type of HDPE membrane as used in Dronninglund might not be able to stand 90°C in 20 years. Instead, the owner decided to use a new developed PP membrane delivered by AGRU from Austria and mounted by G-quadrat from Germany. This membrane was not possible to buy directly from the manufacturer.

The lid was delivered by Aalborg CSP as a total contractor, including insulation material so also insulation material was not bought by the owner. This means higher prices but also more simple situations if guarantees must be activated. The enterprises in Høje Taastrup were:

- Soil excavation including in- and outlet system and concrete work.
- Membrane work (bottom, sides and floating membrane including tightening at penetrations).
- Lid materials and lid construction.

All defined by functional requirements. Additional suppliers for enterprises outside the storage (pipes etc. in pumping building, pipes etc. in heat exchanger building, connection pipes) were found after detailed design from the owners consultant.

10. Implementation and supervision

Total contractors must have their own supervision during implementation, but the owner and his consultant(s) have a coordinating role and are normally responsible for arrangement of construction meetings for instance every two weeks and have to be present at the building site. Also, the owner is normally security responsible for the building site.

Excavation is the first part of the project. It is a good idea to hire a land surveyor to check that the geometry is as promised and especially that the embankments end in the same elevation.

Compression in banks must be controlled by a geotechnical expert, and if groundwater has to be handled by the supplier the geotechnical expert must supervise that this is done in a proper way.

Heavy rain can cause huge problems in the excavation phase. Especially in clay soil.



Figure 31: The PTES in Marstal after a cloudburst.

During excavation pipes for the in- and outlet system are mounted. When excavation is finalized, stones have to be removed from the surface not to harm the tightening membranes. The membrane supplier must accept the quality of the surface.

Next step is the **membrane implementation**

Polymer geomembranes (liners) are the chosen essential sealing component for the storage medium water in a PTES, and must therefore not only be leak-proof, but also resistant to aging at high temperatures. The high-temperature-resistant polymer lining is supported by a protective layer (a geotextile or geocomposite) facing the subgrade surface. As these geomembranes are factory-produced and tested building materials it lays within the responsibility of the on-site installation to transfer the manufactured material properties to the final application as best as possible.

The installation, welding and testing procedures of the high temperature geomembranes shall take place in compliance with technical criteria according to German DVS standards, particularly DVS 2225 and 2226, which is usually required also for lining works in other sectors, such as landfill. It is also recommended that a supervision / quality control is carried out monitoring the sealing work for the project owner.

Care must be taken with regard to temperature-related expansion/contraction of the lining material. Sun/shade on the surface of the lining is a common situation on a construction site, which is handled by experienced personnel in landfill construction, for example. In the case of membranes for PTES, it should be added that material formulations for temperature resistance make the liner material slightly stiffer. Once the bottom and sides have been sealed and water filling starts, various stresses begin to take effect. The surface of the liner that is not covered by water is subject to atmospheric temperatures (day/night) – which shall be considered especially as the filling phases is normally during winter months. A steadily rising water column in the PTES exerts pressure on the liner, that eventually experiences contraction stresses due to low surface temperatures from the atmosphere. To handle this effect occurring later in construction time, a stress free installation of the sealing system beforehand shall be aimed for. This involves planning of the panel direction, seam locations and the time of carrying out seams at critical locations.

After finishing the sealing and before water filling is started it is recommended to carry out an additional liner integrity check. This way it is possible to repair potential damage from the installation period beforehand. This is a relatively simple task that can be done in a few days (depending on the area), but increases the level of security in relation to overall tightness.

Figure 32 shows the principle of electrical leak detection for liner integrity of exposed geomembrane surfaces using the arc test method.

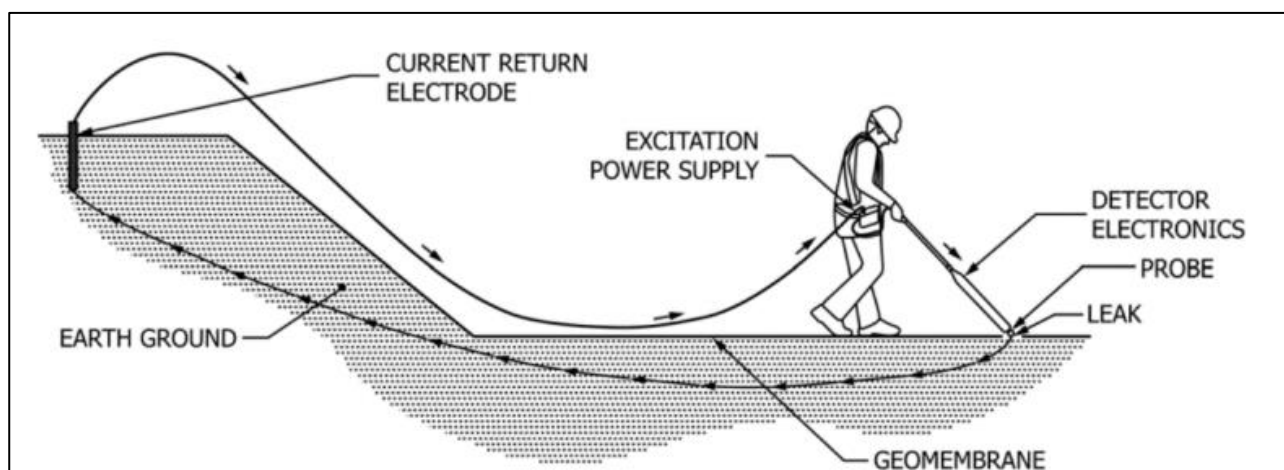


Figure 32: Arc test principle (figure taken from ASTM7953 Standard Practice for Electrical Leak Location on Exposed Geomembranes Using the Arc Testing Method).

Leak Detection System

Furthermore, a permanent leak detection system can be implemented together with the sealing system (similar as used in landfills). This way an operator of a PTES can get information about the tightness of the plant also during the operation period and, in case of a leak, can localize its position. In Høje Taastrup the leak detection system consists of more than 1000 sensors, which were placed in a 2 x 2 meter grid before the liner was installed. In the event of a leak, the current between the sensors will increase and a leak can be localized. Figure 33 shows the location of the sensors in Høje Taastrup. In addition, it can also help to monitor tightness during the filling phase (to be discussed with the supplier). A leak detection system is nice to have, but not a must, since the arc test will normally localize leaks in the implementation phase.

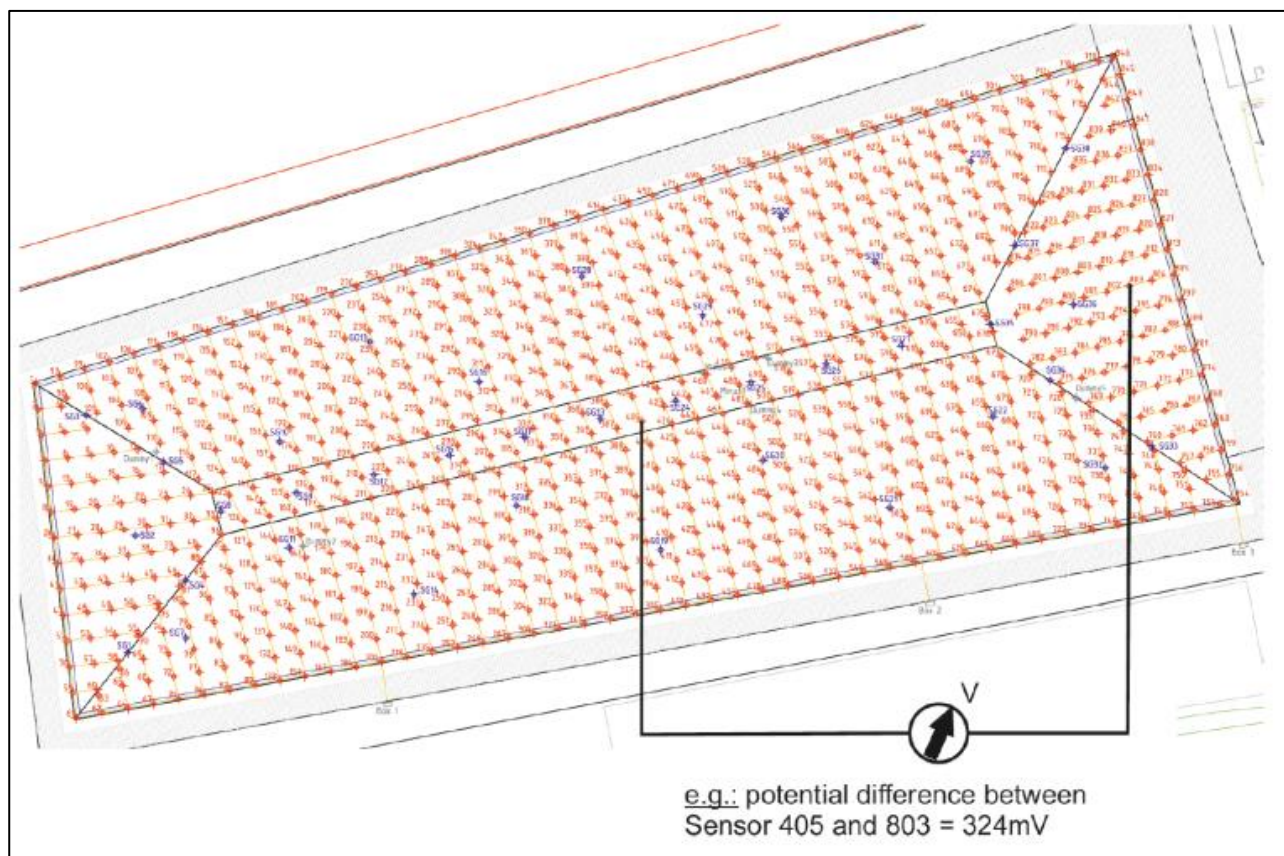


Figure 33: Location of leak detection sensors in Høje Taastrup (Source: SENSOR DKS GmbH).

When membranes are implemented on sides and bottom of the storage and tightness is tested, and the sacrificial polymer liner (see below) is established, the water filling can be started. If a PP-membrane is mounted membrane temperature must be controlled during the water filling to avoid membrane temperatures below 0°C.

Lid construction

The floating lid construction of a PTES must be able to handle the following challenges:

- Water tightness.
- Ventilation of non-condensable gasses that releases from the PTES water in course of heating up the water.
- Drainage of surface water from rain and snow, as well as drainage of water from the storage as a result of diffusion through the liners.
- Handle strong wind situations.
- Supporting loads from the structure itself, weather conditions, access and maintenance.

The construction of the lid starts with disassembling the sacrificial polymer liner used for protecting the water quality during the water filling. It is recommended to dismantle this layer in parallel to the implementation of the floating high temperature resistant geomembrane to avoid an open water surface over a longer period risking a larger pollution of the storage water. Usually, the floating lid geomembrane and its permanent mounting parts are assembled on one side of the embankments (at the

welding zone on the widest dam crown) and then pulled out step by step over the water surface. Once the entire water surface is covered with the geomembrane, a polymer protection layer (geotextile or geocomposite) is distributed on top of it, followed by the individual materials and layers of the chosen lid solution. Each lid solution normally consists of a few layers of insulating components in either the same or different compositions.

For the implementation of the lid components, the floating membrane is the new working surface. This means that the work surface is not a solid surface and work procedures have to take this into account.

The lid components are usually delivered in sheet or panel sizes of up to 10 or more square meters, which can normally be moved by hand. Covering a large lid area (e.g. 10,000 m²) then involves a lot of personnel and material movements, which must be coordinated. Correct placement of each part is important to avoid unwanted thermal bridges. Wind protection is normally done with a huge amount of sandbags distributed in a grid (i.e. 4 x 4 m) to prevent wind uplifting of the components. Care must also be taken in handling rainwater during the implementation.

Care shall be taken for correct placement of penetration parts such as air vents and manholes (with temperature sensors for measuring water temperatures). Welding in of the penetrations is done in the welding zone and has then to be pulled in the correct position.

In general, it can be mentioned that each lid solution has its own challenges during implementation that lay in the individual composition of a design, but all solutions demand a large level of coordination and care-taking on the floating surface.

Before **commissioning** the total system must be tested. The test procedure must be described by the owner and carried out by the owner. Membrane work for side and bottom shall not be commissioned before water filling is ended and, if possible, not before the floating liner is mounted.

10.1 Case Dronninglund

Excavation started in March 2013 and ended mid-May. The in- and outlet system was implemented in the same period.



Figure 34: Dronninglund, mid-May 2013. Photo: Niras.

The excavation went without problems. Membranes were mounted until mid-June. Leakage test using electrical conductance showed no leakages, and water filling took place from end June to August. Lid was mounted until end October.



Figure 35: Dronninglund, October 2013. Photo: Niras.

During autumn and winter 2013-2014, building, solar collectors, pipes, pumps, heat exchangers and control system was implemented, and operation started in March 2014.

10.2 Case Høje Taastrup

Implementation started in 2019 with concrete work (pumping cellar) and pipe work. Soil excavation started in April 2020 and in June membrane work could start at one end of the PTES while excavation was not finalized at the other end.



Figure 36: Høje Taastrup, June 2020. Photo: HTF.

Membrane work was finalized in August. The membrane was covered with a thin PE protection membrane to avoid dirt coming into the water, and water filling took place during winter 2020-2021. Under the membrane in Høje Taastrup a leakage detection system was implemented, and this gave an alert in January 2021. The alert was caused by cracks in the PP-membrane. During spring tests were carried out and it ended up with the supplier's insurance paying for supply and mounting of a new version of the PP-membrane. This new version was mounted from July 2021 to October 2021.

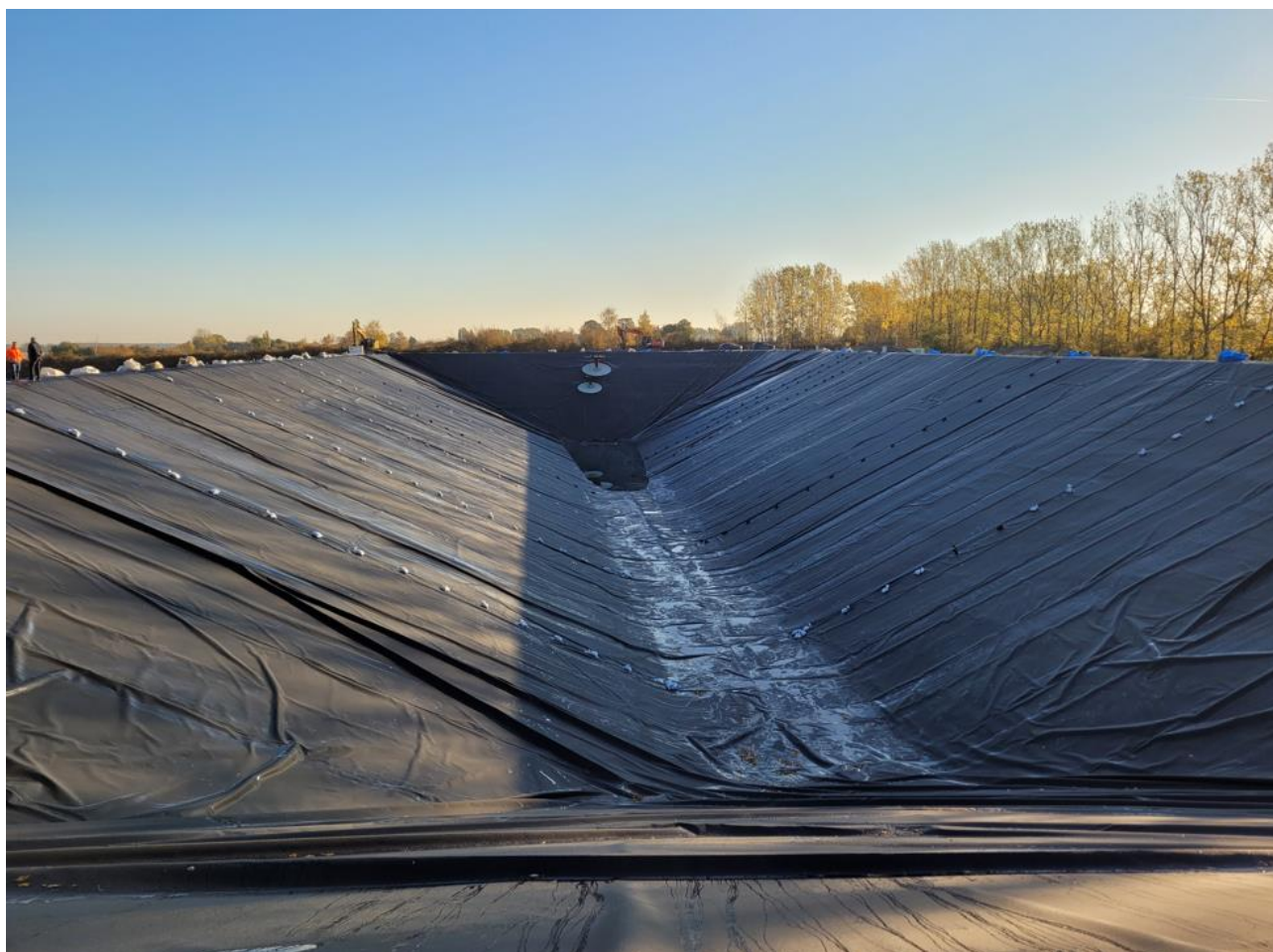


Figure 37: Høje Taastrup with new PP-membrane and sacrificial HDPE membrane on top of it, October 2021. The 3 diffusers of the in- and outlet system can be seen at the far end. Photo: HTF.

Leakage tests showed two leakages, which were repaired before water was filled in during winter 2021-2022. An irrigation system and temperature sensors were mounted to avoid temperatures on the PP-membrane getting below 0°C.

The floating membrane was implemented in April 2022, and the lid was built from May 2022 to September 2022. Commissioning of floating membrane took place in June 2022, of lid in October 2022 and of soil and concrete work in December 2022.

The PTES has been in commercial operation since February 15th, 2023.

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