FLEX_TES

Design and Construction of the Pit Thermal Energy Storage in Høje Taastrup

Foto: Ioannis Sifnaios, DTU

The FLEX_TES project has project number: 64018-0134 at EUDP.

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1 Introduction

In Heat Plan Greater Copenhagen 3 from 2014, which was prepared by the transmission companies CTR, HOFOR and VEKS, the following is stated about heat storage:

”*Heat Plan Greater Copenhagen 3 demonstrates a large economic potential for investing in heat storage in the metropolitan area. The next step is to find suitable locations for the establishment of heat storages in relation to grid connection and space for thermal plants and to assess when the heat storage is best established over the next 20 years.”*

Subsequent analyses showed that a 70.000 m^3 heat storage could be profitable already with the existing heat production system. Høje Taastrup Fjernvarme (HTF) found a suitable site, and VEKS and HTF decided to begin the process before the Final Investment Decision (FID).

The preliminary budget showed a total investment of DKK 74.1 million and an expected income (operational benefit) in 2025 of DKK 6.3 million. The income came from 1) a better optimisation of production in relation to the electricity market, 2) increased production at cheaper units (CHP plants and heat pumps) in the overall heat production system in Copenhagen and 3) increased production at waste incineration plants in the summer.

The pit heat storage was to be charged from VEKS' transmission system and discharged to HTF's distribution system. DKK 47.1 million of the total budget came from expenses for pipes, heat exchangers, etc. for connection to the transmission and distribution systems. In addition, the project involved development of the system, as the storage would be heated to 90 °C in the top during all hours of the year, which previously had not been tested and thus required further development of the polymér membranes used so far. VEKS and HTF therefore applied to the Danish Energy Technology Development and Demonstration Program (EUDP) for support for the implementation of the project under the project name FLEX_TES.

The project was granted a total funding of almost DKK 13.5 million, including a measuring program. The EUDP project has the following deliverables:

- Operational strategy for the pit heat storage
- Design and construction of the pit heat storage
- Monitoring results after 1 and 2 years of operation

This report covers the design and construction of the heat storage. The construction took place in the period from FID in April 2019 to December 2022.

The project is carried out in collaboration between HTF and VEKS, each owning 50% of the heat storage. The project organisation has consisted of

- A **steering committee** with management representatives from HTF and VEKS as well as the project managers
- A **project manager** from VEKS and a **project manager** from HTF
- A **project group** with consultants, project managers and relevant technicians from HTF and VEKS

In addition, a steering group for the FLEX_TES project and a project follow-up group consisting of representatives from CTR, HOFOR, Vestforbrænding, ARC, ARGO, Ørsted, Varmelast and the partners in the FLEX_TES project has been set up.

2 Summary

This report for "Design and Construction of the Pit Thermal Energy Storage in Høje Taastrup" describes the process from tendering the project to commissioning and delivery. It describes the design changes that were decided along the way and the problems that arose and how they were solved.

The first chapters of this report (3-6) contain the design-related starting point and the changes that were made before construction. It then describes the construction phase in section 7, the handover in section 8, and the final economy of the project in section 9.

The Tendered Design

From the beginning, the size of the heat storage was set at 70,000 m^3. The site where the heat storage was to be located is limited by a highway on the south side and a drinking water pipeline on the north side, which led to an unconventional design with a very elongated heat storage, where the inlet and outlet are located at one end of the 170-meter-long storage. It was also expected that the inside of the storage would be sealed with a High-Density PolyEthylene (HDPE) membrane, similar to the pit thermal energy storages already established in Denmark.
Compared to previously established pit heat storages, the diffuser system was changed so that both the top and bottom diffusers are "half" diffusers, where the lid and bottom is the other half respectively.

Design Changes

The top of the storage would be constantly exposed to 90 °C if the storage capacity was to be as assumed by the operators. This presented a challenge for the supplier of HDPE liner, who had previously given Dronninglund District Heating a 20-year warranty for the durability of the liner at up to 90 °C. The supplier did not want to give a similar guarantee again and instead proposed a double liner solution with two liners on top of each other. This solution was expensive, slow to set up, and untested. The giga_TES research project in Austria recommended looking at a Polypropylene High Temperature Resistant (PP-HTR) liner instead. This liner was newly developed and not in production, but laboratory tests showed very long technical lifetimes (33 years at 95°C) for the PP liner. Thereby, the project had a choice between two unproven solutions and ended up choosing the PP liner for sealing the bottom and sides, as well as purchasing a leakage detection system.

The tendered design of the lid of the pit storage was a revised version of the Dronninglund PTES lid design. There had been problems with the stainless-steel anchors used to hold the insulation mats together in Dronninglund and with the trenches where weight pipes were placed. These problems were solved in the tendered design, but new experiences from Dronninglund showed problems with the durability of the insulation, water accumulation on the lid, and moisture and oxygen diffusion through the floating liner that separates the lid structure from the storage water. To address these issues, the tendered design was modified. At the same time, a new lid solution was developed and implemented in the pit storage in Marstal. The solution was marketed by Aalborg CSP and was compared with the revised design. The project steering committee decided on Aalborg CSP's solution.
Testing of the polymer mats, used as lid insulation in Dronninglund, which are also used by Aalborg CSP and in the revised lid solution, resulted in a completely new generation of insulation mats with a significantly longer technical lifetime being delivered to the project in Høje Taastrup.

Construction of the Storage

Construction of the pit heat storage began in spring 2020. Excavation, construction of the inlet and outlet arrangement, installation of the leakage detection system, PP liner and a thin PE liner to protect

against dirt, and UV light during water filling proceeded as planned. The water filling with water from the VEKS transmission system started in November 2020.
In December 2020, a leak alarm came from the leakage detection system. It turned out that a weld was missing. Therefore, the water level had to be lowered for repairing the leak.
At the end of January 2021, there was another alarm from the leak detection system. It turned out that the liner had cracked from top to bottom on one side. The triggering factor was probably that the protective liner was attached with a wooden peg that went through the PP liner. Freezing weather had caused the PP liner to become glassy and burst due to contraction.
The damage spread and proved so extensive that the entire liner ended up requiring replacement. Both the supplier and the client then carried out several investigations, which resulted in the supplier's insurance company covering the delivery and installation of a new liner with a plasticizer additive, but still sensitive to frost.
The newly developed liner was installed in July-August 2021, closely supervised by the client and the PlanEnergi.
To avoid frost impact during water filling, an irrigation system was also developed. Water filling took place from November 2021 to March 2022.

The PP floating liner was to be installed from April 2022. However, during the dismantling of the irrigation system, the PP liner was damaged when a fracture went 60 cm below the water surface. The fracture could be repaired using a "caisson" which kept the water away during the repair.
The PP floating liner was then mounted on the water and from July the lid of the PP liner was constructed.

Handover, Testing and Commissioning
The liner work for the bottom and sides were handed over in March 2022 and for the floating liner in June 2022. The lid contract was handed over in October 2022 and the soil contract in December 2022. From the end of October 2022, water heating, commissioning, and testing of control functions started. The storage reached full temperature by New Year 2022-23 and was handed over for commercial operation on February 15, 2023.
There is an extensive measurement program in connection with the operation of the storage. The results will be reported by DTU. However, it can already be noted that the desired 30 MW can be both charged and discharged, but that the distribution system of Høje Taastrup has difficulties in utilising 30 MW. This is being rectified. The temperature gradient in the storage is the same at both ends despite the long distance.

3 The Tendered Design

The tender for the heat storage is a functional tender divided into two independent turnkey contracts.

A. The earth, concrete, and piping contract, which includes:
   - Earthworks
   - Drainage works
   - Pump basement
   - Inlet and outlet arrangement

B. The liner contract, which includes:
   - Membrane work
   - Construction of the lid

Polymer membrane, protective membrane, hypernet (protective mesh), lid insulation, and roof membrane were client deliveries.

3.1 Location of the pit storage

The pit heat storage is located between the Holbæk highway and a main water pipe (bonnaledning) supplying Copenhagen as shown in Figure 1.

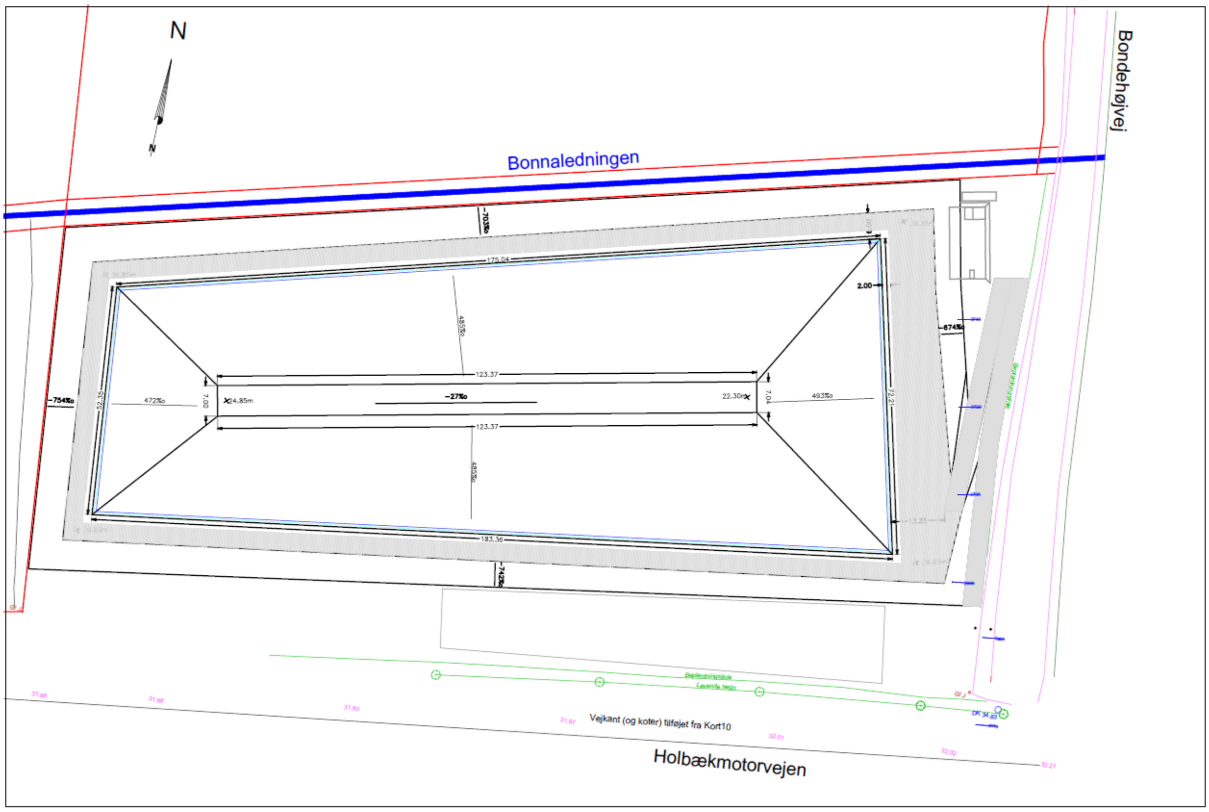


Figure 1: Site plan.

3.2 Geometry of the Pit Storage

As can be seen in Figure 1, the storage facility is squeezed between a main water pipe and the Holbæk highway. This has determined the geometry of the storage in addition to the conditions that are normally included in the design of a pit heat storage. The cheapest way to establish a pit heat storage is with soil balance. This means that the excavated soil is compacted and used as an embankment around the storage facility. In addition, the slope should preferably not be steeper than 1:1.5 for the membrane work, and the heat storage must be 70.000 m^3.

This provides a narrow framework for the storage geometry and results in an elongated, flat, non-rectangular storage, with the most space for the pump building at the eastern end, where the inlet and outlet pipes with diffusers are also located (see Figure 2).

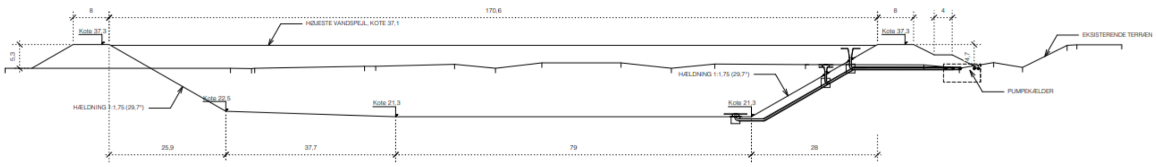


Figure 2: Longitudinal section of the PTES.

3.3 Membrane and Lid Solution

The heat storage was assumed to be constructed with a welded HDPE membrane on the sides and bottom, laid on geotextile and locked in an anchor trench. Water is then filled in. During water filling, a PE protective membrane is placed to prevent oxygen uptake and dirt in the water. Then an HDPE membrane (floating membrane) is welded on land and pulled over the water surface, after which the lid is built up. Figure 3, Figure 4, and Figure 5 show the construction of the membranes and lid.

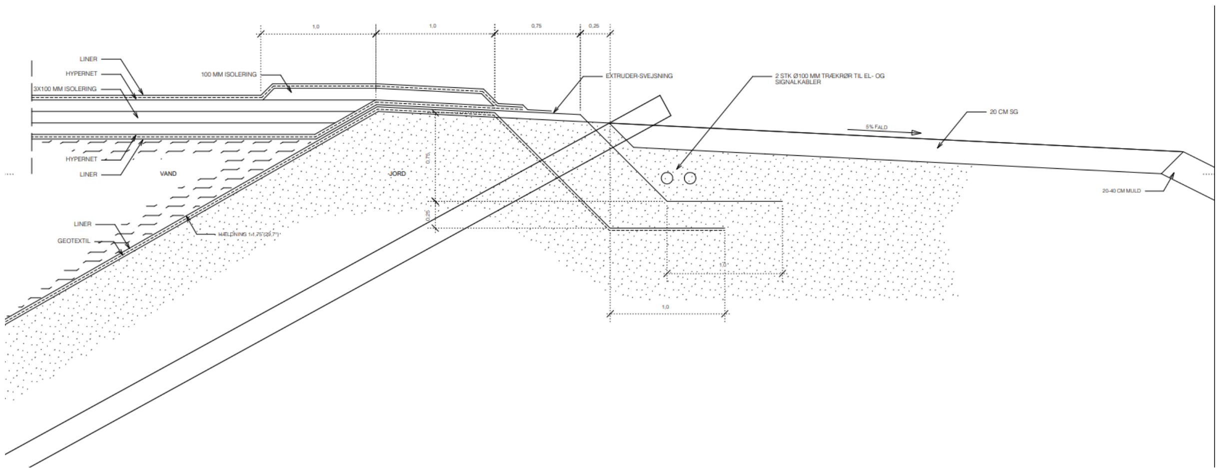


Figure 3: Cross-section of dam crest with membranes and locking ends.

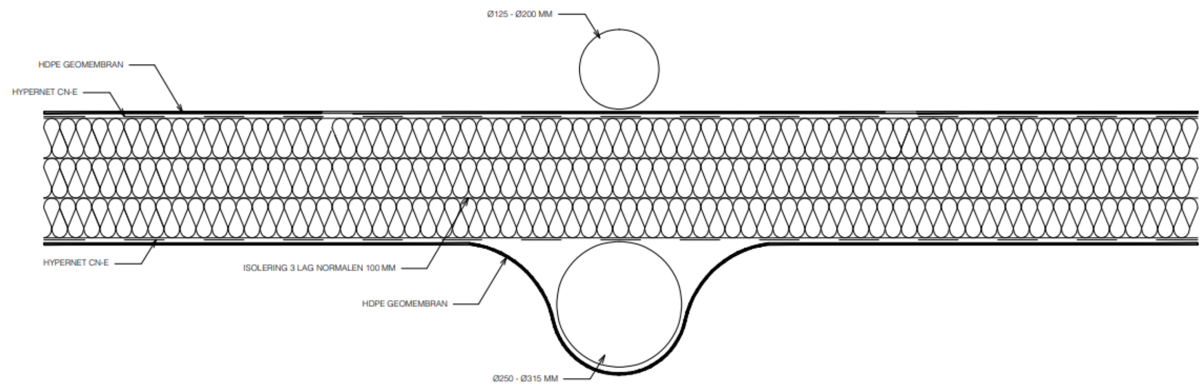


Figure 4: Cross-section of lid with weight pipes.

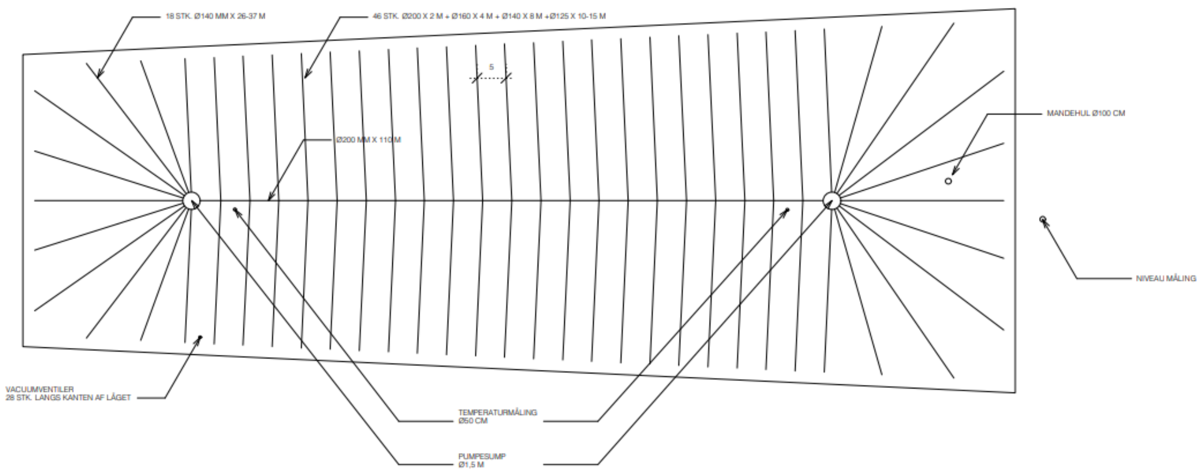


Figure 5: Plan of lid with weight pipes.

3.4 Inlet and Outlet

The requirements for the inlet and outlet were to be able to charge and discharge with 30 MW. The inlet temperature is expected to be 90 °C and the outlet temperature 45 °C, so the 30 MW corresponds to approximately 600 m^3/hour. Diffusers at the inlet and outlet must ensure that the water velocity is reduced to max. 0.03 m/s at the outlet of the diffuser to achieve sufficiently low mixing and a satisfactory separation layer. As a new feature, the upper diffuser is not fitted with a baffle plate, as the underside of the lid acts as a baffle plate. A similar solution has been chosen for the lower diffuser. The location of the diffusers is shown in Figure 6.

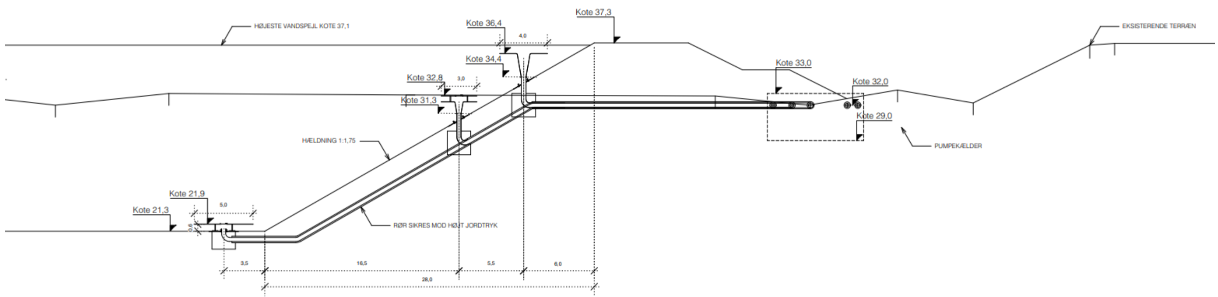


Figure 6: Cross-section with placement of diffuser.

3.5 Water Quality

Experiences from the pit heat storages in Marstal and Dronninglund were that due to the risk of corrosion, water treated as desalinated district heating water should be used in the heat storage facility, especially when, as in Høje Taastrup, black steel is used for the inlet and outlet arrangement and the connecting pipe. The requirements for desalinated district heating water are shown in the right column in Figure 7.

quality in district heating systems		untreated	softened	partially desalinated	desalinated
appearance		clear	clear	clear	clear
odour		odourless	odourless	odourless	odourless
particle content	mg/l	< 10	< 10	< 5	< 1
oil and grease content	mg/l	< 1	< 1	< 1	< 1
ph-value at 25 °C			9.8 ± 0.2	9.8 ± 0.2	9.8 ± 0.2
Remaining hardness	°dH		< 0.5*	< 0.6*	< 0.6*
conductivity at 25 °C	µS/cm		< 1500	< 500	< 50 **
oxygen content	mg/l		< 0.02	< 0.02	< 0.02
chloride, Cl	mg/l	< 300 **	< 300 ***	< 50 **	< 3
sulphate, SO_4	mg/l				< 2
ammonia indhold, NH_3	mg/l		< 10	< 5	< 5
iron content, Fe_{total}	mg/l		< 0.1	< 0.2	< 0.05
copper content total, Cu_{total}	mg/l		< 0.02	< 0.02	< 0.01

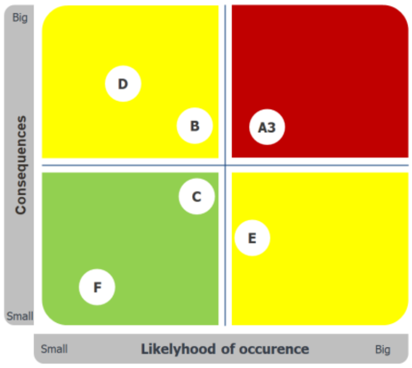
Figure 7: Requirements for water treatment. Source: Danish District Heating.

4 Risk Assessment

Risk assessment has been an integrated part of the preparation work. Under the guidance of the project group, a risk memo was prepared that addressed the risk of leaks, water quality, liner material lifespan, temperature level control, parasites, and flooding in the event of internal leakage. The risk memo formed the basis for a discussion in the project steering committee in connection with the decision to move from analysis and planning to implementation. The risk assessment was summarised in Figure 8, which the steering committee approved:

Key risks – construction: **After** Phase change

Description of risk and when it is expected to occur (time/phase)	Handling	Responsible
A3. Agreement with ARC is delayed	However, must be available after FID Can be capitalised to an extra DKK 4 million	VEKS
B. Cloudburst during excavation work	Starts with lid mount advanced in execution and pump water away when the cloudburst is over.	PL
C. Filling of storage with water from VEKS	Scheduling the first time the storage is filled (based on five months total)	VEKS
D. Pipe burst, filling of heat exchanger station, also during operation	Installing safety shut-off valves on pipes, preliminary costs DKK 500k	PL
E. Radius, additional costs for sockets compared to budget DKK 650k and for delay in execution	Radius is currently trying to get a confirmation from R' decision-makers without success.	HTF
F. Oil prices and thus plastic price index rises sharply, leading to forced price regulation	Offers must be updated. Likelihood of long deliveries on liner.	PE



Key risks – Operation : After Phase Change **Unchanged**

Description of risk and when it is expected to occur (time/phase)	Handling	Responsible
A. Load distribution will not be optimal	Continuous follow-up on operational performance, corrective actions are taken	VEKS , HTF, VL
B. Control of grid/exhangers does not work optimally in relation to the interaction with distribution grid of HTF	Thorough testing of the control concept from Varmelast against control descriptions for grids and exchangers in the distribution center.	VEKS , HTF
C. Pest infiltration, breakdown of liner or lid	The heat radiation deters pests in the bottom and sides of the storage. Any damanges to the lid can be repaired from the outside. Prevent damage with regular rounds/inspections of the terrain around the storage.	HTF
D. Heat storage collapses, possible flooding of highway?	EIA/screening has been conducted without pointing out these risks.	Handled by environmental authority
E. Heat sales in HTF does not increase as expected and return temperature deviates from expected	Focus on the development of heat sales, monitoring nye developments. As well as a program for reducing return temperature.	HTF
F. Lifetimes of liner and lid are not tested in practice but only on trial basis.	Development of an improved design with a reinforced version of the liner/lid with increased thickness and more liner layers, which is likely to last more than 20 years in collaboration between supplier and DTI	Projekt management
G: Increased oxygen content in DVL water	May require increased water treatment, thus increased operating costs	PE and HTF
I: Changed location of Vx station	Can influence operating parameters, hydraulic conditions	VEKS and HTF

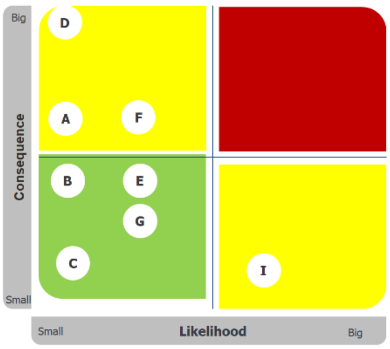


Figure 8: Risk assessments approved by the project steering committee.

As mentioned, risk assessment has been used continuously. Another example is the risk assessment when the PP liner was to be reinstalled, and with liner leaks, the vulnerability of the liner had become very clear. A separate risk assessment was therefore prepared for this part of the work, and risk prevention was incorporated into the Health and Safety Plan.

5 Choice of Liner for Bottom and Sides

Liners for sealing pit heat storages have been developed since the 90s. The work is summarised in the report "Udvikling af linere til damvarmelagre" [1] published by PlanEnergi in January 2015.
Both metal liners and polymer liners have been assessed and tested. The conclusions are:

Aluminium liners. It was not possible to obtain methods for welding the aluminium liner and installation from the supplier. In addition, the pH value of the water must be 6.5-8 to avoid corrosion. It is therefore not considered possible to use aluminium.

Stainless steel liners. Steel liners (0.5-0.9 mm) are supplied in relatively narrow coils (1.5 m) and cost from DKK 200/m^2 and upwards excluding installation. The installation (welding of the liners) is complicated. Welding tests showed that induction welding was the best method, but ESAB, for example, did not have an induction welding machine in its product range at the time (2014). All in all, steel liners are considered too expensive and difficult to work with.

High Density PolyEthylen (HDPE) liners. Liner suppliers have pointed to HDPE as the best option, and five different HDPE liners have been tested by the Danish Technological Institute in the period 2000-2018. The results have been technical lifetimes of up to 6 years at 90 °C. The latest liner has also been tested by RISE (Swedish accredited testing institution), where the result is a 25-year lifetime. The test conditions are different, so the supplier of this liner estimates that the lifetime of the liner is at least 12 years under the conditions in Høje Taastrup, and that a solution with two liners therefore must be used. 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. Polymer liners (HDPE) have therefore been used in Danish pit thermal energy storages.

New possibilities

Professor Gernot Wallner, Institute of Polymeric Materials and Testing, University of Linz, Austria, has for the past 6 years, been working to develop a PP (polypropylene) liner that is better able to withstand high surrounding temperatures. The reason for working with PP rather than HDPE is that PP degrades more slowly in water than HDPE (the opposite is true in air). The development process involves peeling 0.05-0.1 mm strips from a PP sheet. The strips are exposed to high temperatures (humid air being the worst) in a set of ovens. Since polymers degrade faster the thinner they are, results can be obtained relatively quickly. Many tests are performed simultaneously. Figure 9 shows one of the test ovens.

Figure 9: Test oven at the University of Linz.

Samples are taken regularly and tested for elongation at break and antioxidant content, among other things.
The lifetime of a 2mm PP liner is 33 years at 95 °C in air, according to Gernot Wallner. The lifetime of a PP liner is theoretically longer in water.

In the Høje Taastrup project, two different liner solutions (2 layers of HDPE and 1 layer of PP) were offered for the bottom and sides. In the following, the properties of the liners are compared in terms of quality/durability, suitability and safety in the installation phase, suitability and safety in the operational phase and price.

Quality/Durability

HDPE-liner: A similar liner is used for the PTES facilities in Marstal, Dronninglund, Gram, Vojens and Toftlund.
As previously mentioned, the lifetime at 90 °C is estimated by the supplier to be 12 years, which is why a double liner solution was offered.
The supplier does not guarantee the lifetime.

PP-liner: The technical lifetime at 95 °C is stated by the supplier to be 20-47 years on the air side, which is the weakest part. The results are from accelerated testing on 50 µm test strips. The results are scaled up to 2 mm liner.
The supplier does not guarantee the lifetime.

Suitability and Safety in the Installation Phase

The HDPE liner is weldable. Machine welds are tested with air pressure (double seam) and extrusion ring welds with vacuum testing. Subsequent testing of the sealed area can be done with an arc test (see Figure 14). There is good experience with the tightness of the established liner. In Marstal, a welding defect was repaired under water at a later stage. Marstal was not arc tested. In the other storages, no leaks have been found in the bottom and sides.

HDPE is installed in 2.5 mm thickness with a roll width of, for example, 7.50 m. The liner is robust, but sharp stones must be removed, and the supplier recommends a special protective layer between the soil and the liner.
It was not clarified how leak testing, in addition to pressure testing, should be carried out on the inner liner towards the water side. It was also not clarified in detail how to get rid of any condensation between the two layers of liner.
Installation was offered to be carried out by the supplier's employees according to the German DVS standard (which is stricter than the Danish DS/INF 466 standards for plastic welding).

The PP liner is also weldable, and the machine welds are pressure tested (double seam) and the extrusion welds are vacuum tested. Subsequent testing of the sealed area using arc testing (see figure 11). In addition, a permanent leakage detection system was offered.
The PP liner is stiffer than the HDPE liner. According to the supplier, this does not affect the quality of the welds.
PP is installed in 2.5 mm thickness with a roll width of, for example, 5 m.
Installation was offered to be carried out by the supplier's own people according to the German DVS standard (which is stricter than the Danish DS/INF 466 standards for plastic welding).

Suitability and safety in the operational phase

The HDPE liner degrades fastest from the water side. It is expected that the outer liner will take over once the inner liner has degraded. Whether water will accumulate between the liners during the operational phase is uncertain. It is oxygen and high temperatures that cause the degradation.

The PP liner degrades fastest from the air side. Oxygen and high temperatures cause the degradation. From the water side, a lifetime of around 50 years at 95 °C is expected.
PP liners have greater moisture penetration than HDPE liner, but this is unlikely to affect for bottom and side liners.

Conclusion

The PP liner has a significantly longer technical lifetime, and we were able to avoid the double liner solution, which is difficult to install, and the PP solution is approximately DKK 900,000 cheaper. We did not find significant quality differences in welding and installation, and we do not expect the greater moisture penetration of the P liner to be a problem for the bottom and sides.
It was therefore decided to choose the PP solution for the bottom and sides.

Leak Detection System

At the same time, it was decided to purchase a leak detection system. The leak detection system consists of more than 1000 sensors, which are placed in a 2 x 2 meter pattern before the liner is installed. In the event of a leak, the current between the sensors will increase and the leak can be localised.
However, the supplier had reservations about the efficiency in Høje Taastrup, as the conductivity of the storage water is very low, as the water had to be supplied from the district heating transmission network. Figure 10 shows the location of the sensors.

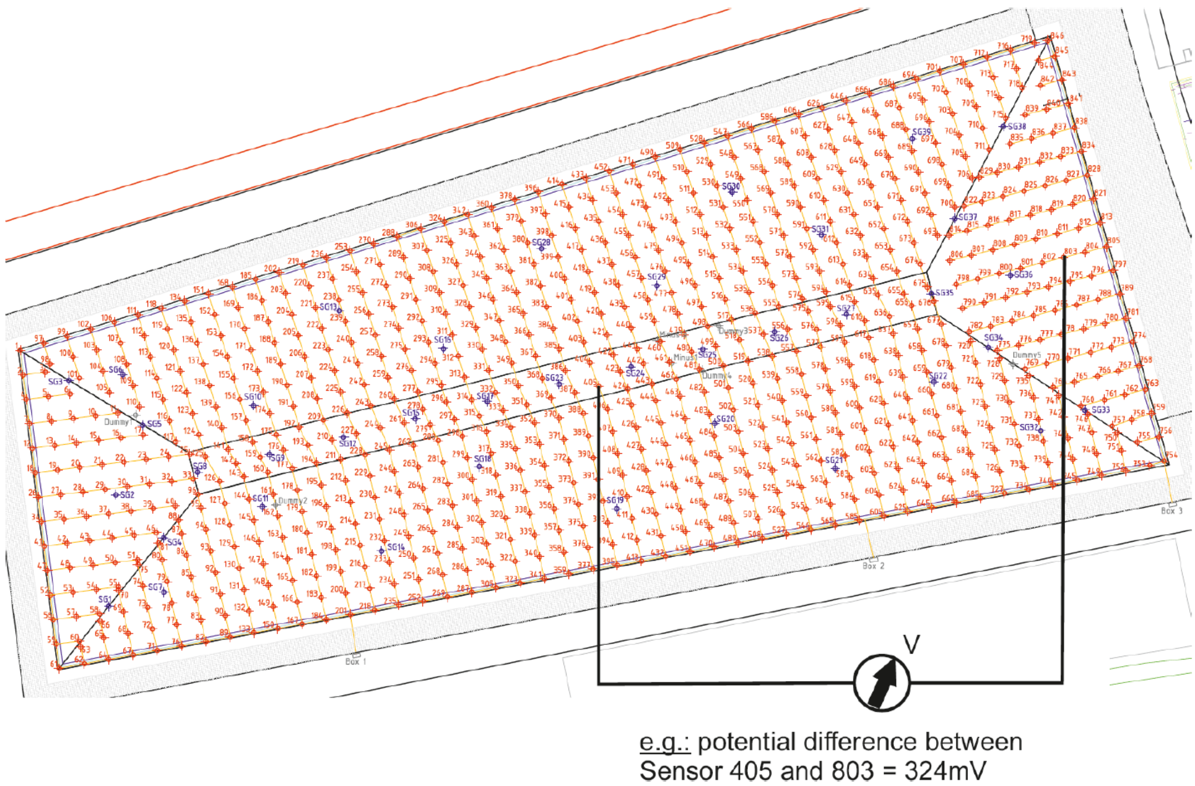


Figure 10: Location of sensors in the leakage control system in Høje Taastrup. Source: SENSOR-DKS GmbH.

6 Choice of Lid Solution incl. Floating Liner

6.1 Insulation Materials

To limit heat loss from the storage, an insulating lid is established that floats on top of the water in the storage. Previous calculations show that it is not cost-effective to insulate the sides and/or bottom of the pit storage.

The primary purpose of the lid is to limit heat loss from the storage, but the lid must also ensure that the water quality in the storage is not reduced.

A thermal insulation material is characterized by poor heat conductivity. It is mainly the stagnant air in the insulation materials that gives this property, and furthermore resulting in a lighter insulation material. Common to all types of insulation is that air is an important component, as stagnant air has very good insulating properties and therefore retains heat well.

Water in the insulation is generally undesirable, partly because it will often reduce insulation performance and partly because water can degrade some insulation materials.

Experience from the established pit storages show that it cannot be avoided that water gets into the lid, either during installation, leaks and/or water diffusion. The insulation material must therefore be able to withstand getting wet without being destroyed. In practice, this requirement excludes all organic insulation materials, including:

- Straw
- Paper wool
- Wood fibre
- Flax
- Sheep Wool
- Hemp
- Isonat (hemp and cotton)
- Cork
- Eelgrass

but also, **mineral wool** (rock wool/Rockwool and glass wool/Isover) can be destroyed by water, as happened in the pilot PTES in Marstal.

Another requirement for insulation is that it must be able to withstand a temperature of at least 90 °C for at least 20 years. **EPS** (Flamingo/polystyrene foam) and **XPS** cannot meet this requirement.

Most insulation materials are available as boards (e.g., EPS) and/or granules (e.g., Leca). Experiences with granules (Leca) show that it can be difficult to control the laying process to achieve the desired layer thickness. This can, among other things, cause challenges in relation to drainage of rainwater from the lid.

The biggest challenge with granules, however, is that there is a high risk of convection in the insulation because the insulation structure is open to air circulation and the temperature gradient in the lid is in the same direction as gravity. This means that the hot water under the lid will heat the air in the lower part of the insulation and this heated air can then rise up through the insulation (thermic). The use of granules therefore requires that the design prevents convection, either by using very fine-grained granules, by compaction (which is not considered possible) or by using horizontal convection barriers.

Due to these challenges, the use of granules is not recommended, which therefore excludes the following materials, among others:

- Lightweight clinker/Leca
- Perlite
- Cellular glass granules/Foamglas gravel
- Seashells

The following insulation materials were excluded because they were deemed too expensive:

- Cellular glass plates/Foamglas plates
- Reflective insulation
- Vacuum panels

And finally, the following insulation materials were excluded due to a lack of experience with pit thermal storages:

- Porous concrete
- Lightweight concrete
- Armatec boards
- PUR or PIR foam boards

The above arguments meant that it was still recommended to use **Nomatec** mats as insulation material (which was also used in Dronninglund, where it was simply called Nomalén). The Nomatec was also further developed compared to the one used in Dronninglund, as moisture and pressure in Dronninglund had caused the insulation to be greatly reduced in thickness in some cases.

6.2 Arcon Sunmarks/Aalborg CSP's Lid Solution

At the same time, Arcon Sunmark had developed their own lid solution for pit thermal energy storages. The solution differed from the concept proposed in Høje Taastrup in several ways:

- The lid is modular, built on the same type of liner as proposed in Høje Taastrup.
- Instead of weight pipes, stones are used to weigh down the center of the modules.
- Rainwater is pumped from each module.
- The insulation is replaced with higher density layers (Nomatec) at the bottom and XPS at the top.
- A semi-permeable roofing membrane is used, which allows water vapor to pass through from the low side (as in a roof structure).

The concept is patent pending and certified by Lloyds. After the closure of Arcon Sunmark, the rights to the lid design were taken over by Aalborg CSP, so the lid solution is now called Aalborg CSP's lid solution.

Figure 11 shows a cross-section of the lid.

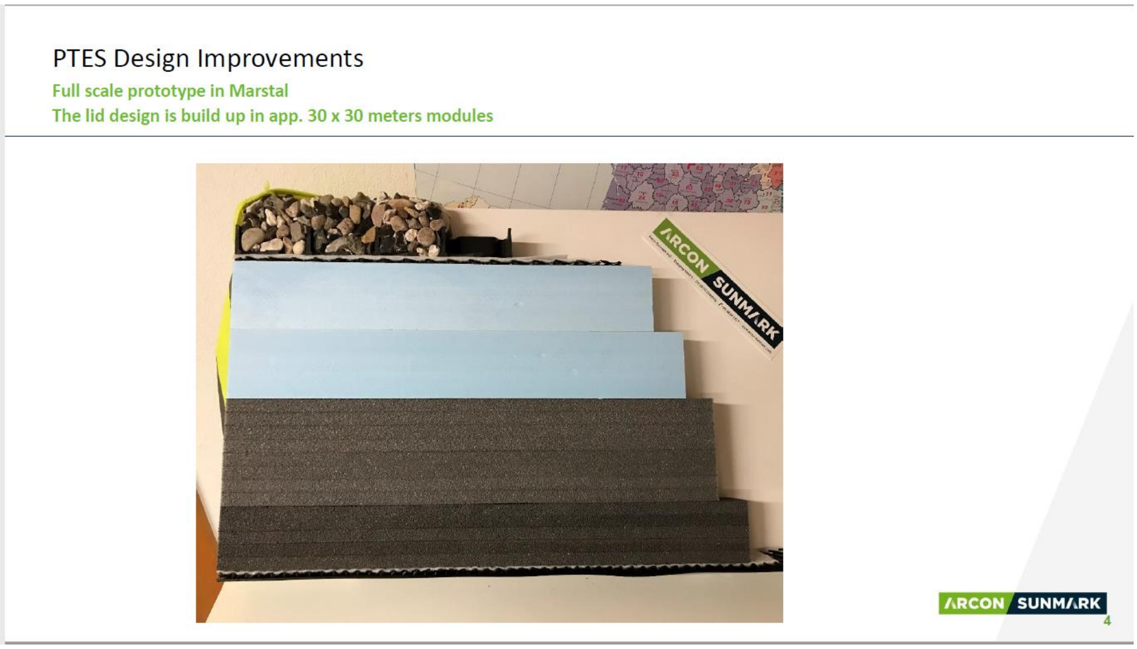


Figure 11: Cross-section of mock-up model of Aalborg CSP's lid construction.

6.3 Choice of Lid for the Pit Storage in Høje Taastrup

From April to September 2020, a working group consisting of consultant and client worked to modify the tendered lid construction, as new information had emerged during the project about problems with the lid solution in Dronninglund, and as the solution by Aalborg CSP seemed expensive. Work was initiated to use the same type of PP liner used for sealing the bottom and sides as floating liner in the lid, if possible.

The development work had to solve the following problems:

- **Moisture permeation**. The PP liner is believed to have 5-10 times greater moisture permeability than the HDPE liner.
- **Oxygen permeation**. Oxygenation of the water in the pit storage is assumed to occur, but the amount is unknown (also a problem for the HDPE liner).
- **Water accumulation** on the lid.
- **Load capacity and lifetime of new insulation material,** Nomatec 30HT86L.
- **Weight Pipes** on the floating liner, which has proven to be a vulnerable solution.

During the work, the problems were investigated, and a new revised lid design was developed:

Moisture Penetration. Danish Technological Institute performed 3 tests measuring water vapor diffusion at 90 °C through a 2 mm PP liner. The result was 7.4 g/m^2/day, which is significantly lower than assumed, compared to the expected 5 g/m^2/day for a HDPE liner.
PlanEnergi performed ventilation resistance tests in the geogrid (layer between floating liner and lid). The test showed that the lid can easily be ventilated for penetrating moisture, but this requires the establishment of mechanical ventilation. This can be solved with three roof fans in the centre of the lid and intake vents at the edge of the lid.

Oxygen Permeation. The Danish Technological Institute has developed an experimental setup and conducted tests with oxygen diffusion from the dry side to 90 °C hot water. The results are uncertain, but all indications are that oxygenation occurs significantly faster than a deoxidation plant, which can deoxidate 5 m^3 of water per hour, can keep up with.

The oxygen permeation could be stopped by an aluminium liner, but aluminium corrodes at pH 9.8. Therefore, it was investigated whether the moisture coming through the liner caused corrosion of aluminium laid on top of the liner. The result was a 10% weight loss after 1,000 hours, so the conclusion was that aluminium cannot be used as an oxygen barrier.

FORCE was asked about recommended requirements for oxygen in the water. They recommended keeping the oxygen concentration below 20 micrograms/litre. FORCE did not believe that it is possible to avoid corrosion by placing sacrificial anodes and possibly combining with cathodic protection. However, FORCE did report that a protective layer of magnetite forms on black steel at pH 9.6-10. If the pH is maintained, any cracks in the magnetite layer will be repaired continuously, so the magnetite layer will protect against corrosion even at higher oxygen concentrations.

Water Accumulations on the Lid. The tendered design was modified to remove the weight pipes on the floating liner. The weight pipes on the lid are laid out with increasing mass towards the center of the lid, creating a natural slope towards the two pumping stations. Compared to previous installations, the weight pipes in Høje Taastrup are laid more densely and made heavier to minimize the problem of rainwater puddles on top of the lid. Water accumulations are easily spotted and can be directed to a pump well with a portable submersible pump. This will be part of normal operation and maintenance.

Water accumulation could be completely avoided if a roof solution - like for covered slurry tanks - was introduced. According to the Danish Agricultural Advisory Center, a solution costs 340 DKK/m^2 for 2.000 m^2. This solution was abandoned due to the price, as Høje Taastrup needs to cover 11.000 m^2 with a larger span.

Load-Bearing Capacity and Lifetime of the Insulation Material, 30HT86L. The insulation material is an improved product from Termonova. The material has been tested by Aalborg CSP using the same method previously used by Arcon-Sunmark. The result is that the new insulation type does not compress like the old one, but this requires that the insulation is dry.

The service life of the insulation material was subsequently tested by JKU Linz. This led the manufacturer to develop an even better version, which ended up being used in the lid solution in Høje Taastrup.

Weight Pipes. Weight pipes on the floating liner have proven to be a vulnerable solution, as cracking of the floating liner has occurred at the Marstal PTES. They have therefore been removed, but heavier and denser weight pipes on the top liner will provide the necessary slope so that air on the underside is directed to the edge, while rainwater is directed to the pumping stations in the middle of the lid.

The studies resulted in a revised lid design, which was priced and compared to Aalborg CSP's solution. For both solutions, it is a requirement that pH, oxygen content and iron in the water are measured regularly, as no oxygen is removed from the water or oxygen barrier is established.

6.4 Conclusion

The table below shows the advantages and disadvantages of the developed solution compared to Aalborg CSP's solution.

	Project solution		Aalborg CSP	
	PRO	**CON**	**PRO**	**CON**
Operation and maintenance		Periodic maintenance during rainfall.	No daily maintenance.	
	Operation and maintenance of 2 pumps			Operation and maintenance of 10 pumps.
		Operation and maintenance of mechanical ventilation.	Water in the insulation layer is drained towards a pump well.	
Topliner		Limited slope increases the risk of puddles.	Well-defined slope minimizes the risk of puddles.	
	Puddles can be easily spotted and removed manually with a submersible pump.		Not relevant.	
	Pump failure will not cause water accumulation as the second pump will remove the water over time.		In the event of a pump failure, there is enough storage capacity for remedial action to be taken.	
	No need for "secondary pumps" to protect against water accumulation.		There is the option to install redundancy pumps in the wells to protect against pump failure.	Pump failure protection requires 10 secondary pumps.
Floating liner	Air pockets and water puddles are expected to disappear after heavy rainfall, as the rainwater will weigh the lid down in the middle.	Expansion of floating liner when heated can cause small air pockets on the underside.		Expansion of floating liner when heated may cause air pockets along the edge for a short time.

	Easier access to floating liner for repairs.			More work to access float liner for repairs.
Water in the lid		Water intrusion through cracked floating liner can spread.	Water intrusion through cracked floating liner will remain in the section.	
		Water intrusion will eventually be captured by pumping activity during dry weather periods.	Water intrusion will be detected quickly as the well pump will be activated to remove the volume.	
Quality	The solution is backed by notes and tests from accredited institutes.	No certification.	The solution is assessed by an independent certification agency (Lloyds).	
Aesthetics		The lid will look dull over time as the surface cannot be kept uniform and neat (dirty).	The lid will look uniform and neat throughout its lifetime.	

It was decided to choose Aalborg CSP's solution, even though it was somewhat more expensive than the solution developed for the project. Aalborg CSP's solution was modified to use PP floating liner and PP solutions where the material is in contact with the water in the pit storage or exposed to high temperatures.

7 Construction of the Pit Thermal Energy Storage

7.1 Original Schedule and Delayed Construction Start

The excavation work was scheduled to start in March 2019. However, the EIA screening for the project was not finalized, including public consultation, until the end of April, when Høje Taastrup Municipality granted an exemption from the EIA requirement. The project steering group did not dare to start the excavation work in 2019, as there was a risk that the liner work would run into winter weather. Therefore, the work was postponed for a year until spring 2020.

7.2 Establishing Excavation and Inlet and Outlet Arrangements

Enterprise A. The soil, concrete and pipe contract were carried out by Wicotec Kirkebjerg A/S as a turnkey contractor. Wicotec Kirkebjerg A/S is 100% owned by Per Aarsleff A/S

Geometry of the Pit Thermal Storage

The contractor chose to make some minor adjustments to the storage geometry compared to the tendered design, including:

- Reducing the slope of the inner sides of the storage,
- Increasing the slope of the outer sides of the storage, and
- Allowing the western embankment to follow the property boundary.

Consequently, the depth of the storage was reduced, and the lid area increased compared to the tendered design.

At the request of the contractor for the liner contract, the width of the eastern embankment was increased, as this was to serve as a work area for the welding of the floating liner (welding zone).

Another request from the liner contractor was that the bottom of the storage was changed from wedge-shaped to 7 meters wide along the entire length of the storage (with a slight slope from west to east). This was done to ensure that the bottom and side liners could be laid and welded together according to DS466 (Danish Standard for the Construction of Landfill Sites). Despite the geometric changes, the storage size of 70.000 m^3 was maintained.

In the tendered design, a drainage system was built into the bottom of the storage to handle rainwater during the construction process. The contractor proposed to drop the drainage system and instead manage rainwater with ad hoc drainage pumping, which was accepted.

Inlet and Outlet Arrangements

The contractor detailed the inlet and outlet arrangements, including the diffusers, liner penetrations, foundations and piping between the storage and the pump basement.

The pipe part of the liner penetrations and the pipe parts that were cast into the foundations were made of stainless steel, while the actual inlet and outlet arrangements, as well as the pipelines between the storage and the pump basement, were made of black steel. This led to some challenges with how to corrosion-proof the welds between the stainless-steel pipes and the black pipes in the ground outside the foundations, partly because there were no pre-installed sleeves on the pipes before they were welded together. This was solved by wrapping the welds in tar tape. The welding work was done before liner installation, as welding should be avoided after liner installation.

The inlet and outlet arrangements are designed with some perforated plates whose primary purpose is to ensure a homogeneous flow from the diffusers into the storage. The hollow plates also act as a coarse filter between the storage and the pumps in the pump basement. It was a design requirement that the hole ratio in the perforated plates was 50%, which was also shown in the production drawings. However, the delivered hole ratio for the top and middle diffuser was only 20% and 18% respectively, which would result in a pressure loss across the perforated plates that were 10 and 12 times greater than the design values. These perforated plates were therefore replaced after the diffusers were installed on the foundations. The replacement involved the use of angle grinders and welds, and a thorough covering was therefore made to prevent sparks etc. from hitting and damaging the bottom and side liner.

Subsequently, the bottom and side membrane throughout the pit storage were replaced due to cracks in the first liner delivery, see the following chapters. This meant that the already installed diffusers had to be removed and reinstalled.

7.3 Establishing the Liner Contract

The liner contract started in June 2020 and was completed in August 2020. A protective liner was then installed, which protects against fallen leaves, dirt, and oxygen diffusion during water filling.
The installation of the PP membrane went according to plan. It was very hot at times and the temperature on the liner could reach over 40 °C. Figure 12 shows the liner installation:

Figure 12: Reporting on the liner work at the steering committee meeting on July 8, 2020.

Water filling began in November 2020. The transmission line to the substation was not ready for use, therefore a temporary solution had to be rigged. The storage was filled with water from VEKS' transmission system.

7.3.1 Leakage 1

Leak 1 occurred shortly after water filling began, which triggered an alarm from the installed leak detection system. It was then discovered that a weld seam was not fully welded in the lowest area of the slope edge between the south and west slope. The water level was lowered, and the repair carried out in December 2020.

7.3.2 Leakage 2

Leak 2 also occurred during filling, which in late January 2021 again triggered an alarm from the leak monitoring system.
Subsequently, a diver discovered damage at the bottom of the southern slope. In the further course of events, the temporary protective liner (made of HDPE plastic) was opened, which made it possible to see fracture damage to the PP liner in various places.
A large crack led out of the basin on the south side, over the slope and into the anchor trench. In the anchor trench, the temporary plastic liner was secured with wooden stakes to prevent slipping. In some places, it was found that the wooden stakes had also partially penetrated the PP liner buried in the anchor trench. The large crack mentioned above led to one of these wooden piles. However, a crack was also found in the corner between the western and northern slope.

To carry out further investigations, it was decided to empty the storage and remove the temporary protection membrane. As a result of the exposure of the PP liner, further cracks developed over time, and it was decided to replace the PP liner.

Initiated Tests by Supplier

Various studies and stress tests were performed by the manufacturer, both on samples of the material used for the first installation (start-up roll first production) and with new material additives that were optimized to withstand sub-freezing temperatures. These tests included Charpy (impact pendulum) tests, tensile and tear tests, tensile tests, as well as nail hammering in a climate chamber and outdoor exposure to cold temperatures in winter with different stress situations (e.g. hammering). The goal was to find both practical influences and new additives with improved cold impact strength. This led to an optimized material composition with improved properties at low temperatures.

Initiated Tests by the Client

SKZ

From the client's side, material tests were also sent to SKZ (Kunststoff Zentrum Würzburg, Germany). Samples from the pit storage (at different locations), spare samples of the same batch (from an unused roll on the site) and a sample with the new material composition optimized by the manufacturer were tested. The tests performed at SKZ included IR spectroscopy, DSC analysis, OIT, low temperature folding, puncture behaviour at -10 °C, tensile test at 23 °C and -10 °C.
Polypropylene-typical behaviour patterns were found in these tests. It was also found that material degradation occurred on the side of the samples exposed to UV light. However, it could no longer be determined how long the samples had been exposed to the weather (later tests showed that UV exposure for 3 months does not impact material properties). Compared to the samples from the unused roll, the samples from the material installed in the pit had lower mechanical material properties, while on the other hand, significantly better mechanical behaviour was observed for the new material, especially at low temperatures.

DTI

Simultaneously with the installation of the improved PP liner, it was decided to carry out a test program to determine the lifetime according to the method of the Danish Technological Institute [2]. This optimized program includes, in addition to several years of exposure to hot laboratory water at 115 °C on one side of the geomembrane and air on the other side of the geomembrane, pre-weathering of the samples according to ISO 4892-3.
Depending on the geographical location, 18 months of outdoor exposure can usually be simulated in 1,000 hours. Therefore, sampling was planned after 12 days (simulation of approx. 3 months), 3 weeks (approx. 9 months) and 1,000 hours (approx. 18 months). The collected samples are then subjected to accelerated aging using the DTI method for up to 60 months. Samples will be taken at scheduled intervals over the next few years and their mechanical properties will be tested in tensile tests.
The reason for this combined exposure is to better understand the influence on a liner's lifetime from both UV exposure during the construction phase and hot water exposure during the operational phase.

7.4 Re-establishing of the Liner Contract

Geomembranes for construction are factory-produced and tested building materials. It is the responsibility of the on-site installation to transfer the manufactured material properties to the final application as best as possible. Plastic geomembranes as the chosen essential sealing component for the storage medium (water) in a PTES must not only be leak-proof, but also resistant to aging at permanently high temperatures. In Høje Taastrup, a geomembrane made with polypropylene as the raw material was chosen. In general, polypropylene, in addition to having thermoplastic properties that are important for easy installation, has a significantly higher melting temperature than polyethylene. This makes PP more suitable for high-temperature applications, but also means that the material loses flexibility at low temperatures.

Prior to the installation of the improved PP liner, the condition of the surface and protective geotextile layer was inspected during an on-site inspection. It was found that washouts from rain caused damage that made it necessary to repair the underlying soil to achieve a surface as flat and rock-free as possible before implementing the geotextile and PP liner. These repair activities were carried out successively in the time leading up to the placement of the PP liner, considering the sensors of the installed leakage detection system, which were also tested for functionality.

The new installation of the PP liner considered the lessons learned from the first installation and the results of the subsequent material tests. This included, among other things, systematic planning of panel laying, work sequence and welding to achieve an installation as free as possible from stresses. For example, two differently aligned surfaces (e.g. between two slopes or slope and bottom) were connected exclusively in the morning to minimize/avoid a trampoline effect that can occur in geomembrane installation due to temperature-related shrinkage of the plastic material. The geomembrane surface temperature measured in the morning in Høje Taastrup was around 15°C, while the brighter surface of the PP liner reached 37°C during the day.

In addition, a liner panel (Figure 13) was laid in the four sloping edges, moving the seams from the edge further in. In addition, the daily production of laid lanes on a slope were welded together on the same day, while the connection of the last lane was done the next day. The reason for this was to allow any production-related residual stresses in the material (e.g. due to any cooling in the rolled state after having passed the production line) sufficient time to relax in the rolled state before any local stresses are introduced as a result of welding.

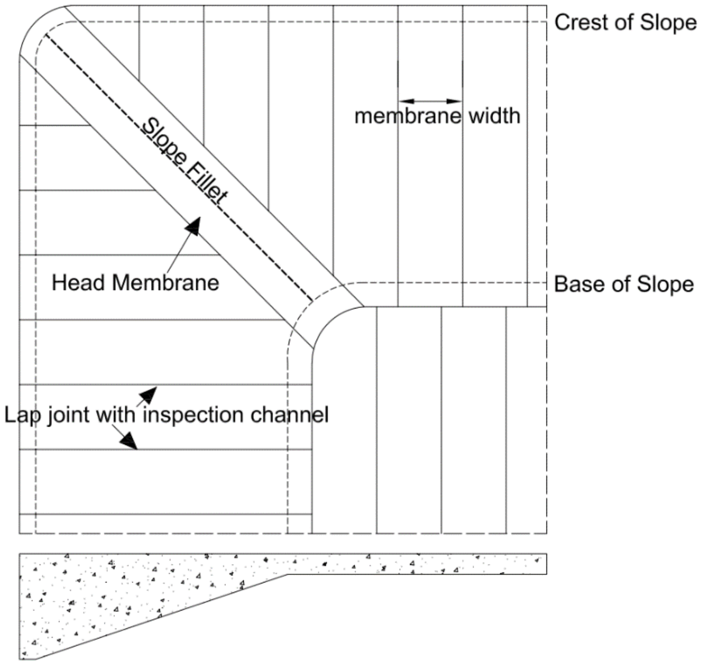


Figure 13: Liner installation principle.

In addition, electrical leak detection for exposed locations was performed after the completion of the PP liner installation using the arc test method (see Figure 14).

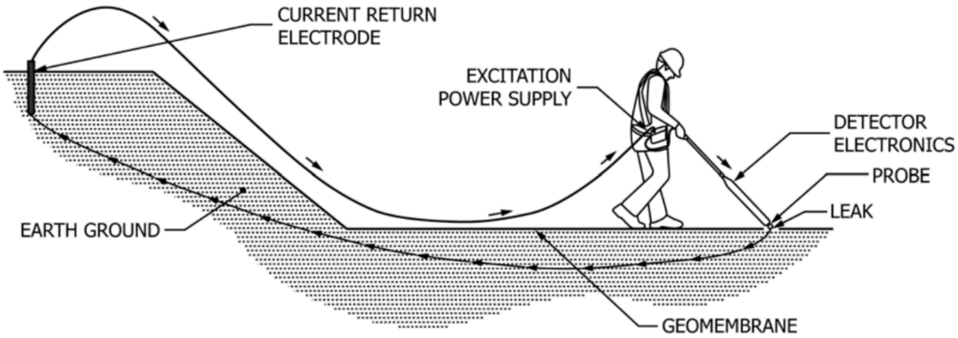


Figure 14: Arc test principle (figure taken from ASTM7953 Standard Practice for Electrical Leak Location on Exposed Geomembranes Using the Arc Testing Method).

Another measure was the involvement of a supervisor to qualitatively monitor the welding and installation activities on site on behalf of the client. Compliance with technical criteria for the installation and welding of geomembranes according to Danish (DS/INF 466) and German (DVS) standards, their documentation requirements and the special requirements for the PP liner used were monitored.

When installing the temporary HDPE protective liner, welding and testing documentation was not required, leading to a faster installation. This liner was later removed again before the implementation of the lid's PP floating liner next spring. The purpose of the protective liner is, on the one hand, to maintain the water quality of the incoming district heating water as much as possible during the filling process to minimize or completely avoid subsequent cleaning efforts. On the other hand, this layer covers the PP liner and protects against UV exposure.

7.5 Water Filling and Protection of the Liner During Filling

After installing the PP liner and before installing the temporary HDPE liner, an irrigation system was implemented throughout the basin. This system was designed to allow heated district heating water to enter the basin from all sides at the same time from the top of the slopes. The district heating water came from the same supply as the water entering through the lowest diffuser for filling. The reason for this measure was the temperature application range of polypropylene, which makes it superior at high temperatures but weaker at low temperatures. And although the HTR PP liner for use at permanently high temperatures was modified to withstand low temperatures, PP as a raw material and its behaviour at low temperatures, for example, is not comparable to polyethylene. In addition, the installation of geomembranes outdoors is basically weather-dependent and certain criteria must be met to achieve a quality weld (dry, not too cold, ...). Therefore, installation work is basically done during the warmer months of a year, while water filling is typically scheduled during the colder winter months.

When filling, the water level rises slowly. As a result, the bottom of the basin is covered with water quite early, while the surface of the geomembrane in the upper part of the slope is covered much later. The areas not covered by water are therefore exposed to ambient temperatures for a longer period of time. This can cause the temperature of the installed liner to drop below freezing during very cold periods. For surfaces covered in water, temperatures between 4 and 5°C could be measured even on the coldest days.
The functionality of the irrigation system was verified with thermal photos and temperature measurements below the top of the dam (see Figure 15).

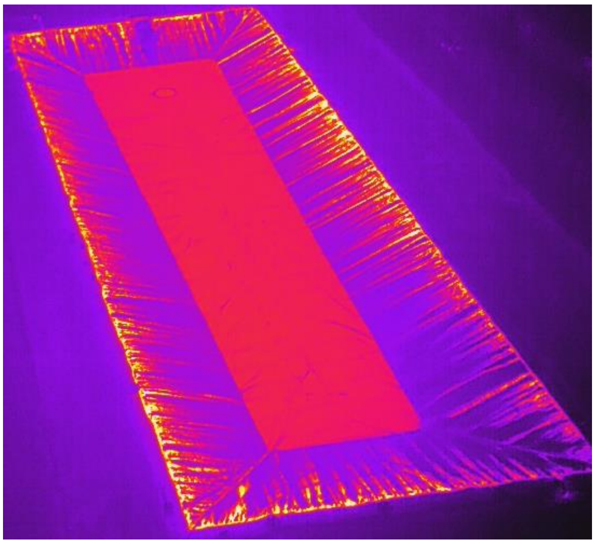


Figure 15: Thermal photo of irrigation system during filling. November 2021.

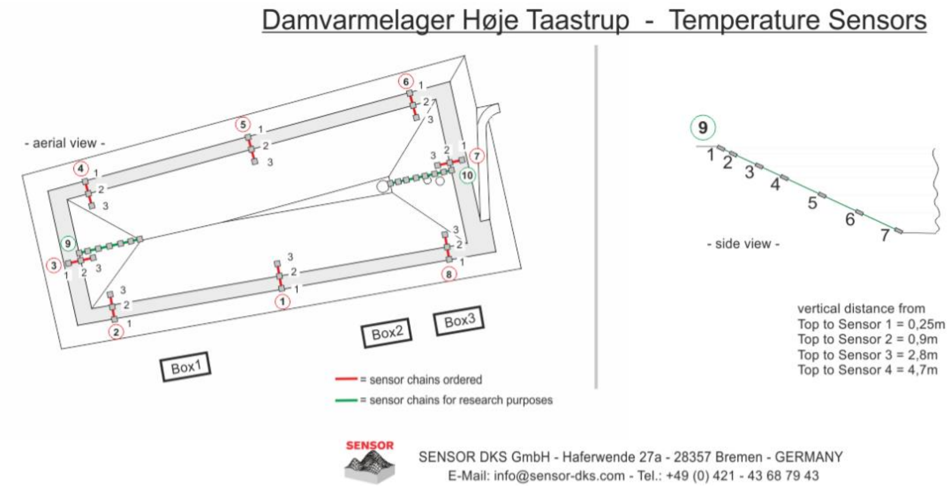


Figure 16: Temperature sensors to check the function of the irrigation system.

In general, it can be distinguished into two main phases regarding the load on the sealing of a PTES. The filling phase, where the liner is partially submerged under (cold) water and partially exposed to the surrounding environment. The water level rises and thus the load increases. And the operational phase, where the liner is fully submerged under heated water. Both situations lead to temperature-dependent elongations/contractions. Depending on the desired use and choice of materials, it is recommended to pay attention to this. (see Figure 17)

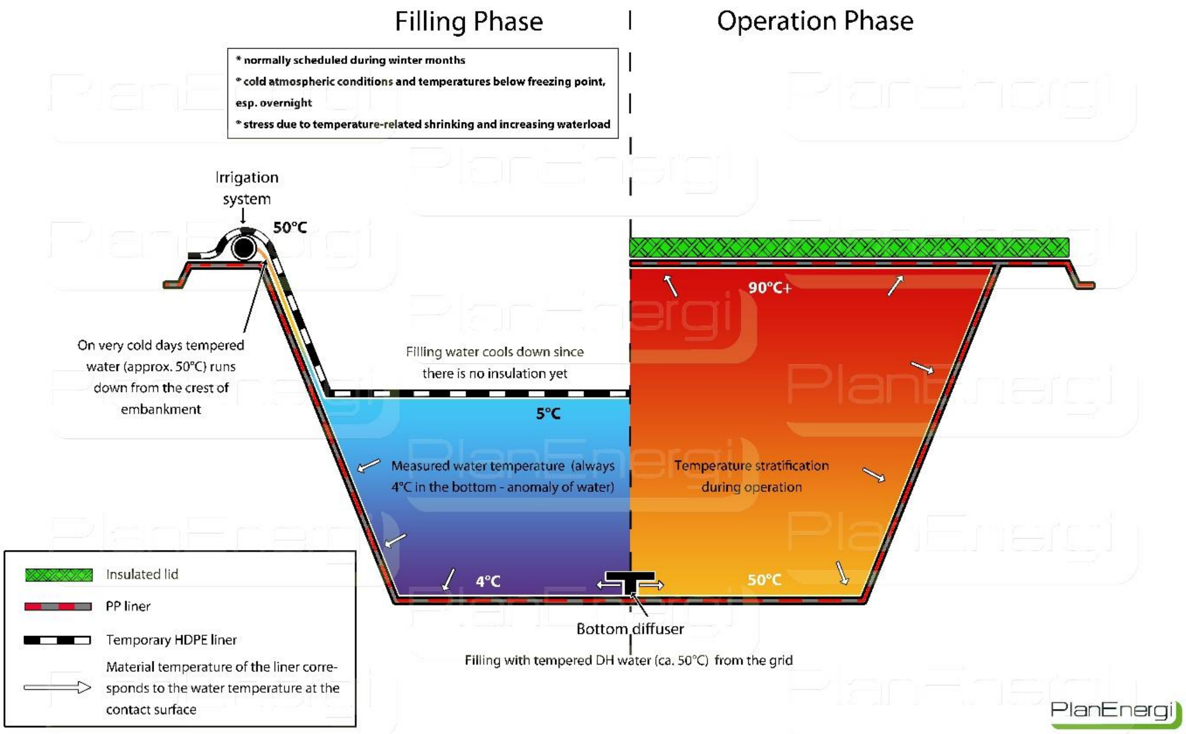


Figure 17: Illustration of the difference in temperatures between the filling and operating phase and technical measures undertaken in Høje Taastrup to protect the liner during filling.

7.6 Leakage 3

Leak 3 occurred after the temporary HDPE liner was removed and before the floating PP liner was installed. Before the floating PP liner was floated out onto the water, it was necessary to dismantle the irrigation system that was attached around the top of the dam. The pipes were attached to the PP side liner with PP straps that were adhered using hot gas. During dismantling, these straps were partially torn off instead of being cut. A hot gas weld is not a welded joint, but this type of joint is nevertheless a thermal fixation of two plastic surfaces to each other. Rough handling during disassembling can therefore cause damage to the material. Such damage to the top of the dam resulted in a crack that extended into the basin about 50 cm below the water level.

For the repair, a caisson was made from plastic sheets. Neoprene seals were attached to the bottom edge of the box. This caisson was lowered from the side edge above the repair site, placed on the PP liner on the slope and subsequently weighted down to press the caisson against the PP membrane. Afterwards, the work area was drained, and the crack was closed with a patch attached with an extruder weld.

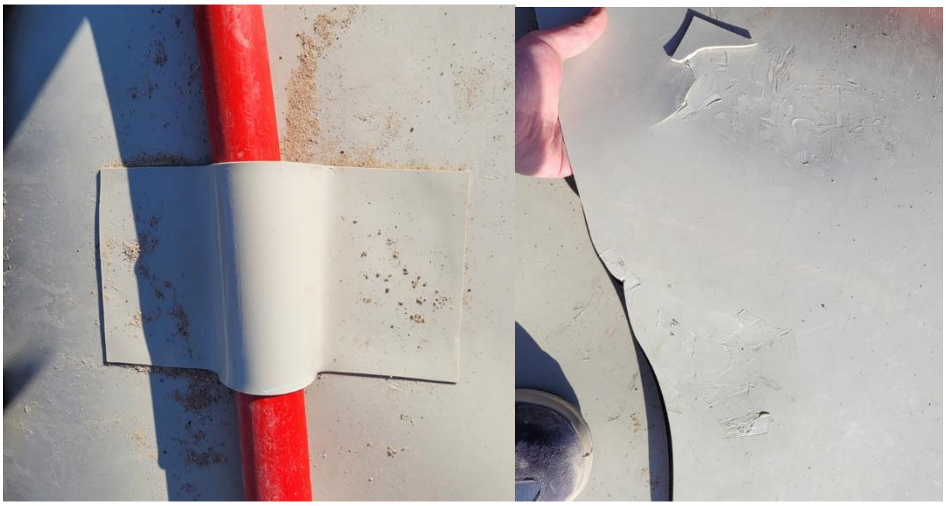


Figure 18: PP strap attached to PP liner and crack in PP liner.

Figure 19: Repairing a crack using a caisson.

7.7 Installation of the Floating Liner

For the installation of the PP liner as a floating liner, the welding work was carried out on the crown edge of the eastern slope. The width of the crown edge was approximately 12 m, which provided sufficient working space (welding zone). The underlying soil was smoothed and covered with geotextile as a protective layer. At the crown edge, the individual panels of the PP liner were then welded together (overlapping seam with test channel) and pulled step by step over the water surface. During the same period, the temporary HDPE liner on the western embankment was successively pulled out and removed.

Some unevenness as well as stones underneath the geotextile caused repairs to be made to the underlying soil after the work had started. As all welding and installation work on the lid's PP floating liner is carried out on this welding zone, there is a lot of activity from the technicians on this surface. Unevenness in the underlying soil of the welding zone can therefore negatively affect the quality of the floating lid liner. For future projects, it is recommended to qualitatively assess and approve the underlying soil of the welding zone in terms of its flatness (compaction) and freedom from rocks before starting the liner work.

In accordance with Aalborg CSP's chosen lid solution, mounting parts (manholes and ventilation outlets for venting) were welded into the geomembrane at designated locations. Care was also taken to ensure that the overlap direction at the overlap seam on the individual courses was aligned with the slope direction as it would occur in the finished installation state of the lid (see Figure 20).

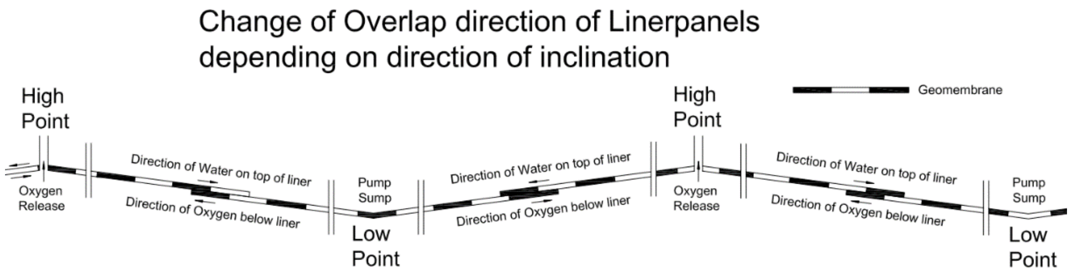


Figure 20: Change of overlap direction of liner paths in the floating lid liner.

During installation, the PP liner is pulled over the water surface as well as over the dam crest. This is where the PP liner from the sides of the dam is placed. When pulling the liner step by step, there is a risk of (small) stones getting between the liner on the crown edge and the pulled liner, that can lead to scratches to the liner.

As a conclusion from this experience and the content in section 7.6, a recommendation would be to consider an extra layer of protection placed on top of the crown edge PP liner. This can reduce the risk of damage during the dismantling of an irrigation system as well as protect the PP liner from potential scratches caused by pulling the lid liner.

7.8 Installation of Lid and Measuring Equipment

After the completion of the floating PP liner, the installation of the individual layers of the lid structure began.

The work began by cleaning some areas of the floating PP liner because dirt and stones had accumulated over time (especially near the edges). A protective layer (Geonet) was then rolled out, followed by the individual insulation layers. The prefabricated pump sumps (low points) were measured in advance, placed in the respective position on the floating liner and the insulation layers were correctly positioned all around afterwards. For drainage and electrical installations, empty pipes were laid into the insulation. The drainage pipes lead into a collection pipe laid in the crown edge with a connection to a nearby 2.000 m^3 retention basin. The stones and associated components were then placed. The laying of the stones was carried out using a vacuum truck.

At the end of the lid installation, the slope established due to the ballast was used for the removal of water accumulated during the installation, with the water flowing under the insulation sheets to the respective pump sumps. During the period of lid installation, there were no significant heavy rain events that would have necessitated additional measures.

Wind protection was done with up to 5 sandbags per insulation mat and layer, which meant that approximately 6,000 sandbags were needed during the lid installation.

Installation of Measuring Equipment in the Lid

The FLEX_TES project includes a measurement program where the measurement results must be reported after 1 and 2 years of operation. The necessary measuring instruments are specified by DTU and are used both to follow up on the operation of the storage facility (temperature profiles, charging and discharging, stratification, water quality, etc.) but also the effects of the nearby surroundings (soil moisture and thermal conductivity, temperature gradients in the soil layers outside the storage facility). Below is a list of the measuring instruments included in the measurement program.

Measuring instruments in the measurement program that are necessary for the operation of the pit storage:

- **Temperature bell strings** that are attached to the manholes and hang vertically down into the storage - each with 14 sensors. Due to the limited number of sensors, a set of 2 bell strings is needed to cover the entire height of the storage profile. The temperature profile is used to calculate the energy and water content of the storage and to forecast charging and discharging. In addition, the maximum temperature is monitored to avoid membrane degradation. The measurements are considered so important that redundancy with an extra set of bell strings in the second manhole is recommended.
- **Water level sensors** (guided radar and pressure transmitter) are placed in an external measuring well with a pipe connection to the storage. The water level measurement monitors both whether the storage unit is leaking and the amount of water and snow on the lid. The measurement is included in the calculation of the energy and water content of the storage together with the temperature measurements. The measurement is considered so important that it is recommended that the guided radar is supplemented with a pressure transmitter.
- **Energy and flow meters**, which are important operational instruments for collecting values for import and export of energy and water flow to and from the storage facility.
- **pH and conductivity meters**, essential for monitoring water quality so potential adjustments can be initiated.

Measuring instruments in the measurement program that are not necessary for the operation of the storage.

- **Additional water temperature sensors in the storage**, attached to the bottom of the pit storage with a plumb line but kept at a certain distance from the bottom via floats. The measurements provide DTU with precise knowledge of the bottom temperature. The bell strings do not provide exact information as the sensors move with the water expansion due to the attachment to the manholes.

- **Temperature sensor placed in the lid** that measures the temperature between the different insulation layers. Measurements are taken in two fields with 5 temperature sensors each. The measurements will give DTU an indication of the heat loss as well as a monitoring of the insulation properties (deterioration of insulation performance over time).
- **Temperature sensors in the ground close to the storage**, measuring the temperature profile throughout the depth of the storage. A temperature bell string is used as in the storage, lowered vertically at the dam crest. The string has 10 temperature sensors that are distributed evenly in a 16-meter-deep drilling.
- **Heat flux meters placed in the lid** that measure the heat loss from the lid. Measurements are taken in two fields with 3 heat flux meters each. The meters are placed in the same layer and connected in series to increase accuracy and get an average over a (larger) area covered by the three sensors.
- **Thermal conductivity sensor in soil close to the storage** to provide DTU with knowledge about the long-term impact of the thermal conductivity of the soil over time.
- **A moisture meter in the soil close to the storage,** located close to the thermal conductivity sensor. The two sensors provide DTU with knowledge about any changes in soil properties.
- **Moisture meters placed in lid** that measure the moisture between two layers of insulation. Measurements are taken in two fields, where the two moisture sensors are placed in an upper and a lower insulation layer. The measurements can be linked to periods of rainy weather but can also detect breaks in the top liner; however, only in the two fields that are measuring areas.
- **Weather station** that monitors weather conditions locally at the storage. In particular, recording the amount of rainfall can indicate whether the pumps in the lid are removing all rainwater from the lid, compared to the water level measurement and humidity meters, among other things.

The program's measurement values are collected and monitored by DTU, and the results are reported annually for the first two years of operation.

Figure 21 below shows the location of temperature sensors, heat flux meters and humidity sensors between the different insulation layers in the lid.

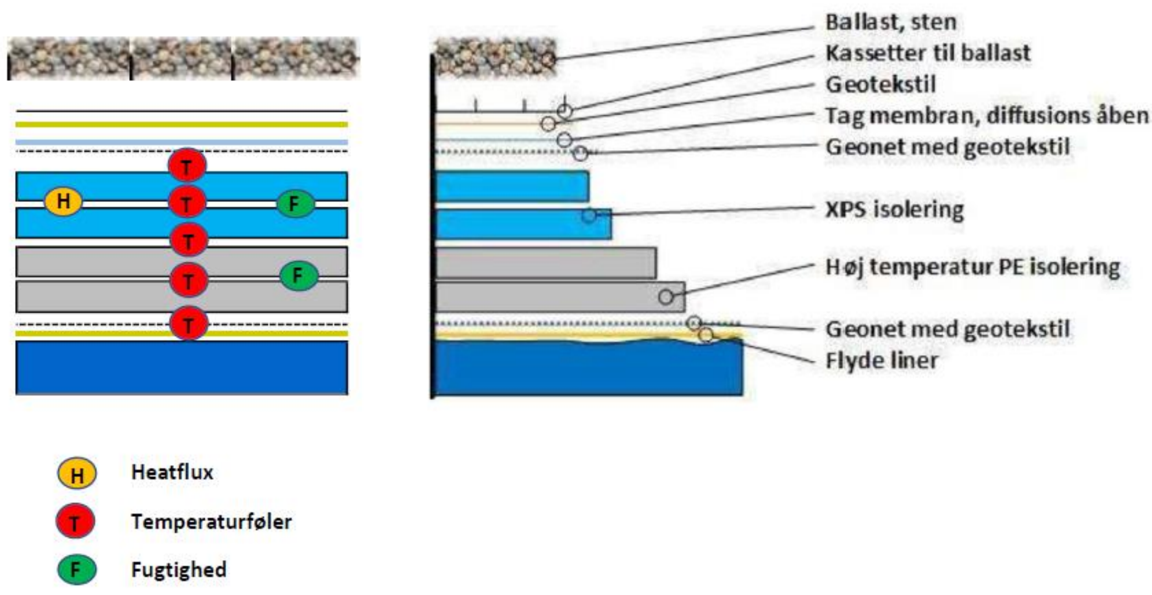


Figure 21: Location of sensors between the individual insulation layers

The lid construction consists of 10 sections, which are built identically. There is no difference between the individual sections, but it was planned to take the measurements at opposite ends of the storage in sections 2 and 4 as shown in Figure 22, as the distances to the electrical cabinets meant shorter cable routing.

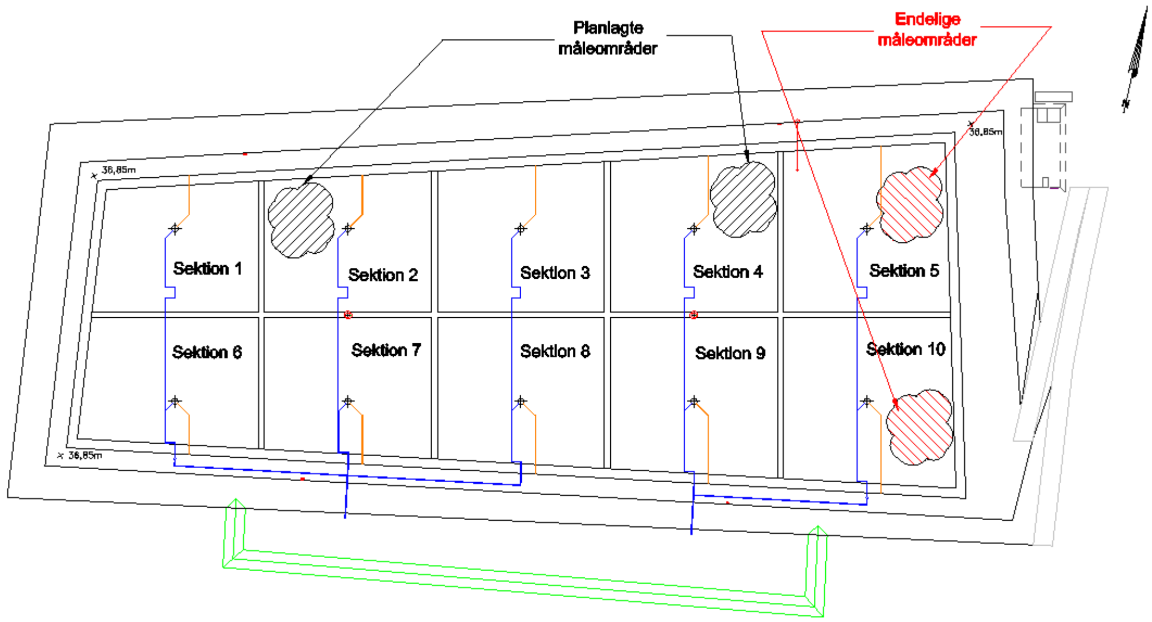


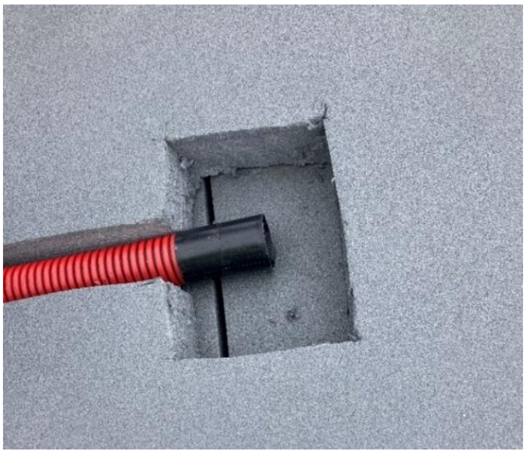
Figure 22: Planned and final target areas on the lid.

Parts of the measuring equipment had unexpectedly long delivery times, so the final placement of the measuring equipment was moved to sections 5 and 10. The lid assembly could begin starting at the eastern end of the storage without extending the overall assembly time.

Building the lid from the eastern end

Placement of the first temperature sensor

PT100 sensor for temperature measurement



Cut-out in insulation for Hygro-Smart humidity sensor HS3

Figure 23: Example of temperature and humidity sensor placement

Figure 24: Location of Hukseflux heat flux meters in the insulation (top view).

7.9 Inspection With Underwater Drone

An inspection with a ROV (remotely operated vehicle) for submarine operation in warm temperatures has been carried out after the heating of the water inside the storage facility was started. The inspection was performed at temperatures below 80°C to see the condition inside the storage at higher temperatures.

Sediments were found on the bottom. It also turned out that the distance between the lid and the top diffuser tower was only about 20 cm, while 40 cm was designed. In addition, small spots were found at the diffusors, indicating an initial corrosion. Calculations showed that the safety distance between the lid and the top diffuser tower is 6 cm, so the 20 cm did not pose an immediate risk. The corrosion probably stemmed from the diffusers having been installed for a period without water.

Temperature measurements showed that the bottom of the storage was around 50°C at the time of the inspection. It was possible to see that the liner surface was smooth and that no noticeable creases had appeared as a result of the temperature increase compared to the time of installation.

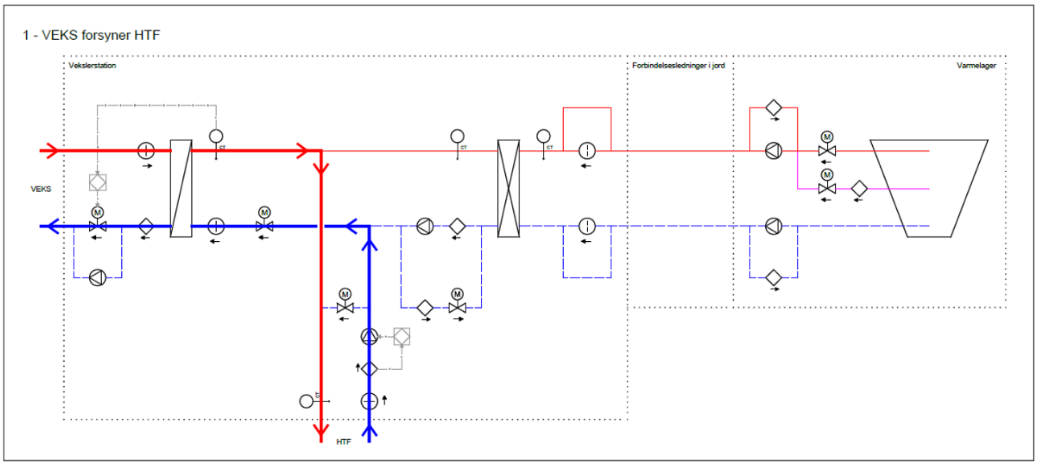
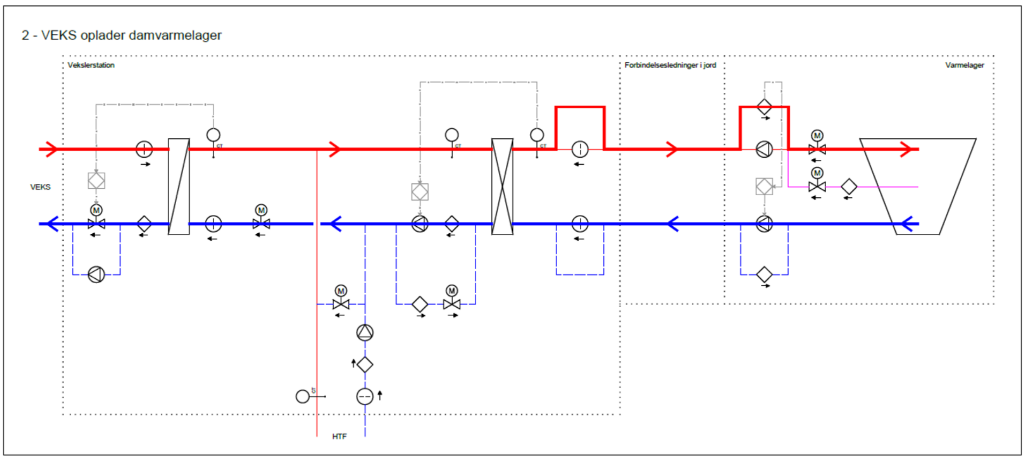
Figure 25: Phantom XTL underwater drone

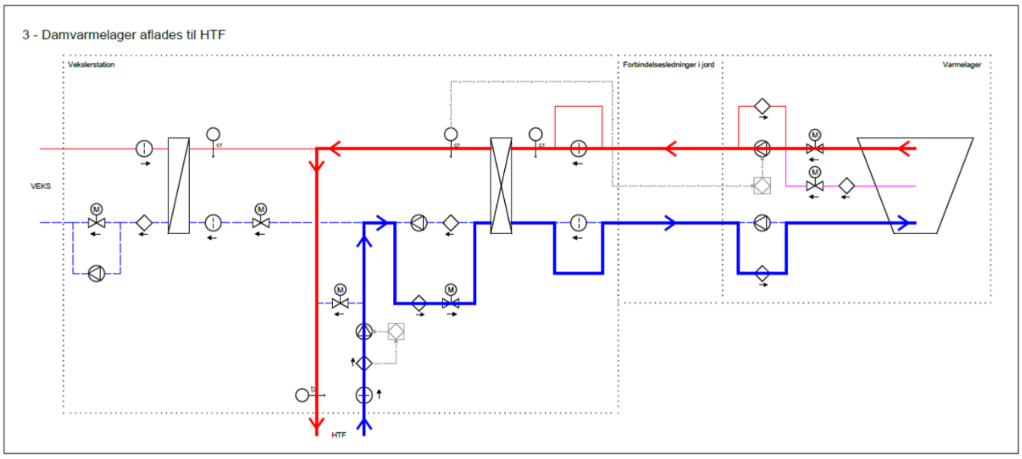
8 Handover, Testing, and Commissioning

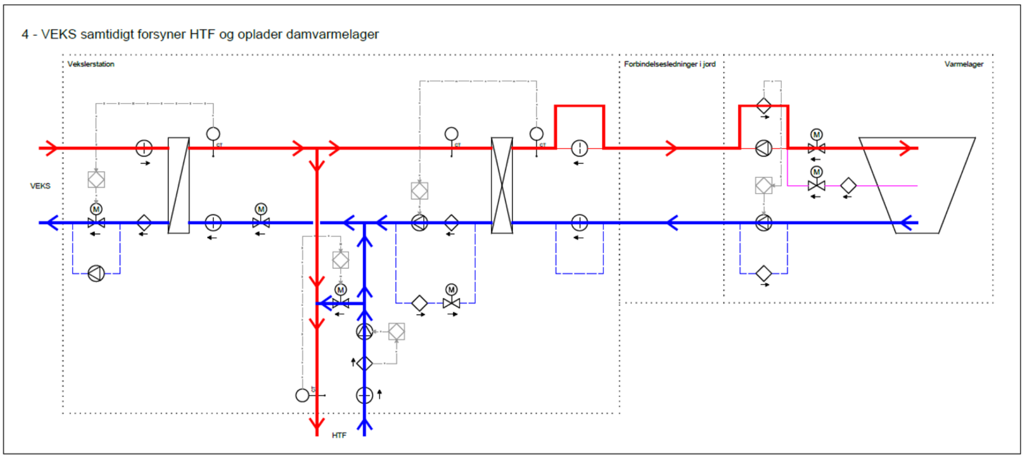
8.1 Time and Activity Plan for Handover

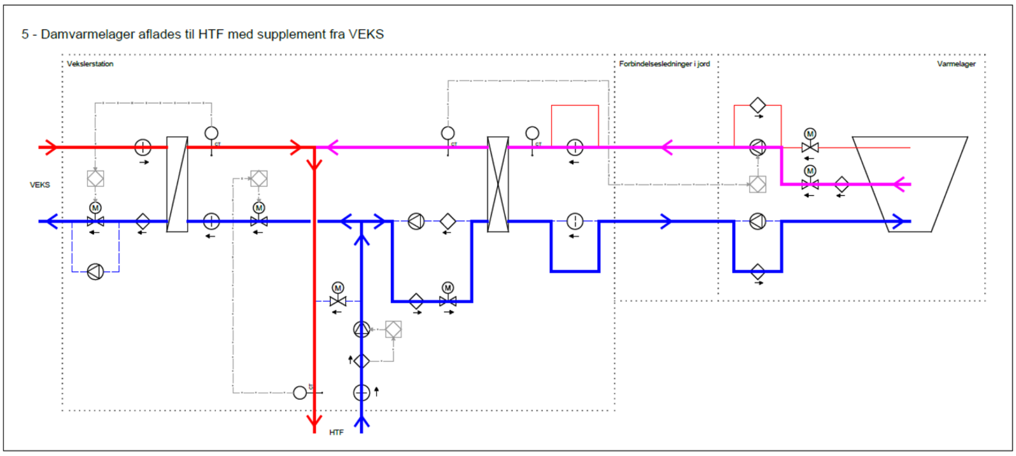
In connection with the planning of the handover, a time and activity plan were drawn up as a Pixi-book based on the project's overall management memo, showing the individual processes to be tested and the timetable for these.

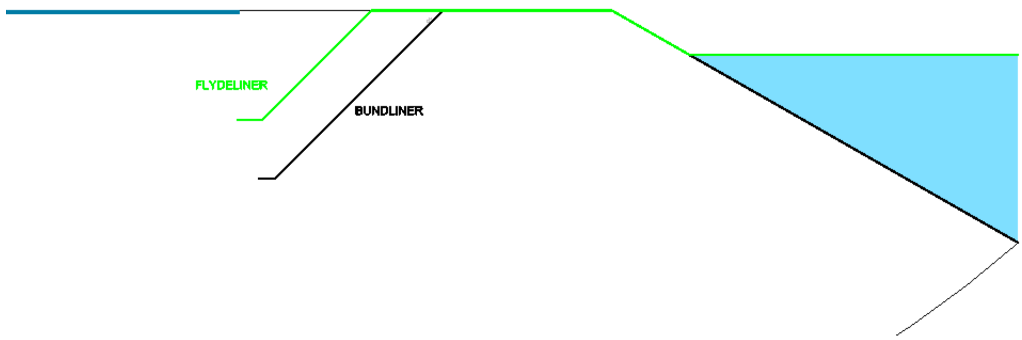
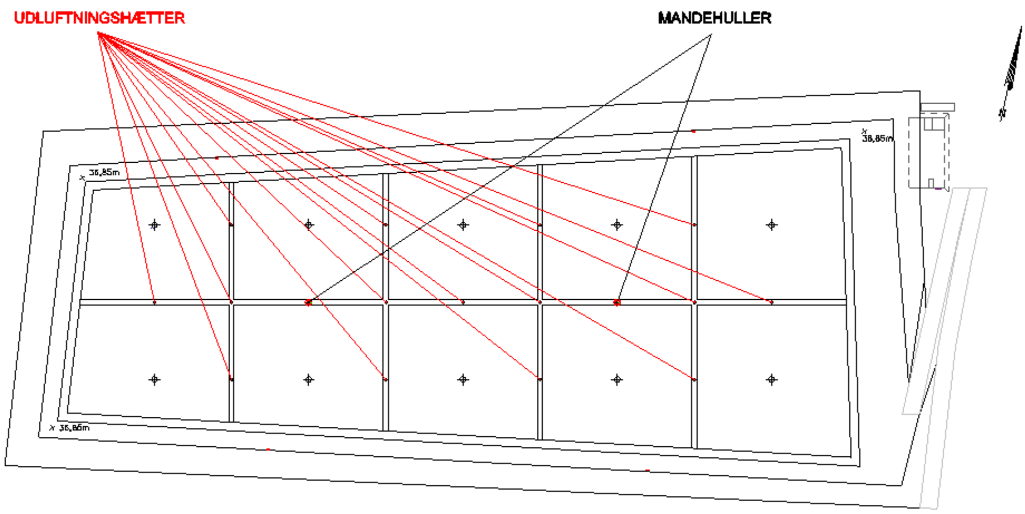
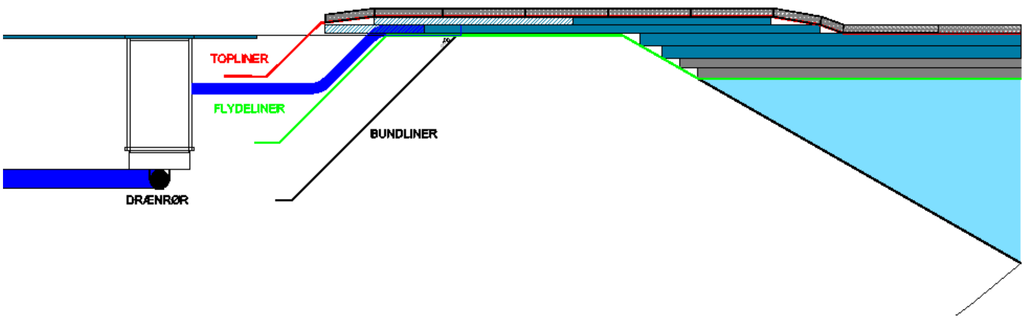
The Pixi-book for the time and activity plan can be seen below:

ID		
1	**VEKS SUPPLIES HTF**	**Client**
		**Cold test of the hy-draulics** **Start week 17 2022**
2	**VEKS SUPPLIES PIT HEAT STORAGE**	**Client**
		**Cold test of the hy-draulics** **Start week 17 2022**

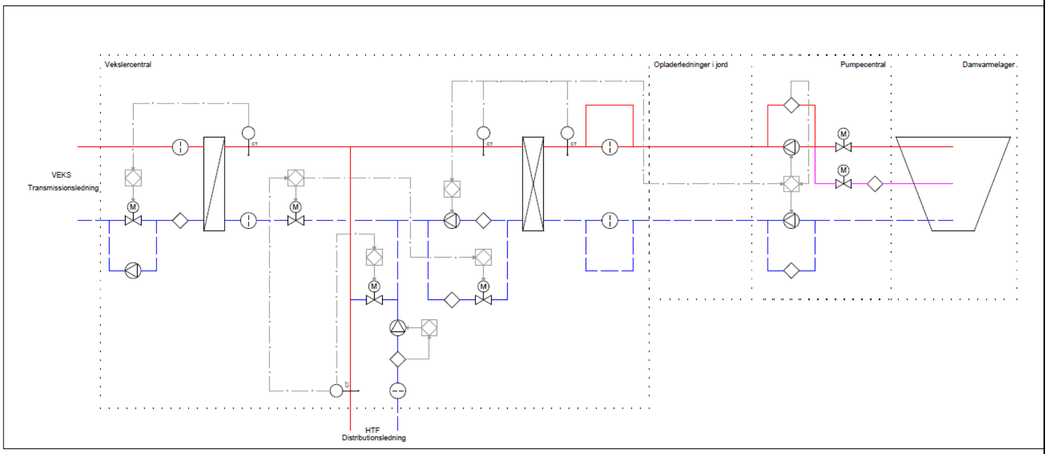
3	PIT HEAT STORAGE DISCHARGES TO HTF	Client
		**Cold test of the hy-draulics** **Start week 17 2022**

4	VEKS SIMULTANEOUSLY SUPPLIES HTF AND CHARGES PIT HEAT STORAGE	Client
		**Cold test of the hy-draulics** **Start week 17 2022**

5	PIT HEAT STORAGE DISCHARGED TO HTF WITH SUPPLEMENT FROM VEKS	Client
		**Cold test of the hy-draulics** **Start week 17 2022**

6	**SITE WALK-THROUGH AND HANDOVER OF BUILDING SITE AND FLOATING LINER**	**All**
		**Checking documen-tation and quality assurance of work. (Checks and proto-cols)** **Week 24 2022**
7	**CHECK THE PLACEMENT OF MANHOLES AND VENTILATION HOODS**	**PBJ/ACSP/HTF/PE**
		**Placement of man-holes and ventila-tion hoods accord-ing to drawing** **Week 24 2022**
8	**HANDOVER OF WELLS AND DRAINAGE SYSTEM INCLUDING DAM CREST**	**ACSP/HTF/PE/WK**
		**Handover of wells and drainage system Week 42 2022** **Handing over the dam crest/roadway Week 42 2022**

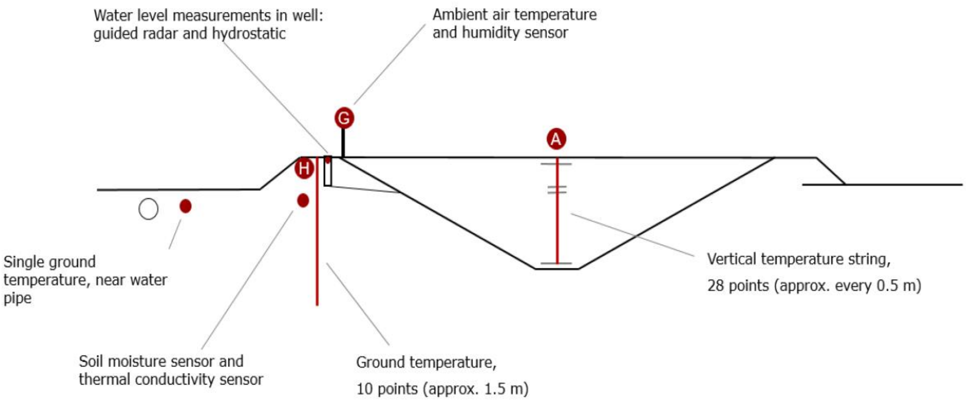
9	CHECKS OF ELECTRICITY AND INSTRUMENTS FOR OPERATION	HTF/PE



Is there connection and are values accurate?

Week 44 2022

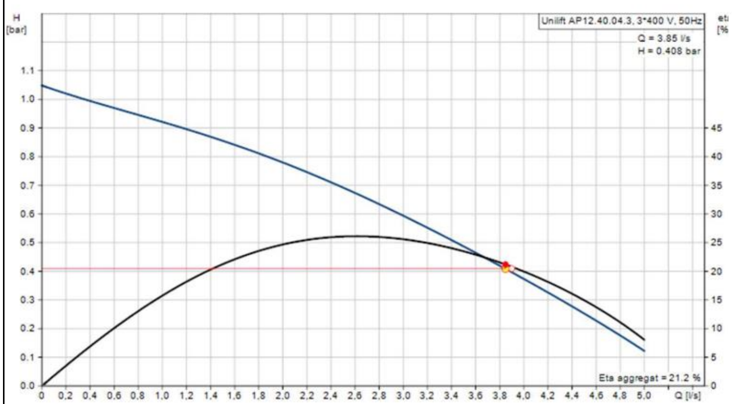
10	CHECK OF INSTRUMENTS FOR DTU MEASUREMENT PROGRAM	HTF/DTU/PE



Is there connection and are values accurate?

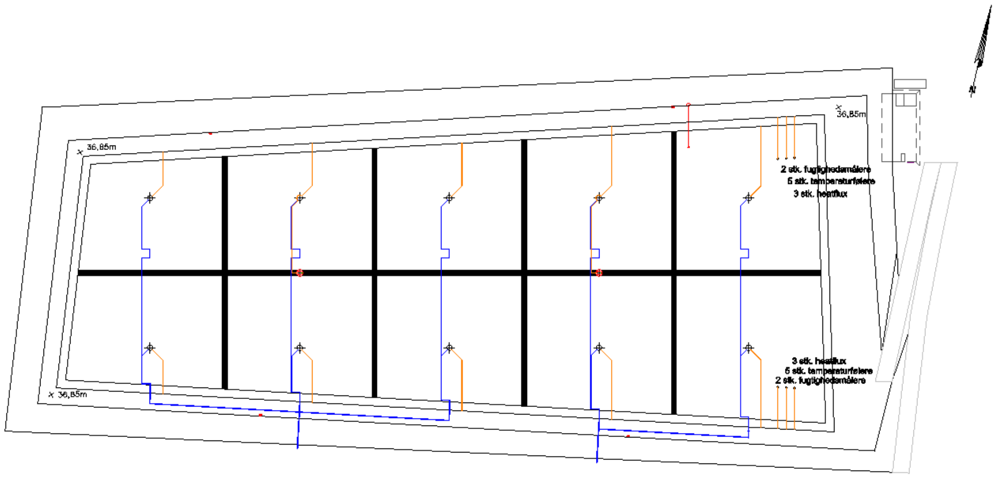
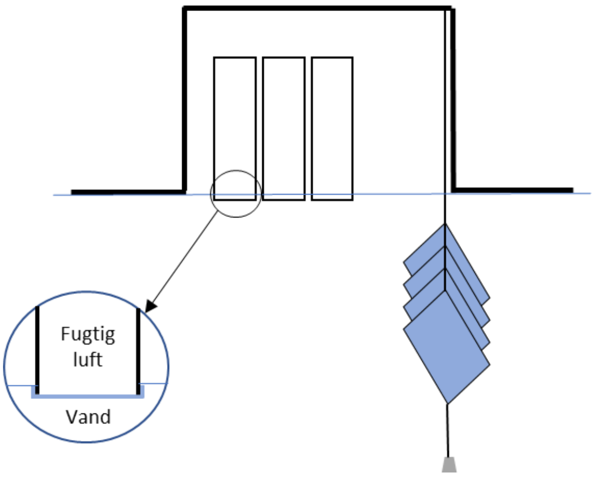
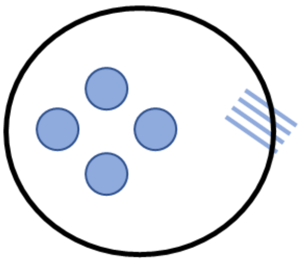
Week 44 2022

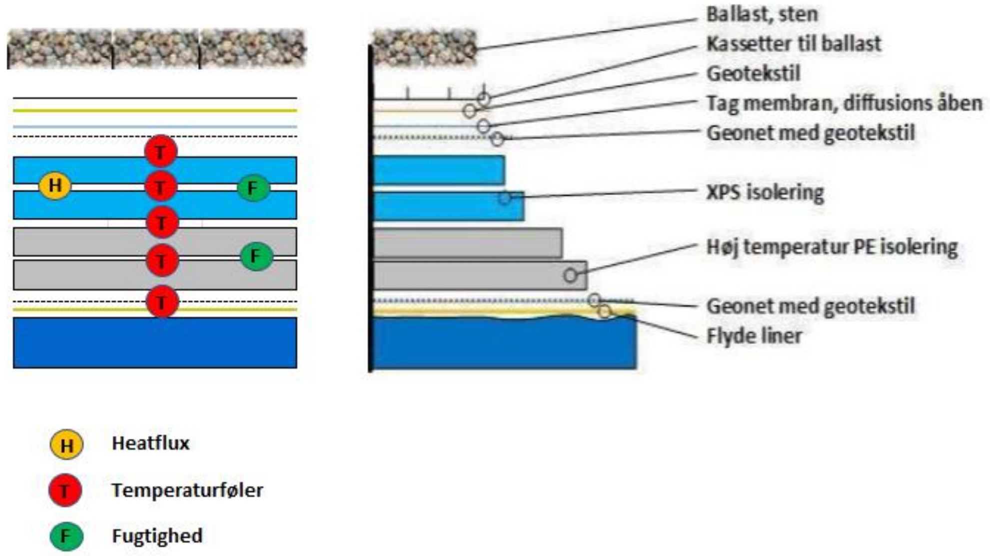
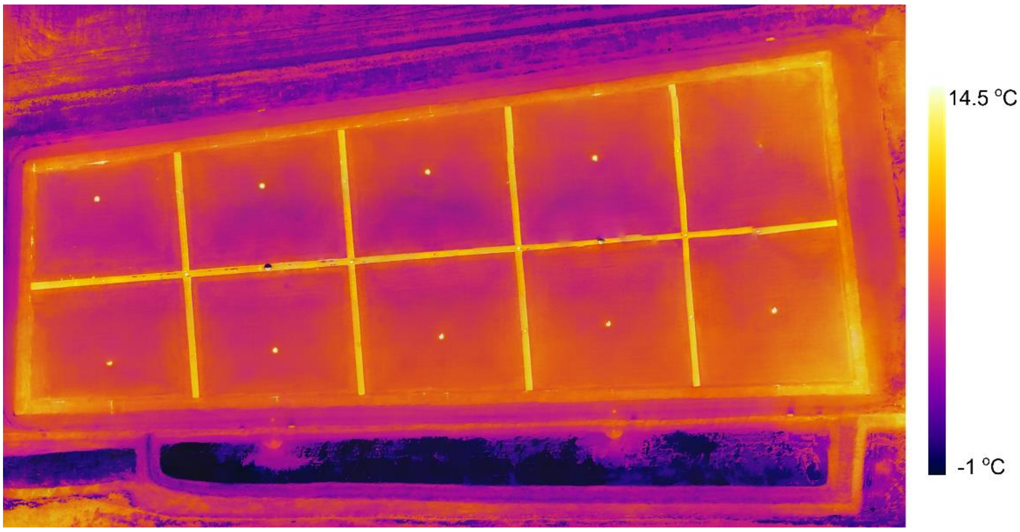
11	CHECKING THE DRAIN PUMP SYSTEM	ACSP/HTF/PE



Checking the drainage system

Week 46 2022

12	DELIVERY OF LID	ACSP/HTF/PE
		**Delivery of lid** **Week 46 2022**
13	MEMBRANE SAMPLES IN MANHOLE	HTF/PE
	 	**Pipes with membrane pieces at the bottom and membrane samples are immersed in manhole after.** **Week 48 2022.** **Frequency of sampling to be agreed.**

14	CALCULATION AND RECORDING OF HEAT LOSS	HTF/DTU
		**Not relevant until the system is in normal operation.** **The heat flux can be recorded after connecting measuring equipment.** **Calculations can be performed after connecting temperature sensors.** **Early 2023**
15	**DRONE FLYOVER FOR THERMOGRAPHY**	**Client**
		**Drone flyover** **Thermographic control of thermal bridges. The image is from a morning with sunrise in the east, which has caused higher surface temperatures at the eastern end.** **Early 2023**

8.2 Handover of Earthworks

On December 19, 2022, a handover meeting was held for contract A. The soil, concrete, and pipe contract, carried out by Wicotec Kirkebjerg A/S as a turnkey contractor.
The handover was approved, and the work is covered by the general contractor warranty (5 years).

8.3 Handover of the Liner Contract

The contract was carried out by PBJ as a turnkey contractor for both bottom and side lines.

The bottom and side lines were handed over on March 29, 2022, after completion of water filling and determination that no leaks had occurred during water filling. The handover was approved.

After water filling and delivery of the bottom and side lines, the floating liner was installed in the period from April 2022 until May 2022.
The floating liner was handed over on June 13, 2022, and the handover was approved.
The liner work is also covered by a general contractor warranty.

After the handover meeting on the floating liner, a handover meeting was held with Aalborg CSP, after which Aalborg CSP took over the floating liner.

8.4 Handover of the lid contract

The lid contract was carried out by Aalborg CSP A/S as a turnkey contractor.

The lid construction was carried out in the period from June 2022 until October 2022, where the delivery of the lid contract was made on October 24, 2022. The delivery was approved.

The lid delivery is covered by a general contractor's warranty.

9 Economy

	pit thermal energy storage with connections						
	ECONOMIC OVERVIEW		Budget	Budget	Rev. Budget	Rev. Budget	
			08.01.2019	01.05.2020	02.10.2020	01.01.2023	23.05.23
Projektnr	Activity	Description of costs					Status
							realized
			mio. kr.				mio. kr.
4000	Development	Costs before FID	4,10	4,10	4,10	4,10	4,10
4008	Project planning, -execution	Project planning, supervision, etc.	5,00	6,00	6,00	6,30	6,02
4009	PTES + pumping station	storage, pump station, liner and lid	27,70	30,00	35,60	39,50	40,14
4010	Pipeline + Highway Crossing	Pipeline + Highway Crossing	13,10	10,00	7,00	7,00	6,99
4011+4012	Exchanger station building	Exchanger station building, site developme	4,30	4,50	4,70	5,00	4,92
4013	Exchanger station technical parts	Technical installations in the exchange stati	11,40	11,90	13,30	14,50	14,36
4014	Pump station technical parts	Technical installations in pumping station	5,60	5,70	4,70	4,90	5,22
4015	Electrical connection	For pump station and exchanger station	3,80	2,80	2,10	2,10	2,03
4016	Water filling (Purchase, Treatment)	Water purchasing/treatment	3,40	3,50	4,50	4,00	4,10
4018	Time (VEKS & HTF)	50%VEKS+50%HTF	1,10	1,10	1,50	2,50	2,61
	Interests		0,10	0,10	0,10	0,10	
	Sum		79,60	79,70	83,60	90,00	90,49
	EUDP		-4,20	-4,40	-10,00	-10,00	
	Total		**75,40**	**75,30**	**73,60**	**80,00**	**90,49**

The table above shows the cost development of the project from the start to the status at the end of May, when the project is almost completed.

The cost increase since the project started is partly due to a more expensive liner solution and partly due to a more expensive lid solution. However, the grant from EUDP and changes in price indices since 2019 mean that the original budget requirement of a maximum of DKK 75 million in construction costs has been met.

New calculations from Ea Energy Analyses show that the system benefit calculated with FFH50 assumptions is DKK 7.8 million compared to DKK 6.1 million in the original calculation.

References

[1] PlanEnergi 2015. Udvikling af linere til damvarmelagre
[2] Paranovska, I., Pedersen, S., 2016. Lifetime Determination for Polymer Liners for Seasonal Thermal Storage

Overview of the main suppliers

Earthworks and inlet and outlet arrangement: WICOTEC KIRKEBJERG A/S www.wicoteckirkebjerg.dk
Lid delivery: Aalborg CSP A/S www.aalborgcsp.dk
Liner works: PBJ Miljø A/S www.pbjas.dk
PP-liner: AGRU Gmbh www.agru.at
Installation of PP liner: G quadrat Gmbh www.g-quadrat.de
Leakage detection system: SENSOR Dichtungs-Kontroll-Systeme GmbH www.sensor-dks.com
Consultant: PlanEnergi www.planenergi.dk
Sub-consultant district heating system: Damgaard rådgivende ingeniører www.damgaard-ri.dk