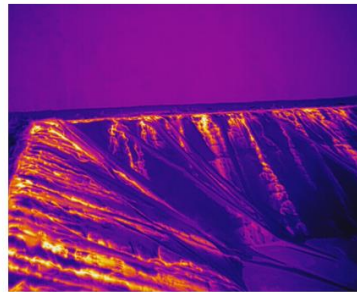
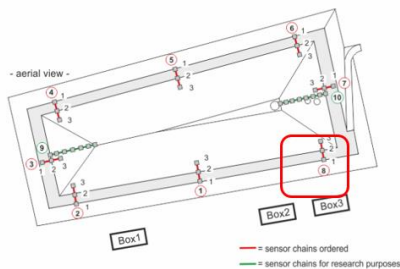


Integrate 2, Deliverable 2.3

New design of lid and in- and outlet systems

Temperatures have not been seen below 0 degrees Celcius

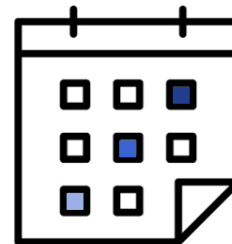


Temperature Chain 8		
Sensor 1	Sensor 2	Sensor 3
4.9	10.4	5.9
4.8	8.6	5.5
4.8	7.8	5.1
4.8	6.9	4.6
4.8	5.6	4.0
4.8	4.4	3.6
4.8	3.7	3.3
4.8	2.9	2.8
4.8	2.3	2.6
4.8	2.3	2.6

PE-FOAM - LIFETIME Assessment



Lid Material	Thickness	λ
PO-X*	125 mm	0.038 – 0.044 W/mK
XPS	150 mm	0.033 – 0.037 W/mK



Failure criteria

heat loss increase	20%
XPS temperature	65°C

Lifetime estimates

seasonal storage	> 38 years
buffer storage	> 14 years

The Integrate 2-project has project number: 64020-2025 at EUDP

Deliverable 2.3 New design of lid and in-and-outlet systems

Participants in the Integrate 2-project:

- PlanEnergi – Project manager
- Vestegnens Kraftvarmeselskab I/S (VEKS)
- EA Energianalyse
- Hjørring kommune
- JKU Linz

Contributors to D2.3:

Per Alex Sørensen (editor)

E: pas@planenergi.dk

Prof. Gernot Wallner, JKU Linz

Lukas Peham, JKU Linz

Daniel Trier, PlanEnergi

Hendrik Wetzel, PlanEnergi

Geoffroy Gauthier, PlanEnergi

Niels From, PlanEnergi

Zenia Lagoni, PlanEnergi

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1 Summary and conclusion

In task 2.3 in the Integrate 2 project the purpose has been to further develop solutions for Pit Thermal Energy Storages (PTES) with focus on:

- A new floating lid construction for PTES that can resist 95 °C for more than 20 years using a new developed PP-liner and a new generation of polymer mats as insulation.
- In – and outlet systems that are corrosion free and with high capacity (200-300 MW)

The work has been carried out in 26 workshops between JKV Linz and PlanEnergi and the results are that a new floating lid construction has been developed, and as part of this development a continuous testing of insulation mats from Termonova has been carried out. The test results showed possibilities for further improvement of the product and test of the improved product is still ongoing. Calculations using the not improved product shows lifetimes of 11 years by 90 °C for a 300 mm insulation layer (lifetimes defined as 20 % extra heat loss). The result for the improved product will probably be ready during 2024. Also investigation of alternative solutions for weight pipes and alternative liner products has been carried out. Alternative liner products have not been found and alternative weight pipe solution are still under consideration.

Corrosion free in- and outlet systems have been investigated for solutions with glass fiber and PP. Tests was carried out for glass fiber products but did not show, that glass fiber could be a solution since internal delamination was observed already after one year at 95 °C. PP looks like a promising solution since pipes are already a product from AGRU in Austria and diffusors can be built. The PP-solutions was investigated late in the project and investigations was not detailed enough to conclude if problems would not occur.

During and after the project the following can be concluded for further work

- A common specification of the polymer liners is needed to be able to compare existing and new products on the market. The test should result in lifetime at the material at different temperatures under specified water and oxygen conditions.
- PP for in- and outlet and to connection pipes might be a solution, where removal of salts and PH>9,5 can be avoided. Model testing (mockups) and solving the details when penetrating liners etc. has to be carried out.

There are development projects where this might be done, such as IEA-Es Task 45 or the EU project TREASURE.

2 A new floating lid construction

During the FLEX_TES project [1] it was recognized that the lid construction proposed by PlanEnergi would have difficulties if it should last more than 20 years. Some of the difficulties were solved during the project, since weight pipes were removed from the floating liner and the floating liner was replaced by a new developed PP-Liner from AGRU in Austria. Also, the PEX insulation mats in the lid, delivered by Termonova in Finland, were replaced by a new generation with higher density and new stabilizer added.

Moreover, a new lid construction was developed during the FLEX_TES project, but still the construction could be optimized because:

- Moisture coming through the floating liner could still be a problem for the insulation material.
- Water ponds on the topline could still be a problem.
- Getting rid of the rainwater for larger storages (>200,000 m³) could still be a problem.
- Maybe there are cheaper and better alternatives to the PP-Liner.

Also, oxygen coming through the floating liner should be avoided, if possible, as it causes corrosion risk in in- and outlet pipes and diffusers.

Tests at Dansk Teknologisk Institut (DTI) showed oxygen penetration of 42 mg/m²/day [2], and for the storage in Høje Taastrup the conclusion was, that it would be impossible to keep the oxygen content low by continuously removing oxygen from the storage water.

As a consequence of the above-mentioned remaining problems, we decided to work with two different lid construction concepts:

- Constructions with a floating liner with convection stop preventing moisture coming from the water and oxygen coming into the water.
- Constructions with moisture and oxygen coming through the floating liner.

In addition, some lid development opportunities have also been studied in the course of the project, such as the techno-economic feasibility of covering the lid solution with PV panels.

In chapter 2 first the final result of the floating lid is shown in chapter 2.1 and in the following chapters tests and investigations carried out as part of the development are presented.

2.1 Description of the final lid solution

We ended up with a lid construction with moisture and oxygen coming through the floating liner. To prevent moisture coming from the water into the insulation materials the lid is constructed with ventilation systems. The lid is constructed in sections and each section can have the same size as the lid in the PTES in Dronninglund (approx. 100 x 100 m).

In the below figures drawings of the final lid construction are shown.

Figure 1 shows the Top View of the Lid Construction in where Air Inlets are located nearby the outer edge. The distance between each depends slightly on the length of the dam crest, normally not exceeding 7,50m. These communicate with four Air Ventilation Wells / Air Outlets, which are located in the nearby vicinity to the middle to create an airflow inside the lid construction to transport permeating moisture away from the insulation. In the very middle a pump well is located, equipped with a pump and connected hoses to accumulate and drain surface water away.

Two Manholes with a diameter of $\varnothing 1000\text{mm}$ are shown of which one shall function as a maintenance entrance for a diver and another one to be placed on top of the Diffusor tower. Furthermore, two manholes with a diameter of $\varnothing 600\text{mm}$ for measures inside water and another one for measures inside the insulation are shown. Only the one for measures inside the water is designed to penetrate the floating geomembrane. The number and position of any of previously described manholes may vary according to the individual project situation and requirements.

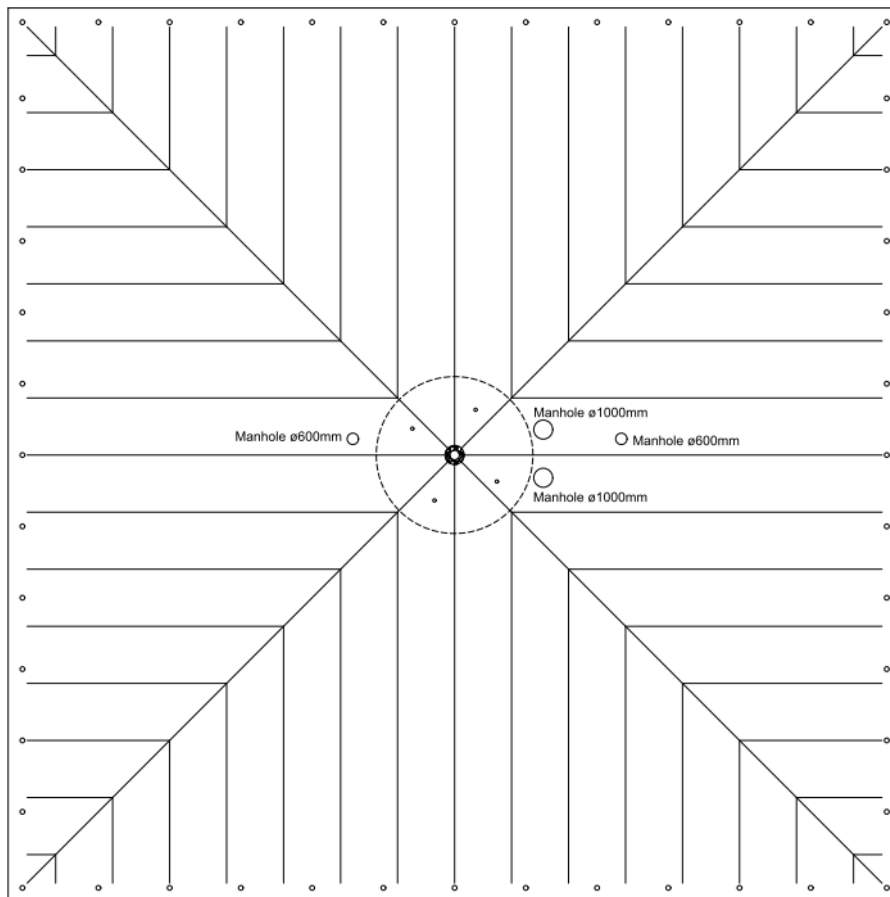


Figure 1. Top View Lid Construction

Figure 2 shows a principle section detail of the lid construction with the insulation layers and different geosynthetic layers (high temp. resistant polymer liner, geonets, UV protection liner). A layer of mineral wool (here from the supplier Rockwool[®], as named in figure 2) is located to ensure inclination between the weight pipes. The special feature here is that the individual parts are wedge-shaped, allowing a gradient to be achieved between and towards

the individual weight pipes. With the previous lid construction, puddles of water occurred randomly in different places, which meant that the drainage did not work as intended. With this combination, improved surface drainage is achieved. Furthermore, the weight pipes have in this design a distance of 6m to each other, which is closer than in the former solution.

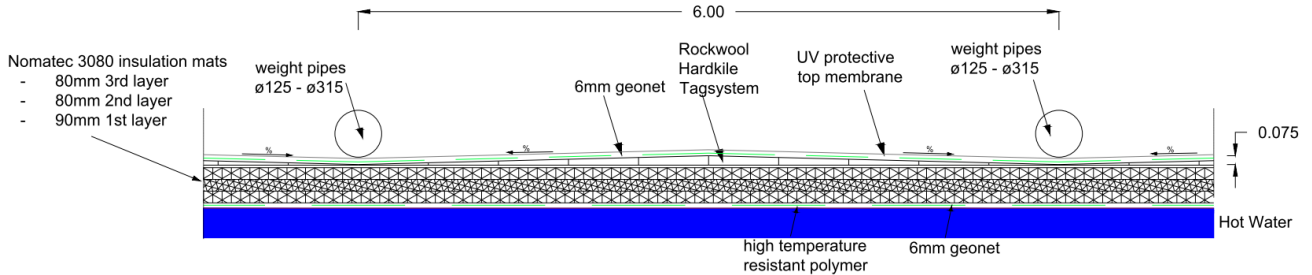


Figure 2. Detail Principle Weight Pipes

Figure 3 shows a top view of the middle with the previously described manholes, pump well and four Air Ventilation Wells / Air Outlets. Also a possible supplier for the ventilators is mentioned.

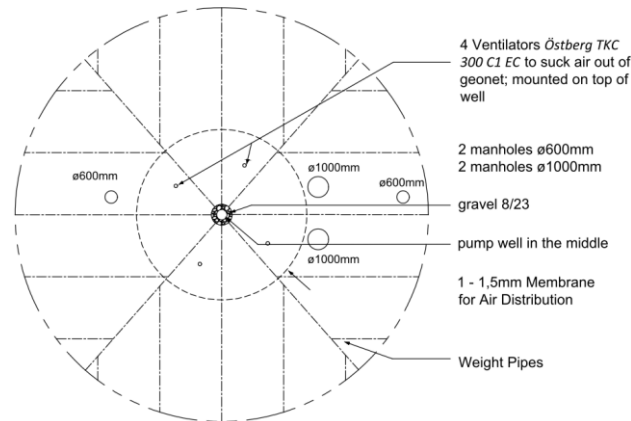


Figure 3. Principle Middle of a Section – Topview

Figure 4 shows a section of the middle area with inclination towards the pump well and one of the four mentioned Air Ventilation Wells / Air Outlets.

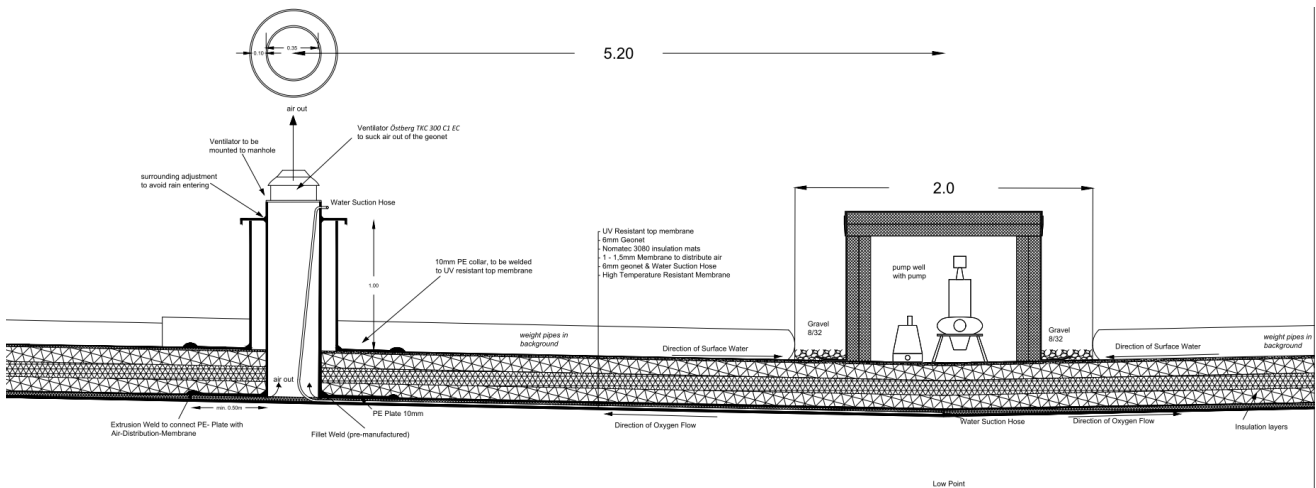


Figure 4. Principle Detail Middle of a Section at the Lowest Point

Figure 5 shows the principle in the area at the edge of the embankment. One layer of insulation is placed on top of the embankment, since formerly an increased heat loss has been measured here. An extrusion seam between the high temperature resistant polymer liner from the bottom and sides and the floating one is indicated but may not become necessary. The shown air inlets do not penetrate the floating liner and thus are not in direct contact with the storage water.

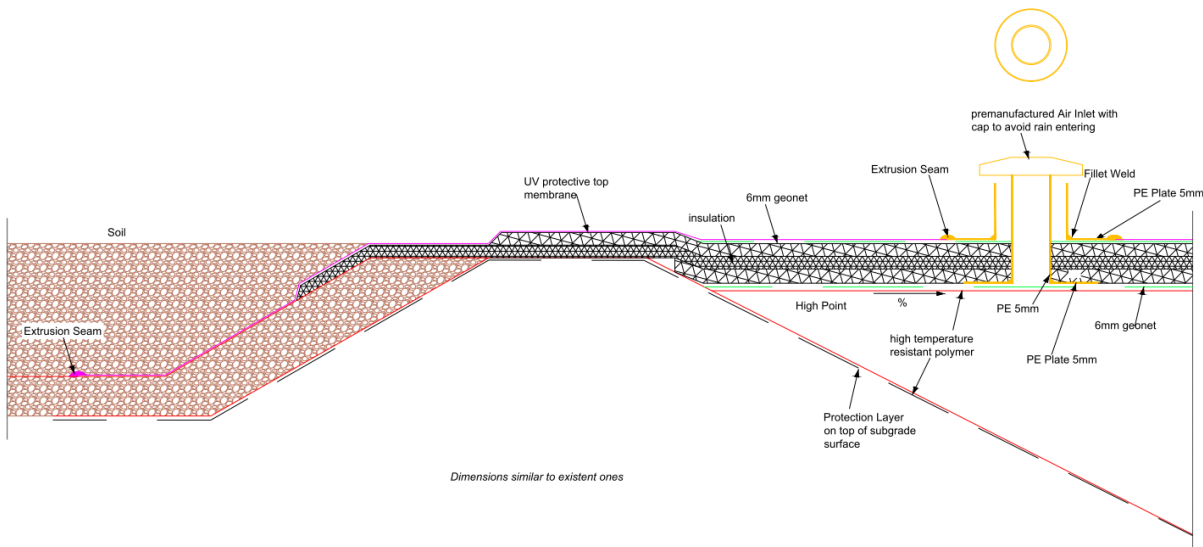


Figure 5. Principle Detail Transition Area Lid to Embankment

2.2 Tests and investigations carried out in connection to the lid development

If we could find a supplier who can deliver a liner with convection stop it could solve both the problems with moisture in the insulation and oxygen in the water, so it was a priority to investigate these solutions first.

2.2.1 Development of liners with convection stop

JKU Linz proposed a solution where a sandwich PE/ALU/PE liner could be developed and used as a convection stop placed on the floating liner. This solution was discussed with a possible manufacturer. It showed up, that sandwich liners with Alu, CU or stainless-steel all had adhesion problems with PE because of different extension behavior. Laboratory tests will continue, but no full-scale product is available.

Another solution could be a stainless-steel liner. JKU Linz contacted possible suppliers of for instance 0.5 mm stainless steel liners, but they were not willing to develop a solution.

Thus, the conclusion was that liners with convection stop is not at the market at present and in the near future.

2.2.2 Choice and tests of liners from PEX, ETFE, HDPE and PP

Until now HDPE and PP has been used for tightening the PTES in the bottom and sides and as floating liner under the lid. HDPE has problems with high temperatures and PP has problems with low temperatures. Therefore new versions of the products and possible other solutions has been investigated.

ETFE is able to stand high temperatures but much more expensive than PE or PP. The material is used by architects to protection of buildings (i.e. as roof-foil). Its lifetime at high temperatures is very long, but practical experiences to date seem only very limited or even inexistent in terms of welding. Delivery is likely in widths around 150 cm rolls, which demands increased installation efforts to seal large areas watertight. With ca. $1,75 \text{ g/cm}^3$ it is heavier than water, which can make it difficult for easy usage as a floating liner. Furthermore, it has a much higher water vapor as well as oxygen diffusion than PE or PP, while the thickness usually used is in the μm range, i.e. $<1\text{mm}$. The high water vapor value demands increased attention in terms of lid design and keeping the insulation dry, the high oxygen vapor can cause additional challenges regarding water quality and used materials inside the pit. Further information on coating options, e.g. with aluminium, is not known. ECTFE could be considered as a more expensive alternative with lower diffusion properties.

It may also be necessary to test the durability in a hot water environment, e.g. regarding the release of fluorine compounds, which could accelerate corrosion processes in black steel, among other things.

Cross-linked PE (**PE-X**) offers superior resistance at high temperatures but is currently not considered an option for large-scale lining of PTES. One of the main difficulties here lies in the limited or non-existent weldability that makes it difficult to easily watertight a large area, another difficulty the non-availability of a ready-to-use cross-linked lining material.

Ideas of HDPE-testing

To date, there is no standardized and generally accepted test method for the durability of geomembranes in a PTES environment, making it difficult for operators to obtain reliable information. The only widely recognized standardized method used in the industry for the accelerated ageing of geomembranes and the resulting mechanical resistance is the measurement of the oxidation induction time (OIT). OIT is measured at 200 °C, therefore may not reflect oxidation resistance at lower operating temperatures and hence provides very limited to no information on whether a geomembrane material is suitable for use in a PTES for at least 20 years, for example.

At DTI (Dansk Teknologisk Institut) a test methodology has been developed and used since 2000 for testing EPDM and HDPE-liners [3]. Testing of the PP-Liner used in Høje Taastrup has been started under the same conditions previous HDPE liners have been tested. This test is planned to last up to 5 years. The main difference to previous tests with HDPE liners is, that this time it has been decided to use laboratory water instead of tap-water as medium. Laboratory water was also used for the accelerated ageing tests at the JKU Linz, when the PE-liner was developed. Samples are taken out yearly for tests at DTI, but following tests are carried out at JKU Linz to compare results from the two different ways of testing.

Before the hot water exposure began, some samples were exposed to different weathering durations (including UV) in order to see how weathering effects (as a result of the construction phase, for example) can affect the service life of the sealing material during operation before a PTES is commissioned.



Figure 6. Sample Preparation at DTI (a fine mesh is used to expose the liner to pressurized water on one side and air on the other side)

Ideas were developed on how to prepare the ground for a joint test procedure. A conclusion is, among other things, that experts in material development, test procedures, manufacturing, consulting and others must come together to disseminate and evaluate. Budget funds should be made available for this, as experience has shown that voluntary participation on a cost-cost basis in a task of this kind does not work.

Weakness using PP

The lower temperature application range of polypropylene is only in the 0°C range and/or a little below, which makes it challenging for large-scale outdoor use. However, a construction site with large earth movements, as is the case when erecting a PTES, must overcome these challenges. This is probably one reason why HDPE is used in almost all other applications, such as landfills, mining, water, ... The big difference to other applications, however, is the duration of the higher and, from a certain point, material-critical temperatures that a PTES must guarantee during operation.

The low temperature application range of PP can to some point be extended by adding plasticizers. An irrigation system that utilizes the filling phase has also been developed and successfully implemented to protect the PP liner during filling as to see in the following figures.

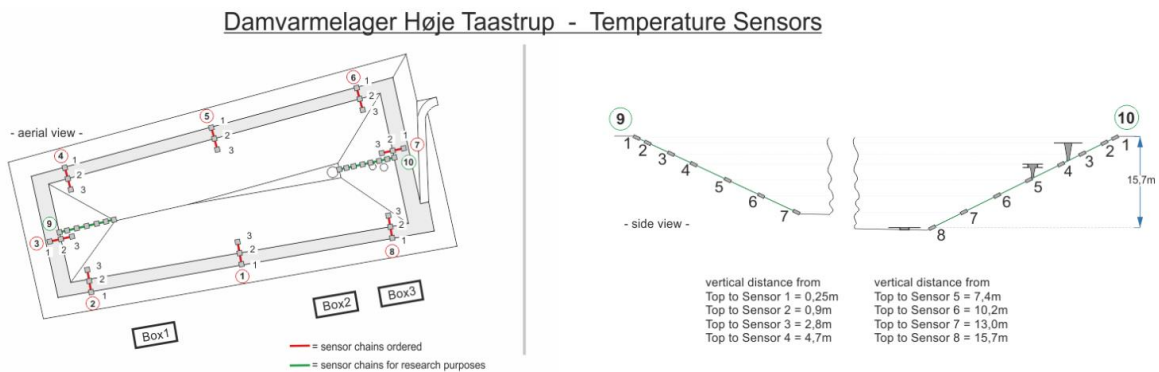


Figure 7. location of temperature sensors

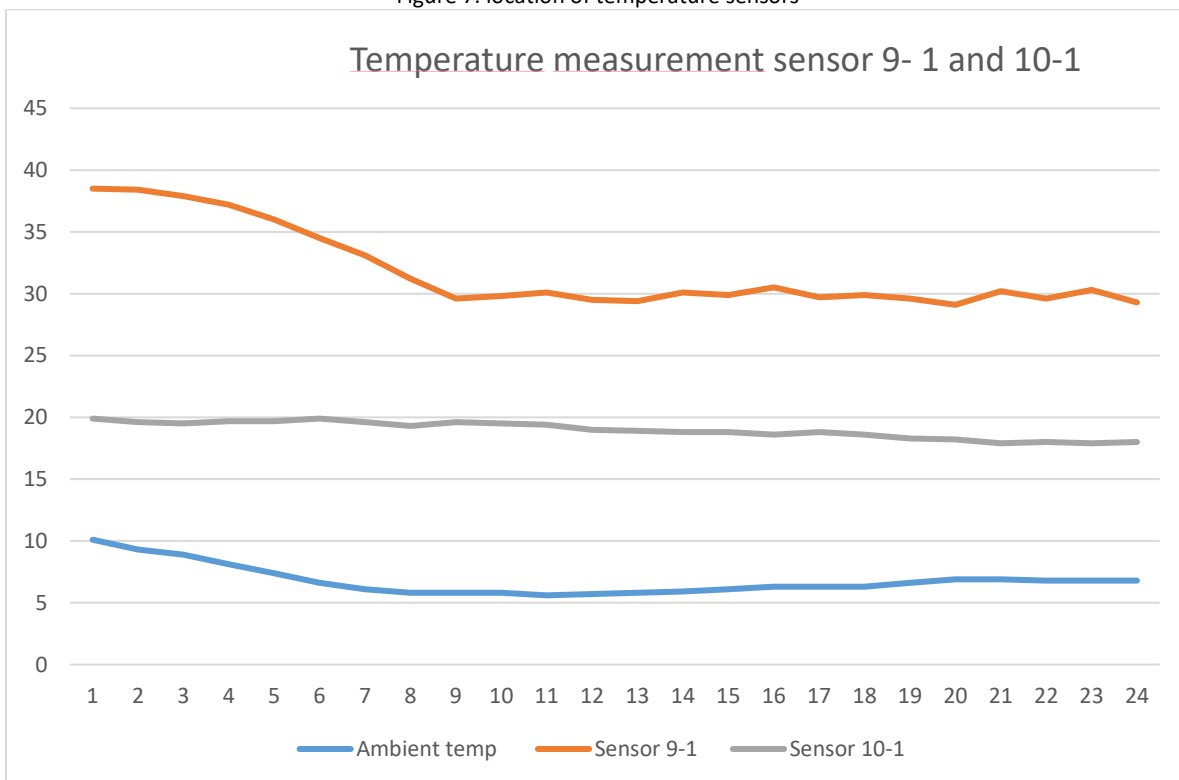


Figure 8. Example of temperature measurement sensor 9-1 and 10-1 during filling

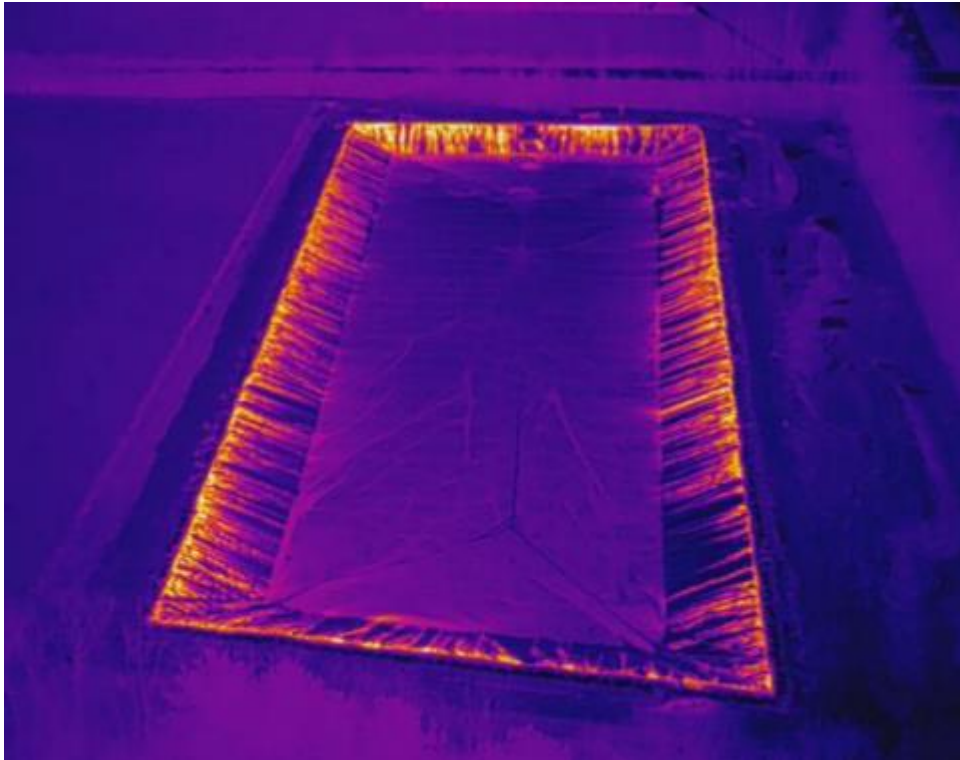


Figure 9. Drone foto irrigation system

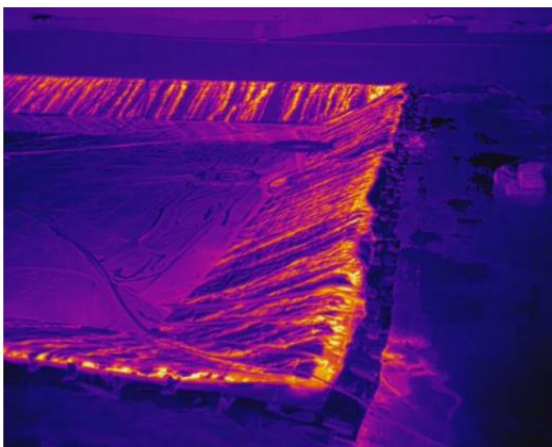


Figure 10. Photograph from the side

The lowest temperatures during filling phase occurred around Christmas 2021 with down to $-10,9^{\circ}\text{C}$ according DMI (Dansk Meteorologisk Institut). The lowest temperatures on the liner surface were at the same time measured around $+4,8^{\circ}\text{C}$, demonstrating the functionality of the development.

2.2.3 Test of insulation material

For the insulation of floating lid structures, commonly expanded clay (LECA) or polymer foams are used. While LECA was installed at the PTES in Vojens and Toftlund, polyolefin foams are a more novel material class, which were considered in Marstal, or the reconstructed cover in Dronninglund (2022) (see. Figure 11).

At lower maximum operating temperatures, extruded polystyrene foam (XPS) is used. However, the maximum operating temperature of XPS is limited by the onset of the glass transition temperature at around 65°C. For thermal energy storages with operating temperatures above this limit, high-temperature-resistant polyolefin materials are required. Within the Integrate 2 project, focus was given to the long-term behavior of these foam materials.

Various PO foams with different densities and stabilizer content were investigated. For acceleration of the degradation process foam samples were exposed to hot air and damp heat conditions at elevated temperatures. Failure and endurance times were assessed by tensile testing and evaluation of strain-at-break. By Arrhenius modelling, temperature-dependent degradation was described, allowing for the extrapolation of endurance times from elevated to service relevant conditions.

For lifetime estimation a cumulative damage model was implemented and used, considering the foam insulation geometry, temperature loading profiles, moisture, and temperature-dependent thermal conductivity values, such as the extrapolated endurance times. Lifetimes were estimated based on the failure criteria of heat loss increase of 20% and a critical interface temperature of the primary and the secondary insulation of 65°C. At this temperature the onset of the glass transition temperature of XPS is limiting.

Due to a lack of endurance data for the better performing stabilized foam grades, extrapolation of ageing data was only performed for the less durable unstabilized grade. Extrapolation of the long-term material of the foam to service relevant temperatures was based on the current maximum exposure time at 95°C of 24500 hours and an Arrhenius factor of 3. In the following, details of the storages in Dronninglund and Høje Taastrup and the according lifetime estimates are given.

Lid structure (Høje Taastrup & Dronninglund)

- PO foam: 150 mm (unstabilized)
- XPS foam 150 mm.

Annual temperature profiles:

- Dronninglund: 24 - 85°C
- Høje Taastrup: 90°C
- ambient Copenhagen (2023): 2 - 24°C.

Based on the unstabilized foam grade, lifetime estimates of more than 28 and 8 years were deduced for the lid structures in Dronninglund and Høje Taastrup, respectively. Mainly the critical interface temperature due to the low service temperature of XPS is limiting. Therefore, an alternative lid structure without XPS and 300 mm of PO foam for the temperatures of the thermal energy storage in Høje Taastrup is proposed. Based on this concept a lifetime of at least 11 years can be expected. Further exposure will improve the Arrhenius model.

Exposure experiments confirmed a high potential for significant improvement of the lifetime by adequate stabilization of the PO foam materials. At an exposure temperature of 105°C a

higher endurance time value by a factor of 3.5 was deduced. The lifetime estimation is based on assumed moisture values in the lid structure. Higher humidity can lead to a reduction in service time.

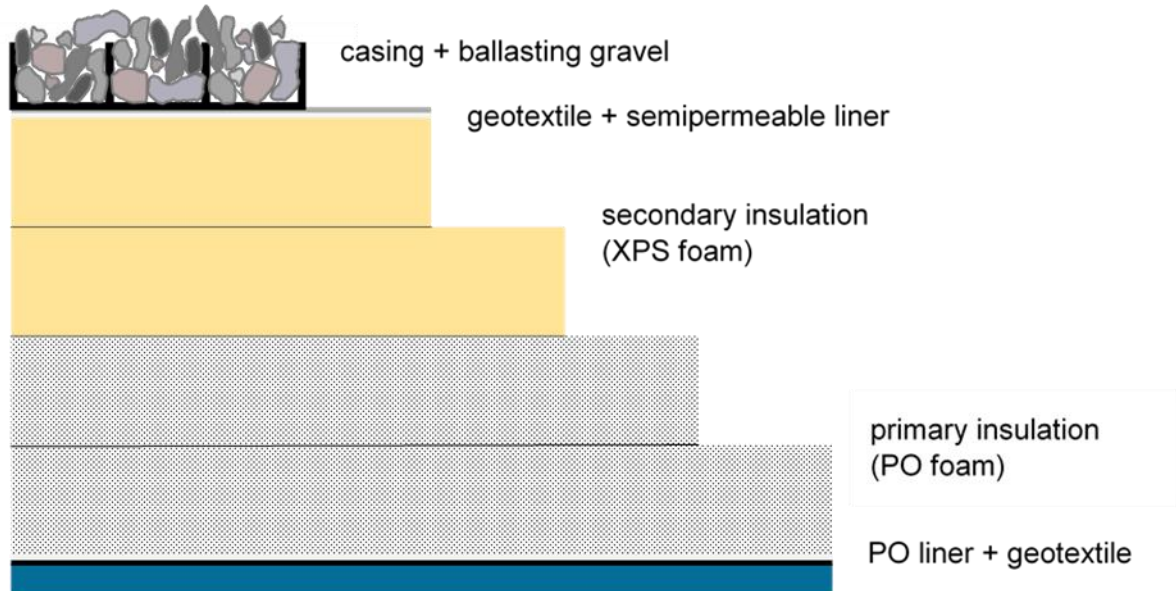


Figure 11. Structure of the floating lid implemented in the PTES of Dronninglund

2.2.4 Material test of hoses used as weight pipes

Currently and in the past, the weight pipes are made of plastic pipes out of black HDPE, filled with concrete or other ballast (e.g. stones). In order to achieve a gradient from the high point (e.g. at the edge of the pool) to the low point (e.g. in the middle of the pool), different diameters are used for the pipes. Depending on the distance between the high and low points, certain lengths of the different pipe dimensions are then arranged together to achieve a gradient - comparable in the broadest sense to a conical shape. To enable handling on the construction site and distribution on the lid area, only individual short pipe sections (perhaps up to 2 or 3 m in length at most) can be filled with weight and then carried to the appropriate position (manpower). In some cases, individual pipes may be welded together, or plastic-lids welded to the pipe ends. All in all, a relatively laborious and time-consuming task, that offers potential for improvement.

The next figure 12 shows how it looked in Dronninglund before the lid has been exchanged.



Figure 12. Foto from Dronninglund Lid Design with black HDPE pipes

As an alternative to this, the weight tubes could also be manufactured as a geosynthetic plastic tube fabricated to the desired length at the factory instead of consisting of individual HDPE tube segments of different diameters. This can also vary in width during production in order to obtain a conical contour with different diameters along the length.

An exchange with the geosynthetic manufacturer HUESKER has been established discussing the idea and in course of this HUESKER produced a sample at its manufacturing plant in Dülmen, Germany, to test both the dimensions and the filling. The material from which these plastic hoses are made is named TechnoTex 52.144 DG from the manufacturer HUESKER, which is an open fabric made of polyethylene terephthalate (PET) multifilaments with a solid polymer protective coating, similar to truck tarpaulin. The sample was about 50m long and with a conic shape. Figure 13 below shows the transportation size.



Figure 13. Foto of transportation size of test sample

A type of liquid soil was used for filling, which is also used to seal old sewer pipes and underground cavities in order to plug them. This material had the following properties: Density 1.7 kg/l; Compressive strength 3- 7 N/mm². In comparison: For the weight pipes that were used to handle the excess material of the floating liner in Vojens, Toftlund and Gram a liquid concrete was used with the name "Rørpasta".

The result of the filled pipes from the test in Germany is to see in the following figure 14.



Figure 14. Foto of transportation size of test sample

Due to the uneven floor and no manual straightening during filling of the hoze some imperfections in appearance were caused. Valves are fitted at various points to allow the air to release in a controlled manner which is pushed forward due to the one-sided filling. The filling procedure was relatively quick with ca. 15 min for about 3 to 3,5m³ over the entire length. Later on a comparison between the approaches of HDPE pipes and hozes has been made, concluding that the hoze solution could offer a deduction in implementation-duration of about 80% and a reduction of material costs about 50% compared to the HDPE pipe solution.

As the weight pipes are placed on the surface of the lid and are therefore exposed to UV radiation, this would also apply to an alternative material. An expert opinion on UV resistance dated 29 February 2016 reveals that the tensile strength of the material is still approx. 30% due to, among other things, exposure to outdoor weathering for over 20 years. (see figure 15). The conclusion from this report is therefore that there is sufficient UV resistance in Germany for more than 20 years.

	Längsrichtung (MD)	Querrichtung (CMD)
Zugfestigkeit fabrikneues Produkt	38,47 kN/m	33,56 kN/m
Zugfestigkeit exponiertes Produkt nach 20 Jahren	12,34 kN/m	12,10 kN/m
Restzugfestigkeit nach 20 Jahren	32,07 %	36,05 %

Figure 15. Average values of tensile strength from expert opinion 29 February 2016

However, the intended use of the material in the PTES cover design is not necessarily compatible with previous applications, so there may be differences to result in terms of lifetime. For example, the effect of the expansion of the material in the course of filling may result in an increased surface area exposed to UV radiation. On the other hand, lifetime extension approaches could be possible, for instance with another formulation or a 2 layer solution.

2.2.5 PV on the lid

The scope of the investigation is to examine the feasibility of installing photovoltaic (PV) panels on the lid of a pit thermal energy storage (PTES).

The investigation examines PV placed in Denmark near Roskilde and PV placed in France near Lille.

Since the calculations are done as a preliminary investigation, the assumptions and results are very rough and are not suited for final investment decisions.

Construction

The lid in the example calculations is having an area of approx. 46,000 m². As seen in figure 16 there is assumed a slight inclination between the weight pipes.

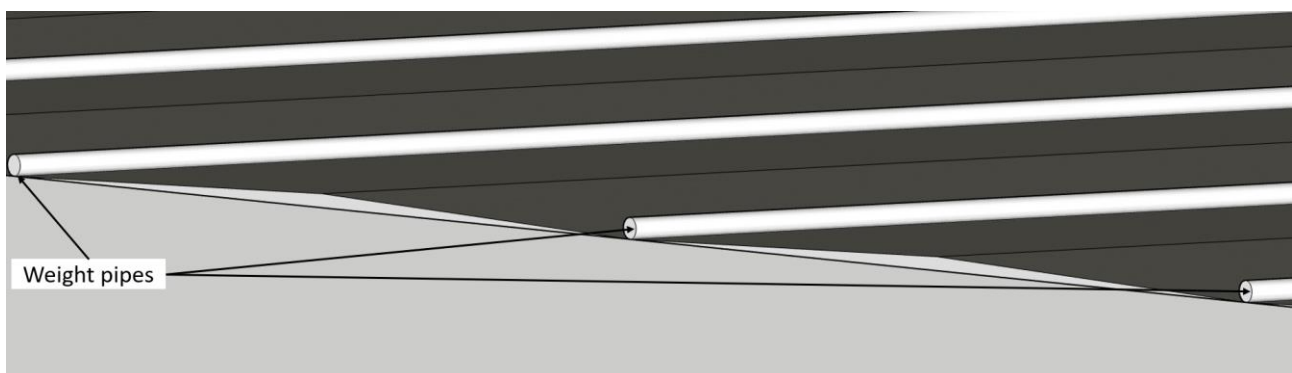


Figure 16. Sketch of weight pipes on PTES lid with slightly sloped surfaces between these

Figure 17 illustrates a drawing of a PTES lid section seen from above. The red square illustrates what is shown in figure 18. The PV system is assumed to be possible to construct as indicated in Figure 18 – Figure 20.

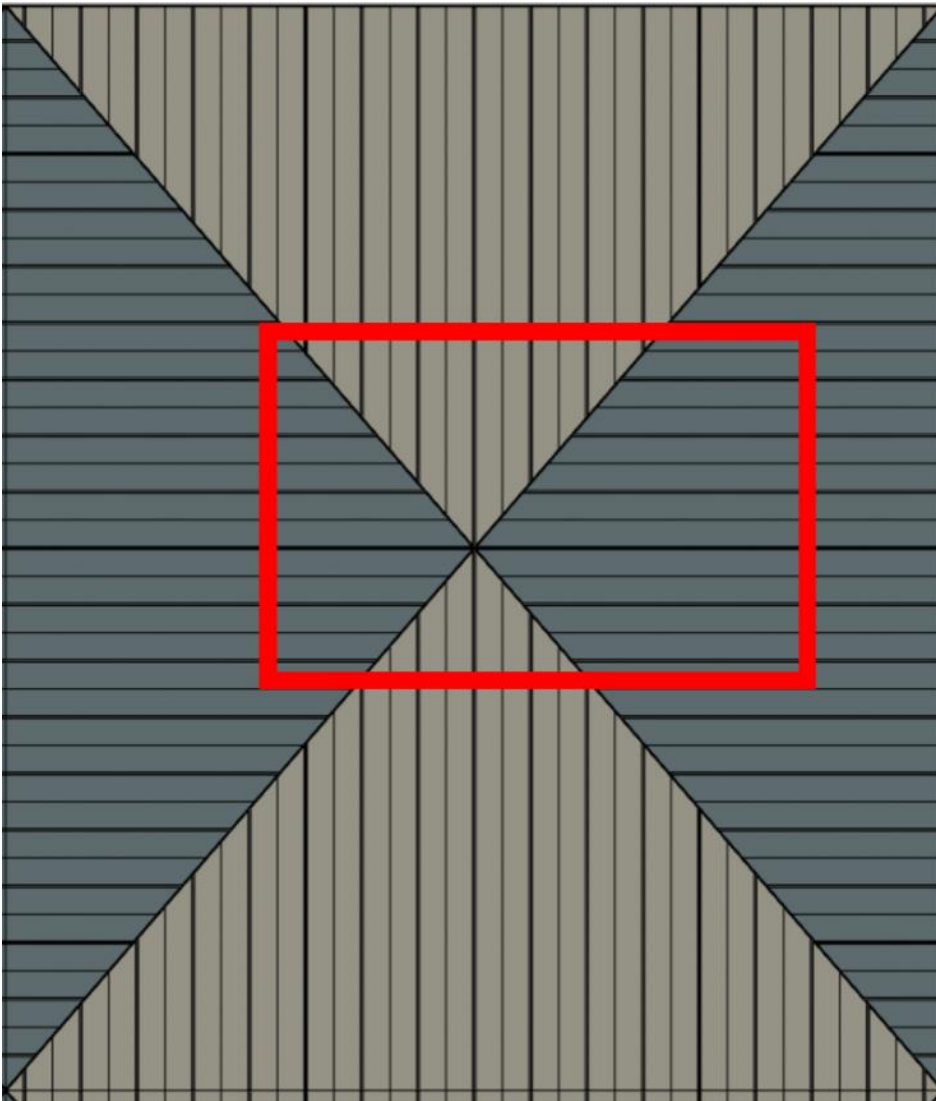


Figure 17. Sketch of PTES lid section seen from above. Thick black lines indicate weight pipes. Thin black lines indicate the centre between weight pipes. The area highlighted in red illustrates what is shown in Figure 18.

Figure 18 to Figure 20 indicate how the PV panels could be placed between the weight pipes. This means that there will be four different collector orientations. It is assumed that the storage is placed with north being upwards in Figure 17. Hence, the PV panels will be either facing (slightly) north, south, east or west (at a share of 25% in each direction if all the available area is utilized).

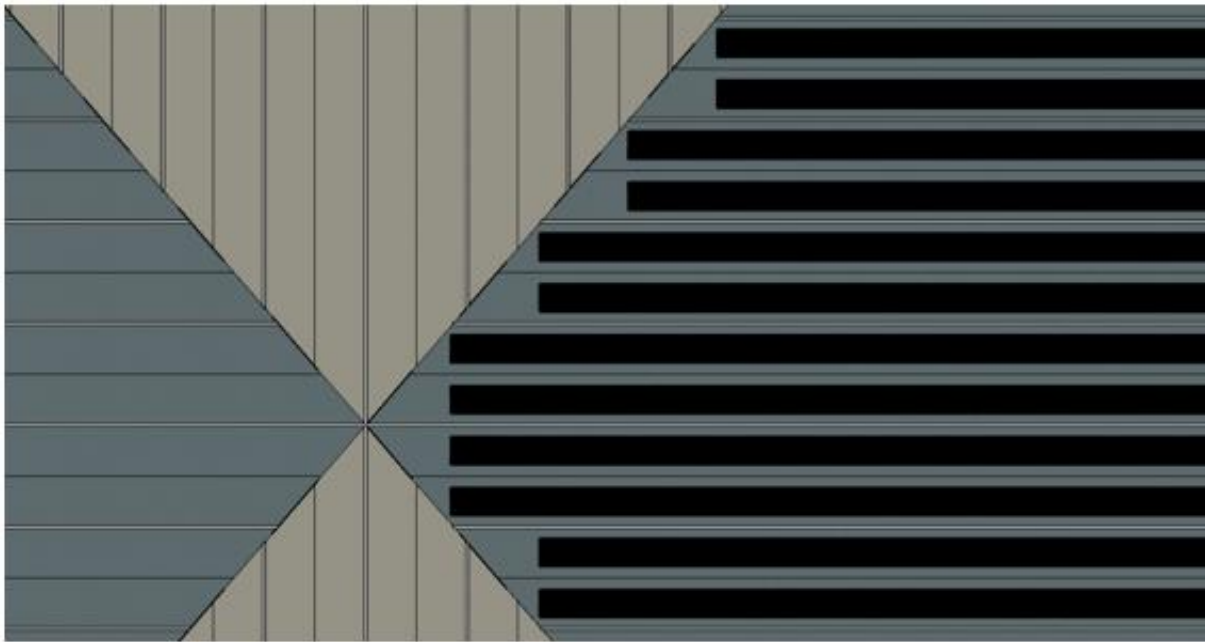


Figure 18. Indication of PV panels on part of the lid facing north/south seen from above (black areas)

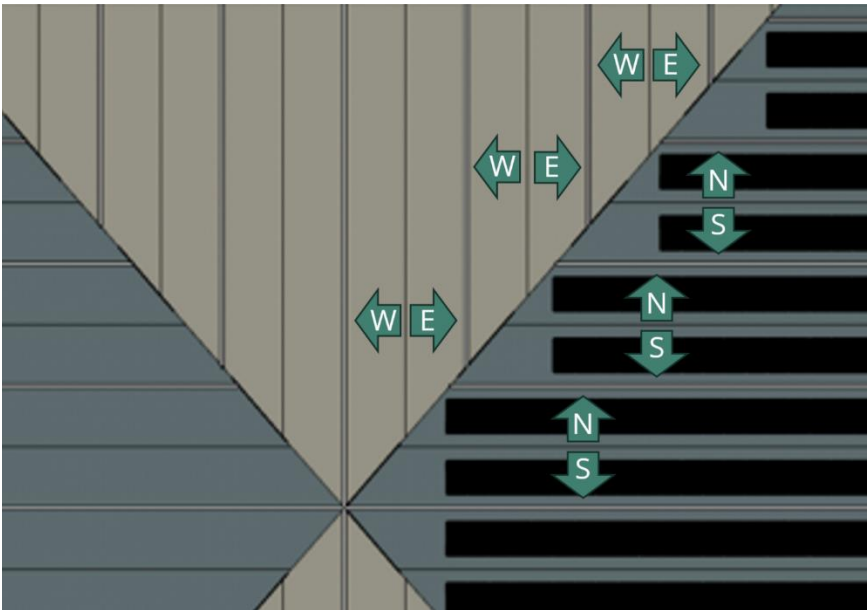


Figure 19. Indication of orientation of slopes, west (W), east (E), north (N) and south (S) in the different sections of the storage lid. (Panels could also be placed on the east and west facing areas)

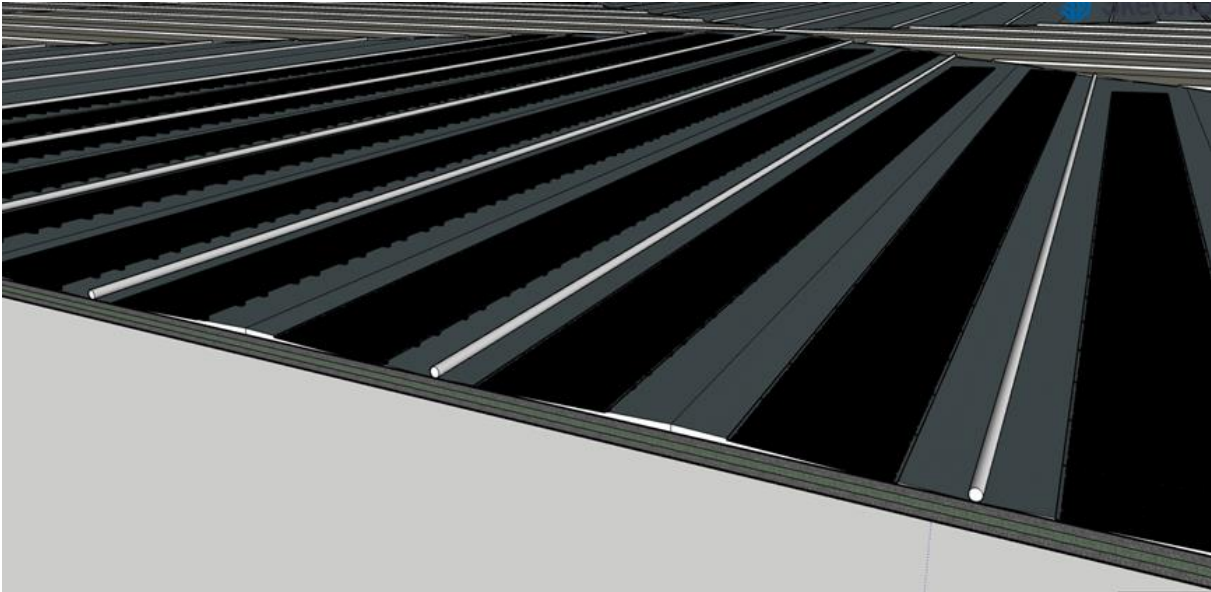


Figure 20. Closer look at an illustration of PV panels placed on the lid indicated with black

Estimating that around 60 % of the lid area can be covered by PV results in a potential total PV panel area of ~28,000 m².

Each PV panel of the assumed 550 W example has an area of 2.56 m² resulting in 4 x 2,700 panels split in four directions, north/south/east/west.

Assuming the panel of 550 W multiplied with 2,700 panels correspond to approximately 1.5 MW per orientation. In total this is then 4 x 1.5 MW = 6 MW installed.

To allow rainwater to run off without accumulating near the frame of the panel it might be relevant to consider a frameless panel. In the example of a system with small slope seen in Figure 21, dust has accumulated near the edge while the water has evaporated.



Figure 21. Example of dust accumulated near the lower edge frame of a PV panel

Methodology and assumptions

The yield and feasibility at different slopes of the PV panels are investigated. Laying flat on the lid means a tilt angle of only $\sim 1^\circ$. The panels are distributed with $\frac{1}{4}$ of the panels oriented north, $\frac{1}{4}$ south, $\frac{1}{4}$ east and $\frac{1}{4}$ west.

Calculations are carried out comparing the reference with a solution assuming an additional sloped structure underneath the panels to increase the angle thus better allowing rainwater to run off while cleaning the surfaces.

This results in the following parameters used for the slope:

- 1° north, south, east and west
- 5° north, south, east and west
- 10° north, south, east and west.

The investigation is conducted in energyPRO, which is a techno-economic modelling tool, where the following parameters are considered:

- Technology specific parameters for a PV panel example of 550 W
- Geographical dependent meteorological data (solar radiation and ambient air temperature) for 2023 (CFSR2-data)
- Electricity spot prices and electricity tariffs from 2023 for Denmark and France are used in hourly calculations. (This corresponds to a weighted average of electricity price related to the amount of electricity produced.)
- Financing is based on an annuity loan of 4 % real interest rate paid over 20 years
- Shading effect is neglected, losses in inverter and other equipment is included
- The price of the PV system is assumed to be 600 €/kW_p in total (including installation).

Results

The overall economic results of the techno-economic analysis are presented in Table 1. The economic results are based on rough estimates and should therefore only be used to depict overall trends. The simple payback time is based on the investment cost divided by the annual income (“electricity sold”). Net revenue is the annual income (electricity sold) minus the CAPEX.

		DK slope 1°	FR slope 1°	DK slope 5°	FR slope 5°	DK slope 10°	FR slope 10°
Electricity sold	€/year	321,000	375,000	320,000	374,000	318,000	372,000
Investment	€	3,564,000	3,564,000	3,564,000	3,564,000	3,564,000	3,564,000
CAPEX	€/year	262,000	262,000	262,000	262,000	262,000	262,000
Net revenue (income minus CAPEX)	€/year	59,000	113,000	58,000	112,000	56,000	110,000
Simple payback time	years	11	10	11	10	11	10
Power production	MWh/year	5,518	5,753	5,504	5,739	5,469	5,704
Performance	kWh/kWp	929	968	927	966	921	960

Table 1. Economic results of techno-economic analysis of PV on PTES

If instead of the simple payback time the cost of financing is taken into account, then the cash flow could be illustrated as the combination of debt (negative), the income (positive) and the cost of financing based on the average interests (negative). In this case the cash flow becomes as shown in Figure 22.

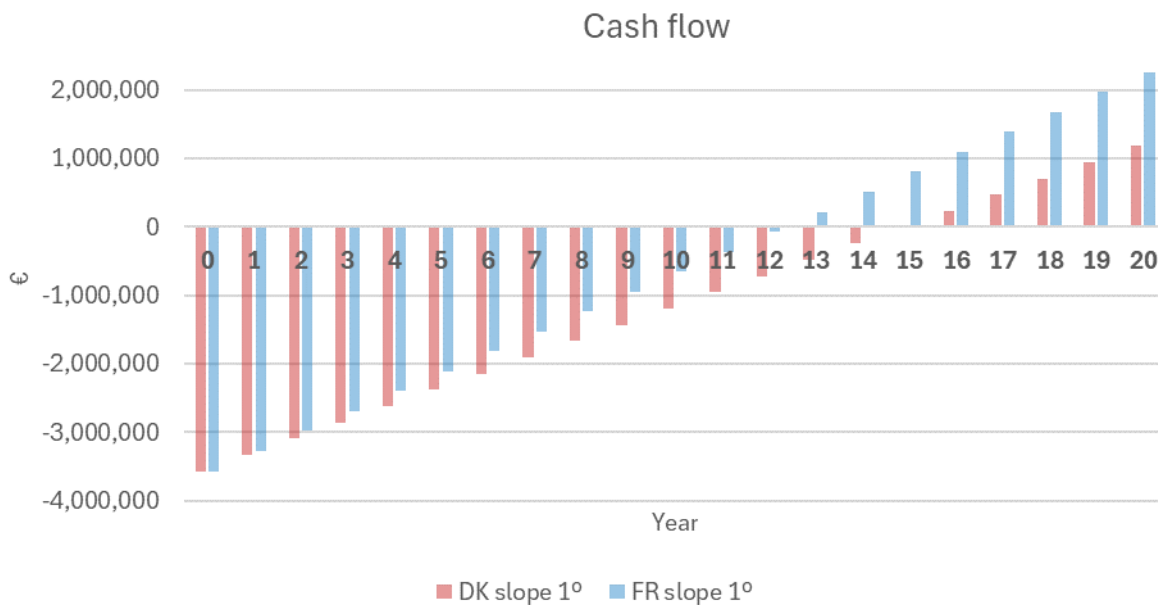


Figure 22: Cash flow for the Danish and French case with PV panels installed at a 1° slope

In general, it is found that the different slopes are not affecting the power production significantly (see Figure 23) if all are aligned in the same angle. The simple payback time for both the Danish and the French cases are around 10-11 years whereas if the cost of financing is taken into account, the payback time is between 12 and 15 years. If the real interest rate is increased to 6%, this payback time increases to 15-19 years.

Calculating the total feasibility for the different scenarios, it is found that PVs on PTES in a Danish context could lead to an annual saving of approx. 60,000 €/year, where PVs on PTES in a French context could lead to an annual saving of approx. 110,000 €/year. However, the assumptions and calculations are somewhat uncertain.

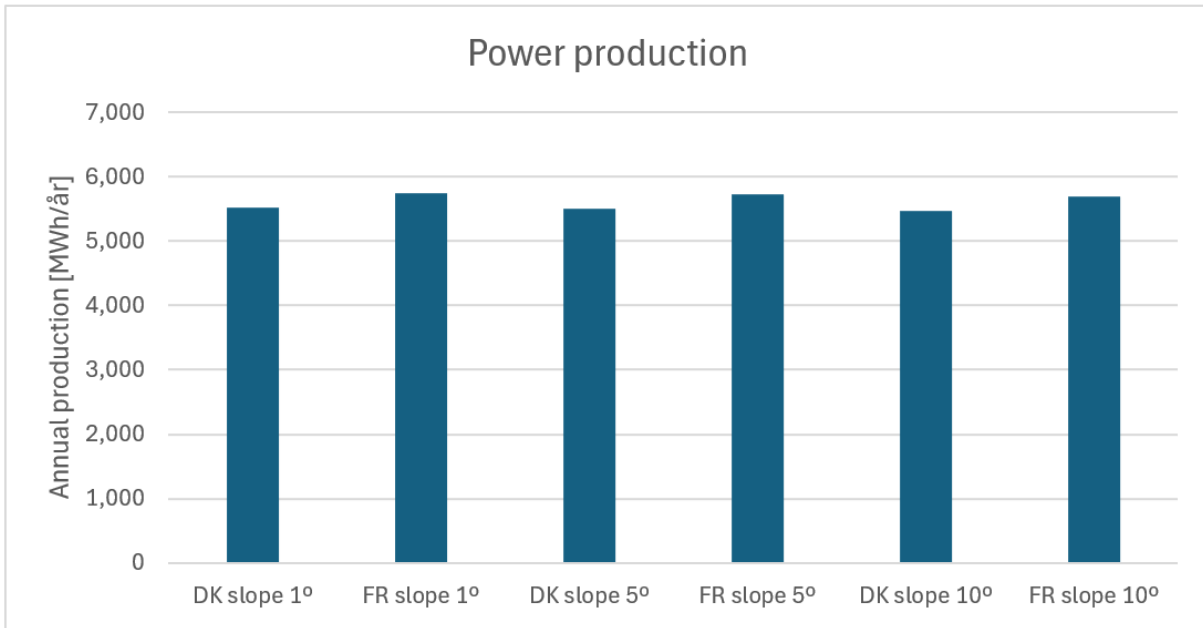


Figure 23. Annual power production for in Denmark and France for the different cases

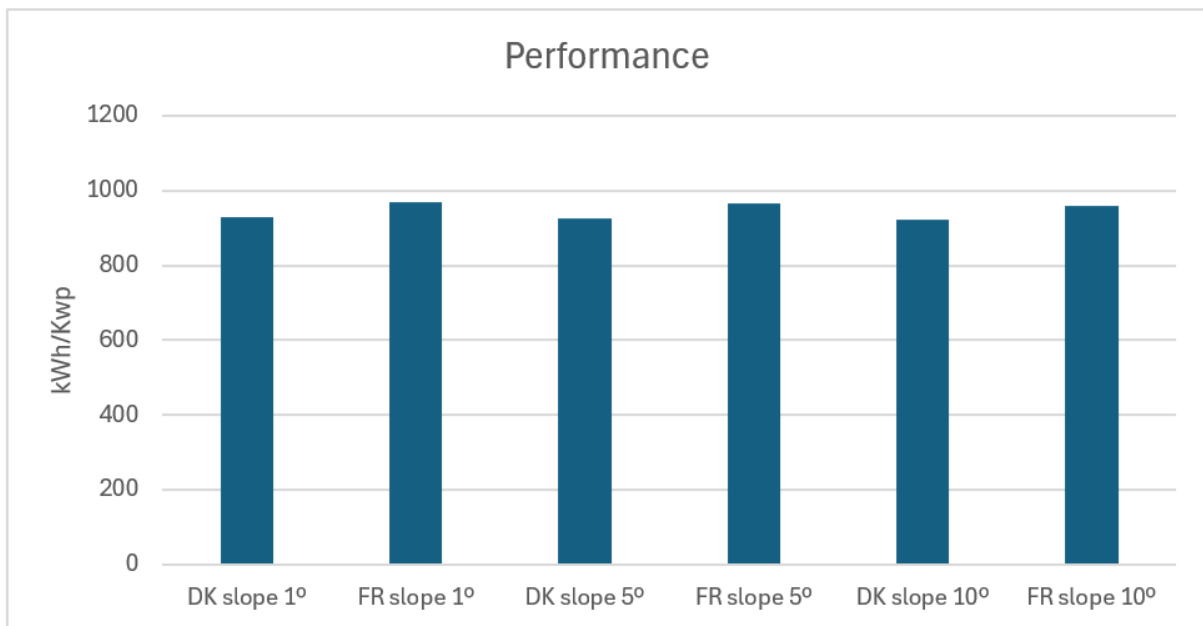


Figure 241. Calculated average yield for the different cases

Summary

In order to summarize this techno-economic study of installing PV on the surface of PTES:

As a summary:

- The different slopes are not affecting the profitability significantly

- Additional slope might be relevant to ensure rainwater runoff
- There are similar energetic results in Denmark and Northern France
- A financial benefit is seen when using a loan of 20 years and 4 % interest rate, however a higher interest rate could threaten feasibility
- Electricity prices will affect feasibility (depending also on feed-in tariffs)
- The payback time is found to be between 12 and 15 years with the given assumptions
- There would be an additional value of self-consumption e.g. using the electricity to supply pumps etc. However, the capacity of the PV system – if the area is utilised to the full extent – will be higher than what is expected to be needed for the pumps, SCADA system etc.

3 In and outlet systems that are corrosion free and with high capacity (200-300 MW)

In the FLEX_TES project it was decided to use storage water of district heating quality and to use black steel for diffusors and in- and outlet pipes, but during the construction period monitoring of oxygen content in the storage in Dronninglund showed that the storage water was saturated with oxygen. It means that in future projects it will be needed to use stainless steel for diffusors and in- and outlet pipes. It also means that future projects will suffer from expensive water treatment, and expensive stainless-steel solutions.

If we could develop corrosion free in- and outlet we could avoid using water of district heating quality, where we have to remove oxygen and salts and raise the pH value to >9.5.

We decided to work with the following solutions:

- Solutions if oxygen remains and salts are removed (the present solution)
- Solutions if oxygen and salts remain in the water (solution with corrosion free in- and outlets).

3.1 Solutions if oxygen remains and salts are removed

In 2018 the Danish corrosion experts from FORCE Technology analysed water quality and oxygen content in the PTES in Dronninglund. The conclusions were that the water was saturated with oxygen and chloride content was very low (approx. 1 mg/l). Thus, there would be no corrosion risk for stainless-steel (AISI 304 and AISI 316) even up to 100 °C, but for black steel local corrosion of 0.1-0.2 mm/year might occur.

The water in Dronninglund is treated with reverse osmosis and pH is 9.6 (quality as district heating water but saturated with oxygen). Tests at DTI showed oxygen penetration of 42 mg/m²/day through a 2 mm PP-liner. Similar penetration is expected for HDPE. These amounts of oxygen will be very expensive to remove and for Høje Taastrup PTES the estimation was, that it would not be possible.

The conclusion has been that the storage water must have the same quality as district heating water and since oxygen will diffuse into the water, stainless-steel must be used for installations of in- and outlet and connection pipes.

3.2 Solutions if oxygen and salts remain in water

In the first full scale storage in Marstal, tap water was used as storage medium. The only treatment was to soften the water to prevent calcium in the heat exchangers. This was a cheap solution (~2 €/m³ compared to 8-10 €/m³ for district heating quality), but corrosion occurred on in- and outlet pipes already after one year. If in- and outlet pipes were corrosion-free, expensive district heating water can be avoided. We have therefore investigated solutions with use of:

- Glass fiber

- PP-diffusers and pipes

3.2.1 Use of glass fiber

Glass fiber reinforced composites were supplied by Haase (GER). The edge sealed flat specimens were fully immersed by and aged in deionized water at temperatures of 95, 115 and 135°C. Therefore, small autoclaves and heating chambers were employed.

At 135°C, the edge sealed specimen revealed visually discernible internal delamination after 2500 hours of hot water exposure. Pronounced cross-sectional yellowing was observed after 3600 hours at 135°C. Full embrittlement and ultimate failure by manual bending was detected after 4500 hours.

At 115°C, the internal delamination failure was discernible after 4500 hours and hence, retarded by a factor of 1.8 compared to 135°C. Assuming a similar retardation factor from 115 to 95°C, delamination phenomena were expected after about 8000 hours at 95°C. This is just about 1 year for a service-relevant storage temperature of PTES (e.g., Høje Taastrup). By tensile testing of dogbone specimen, a continuous hot water ageing induced decrease of tensile strength was ascertained at 95, 115 and 135°C.

So far, no internal delamination, pronounced yellowing or embrittlement was observed at 95°C up to 6000 hours of hot water exposure. Nevertheless, significant yellowing of the non-reinforced edge sealing layer was detected also at 95°C. Together with Haase and their resin supplier Remapol (Slovakia), options for alternative resins with improved hydrolysis behavior were discussed.

Due to the fact, that no alternatives could be recommended, the overall long-term performance of glass fiber reinforced piping was classified as not sufficient for 30 years of operation in PTES. Hence, in further work special attention was given to PP-based pipes and fittings which could be in principle manufactured from PP-HTR liner material grades with remarkable long-term durability proven on (micro-)specimen level.

3.2.2 Use of PP

As mentioned in 3.2.1, initial investigations were carried out to discuss the suitability of PP as a material for the PTES inlet and outlet arrangement for the parts directly inside the PTES water. For such a meeting with AGRU took place to discuss the demands, which were amongst other things the following: design volume flow up to 3,000 m³/h, horizontal discs with up to Ø 10m and vertical distance of 140 mm.

The following feedback has been given:

- Reduction of chemicals if there are mainly plastic parts in the system, this will have advantages on the suitability of PP generally.
- The weldability of PPH/PPR to PP-HTR should be ok, but welding tests are recommended.
- The diffuser would be generally possible to make out of plastic, but design must be checked. To the large diameter up to 10m AGRU thinks a local fabricator must be

welded on side. For transport reasons it will be complicate to transport. Smaller single parts AGRU could carry out in house.

- as a PP pipe requires a transition to a steel pipe, this interface can be done by flange connection
- In the area where the pipe passes concrete manhole a shoulder fix point should be installed (fixed in the concrete)
- For the fixation of the diffuser also PP pipes or sheets could be used.

Thus PP might be a solution, but further development is necessary.

4 References

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