Evaluation of the potential for geo-logical heat storage in Denmark

Work Package 3

Deliverable: D3.1

Upscaling a Hybrid Storage Pilot Installation in Brædstrup

NORDJYLLAND
Jyllandsgade 1
DK–9520 Skørping
Tel. +45 9682 0400

MIDTJYLLAND
Vestergade 48 H, 2. sal
DK–8000 Århus C

SJÆLLAND
Postadresse:
A.C. Meyers Vænge 15
DK–2450 København SV

www.planenergi.dk
planenergi@planenergi.dk
CVR: 7403 8212½

December 19, 2018

Table of Content

The report created by PlanEnergi Nordjylland

Niels From
Nordjylland
Mobil +45 2064 6084
nf@planenergi.dk

Søren Alstrup Nielsen
Nordjylland
Tlf. +45 9682 0401
Mobil +45 4038 9724
san@planenergi.dk

Magda Kowalska
Nordjylland
Mobil +45 2266 9219
mk@planenergi.dk

Internal project ref.: 953

Customer
Energiteknologisk udviklings og Demonstrationsprogram (EUDP)

EUDP journalnummer: 1887-0017

1 Executive summary

This deliverable summarises the findings for work package 3 (WP3) of the evaluation of potential for geological heat storage in Denmark projects for EUDP. The purpose of this work is to investigate different technical solutions and configurations for shallow hybrid storage at the Brædstrup Fjernvarme DH plant. As an alternative, two other potential investment scenarios are considered and compared with the earlier mentioned storage option. This includes a full-scale pit thermal energy storage (PTES) and a full-scale borehole thermal energy storage (BTES).

The investigated heat storage technologies are assumed to be integrated with the additional solar thermal installation which would extend the existing collector area of 18,600 m^2 up to the total comprising around 50% of total annual heat supply.

This deliverable explains the design process and cost elements for the hybrid storage. This is followed by performance calculations (Chapter 8) of the upscaled plant in Brædstrup and an economic analysis (Chapter 9) for the combined BTES and PTES storage solution as well as the alternative options with full-scale pit storage and full-scale borehole installation.

The hybrid storage was designed as a thermal pit storage which is built as an underground tank cast on site in reinforced concrete with a water volume of 16,500 m^3, surrounded by a borehole storage consisting of 420 boreholes with a depth of 46 m.

The total cost of the hybrid storage, comprising of the borehole storage, the thermal pit storage in the middle, along with transmission lines along with the establishment of an additional heat pump amount to approximately DKK 58 million exclusive of a VAT, or approximately € 7.8 million without a VAT. The total investment is estimated at circa DKK 110.5 million exclusive of VAT which is an equivalent to circa € 14.9 million. A detailed budget can be found in section 6.2.

The decision-making process for the choice of design principles for the thermal pit storage in the middle of the borehole storage, is described in detail in chapter 5.

The development of the Brædstrup Fjernvarme plant with the integration of hybrid thermal energy storage is the most financially viable for 25-year project timescale and with the financial support which can be obtained for the underground water tank and the borehole installation. The lowest heat tariff with a hybrid storage is typically achieved for circa 55% overall solar heat production.

The hybrid solution is outdistanced by the full-scale pit hot water storage investment with a reduced heat cost by between 80 DKK/MWh and 150 DKK/MWh, depending on the depreciation period and if the financial support is in place. This lower cost of heat with the pit storage, however, is achieved for much smaller solar coverage (~45%).

The investment into the full-scale boreholes installation results in heat tariffs 20 DKK/MWh or 40 DKK/MWh lower compared with the hybrid storage for the 20-year and 25-year depreciation, respectively. In the options with the financial support, the hybrid storage is the cheaper option than the BTES by between 15 DKK/MWh and 20 DKK/MWh.

It needs to be noticed that the heat prices are calculated only for heat produced by the extended plant and not for the entire system including conventional generators (gas boilers and CHP).

2 Resumé

Dette dokument opsummerer de fund som er gjort i ”work package 3” (WP3): Evaluering af potentiale for varmelagere i Danmark, et projekt for EUDP. Formålet med arbejdet er at undersøge forskellige tekniske løsninger og konfigurationer for et underjordisk placeret hybridt lagringsanlæg ved Brædstrup Fjernvarmeværk. Som et alternativ hertil overvejes to andre potentielle investeringsscenarier gennem sammenligning med tidligere lageropsætninger. Dette omfatter et fuldskaleret damvarmelager og et fuldskaleret borehulslager.

De undersøgte teknologier for et varmelager forventes at blive integreret med installation af solpaneler, hvilket vil udvide det eksisterende panelareal på 18.600 m^2 og dermed udgøre 50 % af den samlede varmeforsyning.

Det hybride lagringssystem er designet som et varmelager, hvor en underjordisk betonstøbt beholder, med et vandvolumen på 16.500 m^3, omgives af et borehulslager bestående af 420 borehuller med en dybde på 46 m.

Dette dokument beskriver konstruktionsprocessen og de estimerede investeringsomkostninger for det hybride lager. Beslutningsprocessen for valg af konstruktionsprincipper er beskrevet i detaljer i kapitel 6. Yderligere findes et detaljeret budget i afsnit 6.2.

Efterfølgende er der opsat beregninger for ydeevnen og optimeringen af varmelageret med tilhørende solvarmepaneler for fjernvarmeværket i Brædstrup (kapitel 8). Den økonomiske analyse af det kombinerede vand- og borehulslager, såvel som alternativet for fuldskalerede løsninger, er præsenteret og sammenlignet gennem scenarier i kapitel 9.

De totale økonomiske omkostninger for det hybride lager, består af et borehulslager med en vandtank i midten, transmissionsledninger og etableringen af yderligere en varmepumpe, beløber sig til ca. 58 millioner kr. eksklusiv moms, eller hvad der svarer til ca. 7,8 millioner €. Den samlede investering er anslået til ca. 110,5 millioner kr. eksklusiv moms, hvilket svarer til ca. 14,9 millioner €.

Udviklingen af Brædstrup Fjernvarmeværk vil med integration af hybridvarmelagering være økonomisk levedygtigt i 25 år med den støtte som forventes ydet til undergrundsvandbeholderen og borehulsinstallationen. Den laveste varmetarif ved hybrid lagring, opnås typisk for 55% solvarmeproduktion.

Den hybride lageringsløsning bliver dog distanceret af et fuldskaleret damvarmelagers investering, med en reduceret varmeomkostning på mellem 80 DKK/MWh og 150 DKK/MWh, afhængig af afskrivningsperioden eller om den finansielle støtte er på plads. Denne lavere varmeomkostning ved dampvarmelageret opnås dog for en meget mindre soldækning (~45%).

Investeringen i et fuldskala borehulslager resulterer i varmetariffer der er mellem 20 DKK/MWh og 50 DKK/MWh mindre, sammenlignet med det hybride lagringssystems varighed 20 år eller 25 år. Blandt mulighederne, som kan få finansielle støtte, er hybrid lageret billigere end BTES med ca. 15-20 DKK/MWh.

Det skal dog bemærkes, at varmepriserne kun beregnes for det udvidede anlæg, og dermed ikke for hele systemet, herunder konventionelle generatorer (gaskedler og kraftvarme).

3 Glossary

BTES - Borehole Thermal Energy Storage

CHP – Combined Heat and Power

DH – District Heating

GAF - graddage-afhængigt forbrug (degree days dependent heat demand)

GUF - graddage-uafhængigt forbrug (degree days independent heat demand)

PTES - Pit Thermal Energy Storage

TRNSYS – Transient System Simulation Tool

4 Introduction

Work package 3 aims to investigate different technical solutions and configurations for shallow hybrid storage at the Brædstrup Fjernvarme plant. This is assumed to be integrated with the additional solar installation which would extend the existing collector area of 18,600 m^2 up to the total comprising up to 50% of total annual heat supply. The hybrid storage consists of a thermal pit storage made of an underground water tank cast in a reinforced concrete that is surrounded by a borehole storage.

Currently Brædstrup Fjernvarme supply approximately 40,000 MWh of heat demand per year through a district heat network. The heat production in solar collectors is supplemented by natural gas fired boilers, CHPs and 5,000 m^3 + 2,000 m^3 accumulation tanks. The existing solar thermal plant is operated in conjunction with a pilot BTES installation rated at 19,000 m^3 soil volume and a 1.2 MW_{th} heat pump.

This deliverable begins with a construction process of the hybrid storage examining a few thermal pit structure models ranging by excavation and casting solutions. The different options are evaluated based on the material properties, cost and potential construction risks. The most optimal construction methodology is determined which is fully priced and a detailed investment cost breakdown is presented.

The performance of the upscaled plant in Brædstrup along with the hybrid storage is modelled in the dynamic simulation programme, TRNSYS 16. The system is optimised for maximising the heat generation benefit. The annual heat outputs of the additional plant are then used in an economic model where the cost of heat supply is calculated. The results are compared with two separate scenarios of full scale storage, both, PTES and BTES.

The next chapter explains the differences and operating principles of the thermal heat storage solutions analysed in this study.

5 Types of thermal storage

This study investigates a hybrid shallow storage integrated with an upscaled solar plant in Brædstrup. The hybrid storage solution is then compared with a full scale standalone PTES storage and a full scale standalone BTES storage that would liaise with the same solar collectors' extension.

The operating principles of the analysed heat storage systems are summarised in this chapter.

5.1 Hybrid thermal storage

The hybrid storage consists of an underground concrete water tank surrounded by a borehole storage. The operation of the hybrid thermal storage is investigated in conjunction with the solar plant extension which is anticipated to achieve the overall solar coverage supplying up to 50% of total annual heat consumption.

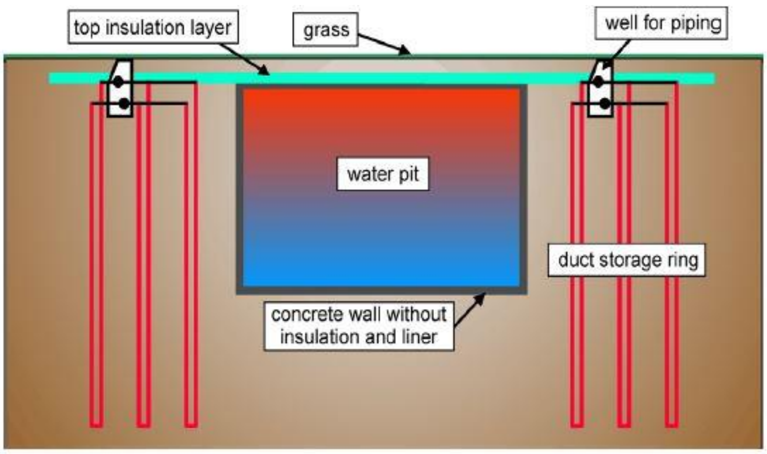

Figure 1 Hybrid storage consisting of a combined water pit and borehole storage [1]

The hot water from the solar collectors is stored within the underground concrete tank and the surroundings vertical borehole heat exchangers. The inner tank acts as a thermal buffer and short-term store and discharge the heat to the district heating supply on a daily basis. The BTES part is used as a low temperature seasonal storage that is charged and discharged when water from the tank is circulated in the boreholes as well as utilises heat conducted through the uninsulated concrete walls of the water tank. The heat is accumulated in the boreholes between April and September and discharged during the winter period using an electric heat pump.

The construction process of the hybrid storage along with the estimated investment cost is explained in Chapter 6.

[1] Solar district heating with seasonal storage in Attenkirchen, Bavarian Center of Applied Energy Research, Manfred Reuss, W. Beuth, M. Schmidt, W. Schoelkopf, ZAE Bayern.

5.2 Full-scale pit thermal energy storage (PTES)

A scenario with a standard pit heat storage in place of the hybrid storage is modelled for comparison. This is built as a large pit dug in the ground with an anti-leakage membrane fitted at the bottom and along the walls. It uses water as storage medium and is covered with an insulating lid which floats on the surface of the water to reduce the energy losses.

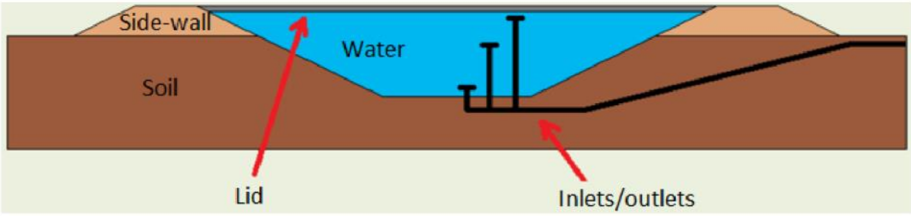

Figure 2 The principle of pit thermal energy storage (PTES). (PlanEnergi, 2013).

5.3 Full-scale borehole thermal energy storage (BTES)

The borehole heat storage as standalone installation is comprised of a number of boreholes made in the ground and fitted with U-shaped water pipes. The storage is charged through pumping of hot water from the buffer tank of the solar collectors which then transmits heat to the surrounding ground. The storage medium in this case is the soil adjacent to the ducts, whereas water pumped through the pipes acts as a transfer medium.

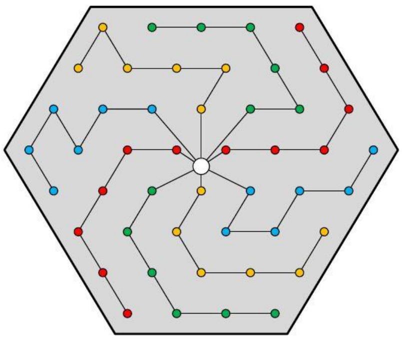

Figure 3 Borehole layout including U-pipes for the pilot borehole storage. (PlanEnergi, 2013).

PlanEnergi

6 Construction and cost estimate of a hybrid storage

This section explains the construction process for a hybrid storage at Brædstrup District Heating and presents a price breakdown for the chosen solution.

The hybrid storage was designed as a thermal pit storage which is built as an underground tank cast on site in reinforced concrete with a water volume of 18,300 m^3, surrounded by a borehole storage consisting of 550 boreholes with a depth of 46 m.

6.1 Design principles for the hybrid storage

Several models for the design of a thermal pit storage in the middle of the hybrid storage have been discussed and evaluated during the process.

Common to all solutions is that a design with vertical sides, which does not require extensive excavations with sloping sides, are required because the thermal pit storage is to be surrounded by the borehole storage with vertical boreholes.

Another requirement for the solution is to have an attached lid, which would enable the area above the hybrid storage to be used for technical installations (e.g. solar thermal panels) or recreational purposes.

The different solutions are based on information from the geotechnical boreholes from the established pilot borehole storage on site.

There are expected to be silt and clay deposits with stones down to a depth of about 10 m, after which there is expected to be sand with stone down to the level of the bottom of the thermal pit storage. The depth of the groundwater level is expected to be approx. 50 m or deeper, and is not expected to affect the performance of the thermal pit storage.

The required design parameter of the thermal pit storage is with a volume between 15-20,000 m^3.

The principles of the preliminary structures that have been considered are described in detail in the following sections:

6.1.1 Bentonite solution

This is a well structure made by excavating a trench with a wire machine with a grab.

While the trench is being excavated, it is simultaneously filled with bentonite in order to stabilize the soil-form.

Once the trench is excavated as a wreath at full depth and filled with bentonite, it is cast with concrete from the bottom, which displaces the bentonite.

The concrete cast can be additionally reinforced with steel fibers, or with traditional rebar.

Afterwards, the concrete sides can be cast inside the excavation.

Objection stiffening ring-beams for relief the external earth pressure on the structure can be made in line with the excavation, if statics determine so.

The use of bentonite for stiffening the excavated trench may be a good solution for some types of soils, but there are substantial risks that the liquid bentonite may leak into the permeable sand deposits and stone heap, increasing the risk of the sand layer to slip in the narrow trenches.

This solution is then evaluated technically and financially by Aarsleff and the construction contractor Jorton, which unanimously conclude that the solution is technically feasible, but too risky and economically costly compared to other solutions.

6.1.2 Sheet piling solution

The thermal pit storage is established as a round tank, where the sides of the tank are made with down vibration of the sheet piling. After the piling is established, the storage tank is excavated at about 6 m depth and an inner concrete wall is cast to relief the soil pressure against the sheet piling. Afterwards, the next section is excavated and a new section of the wall is poured. The casting of the tank walls is as follows in sections from top to bottom, creating challenges in connection to the horizontal joints.

If the wall of the casting is separated from the sheet piles, they can be pulled up and reused.

Moreover, “Copenhagen sheet piling” can be used as an alternative to down vibration (of driven sheet piles). This method consists of vertically framed sections, between which are placed horizontal wooden planks. The storage tank is then excavated from within, as wooden planks can be pressed in depth, in order to reinforce the sides of the excavation. Finally, concrete sides are poured following the same principle as of a framed sheet piling.

The major advantage of the sheet piling construction is that it is a proven design and technology. However, an economic assessment of the solution is made by Aarsleff, and it is found to be too expensive when compared to the other alternatives.

6.1.3 Secant pile wall solution

The thermal pit storage is established as a circular tank by drilling Ø 120 cm holes cast with unreinforced concrete and placed shoulder to shoulder. After casting the holes, the inside of the tank is excavated and the void space between the holes are cast. This is done so that the design is waterproof and ring-forces on the sides of the tank can be absorbed as comprehensive stress in the tank walls.

The drilling process has a high noise level and the construction results in very thick walls. Hence, if the tank is established with the same outside diameter as the other circular tank construction, the volume of this tank would be considerably lower.

Aarsleff have estimated the price of this solution to be around DKK 7.8 million or approx. € 1 million, with an internal diameter of 31,7 m and a depth of 20 m. This price is not competitive with alternative tank solutions.

6.1.4 *Under dug well*

The principle of this tank structure is that a well is moulded in the rim sections, after which the well is excavated from the inside with the well rim thus slipping down into the excavation with the help of its own weight. Afterwards, the other sections can be cast and undercut following the same principle.

This method is known to be used for ordinary wells with a small diameter (2-4 m), but according to our knowledge has never been utilized in large-scale applications.

The solution is proposed by Jens Erik E. Nielsen, who has many years of experience in the construction industry with casting of large concrete structures.

The execution principles are illustrated in the following section:

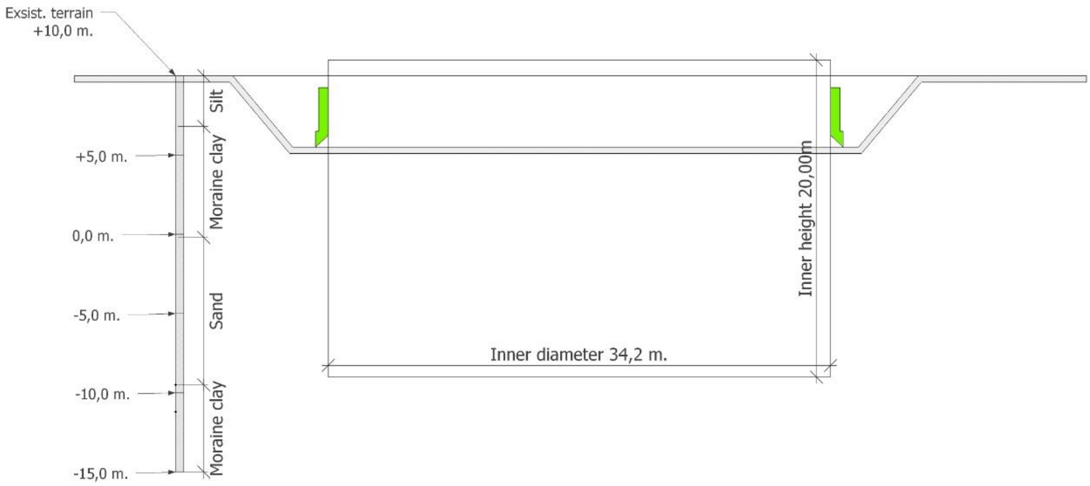

Figure 4 Step 1: Casting of the bottom ring

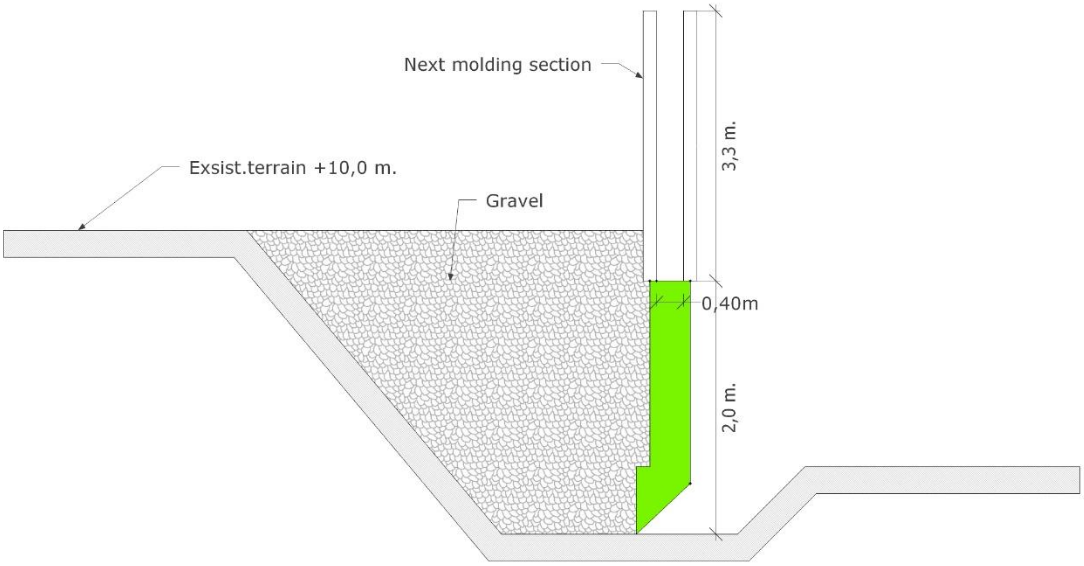

Figure 5 Separation layer of pearl gravel between the tank wall and soil deposit.

The soil is excavated and placed in a soil depot.

A construction pit is excavated in the upper soil sediments with a depth of 2-4 m (possibly the edge layer of clay at 6-10 m –subject to a detailed geotechnical/economic assessment).

A ring with an inclined cut is cast at the bottom. Its outer diameter is 35 m, with a height of 2-3 m and with a shelf approx. 20 cm wide.

Outside the bottom wreath, it is filled with pearl gravel or something similar, with the purpose of minimizing friction between the bottom wreath/tank sides and the soil deposits.

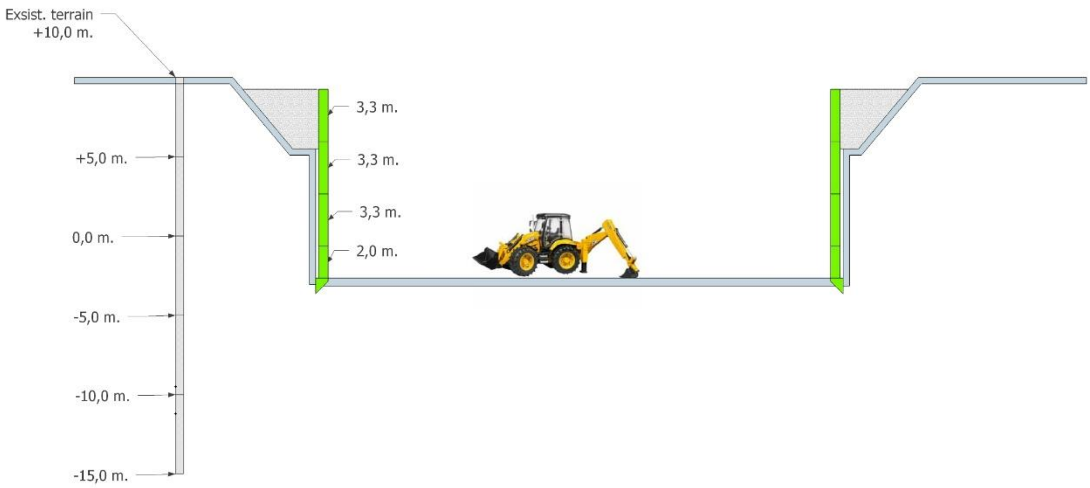

Figure 6 Step 2: Casting of walls and undercutting of the tank construction.

The sides of the tank are cast over the bottom wreath in modules of approx. 3.3 m in height, with a wall thickness of approx. 40 cm. The waterproof concrete casting of min. 40 MPa is reinforced with regular restressed reinforcement.

As with the casting of the walls, the sides of the tank are undercut, and the inside is excavated, with the idea of sliding into the excavation. Pearl gravel on the outside of the tank prevents clay deposits from sticking to the tank sides in the upper soil deposits.

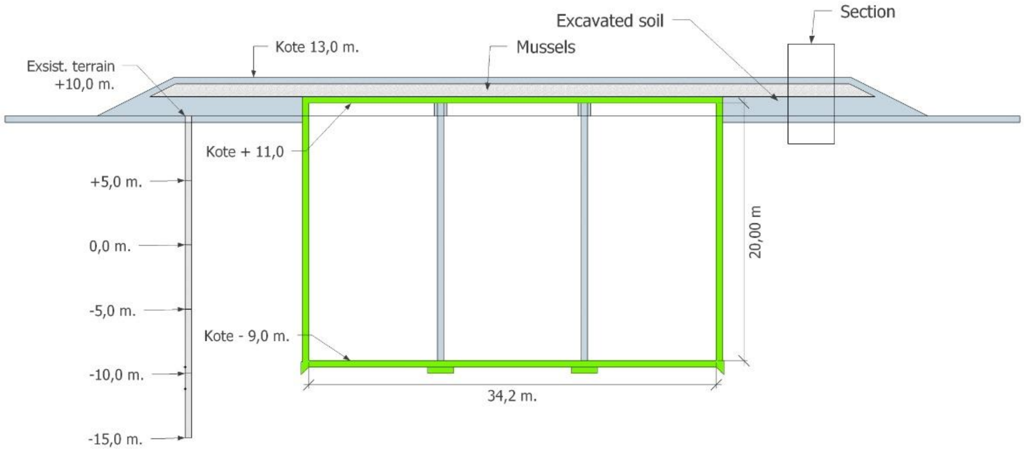

Figure 7 Step 3: Casting of a reinforced base plate and a tank lid.

When the tank sides are cast in full height (approx. 20 m.) and the tank is undercut in level, so the side of the tank is approx. 1 m. above the existing terrain, the reinforced base is cast to 40-50 cm in thickness.

Construction joints are then sealed/waterproofed with products that can withstand heat from water heated up to 90˚C.

The lid over the tank is made out of concrete, either as prestressed concrete elements or as site cast filigree supported by an inner column and beam system. This way the lid is dimensioned for subsequent soil backfilling and weight of people etc., but not for heavy traffic. The lid is sealed with bitumen at its upper side, in order to prevent water penetration from the surface, and be carried out with the shaft of the lid for a subsequent inspection. Inlet and outlet arrangements are established through the sides and mounted inside the side of the tank.

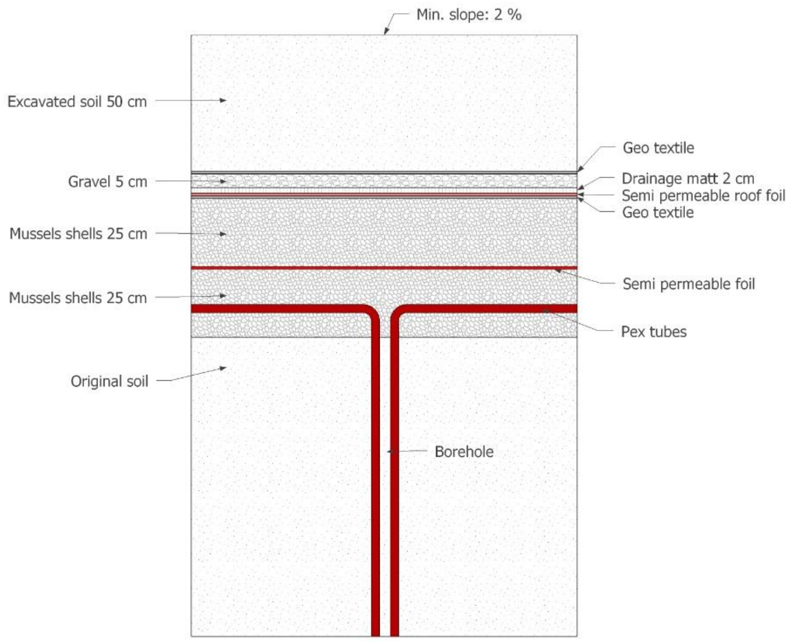

Figure 8 Step 4: Insulation and ground control.

After the establishment of the surrounding borehole storage, inlet and outlet arrangement in the tank and refilling system for the tank, the insulation lid of the tank and the borehole storage is established. The lid is made out of seashells, geotextile and drainage mats, following the same principle as the established pilot borehole storage in Brædstrup.

Finally, the surplus soil from the excavation for the borehole storage and the thermal pit storage is laid out, levelled and grass sown or affirmed, depending on the future use of the land.

The main risks in connection with this model are considered the adhesion (bonding) between clay deposits and exterior walls, so the tank could not slip into the excavation only with the help of its own weight. There is also a risk that the erosion of the well cannot be controlled, so the tank may slide askew into the excavation and therefore be wedged in the process.

The model has been presented to Andreasen & Hvidberg, geotechnics and environment in Aalborg, which after a consultation with Lars Andersen from AAU say:

"It is recommended that the ground pressure on the external wall is dimensioned for the pressure at rest in the permanent situation.

The roughness/friction coefficient between the ground and the concrete can be set to 0,6 (after it is filled with a suitable friction material). Gravel acts as a suitable solution. It is important that the measured clay does not "stick to the walls" of the storage tank, since the adhesion will be difficult to overcome solely with the weight of the tank.

We believe that the specific weight of the tank is sufficient, if sand/gravel can be laid as a vertical layer between the walls of the tank and the intact soil. Nonetheless, this should be verified by e.g. an examination for sliding washer fractures, which can be done in the program Optum, which is a 2D finite element program. The calculation can be performed by Andreasen & Hvidberg."

The risk of the tank sliding down askew due to erosion or sticking of clay deposits has been discussed with Aarsleff. It is estimated that the risk of the tank to adhere to clay sheets is minimal, since there are clay deposits in up to 10 m depth. This risk can be partially countered by excavating the plant into the practice part of the clay layer, before the well is undercut. If the tank still sticks to the clay layer, or slides wrapped into the excavation, it is possible to establish ground anchors on the inside of the well, which are anchored into the ground following the same principle as with the anchored sheet piles. Soil anchors can be used to set up the tank and possibly drag it into the excavation. Ground anchors may be deployed for about DKK 30.000 per anchor and must be placed 2 m apart in the worst cast case scenario – if everything goes wrong. The risk is evaluated to a total of DKK 1,6 million excl. VAT.

After a comprehensive risk assessment of the four alternatives is made, the solution where the well is undercut is determined to be the cheapest option with the fewest possible risks involved.

The chosen solution is subsequently processed in cooperation with the contractors Jorton, which have prepared an estimated price for performing the operation incl. an insulated lid above the tank along with a tank in the middle, surrounded by the borehole storage.

6.2 Investment budget

The price breakdown provided by Jorton is included into the overall construction budget for the hybrid storage.

The total construction budget for the establishment of a hybrid storage incl. transmission lines from the hybrid storage to the engineering building is shown in the following table.

Estimate, Hybrid storage in Brædstrup	Amount	Unit price (DKK)	Sum (DKK)
Geological storage in the middle, DO=35m, H =20m, net volume of ca. 18,300 m^3 (Price estimated by Jorton)			
Excavation and undermining of the wells, site levelling of surplus soil			7,250,000
Moulding of the sides of the tank in 40 cm reinforced concrete			4,210,000
Moulding of the bottom of the tank in 40 cm reinforced concrete			2,520,000
Lid of the tank with inner column supports			3,240,000
Inner waterproofing membrane			620,000
Crane			275,000
Construction Site Management and quality assurance			775,000
Misc.			1,110,000
Total price of the geological storage			20,000,000
Inlet and outlet arrangement			
Inlet and outlet arrangement in the tank with 4 levels. Incl. inside pump well.			1,500,000
Boreholes, Offer from PC Drill			
Mob. Demob of drilling equipment, 3 rigs			90,000
Boreholes 550 pcs. at 46 m. depth	25,300	300,00	7,590,000
Setting og Raugeo green PEX-A 32 mm x 50 from Rehau incl. 55 kg. counterweight	550	5,500,00	3,025,000
Delivery and laying of 825 t. DantoCon Termal C2H as a seal around the boreholes	825	5,300,00	4,372,500
Rental of a site hut for 11 months	11	20,000,00	220,000
Total price of the boreholes			15,297,500

Table 1 Investment budget for the hybrid storage (part 1).

Distribution pipes			
Hose, fittings, manifold. 10 m. pipes and 2 press fittings pr. borehole. 12 pcs. distribution wells for full-scale storage.			
Hoses between the drill holes, 550 holes with 10 m. hose	5,500	100,00	550,000
Fittings, 4 x 550 pcs,	2,200	100,00	220,000
Total price of the distribution pipes			770,000
Distribution wells			
12 pcs. distribution wells	12	200,000,00	2,400,000
Isolated lid of the tank and borehole storage			
Building with seashells, geotextile and drainage mats which exist, cost estimated by Jorton. Diameter 95 m	7,041	452,00	3,182,500
Total price of the isolated lid			3,182,500
Technical installation and service building			
Pipes, heat exchangers, etc. incl. solar thermal unit for the existing building			2,000,000
Valves and pumps in the new building			5,500,000
New service building at the solar thermal plant			4,000,000
Total price of the installations and new building			11,500,000
Transmission lines, hybrid storage			
			1,500,000
Total price of the transmission lines			1,500,000
Total budget of the hybrid storage excl. VAT:			**56,150,000**

Table 2 Investment budget for the hybrid storage (part 2).

Additional expenses			
New Solar thermal heating system			
Solar thermal panels: 52,600-8,000-10,600 = 34,000 m^2.	34,000	1,300,00	44,200,000
Basic expenses, solar thermal field			4,000,000
Dry cooler for solar thermal field			500,000
Total price of the new solar thermal heating system			48,700,000
New heat pump 2 MW			
Heat pump			6,000,000
Electrical connection			800,000
Total price of the heat pump			6,800,000
Land acquisition 110,000 m^2	110,000	15,00	1,650,000
Energy savings 8,000 MWh	8,000	-350,00	-2,800,000
Total budget for the additional expenses excl. VAT:			**54,350,000**
TOTAL EXPENDITURE, ENTIRE SYSTEM excl. VAT			**110,500,000**

Table 3 Investment budget for the hybrid storage (part 3).

6.3 Summary

The hybrid storage was designed as a thermal pit storage which is built as an underground tank cast on site in reinforced concrete with a water volume of 18,300 m^3, surrounded by a borehole storage consisting of 550 boreholes with a depth of 46 m.

The thermal pit storage is moulded in the centre, with a diameter of 35 m and an inner depth of 20 m. The sides are moulded in sections with a height at about 3.3 m. The well is undercut from within and slides into the hole from the weight of the well walls. When the well reaches the maximum depth, a base plate is casted, and a concrete lid is established, which is supported by an inner column and beam system. The top lid of the storage ends about 1 m above ground level.

The borehole storage encircles the storage in the middle, so the heat loss from the sides of the thermal pit storage can be utilised in the boreholes. The borehole storage design follows the same principle as the pilot installation already established in Brædstrup. An isolation lid made out of seashells, with inlaid geotextile and drainage membrane, is used above the borehole storage and the thermal pit storage, following the same principle as in the existing pilot borehole storage.

The excess soil from the excavation for the thermal pit storage in the middle is laid out on top of the borehole storage and thermal pit storage. The area above the two storages can afterwards be used for a solar thermal installation, recreational purposes, etc.

The total cost of the hybrid storage, comprising of the borehole storage, the thermal pit storage in the middle, along with transmission lines and other installations is calculated to approx. DKK 56 million excl. VAT, or approx. € 7.5 million excl. VAT.

Further expenses for the expansion of the existing solar thermal field with associated additional transmission lines, along with the establishment of an additional heat pump amount to approximately DKK 58 million excl. VAT, or approximately € 7.8 million excl. VAT. The total investment is estimated at circa DKK 110.5 million excl. VAT which is equivalent to circa € 14.9 million. A detailed budget can be found in section 6.2.

The decision-making process for the choice of design principles for the thermal pit storage in the middle of the borehole storage, along with the investment budget for the entire hybrid storage are described in detail in chapter 5.1.

7 Optimisation of hybrid storage

This chapter focus on an optimisation of the shallow hybrid storage design and operation. The initially sized with a 18,300 m^3 water tank, surrounded by a borehole storage consisting of 550 boreholes, the hybrid storage dimensions have been revaluated and adjusted to improve the efficiency of the system performance. The new design option includes a 16,500 m^3 concrete water tank and 420 boreholes.

As a comparison, an operation of a full scale standalone PTES storage and a full scale standalone BTES storage is modelled.

7.1 Modelling scenarios

To better understand a feasibility and commercial benefits of the new heat storing solution, the model of **hybrid storage** has been built and investigated in the following steps:

- #0. The reference consisting of the existing solar plant with a total collector area of 18,600 m^2 and a heat accumulation tank of 5,000 m^3. The pilot borehole storage and the existing heat pump are not included in the reference.
- #1. As (0) supplemented with a new solar plant providing up to 50% of total DH heat supply. The new solar plant is varied from 0 to 100,000 m^2.
- #2. As (1) supplemented with an underground concrete water tank of 16,500 m^3.
- #3. As (2) supplemented with a BTES consisting of 420 boreholes.
- #4. As (3) supplemented with a new heat pump for discharging the borehole storage.

The first alternative scenario with a **pit thermal energy storage** is set up based on the principle:

- #5. As (1) supplemented with a full-scale pit heat storage filled with 100,000 m^3 of water.

The second alternative scenario with a **borehole thermal energy storage** was modelled in the two following steps and each one utilises the existing small water storage tank:

- #6. As (1) supplemented with a BTES consisting of 420 boreholes.
- #7. As (6) supplemented with a new heat pump for discharging the borehole storage.

8 Performance calculations

This section summarises the results of the Brædstrup Fjernvarme's plant operation for the expanded solar installation configured with different thermal storage technologies.

8.1 Heat demand

Hourly metered data for almost 30 different parameters collected in the period between 01/01/2014 and 31/12/2016 were provided by Brædstrup Fjernvarme.

The most recent year's heat consumption data were used to create the heat demand characteristic for the Brædstrup system. A monthly profile for 2016 is presented in Figure 9. The actual measured energy consumption data is shown in the blue columns. These values have been altered to reflect the energy consumption data for a typical year which was done using the number of degree days recorded in the nearest region (Øst-Midtjylland).

The heat demand independent of degree days is highlighted on the graph in red. This indicates the proportion of the heat demand that was consumed in a month regardless of the external temperature. The thermal energy demand that is dependent on the weather conditions and hence the number of degree days, is illustrated by the green sections of the graph.

The total annual consumption of the Brædstrup heating system was estimated at circa 41,111 MWh. This, adjusted for degree days the heat demand equals to 43,100 MWh/annum and is further used to the performance calculations in TRNSYS.

The baseload demand is approximated at 2.1 MW_{th} according to the typical heat consumption during summer period reaching about 1,500 MWh/month.

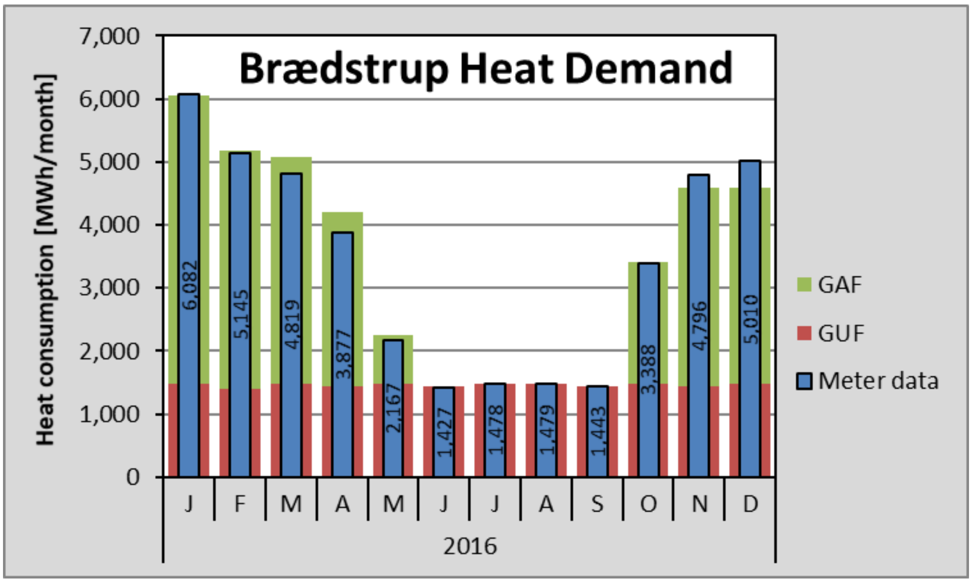

Figure 9 Measured monthly heat demand for 2016 divided into degree days dependent demand (GAF) and degree days independent demand (GUF).

8.2 Heat network temperatures

The flow and return temperatures of the district heating system in Brædstrup measured for the entire 3-year period have been incorporated into the technical simulation in TRNSYS. The initial two years of data are illustrated in the following Figure 10.

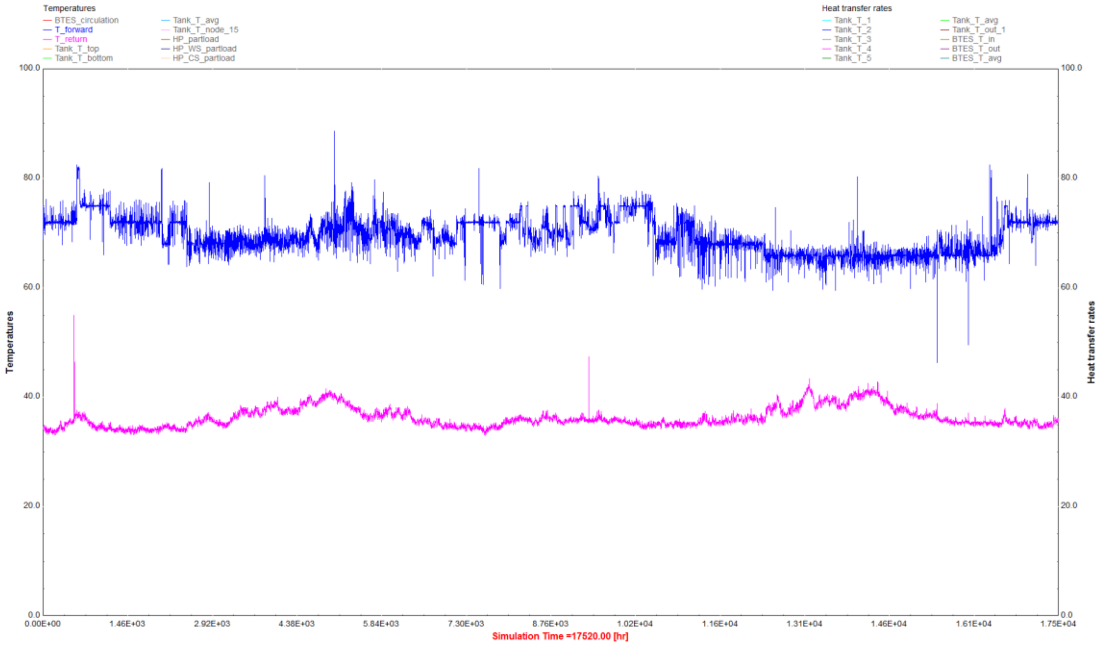

Figure 10 Measured flow (dark blue) and return temperatures (pink) [°C] for 2014 and 2015.

8.3 Simulation model

The performance of the upscaled plant in Brædstrup along with the hybrid storage is modelled in the dynamic simulation programme, TRNSYS 16. The system layout for the existing plant (top section) and the anticipated extension (bottom section) is presented in Figure 11.

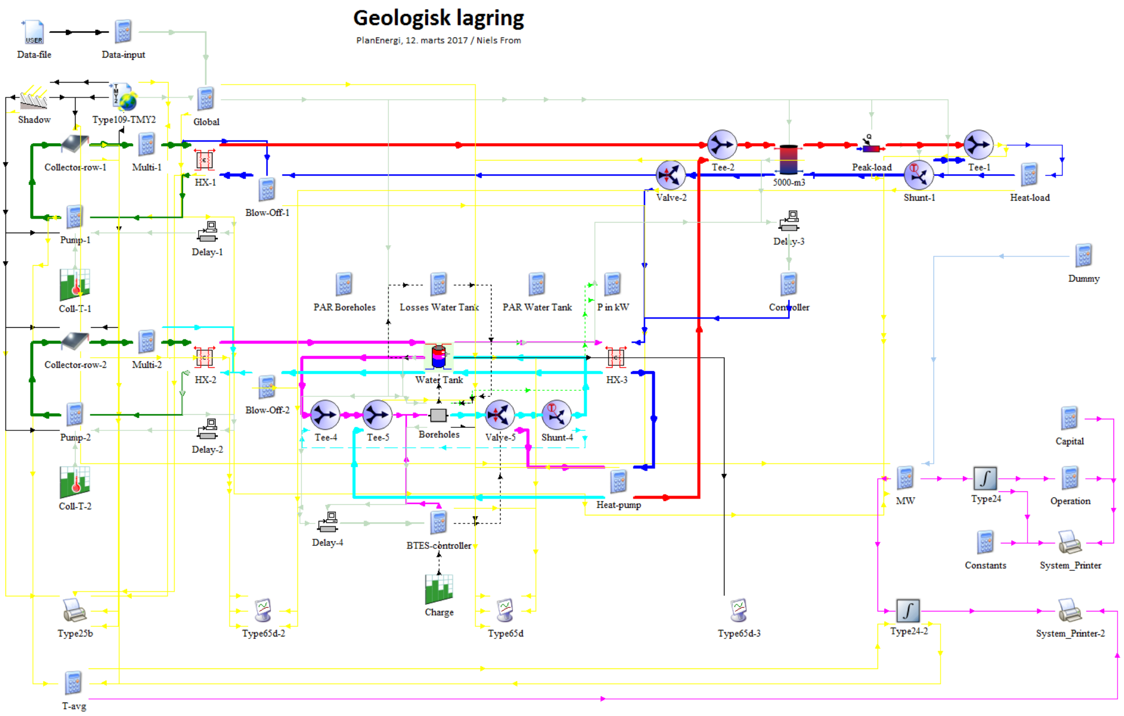

Figure 11 The user interface in the TRNSYS model (with all layers shown).

This shows the full view of the graphical user interface in the TRNSYS model including individual units of the plant such as solar collectors, existing gas boilers/CHP acting as a peak load heat supply, new hybrid thermal energy storage and ancillary systems (heat exchangers, pumps, three port valves, heat rejection). Besides that, the model contains heat consumption and weather data files, controlling functions, bespoke equations and output/display modules. The interconnecting lines indicate the flow direction of the energy transport medium and links between the function blocks.

Figure 12 highlights the fluid circuits in the system.

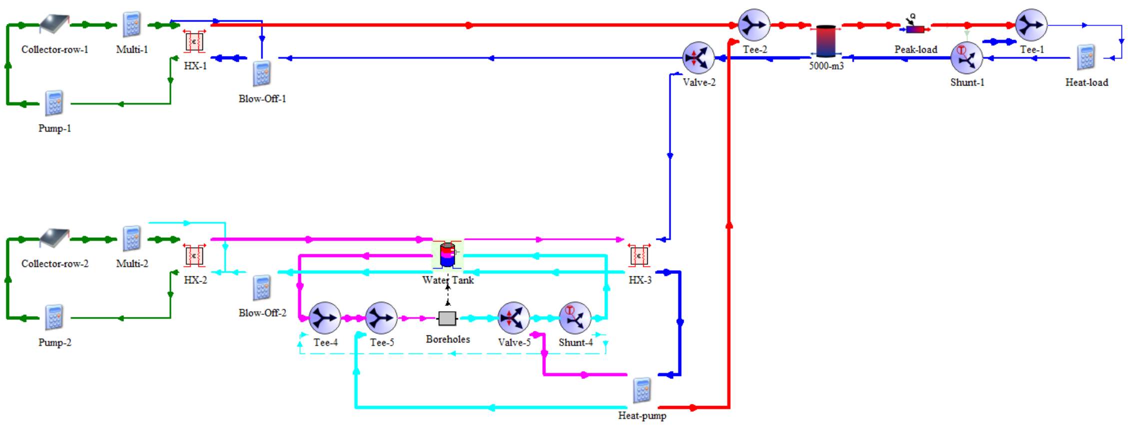

Figure 12 The fluid circuits in the TRNSYS model. Green lines represents glycol, red and dark blue line represents district heating water (flow and return), and pink and light blue lines represents storage water (warm and cold). Heat transfer direction is from left to right.

8.3.1 *Existing heating system*

The top section of the distinguished layer in Figure 12 corresponds to the reference case with the existing installation of 18,600 m^2 of solar collectors (left hand side of the figure) and the heat accumulation tank rated at 5,000 m^3 (right hand side of the figure).

It is assumed that the base heat load of the DH network is supplied by the solar plant and this is supplemented by the gas boiler output ("Peak-load" unit) at the time the heat production from the collectors is insufficient.

The heat demand adjusted for degree days (section 8.1) is a part of the component "Heat-load" to the very right of the figure. A return shunt ("Shunt-1") is responsible for controlling the flow temperature to never exceeds the measured flow temperature (section 8.2) whereas "Blow-Off-1" component ensures that the inlet temperatures to the secondary side of the solar heat exchanger "HX-1" never exceeds 60°C.

Figure 13 shows the results for the reference case (scenario #0). In addition to the DH flow and return temperatures, the graph illustrates other example parameters as the temperature distribution at the bottom (green curve) and at the top (orange curve) of the heat accumulation tank. The light blue curve indicates the average temperature calculated across the entire accumulator. Based on the chart, the water flow from the water tank to the solar plant heat exchanger rarely exceeds 60°C (in a standard year). The need for heat blow off is therefore limited which is calculated to approx. 60 MWh/annum corresponding to approximately 7 ‰ of the annual solar heat production.

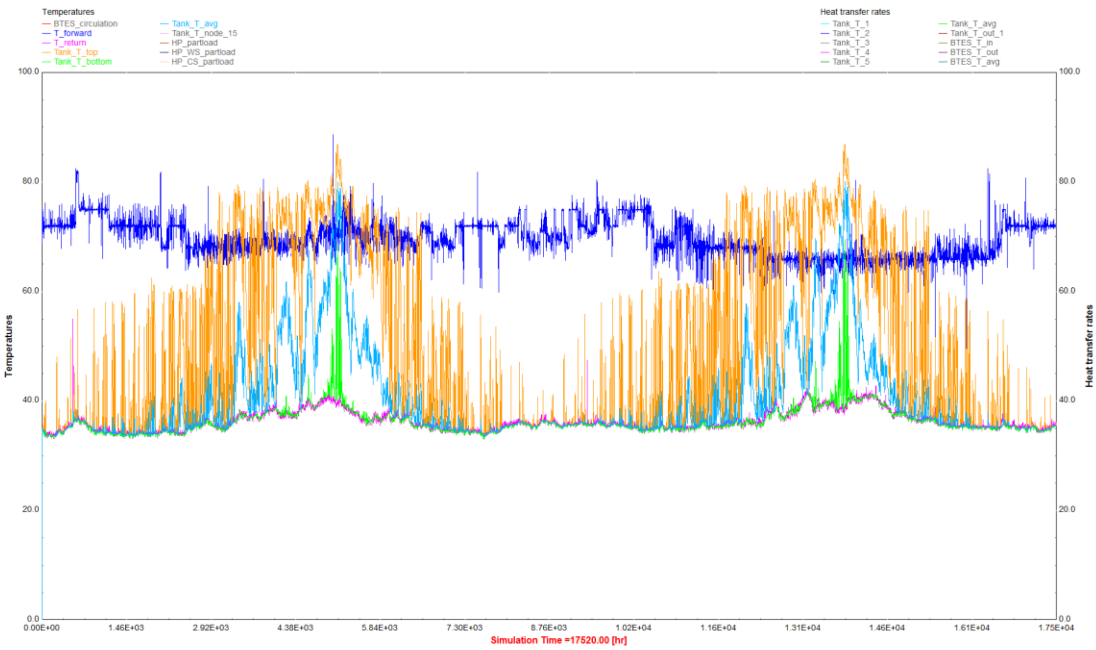

Figure 13 Example of top (orange line), bottom (green line) and average (light blue line) temperatures in the heat accumulation tank [°C] in the reference (scenario # 0), as well as flow (dark blue line) and return (pink line) temperatures [°C] during 2 simulation years.

8.3.2 Heating system development

The bottom section of the fluid circuit in Figure 12 illustrate the elements of the extended plant. From the left-hand side, it begins with the new solar plant rated at circa 30,000 m^2. The heat output from the solar collectors is pumped to the water tank located in the middle of the figure ("Water Tank").

The water sourced from the water tank at ⅓ height from the top is stored in the surrounding borehole storage ("Boreholes") and returned at ⅓ height from the bottom of the tank. This divides the water tank into 3 layers: a warm top, a lukewarm middle and a cold bottom. The hot water from the upper layer of the water tank is pumped to the heat exchanger which transfers the heat from the new plant to the district heating ("HX-3").

The borehole storage is charged for a period of 6 months between April and September and is discharged by the new heat pump ("Heat-pump") for the rest of the year. This heat volume is transferred to the district heating return water that passes through the heat pump after exiting "HX-3".

The system is equipped with control safety settings to avoid overheating of the heat generation and storage units. Two components: "Blow-Off-1" and "Blow-Off-2" ensure that the inlet temperatures to the secondary sides of the solar heat exchangers "HX-1" and "HX-2" never exceeds 60°C. Item "Shunt-4" similarly ensures that the inlet temperature to the borehole storage never exceeds 85°C.

8.3.3 Complete heating system simulation

The existing and the new solar plant operate in series providing the base heat load to the Brædstrup district heating system. The hot water from the existing collectors ("HX-1") and the upscaled plant (water flow from "HX-3" and "Heat-pump") is combined in the mixing valve ("Tee-2") and passed to the accumulation tank ("5000-m3"). This heat flow is topped up with the peak load boiler output and supplied to the district heating.

Figure 14 demonstrates the outcomes for scenario #4 which is the complete hybrid storage system consisting of a PTES, a BTES and a heat pump. In addition to the DH flow and return temperatures, example parameters for the heat storage are shown. This are the average temperature across the BTES system (dark green curve) and the water tank temperatures including the top layer of the tank (light blue curve) and the bottom one (dark green curve). The light green curve indicates the average temperature calculated across the entire water storage.

Two-year modelling period is a minimum timescale to calculate adequate performance outputs of plant with the borehole storage and the heat pump heat recovery. This is the required time to almost balance the heat losses from the boreholes to the surrounding ground. Therefore, the results from year 2 are used to the further economic analysis.

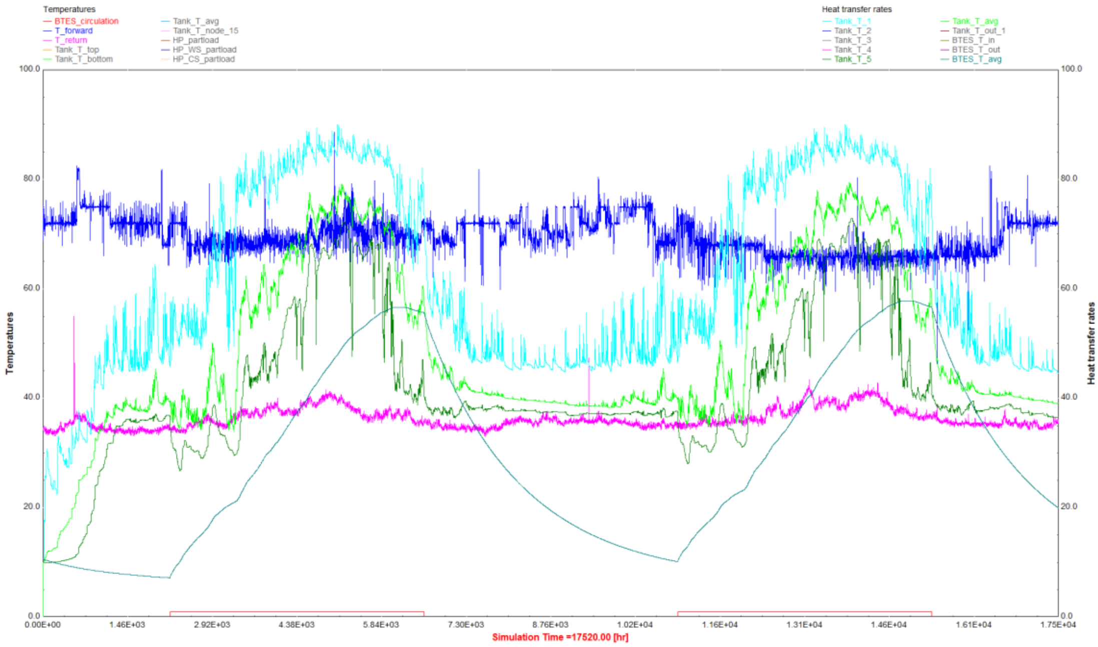

Figure 14 Example of top (light blue), bottom (dark green) and average (light green) temperatures in the concrete tank [°C], as well as forward (dark blue) and return (pink) temperatures [°C] during 2 simulation years in scenario # 4. Further the average soil temperature in the borehole storage (turquoise) [°C] and periods with charging of the borehole storage (red) [–]. The borehole storage is here heated to approx. 58°C (in September) and cooled to approx. 10°C (1st April).

8.3.4 *Validation of the borehole storage model*

The simulation model for the BTES system created in the TRNSYS tool, has been compared with the measured data for the existing borehole pilot storage installation.

The data provided by Brædstrup Fjernvarme for period between 2014 and 2015 including inlet (red curve) and outlet (dark blue curve) temperature from the boreholes, average temperature of the surrounding soil (pink curve) and BTES mass flow (brown) is presented in Figure 15.

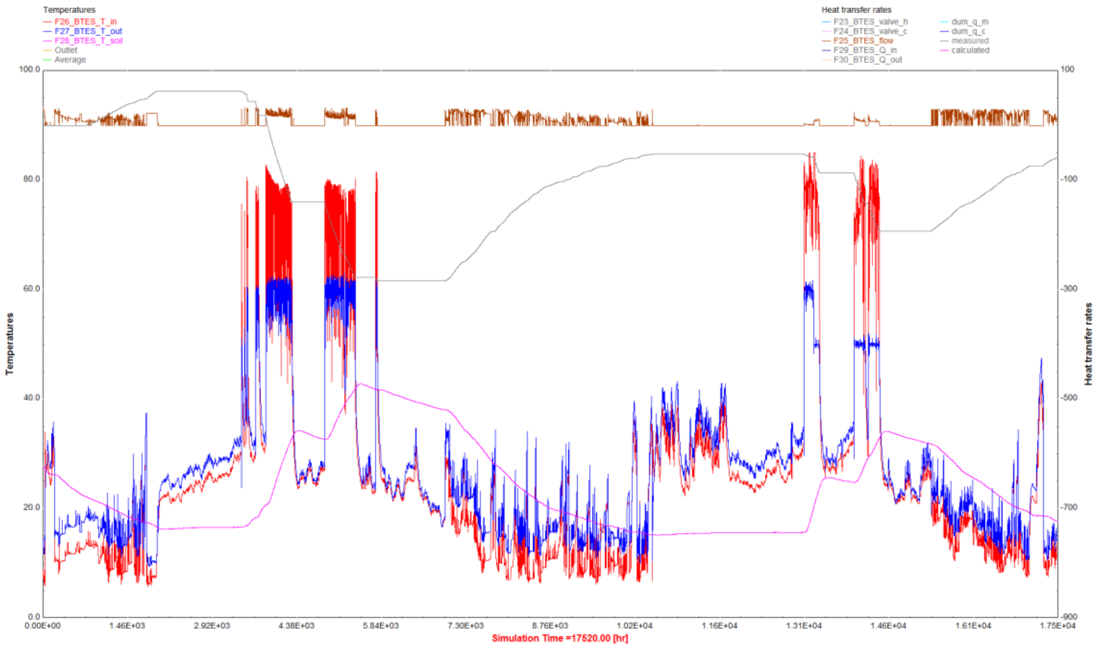

Figure 15 Measurements from the pilot borehole storage for 2-year period (2014 – 2015): water flow [m^3/h] (brown line), borehole storage inlet and outlet temperatures [°C] (red and blue lines), average soil temperature in the storage [°C] (pink line) and calculated charging and discharging heat capacity [MWh] (grey line).

The heat capacity and the heat conduction of the simulated borehole storage has been aligned with the actual measured conditions of the soil in Brædstrup. This includes 2,100 kJ/(m^3·K) and 1.8 W/(m·K), respectively. The resulting calculated parameters of the borehole storage when compared with the measured data – which is shown in Figure 16 – evidence that there is a good compliance between the measurements at the pilot borehole storage and the borehole storage model in TRNSYS.

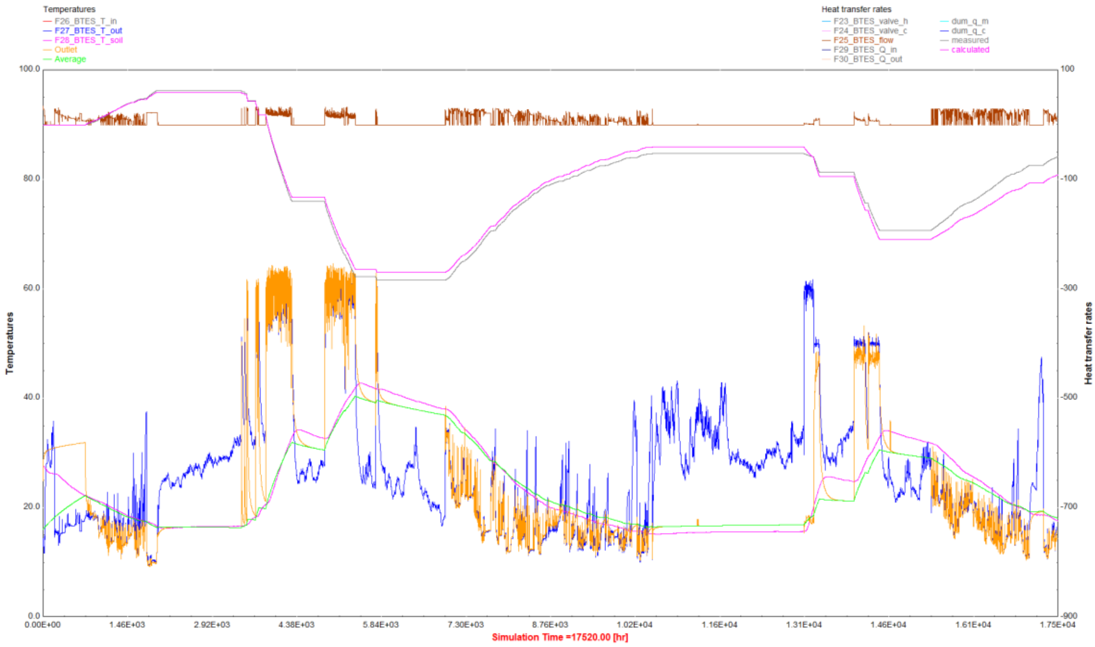

Figure 16 Comparison of measured and simulated values for 2-year period (2014 – 2015): measured flow [m3/h] (grey line), measured (blue line) and simulated outlet temperatures [°C] (orange line), measured (bottom pink line) and simulated storage temperatures [°C] (green line), measured (grey line) and simulated accumulated charging and discharging volumes [MWh] (upper pink line). The first month is used for preheating the model and therefore, is not a part of the comparison.

8.4 System optimisation

The performance simulation for the thermal energy storage in Brædstrup was taken to further analysis which aimed to optimise the size of the new solar plant in respect of the heat production benefit. The solar collector extension was investigated within a range up to 100,000 m^2 of collector aperture area.

The effect of the parametric calculation for all simulation scenarios (#1 - #7) was collated in Figure 17. This illustrates the cumulative heat output from the existing and the upscaled solar installation as a function of the total solar collector area. The existing plant of 18,600 m^2 which is represented by #0 Reference case supply circa 20% of total heat demand.

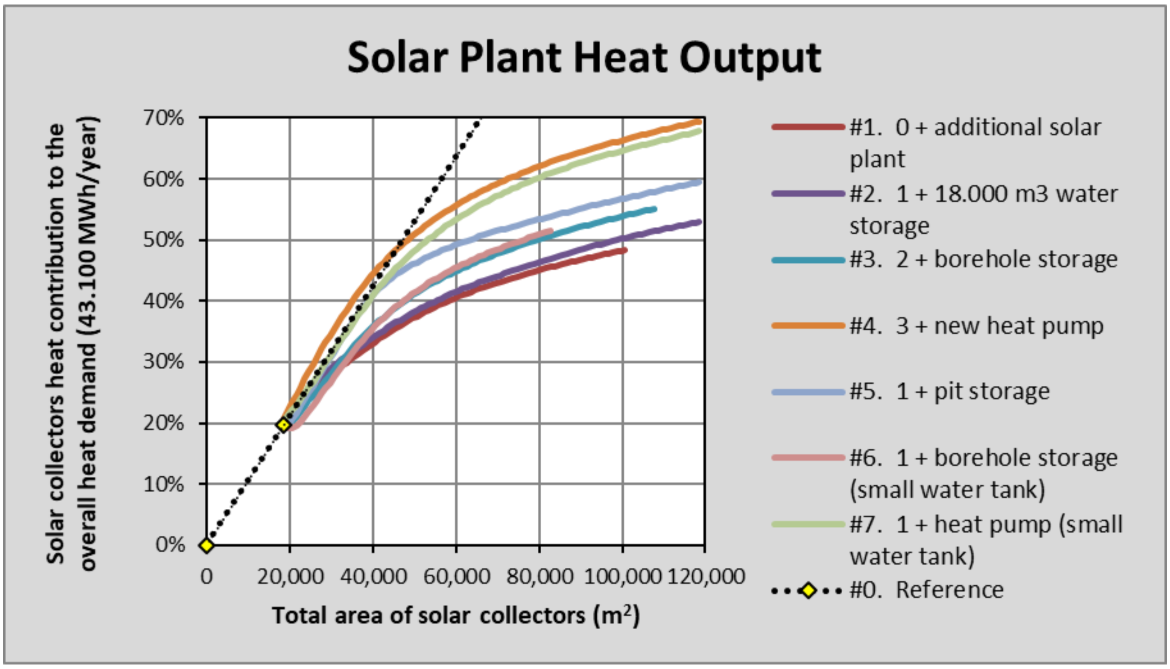

Figure 17 Annual solar heat plant output as a function of the total solar collector area.

It is noted that scenario #4 in comparison with the remaining scenarios has the highest gain of heat output per m^2 collector area regardless of the size of the solar plant.

9 Economic analysis

The commercial assessment of the hybrid storage installation is presented in this chapter. The economic factor that was determined and compared among all modelling scenarios is the cost of heat generated by the new plant.

9.1 Assumptions

9.1.1 Investment cost

The investment cost for the new installations was estimated using the following assumptions:

- Additional solar plant has an upfront cost of DKK 5.0 million plus 1,300 DKK/m^2.
- The price of the underground water storage is DKK 20.0 million (without the financial support).
- The price of the borehole storage is DKK 20.0 million (without the financial support).
- The price of the heat pump (including building infrastructure, electricity supply etc.) is DKK 10.0 million.
- The price of the pit heat storage is DKK 25.0 million.
- The financial support is only offered to the hybrid thermal storage and is assumed to provide 50% of total investment cost which refers to DKK 10.0 million fund for the concrete water tank and the borehole storage, each.

The economic analysis has been run using an average annual capital cost which was approximated as 4.35% of the total investment cost for a 25-year annuity loan (see example in Figure 18) and 5.38% of the investment for a 20-year annuity loan.

Amortisation plan - Annuity loan: Loan example for Brædstrup

Amount (expected revenue)	1,000,000	DKK
Depreciation rate	98.00	
Number of terms	4	per annum
Nominal interest rate	2.00%	per annum
Loan timescale	20.0	years
First instalment payment date	01-07-2017	
One-time guarantee commission	1.00%	per annum
Ongoing guarantee commission	0.50%	per annum
Amount incl. depreciation loss	1,020,408	DKK
Net amount incl. potential front-end fe	1,030,612	DKK
Quarter repayment instalment	15,662	per term
Annual repayment instalment	62,649	per annum

Input cell		
Cells used in calculations		
Average annual repayment instalment		
Total Interest rate	222,368	DKK
Total repayment amount	1,030,612	DKK
One-time guarantee commission	10,204	DKK
Total ongoing guarantee commission	56,238	DKK
Total repayment amount incl. guarantee commission	1,319,421.88	DKK
Average annual repayment installement incl. guarantee commission	53,806	2016-DKK

Year	No.	Settlement period	Repayment instalment	Interest	Total repayment instalment	Remittance	Guarantee warranty provision	Repayment installement incl. guarantee commission (2016-DKK)
0	0	01-04-2017	-	-	-	1,030,612.24	-	
1	1	01-07-2017	10,509.19	5,153.06	15,662.25	1,020,103.05	5,100.52	20,446.86
1	2	01-10-2017	10,561.74	5,100.52	15,662.25	1,009,541.32	-	15,423.95
1	3	01-01-2018	10,614.54	5,047.71	15,662.25	998,926.77	-	15,423.95
1	4	01-04-2018	10,667.62	4,994.63	15,662.25	988,259.16	-	15,423.95
2	5	01-07-2018	10,720.96	4,941.30	15,662.25	977,538.20	4,887.69	19,779.55
2	6	01-10-2018	10,774.56	4,887.69	15,662.25	966,763.64	-	15,075.09
2	7	01-01-2019	10,828.43	4,833.82	15,662.25	955,935.21	-	15,075.09
2	8	01-04-2019	10,882.58	4,779.68	15,662.25	945,052.63	-	15,075.09
3	9	01-07-2019	10,936.99	4,725.26	15,662.25	934,115.64	4,670.58	19,182.82
3	10	01-10-2019	10,991.67	4,670.58	15,662.25	923,123.97	-	14,776.41
3	11	01-01-2020	11,046.63	4,615.62	15,662.25	912,077.34	-	14,776.41
3	12	01-04-2020	11,101.86	4,560.39	15,662.25	900,975.47	-	14,776.41
4	13	01-07-2020	11,157.37	4,504.88	15,662.25	889,818.10	4,449.09	18,560.75
4	14	01-10-2020	11,213.16	4,449.09	15,662.25	878,604.94	-	14,454.69
4	15	01-01-2021	11,269.23	4,393.02	15,662.25	867,335.71	-	14,454.69
4	16	01-04-2021	11,325.57	4,336.68	15,662.25	856,010.14	-	14,454.69
5	17	01-07-2021	11,382.20	4,280.05	15,662.25	844,627.94	4,223.14	18,004.79
5	18	01-10-2021	11,439.11	4,223.14	15,662.25	833,188.83	-	14,181.04
5	19	01-01-2022	11,496.31	4,165.94	15,662.25	821,692.52	-	14,181.04
5	20	01-04-2022	11,553.79	4,108.46	15,662.25	810,138.73	-	14,181.04

Figure 18 Example of the annuity loan calculation for 20-year period.

9.1.2 Operation and maintenance cost

The price of O&M is respectively 5, 10, 15, 20 and 10 DKK/MWh for scenarios #1, #2, #3, #4 and #5. Scenarios #6 and #7 have the same specific cost of the operation and maintenance as scenarios #3 and #4.

9.1.3 Electricity consumption

The COP of the heat pump is assumed to be 4.0 and the variable price of the electricity for the heat pump is assumed to be 0.80 DKK/kWh (including distribution cost and taxes).

9.2 Heat cost analysis

In this section, the hybrid storage system optimisation results are costed and assessed commercially. The most financially viable solar heat coverage (including the existing solar installation) in the region of the 50% target set by Brædstrup Fjernavarme is examined.

The economic calculations have been performed for four different combination of depreciation periods and financial support scenarios. These are defined by a 25-year and 20-year depreciation evaluated with and without the funding. The financial support is only offered to the hybrid thermal storage and is assumed to provide 50% of total investment cost which refers to DKK 10.0 million fund for the concrete water tank and the borehole storage, each.

9.2.1 25-year project without support

The following graphs illustrate the cost of the heat generated by the new solar plant liaising with the hybrid storage, the standalone pit storage and the standalone borehole installation. The results are compared for all individual modelling scenarios. The heat cost for 25-year project with the full investment cost is shown in Figure 19.

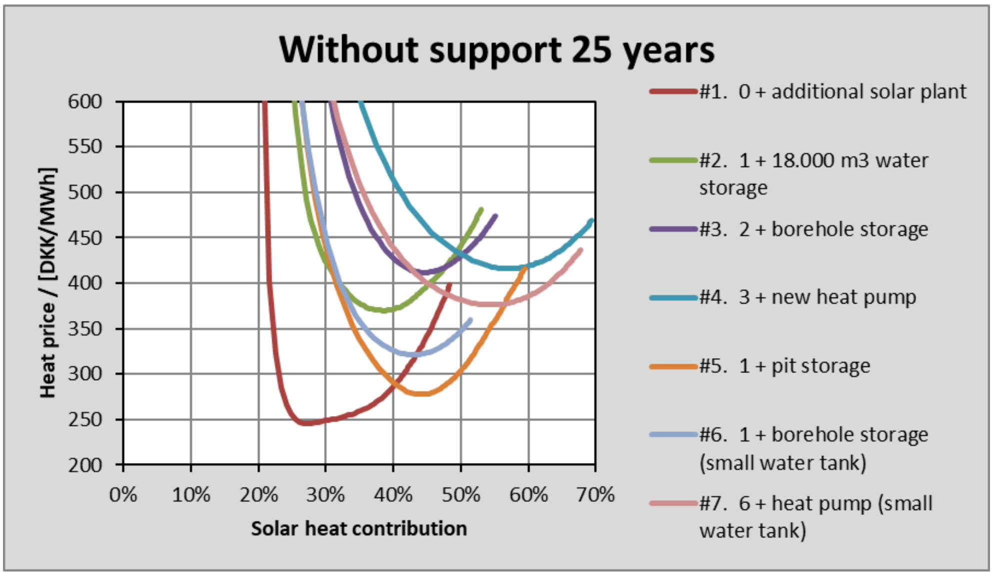

Figure 19 Heat price estimate for the extended plant with different solar energy coverage for 25-year project without the support.

The price per unit of heat output (DKK/MWh) decreases in inverse proportion to the capacity of solar collectors up to the limit point which is the most optimal total size of the solar plant (including the existing collectors) with the lowest heat cost. Any further increase of the installation would not reduce the heat price any further, quite the contrary, it would make it more expensive.

The most cost-effective scenario for plant extension providing solar thermal output in the region of 50% of total heat demand in Brædstrup (which is circa 280 DKK/MWh for 45% of solar contribution), is the full-scale pit hot water storage (Scenario #5). The integration of a hybrid storage with the full technology cost paid by Brædstrup Fjernvarme (Scenario #4), envisages the heat cost of approximately 415 DKK/MWh (at ~55% heat coverage). The standalone borehole thermal energy storage case offers heat at 375 DKK/MWh (at ~55% heat coverage).

9.2.2 25-year project with support

In case the project obtains the fund for the concrete water tank and the borehole storage, the heat supply prices in the 25-year project timescale would reduce scenarios #2, #3 and #4 as demonstrated in Figure 20.

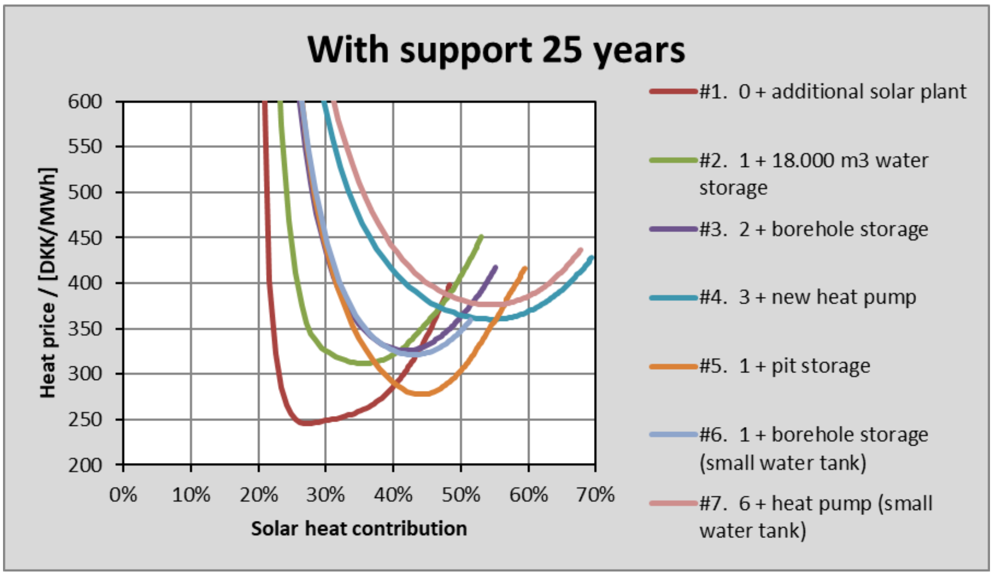

Figure 20 Heat price estimate for the extended plant with different solar energy coverage for 25-year project with the support.

The cost of heat supply for the extended solar plant with incorporated hybrid storage system (Scenario #4) is the lowest (circa 360 DKK/MWh) for 55% solar coverage. This is slightly cheaper than the full-scale borehole heat storage investment (Scenario #7) which heat price is not affected by the financial support (375 DKK/MWh also for circa 55% solar coverage). The heat tariff for pit storage option (Scenario #5) remains unchanged as it is not subsidized by the funding.

9.2.3 20-year project without support

The more conservative approach is taken in the economic calculations for the shorter 20-year project duration. The heat prices range for different solar heat contribution in scenario without the financial support is shown in Figure 21.

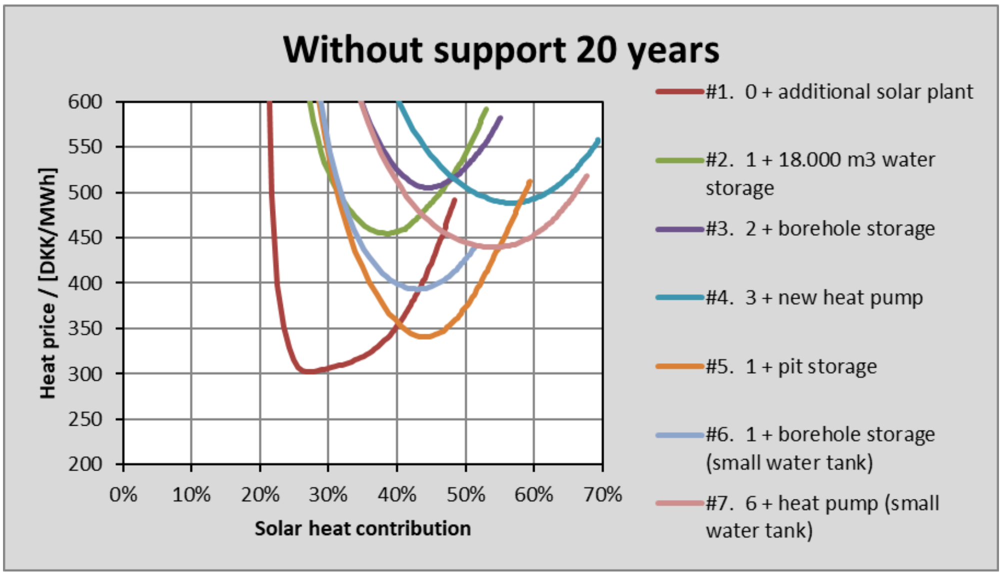

Figure 21 Heat price estimate for the extended plant with different solar energy coverage for 20-year project without the support.

The heat price in the scenario with integrated hybrid thermal storage (Scenario #4) increased to around 490 DKK/MWh (at ~55% heat coverage) for the 20-year project lifetime period. In the full-scale pit hot water storage option (Scenario #5) the cheapest heat supply from the new plant can be provided at circa 340 DKK/MWh (at ~45% heat coverage). The standalone borehole thermal energy storage case (Scenario #7) offers heat at 440 DKK/MWh (at ~55% heat coverage).

9.2.4 20-year project with support

In case the project obtains the fund for the concrete water tank and the borehole storage, the heat supply prices in the 20-year project timescale would reduce as demonstrated in Figure 22.

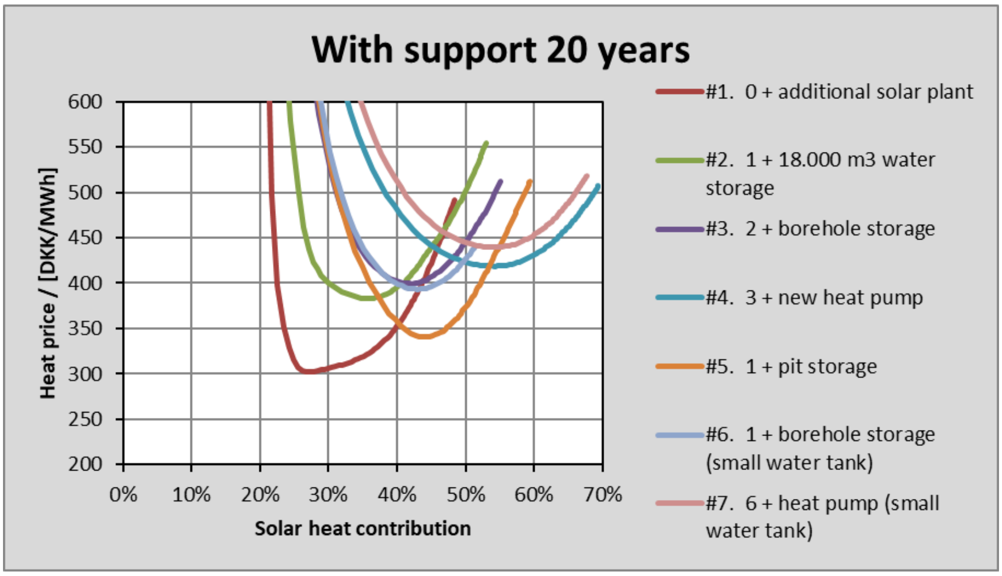

Figure 22 Heat price estimate for the extended plant with different solar energy coverage for 20-year project with the support.

The cost of heat supply for the extended solar plant with incorporated hybrid storage system (Scenario #4) is the lowest (circa 420 DKK/MWh) for 55% solar coverage. This is slightly less expensive than the heat supply in scenario with the full-scale borehole heat storage investment (Scenario #7) estimated before at 440 DKK/MWh per MWh for similar size of solar collectors. The heat tariff ´neither for the borehole storage (Scenario #7) nor for the pit storage option (Scenario #5) is modified as it is not affected by the funding.

It needs to be noticed that the heat prices are calculated only for the heat produced by the extended plant and not for the entire system including conventional generators (gas boilers and CHP).

10 Sensitivity analysis

10.1 Electricity supply price

Since the electricity tariff at 800 DKK/MWh was sourced from the previous feasibility study for Brædstrup performed in 2013, this assumption has been revisited with the reduced value reflecting the reduced electricity tax. This was selected as 600 DKK/MWh of grid power supply. The example of heat tariffs in relation to solar coverage of the current and extended installation for the adjusted electricity price is presented in Figure 23.

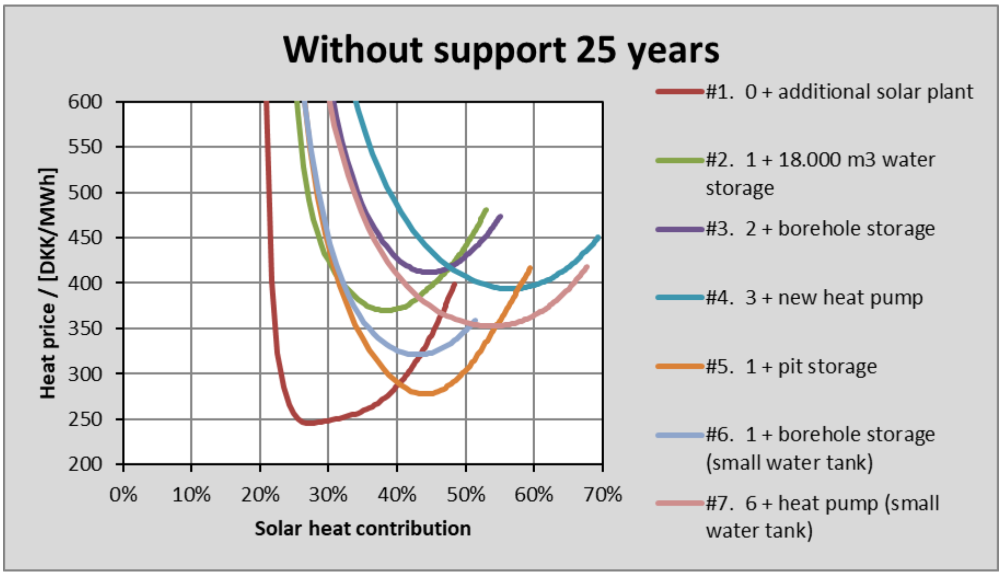

Figure 23 Heat price estimate for the extended plant with different solar energy coverage for 25-year project with the support (for electricity supply price of 600 DKK/MWh).

The amended electricity price affected only the scenarios utilising electric driven heat pump (Scenario #4 and Scenario #7), reducing the heat cost for both, the hybrid storage case (Scenario #4) and for the full-scale borehole storage (Scenario #7) by slightly more than 20 DKK/MWh.

10.2 Water tank and borehole storage capacity

The base calculation in **scenario # 4** consists of 30,000 m^2 new solar collectors, a hybrid storage of 16,500 m^3 water storage, a borehole storage with 420 boreholes and a heat pump. In this section the sensitivity of the size of the water storage (+/– 50%) as well as the number of boreholes (+/– 50%) is shown.

DKK/MWh		Tank		
		50%	100%	150%
BTES	50%		44.7%	
	100%	49.6%	50.1%	50.5%
	150%		54.0%	

Table 4 Annual solar coverage.

DKK/MWh		Tank		
		50%	100%	150%
BTES	50%		456	
	100%	428	431	436
	150%		422	

Table 5 Heat prices [DKK/MWh] without support and with 25-year project duration.

DKK/MWh		Tank		
		50%	100%	150%
BTES	50%		375	
	100%	361	365	370
	150%		363	

Table 6 Heat prices [DKK/MWh] with support and with 25-year project duration.

DKK/MWh		Tank		
		50%	100%	150%
BTES	50%		543	
	100%	501	505	511
	150%		489	

Table 7 Heat prices [DKK/MWh] without support and with 20 -year project duration.

DKK/MWh		Tank		
		50%	100%	150%
BTES	50%		443	
	100%	417	423	430
	150%		417	

Table 5: Heat prices [DKK/MWh] with support and with 20-year project duration.

10.3 Combined heat price

The price of heat generated using the existing conventional plant (gas CHP and boilers), or other future production units, is not provided. However, this sensitivity analysis aims to investigate the combined cost of the thermal energy generated by the entire system in Brædstrup. A range of heat prices incurred due to operation of the existing technologies between 200 DKK/MWh and 500 DKK/MWh was tested and the estimated total heat price was derived depending on solar heat coverage.

This sensitivity analysis was performed for **scenario #1**, the red curves in Figure 19 - Figure 23, and the 25-year project timescale with the full investment cost (no financial support). The cost of heat from the existing solar collectors is assumed at 5 DKK/MWh.

The results of the modelling are presented in Figure 24.

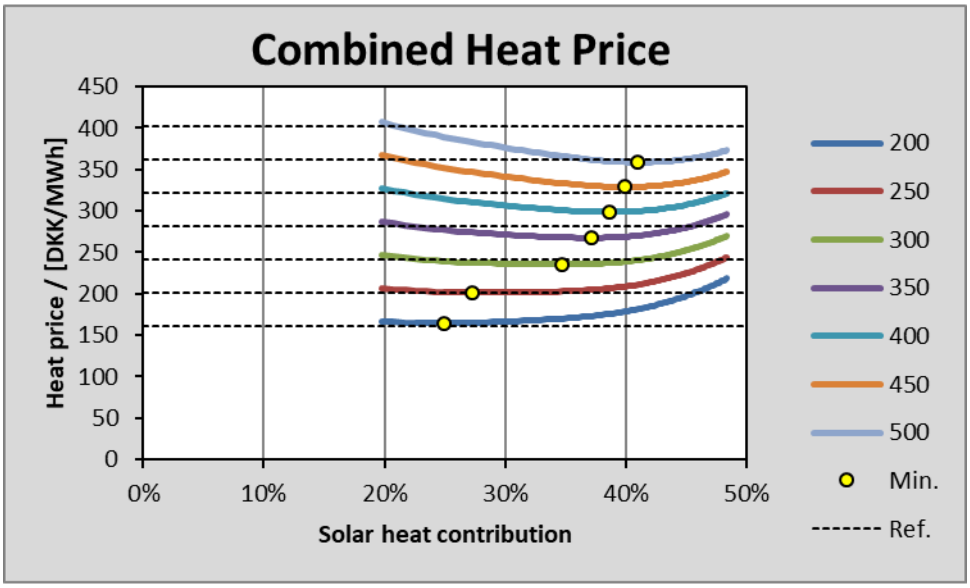

Figure 24 Combined cost of heat supplied by the existing and the new plant in Brædstrup for different scenarios of conventional heat tariffs. The dashed lines show the heat prices for the reference case (WITHOUT FINANCIAL SUPPORT).

If the marginal heat price is 200 DKK/MWh, the combined heat tariff for Brædstrup heating system including the extended solar plant can be kept at around 160 DKK/MWh with an annual solar coverage of around 25%.

If the marginal heat price instead is 450 DKK/MWh, the combined heat tariff will get the lowest average heat price at circa 330 DKK/MWh with an annual solar coverage around 40%.

Scenario #1 is feasible with an annual solar coverage up to 42% if the marginal heat price is 300 DKK/MWh.

11 Conclusions

The development of the Brædstrup Fjernvarme plant with the integration of a hybrid thermal energy storage (Scenario #4), is the most financially viable in case of the 25-year project time-scale and with the obtained financial support. This is estimated at circa DKK 360 per MWh of heat supply from the extended plant. The lowest heat tariff with hybrid storage is typically achieved for circa 55% overall solar production.

The hybrid solution is outdistanced by the full-scale pit hot water storage investment with a reduced heat cost by between 80 DKK/MWh and 150 DKK/MWh, depending on the depreciation period and if the financial support is in place. This lower cost of heat with the pit storage, however, is achieved for much smaller solar coverage (~45%).

The investment into the full-scale borehole installation results in heat tariffs 20 DKK/MWh or 40 DKK/MWh lower compared with the hybrid storage for the 20-year and 25-year depreciation, respectively. In the options with the financial support, the hybrid storage is the cheaper option than the BTES by between 15 DKK/MWh and 20 DKK/MWh.

The summary for heat tariffs in three main scenarios is presented in the table below.

	Hybrid Storage		**BTES**		**PTES**	
	Heat price (DKK/MWh)	Solar coverage (%)	Heat price (DKK/MWh)	Solar coverage (%)	Heat price (DKK/MWh)	Solar coverage (%)
20 years	490	55%	440	55%	340	45%
20 years + support	420	55%	440	55%	340	45%
25 years	415	55%	375	55%	280	45%
25 years + support	360	55%	375	55%	280	45%

Table 8 Summary of the heat cost estimate for hybrid storage and alternative full scale BTES and PTES installation in 20-year and 25-year depreciation.

It needs to be noticed that the heat prices are calculated only for the extended plant and do not account for the avoided energy cost from conventional generators (gas boilers and CHP).

12 List of tables

13 List of figures