Final report

1. Project details

Project title	Follow up on large scale heat storages in Denmark
Project identification (program abbrev. and file)	64014-0121
Name of the programme which has funded the project	EUPD2014
Project managing company/institution (name and address)	PlanEnergi Jyllandsgade 1 9520 Skørping
Project partners	**PlanEnergi (Projekt manager)** Jyllandsgade 1 9520 Skørping Contact: Per Alex Sørensen, pas@planenergi.dk **Brædstrup Fjernvarme** Fjernvarmevej 2 8740 Brædstrup Contact: Jim Larsen, jim@braedstrup-fjernvarme.dk **Marstal Fjernvarme** Jagtvej 2 5960 Marstal Contact: Lasse Kjærgaard, info@solarmarstal.dk **Dronninglund Fjernvarme** Tidselbak Allé 18 9330 Dronninglund Contact: Johan Frey, frey@drlund-fjernvarme.dk

	Solites Meitnerstrasse 8 D-70563 Stuttgart Contact: Thomas Schmidt, schmidt@solites.de **VIA University College** Chr. M. Østergaardsvej 4 8700 Horsens Contact: Henrik Bjørn, hbj@viauc.dk **DTU Byg** Bygning 118, Brovej 2800 Kgs. Lyngby Contact: Simon Furbo, sf@byg.dtu.dk
CVR (central business register)	74038212
Date for submission	January 2018

Content

2. Short description of project objective and results

Objective 1. Export of monitoring results from Brædstrup, Marstal and Dronninglund to SOLITES and analyse of monitoring results for 2015, 2016 and 2017.
Result: Monitoring results for all 3 years have been exported to SOLITES. The results have been discussed at meetings in April 2015, 2016, 2017 and 2018. The storages have performed as expected according to heat loss and storage efficiency.

Objective 2. Export of real time monitoring results to "Solvarmedata.dk"
Result: A website with a similar design and setup as solvarmedata.dk but dedicated to the continuous monitoring of the storages has been created. Here the real-time charging/discharging can be seen together with present energy content for each storage. Besides this, it is possible to present graphically and/or download historical data of energy and temperature levels for user-defined periods. The website address is http://varmelagre.dk

Objective 3. Solve corrosion problems in in- and outlet pipes.
Re4sult: The problem showed up in Marstal after one year of operation. During the "Follow up on large scale heat storages in Denmark" project, Marstal have raised pH in the pit heat storage to 9.8, replaced galvanised metals and placed offer anodes. Yearly diving inspections confirm that the corrosion has stopped.

Objective 4. Test of the liner used in Dronninglund.
Result: The liner has been tested by Teknologisk Institut under different conditions. The result is that the guaranteed lifetime of 20 years by 90 °C is not reached in any of the tests. Thus the lifetime cannot be confirmed through accelerated tests (110 °C) as they are defined by Teknologisk Institut. A test carried out by R.I.S.E. in Sweden show longer lifetime.

Objective 5. Test of durability of insulation material.
Result: The insulation material has been tested by Teknologisk Institut by different temperatures. The result is that none of the tests indicate a lifetime of 20 years by 90 °C. The supplier of the insulation material has as a consequence developed a new type of insulation material.

Objective 6. Discuss other operation experiences.
Result: The project partners have met every year and exchanged experiences and results. Beside status for objectives 1-5 the following topics have been discussed

- Problems with water puddles on the pit heat storages
- Problems with leakages in liners in pit heat storages and how to solve them

3. Project objectives and executive summary

Long term heat storages are important in the future energy system in Denmark. This can a.o. bee seen in two reports required by the Danish Energy Agency during 2013:

- "Status and Recommendations for RD&D on Energy Storage Technologies in a Danish Context" and
- "Udredning vedrørende varmelagringsteknologier og store varmepumper til brug i fjernvarmesystemet" (analyses of heat storage technologies and large heat pumps for district heating).

From 2011 to 2013 three large long-term storages has been implemented in Brædstrup (borehole storage), Marstal (pit heat storage) and Dronninglund (pit heat storage) connected to large scale solar heat plants and heat pumps for district heating. The monitoring programs for these storages ended when the projects were finalized. But long-term heat storages change performance the first years because the surrounding soil is heated up. Therefore there was a need to continue the monitoring programs. This project had as purpose to secure a continuation of the monitoring programs and to analyze and make the results public. Beside the project included test and measures that can support future storage projects.

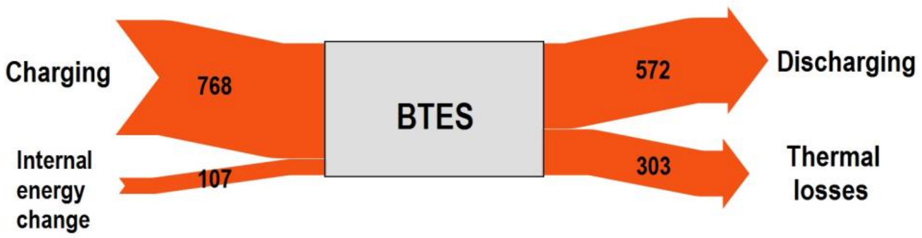
A main activity in the project has been real time publication of monitoring results at varmelagre.dk and yearly analysis of performance of the storages. Pit heat storages has beside that three problems, that the application should solve for existing and future owners:

- Corrosion in in- and outlet pipes. The problem had showed up in Marstal. Effect of actions taken and future development had to be carefully supervised.
- Lifetime for the liner in Dronninglund. The liner had until this project not been tested for long term durability, but the supplier has guaranteed 20 years life time by 90 °C. This had to be tested, because such a liner can extend the market for pit heat storages to storing heat from incineration plants, combined heat and power plants (CHP) and industrial processes.
- The durability of the insulation material in the floating lid constructions in Marstal and Dronninglund. Also here a test will show if the market can be extended.

Monitoring

Brædstrup

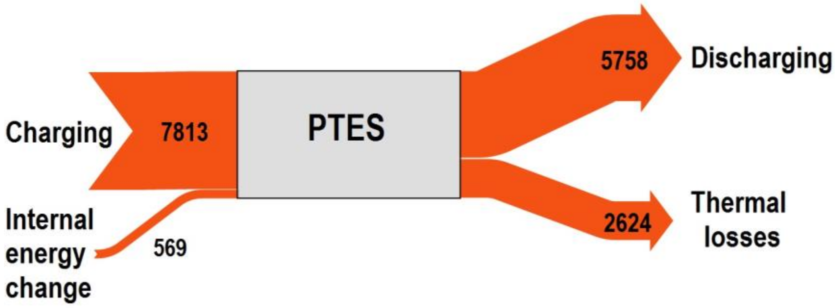
Monitoring results is illustrated as the heat balance in the period 2014-2017 (Figures in MWh).



The storage efficiency has been 61% which is lower than the design calculation for long term operation, but the storage has not been fully charged every year and was still in the start-up phase.

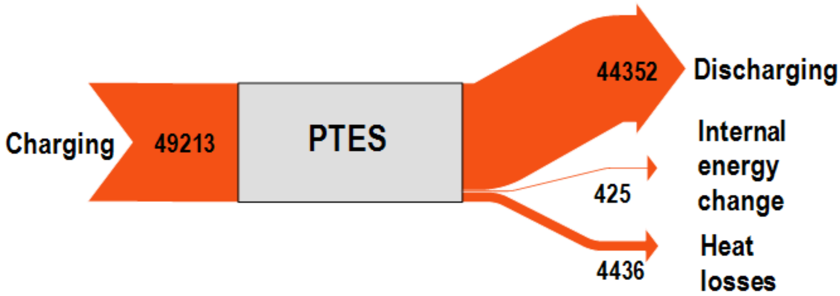
Marstal

Monitoring results for 2015 is illustrated below (Figures in MWh).



The storage efficiency in 2015 was 66%, a little higher than the design value of 61%.

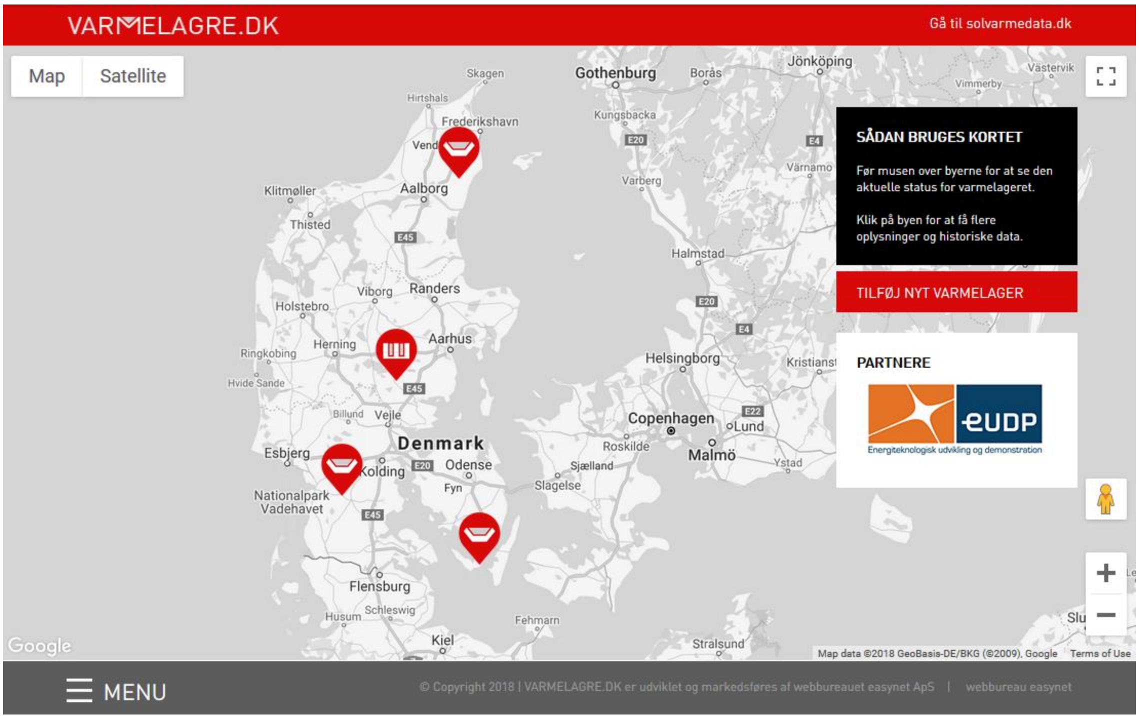
Dronninglund
Monitoring results for 2014-2017 is illustrated in the heat balance (Figures in MWh).



The storage efficiency was 92%. This is better than the design calculation, but the storage is cooled to lower temperatures than expected.

The results from the evaluations of the monitoring data of two large-scale pit thermal energy storages in Marstal and Dronninglund and one borehole thermal energy storage in Brædstrup prove the efficiency and reliability of the presented storage technologies. The results show good agreements with the design figures in terms of storage efficiency, usable temperature ranges and contributions to the heat supply of the connected district heating networks. Deviations are explainable by different operational conditions or other site-specific effects. Especially the example of the PTES in Dronninglund shows a high storage efficiency, which is on the one hand a result of the good technical quality of the storage construction that leads to low thermal losses, on the other hand the storage has a large energy turnover as it is used for seasonal storage and for short-term storage simultaneously. In addition, the low temperatures in the storage in the winter period result in negative thermal losses in the bottom parts of the storage.

Monitoring results to Varmelagre.dk
Data from monitoring of the storages in Brædstrup, Marstal, Dronninglund and Gram is not exported to Solvarmedata.dk as initially expected, but to a new website called Varmelagre.dk



The front page gives an overview map of the storages and by clicking on the storage icons historical and real time data for the chosen storage is presented and can be downloaded. The website is open for new storages in- and outside DK to be uploaded and presented.

Solving of problems for the owners

Corrosion problems in Marstal have been solved by placing sacrificial zinc anodes and raising pH in the water to 9.6.
Lifetime of the liner was tested to app. 5 years by 90 °C at Teknologisk Institut. The supplier has requested own tests by RISE in Sweden that shows longer lifetime (>25 years by 90 °C) but still a single liner might not be able to stand in >20 years in 90 °C. The lifetime depends mainly on temperature and oxygen content in water and air.
Lifetime of the insulation material is for less than 20 years by 90 °C, but the supplier is developing a new material with remarkably higher melting point.

Dissemination

The project results have been disseminated to

- Danish DH stakeholders through Dansk Fjernvarmes solar group and thematic arrangements and plant visits
- German DH stakeholders through AGFW arrangements, seminars and plant visits
- European DH stakeholders through the projects SDHplus and SDHp2m (seminars and plant visits)
- Chinese and Japanese DH stakeholders (plant visits and seminars)
- All stakeholders through District Heating Conferences in Toulouse, Billund and Graz.
- All stakeholders through IEA ECES conferences in Beijing and Adana.

Beside that a brochure presenting the plants has been produced and “Best Practice” described in a separate document [Sørensen, 2018].

4. Project results and dissemination of results

4.1 Monitoring results

In this section a summary of evaluation results for the three solar district heating (SDH) plants in Brædstrup, Marstal and Dronninglund is given. A detailed evaluation report for the period covered by this project is available for each of the plants in separate reports [Schmidt, 2018; Schmidt, 2018-2; Winterscheid et.al., 2018].

For the comparison of the efficiencies of different system concepts a number of characteristic numbers, often called key performance indicators (KPI) can be calculated. The ones used here are:

Solar fraction $$F_{Sol} = \frac{Q_{Load} - Q_{Aux}}{Q_{Load}} = \left(1 - \frac{Q_{Aux}}{Q_{Load}}\right)$$

Q_{Load}: heat supply to the DH network

Q_{Aux}: auxiliary heat delivered to the system (by boilers, CHP, el. demand heat pump etc.)

Solar collector field efficiency $$\eta_{Coll} = \frac{Q_{Coll}}{G_{sol}}$$

G_{Sol}: global irradiation in solar collector pane

Q_{Coll}: heat delivered by the solar collector field

Storage efficiency $$\eta_{STES} = \frac{Q_{STES,out} + dQ_{STES}}{Q_{STES,in}}$$

$Q_{STES,in}$: heat charged into the seasonal thermal energy storage (STES)

$Q_{STES,out}$: heat discharged from the STES

dQ_{STES}: difference in STES internal energy change in the period

No. of storage cycles $$N_{cyc} = \frac{Q_{STES,out}}{Q_{STES,max}}$$

$Q_{STES,max}$: maximum heat capacity of the STES

4.1.1 Brædstrup

This section gives a summary of the monitoring data evaluations for the Brædstrup Fjernvarme solar district heating plant for the years 2014 to 2017. The summary starts with a system concept and an overview of the overall system heat balance including performance indicators for the considered evaluation period. Afterwards, the summary focuses on the seasonal borehole thermal energy storage, as this is the component of major interest in this project. For the BTES an exemplary energy flow diagram is discussed and data on the utilization and the development of storage temperatures is presented.
More evaluations are documented in a separate evaluation report for the period covered by this project [Schmidt, 2018].

Figure 1 shows the system concept of the plant.

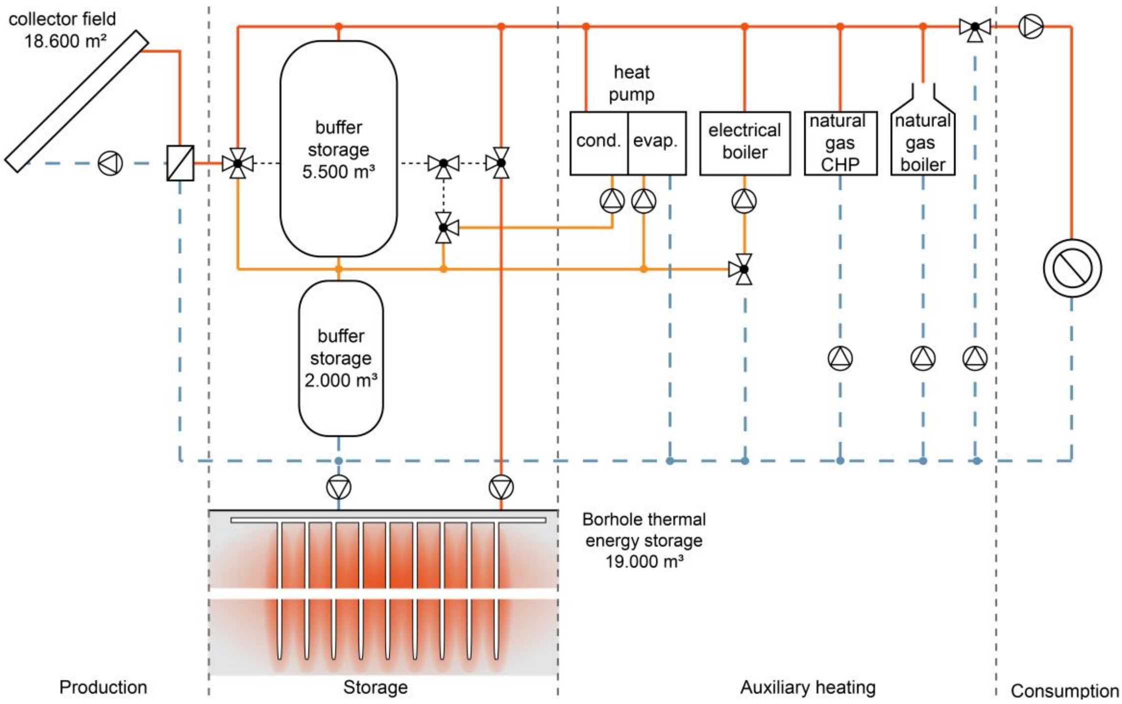


Figure 1. *Brædstrup SDH system concept.*

The Brædstrup pilot borehole thermal energy storage (BTES), with a soil volume of 19,000 m³, was set into operation in spring 2012. **Table 1** shows the main heat balance values and a number of performance indicators.

Table 1. *Overview of evaluation results for the considered evaluation period in Brædstrup.*

		2014	**2015**	**2016**	**2017**
solar irradiation on solar collectors	*MWh*	20321	21261	17249	20298
heat from solar collectors	*MWh*	8093	8038	7642	7146
heat charged into BTES	*MWh*	380	152	194	41
heat discharged from BTES	*MWh*	276	182	74	40
BTES internal energy change	*MWh*	-89	-25	15	-27
BTES thermal losses	*MWh*	193	-4	106	28
heat pump heat delivery	*MWh*	1012	1533	564	324
heat pump electricity demand	*MWh*	369	495	188	113
heat from CHP	*MWh*	5217	3935	7485	7859
CHP electricity production	*MWh*	4677	3526	6624	6952
heat from electrical boiler	*MWh*	1613	6416	3535	5973
heat from boilers	*MWh*	21278	18976	20929	20185
heat delivery to DH	*MWh*	36693	38986	40890	41780
key performance indicators					
solar collector field efficiency	*%*	40	38	44	35
BTES storage efficiency	*%*	49	103	45	31
BTES no. of storage cycles	-	0.6	0.5	0.1	0.1
BTES maximum temperature	*°C*	56	49	29	21
BTES minimum temperature	*°C*	10	11	12	11
BTES used heat capacity	*MWh*	480	400	672*	672*
heat pump COP	-	2.7	3.1	3.0	2.9
solar fraction	*%*	22	24	21	18

* for 64 K nominal temperature difference

Figure 2 shows the energy flow diagram for the energy production according to monitoring data for the year 2014. With these numbers a solar fraction of 22% can be calculated (design value: 18%) for the plant.

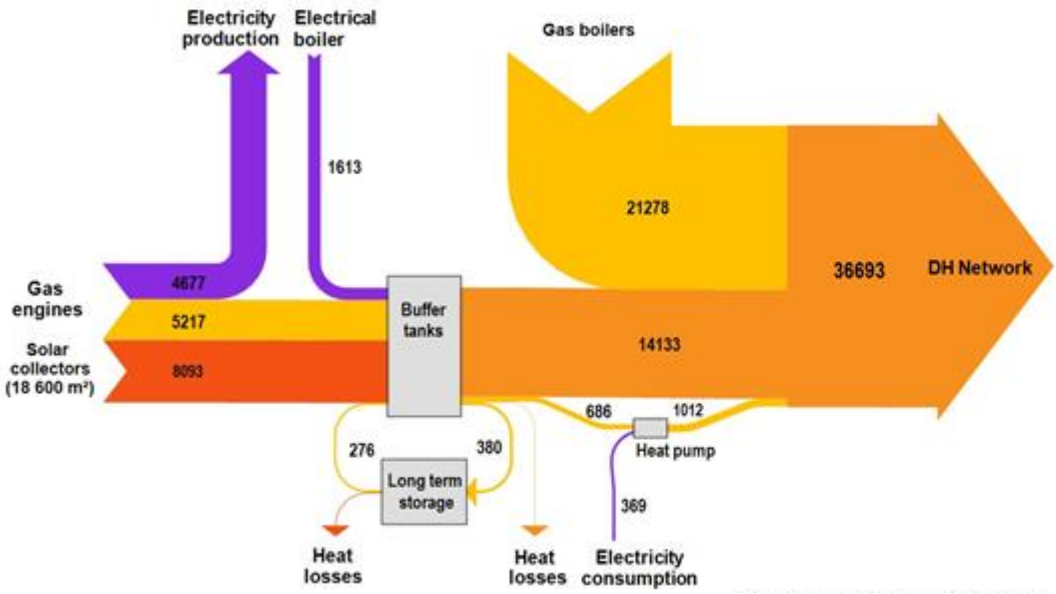


Figure 2. *Brædstrup SDH heat flow diagram according to monitoring data for 2014, numbers in MWh.*

For the four years from the beginning of 2014 to the end of 2017, the heat flows as presented in **Figure 3** were calculated for the BTES from the monitoring data. The calculation of the internal energy values in the BTES volume is based on an arithmetic mean temperature derived from 32 ground temperature sensors located between the borehole heat exchangers (BHE). Thermal losses are subsequently calculated from the storage energy balance. With the given numbers a storage efficiency of 58% and a storage cycle number of 1.4 can be calculated.

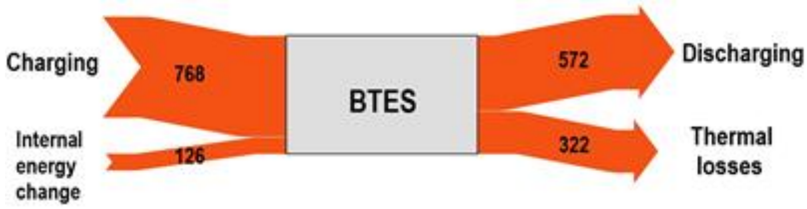


Figure 3. *Heat balance for the BTES in Brædstrup for the period 2014-2017, numbers in MWh.*

The storage efficiency of 58% is lower than the design value of 77% that was calculated for long-term operation. The difference can mainly be explained by the fact that the Brædstrup BTES in the considered period was still in its start-up phase that, according to simulations, normally takes between 3 to 5 years. In this start-up phase, the surrounding ground is preheated and hence thermal losses are higher. The storage was furthermore not used as extensive as assumed in the simulations, see also **Figure 4**. The storage cycle number of 0.8 for the four-year period indicates a small utilization of the storage. The low maximum temperatures are intended for this small-sized BTES, which is not heat insulated at the sides and at the bottom, in order to keep the thermal losses in an acceptable range.

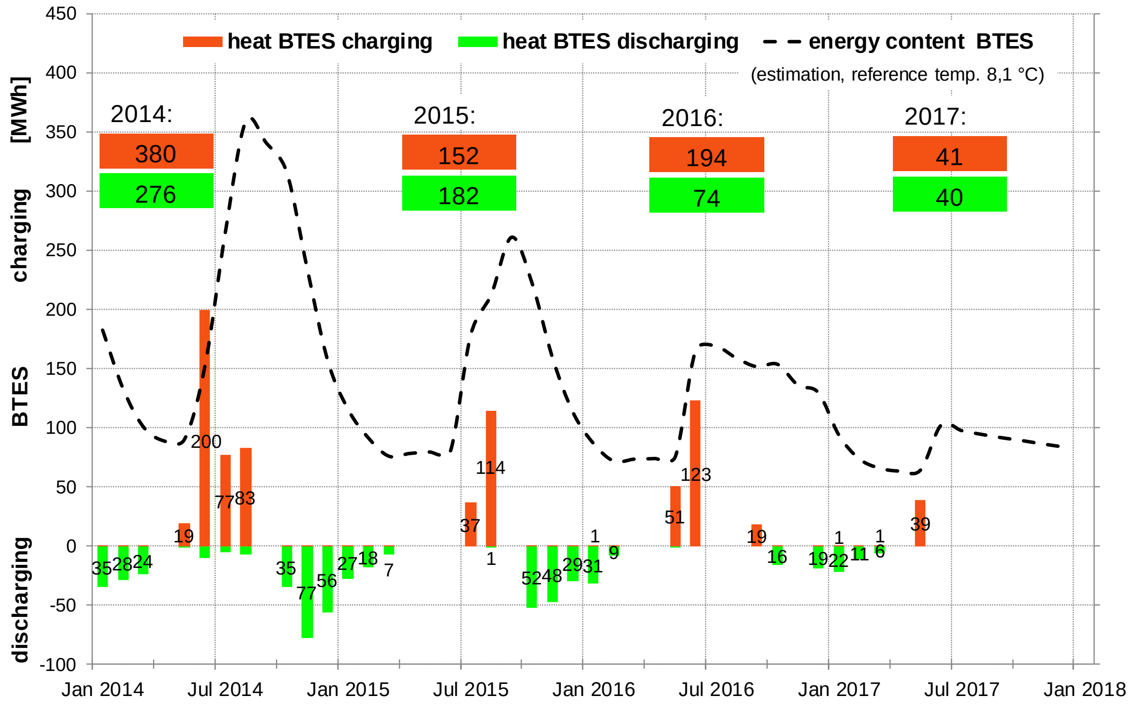


Figure 4. *Monthly heat balance for the BTES in Brædstrup for the period 2014-2017.*

For observation purposes 100 temperature sensors were installed in the ground between, below and in the surroundings of the borehole heat exchangers, see **Figure 5**. In each of the five positions NDE 501 to NDE 505 20 sensors were installed in separate boreholes down to a depths of 59 m below the ground surface.

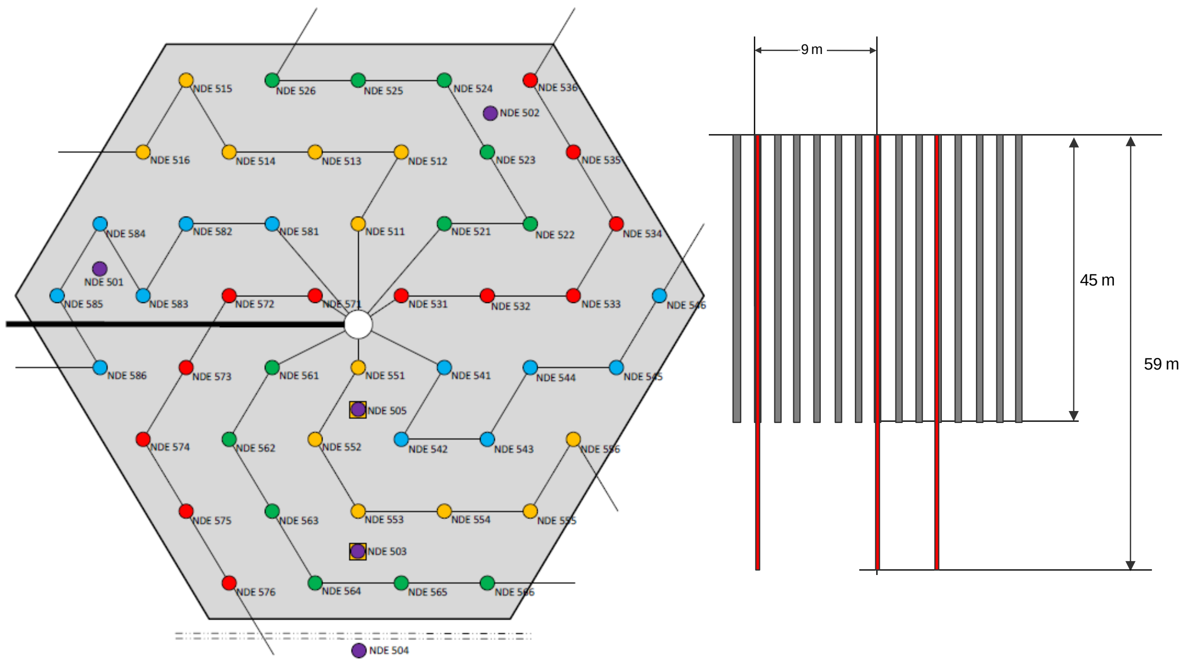


Figure 5. *Positions of borehole heat exchangers and temperature sensors inside and outside the Brædstrup BTES (left: top view, NDE 501 to NDE 505: positions of temperature sensors, NDE 504 is located 11 m outside the BTES boundary, right: side view, red lines: positions of temperature sensors, grey lines: borehole heat exchangers. Source: [Sørensen et. al 2013])*

Figure 6 shows the ground temperature development at the central position NDE 505 for the years 2014 to 2017. Inside the storage volume (depths range 0 to 45 m) a rather uni-form temperature development can be seen. Only the temperatures close to the top (-1 m) and to the bottom (-44 m) show lower temperatures because of the heat transfer to the ambient. In comparison with e.g. water filled tank or pit thermal energy storages no vertical thermal stratification is existent. The ground area below the storage (sensors -48 m to -59 m) follows the temperature development inside the storage volume at a lower temperature level and with an increasing time delay with an increasing distance from the storage.

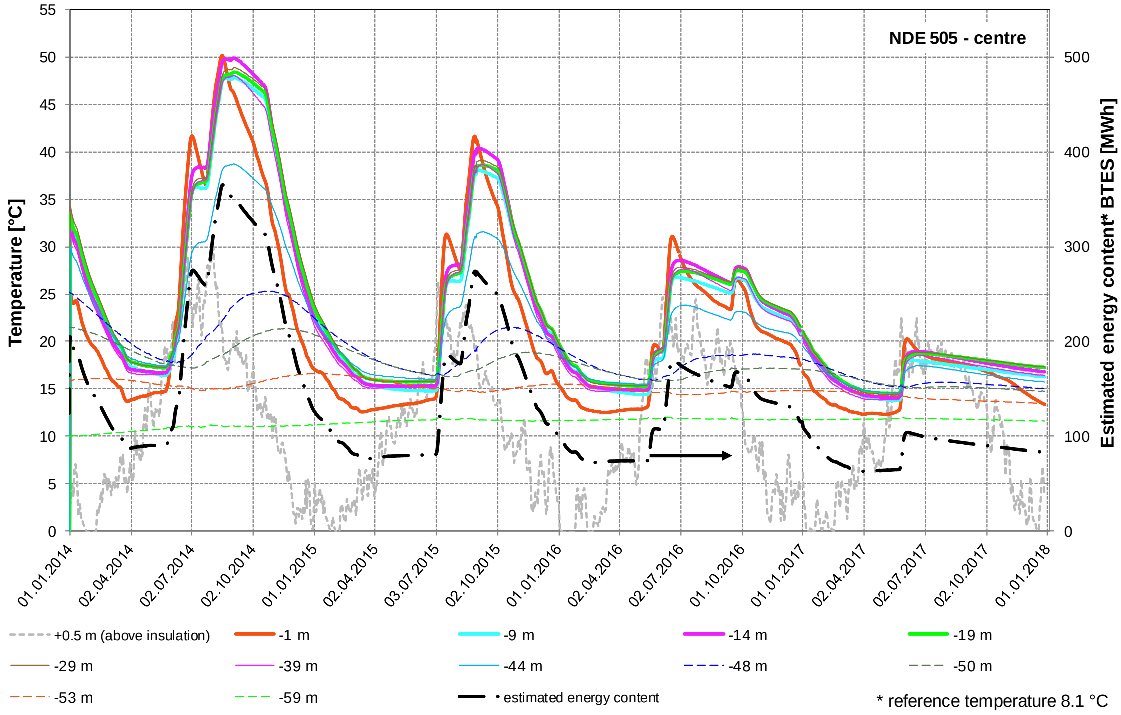


Figure 6. *Development of ground temperatures in the central part of the Brædstrup BTES and internal energy content for the period 2014-2017.*

Figure 7 offers a different view to the ground temperature development at position NDE 505 in 2014. The lines represent the temperatures at the beginning of each month in 2014. From January to April a discharging period can be seen followed by a charging period from May to August with a temperature increase from around 17 °C up to almost 50 °C. In October the next discharging period starts with a temperature decrease down to 22-23 °C at the end of the year, compare also **Figure 4**.

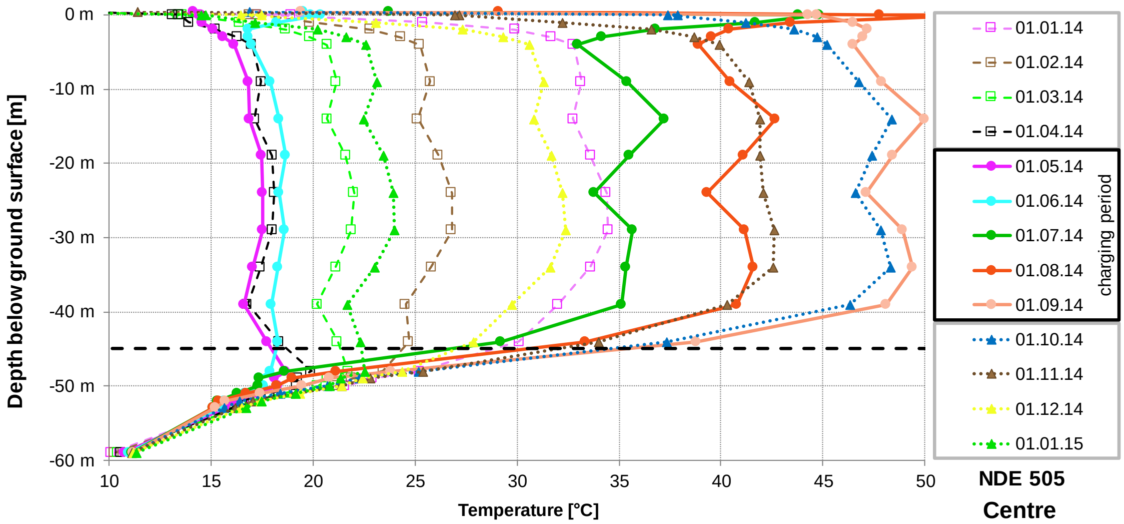


Figure 7. *Monthly ground temperature development in the centre of the BTES in Brædstrup at position NDE 505 (see* ***Figure 5****) in 2014.*

Figure 8 shows the ground temperatures at one of the positions close to the side margin (NDE 503). The developments are similar to the ones in the centre (**Figure 7**) but on a lower temperature level. Temperature developments at positions NDE 501 and NDE 502 show a similar behaviour (not illustrated here).

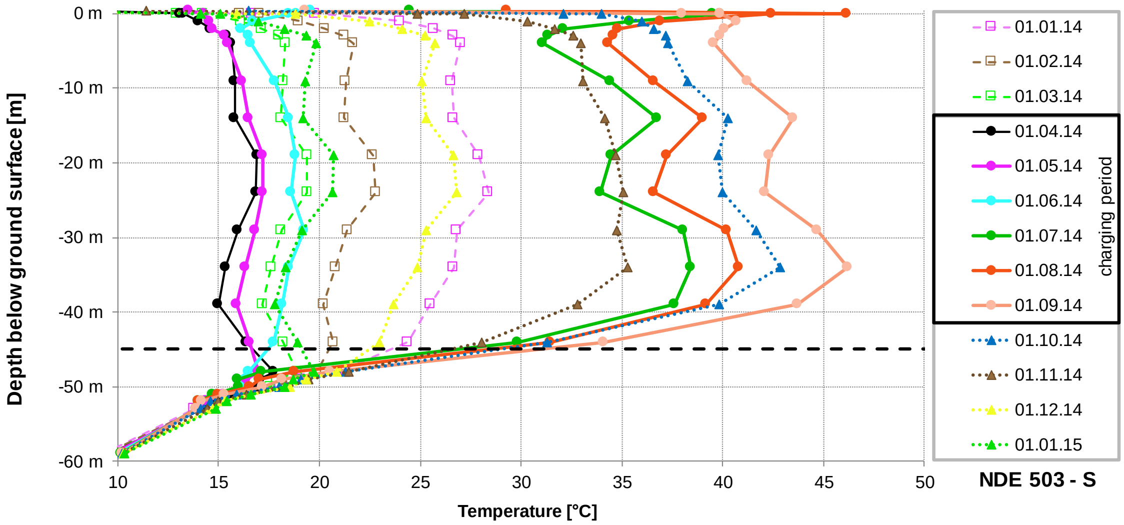


Figure 8. *Monthly ground temperature development in the BTES in Brædstrup at position NDE 503 (see* ***Figure 5****) in 2014.*

Figure 9 illustrates the situation outside the storage volume in a distance of 11 m from the BHEs. In this position the heating-up of the ground surrounding the BTES volume can be observed. For comparison, also the first available data from March 2013 and two dates after 2014 are given. Until 2015 a steady temperature increase can be seen. From April 2015 to April 2016 temperatures slightly decreased. This follows the decreasing temperatures also inside the storage (see **Figure 6**) with a certain time delay.

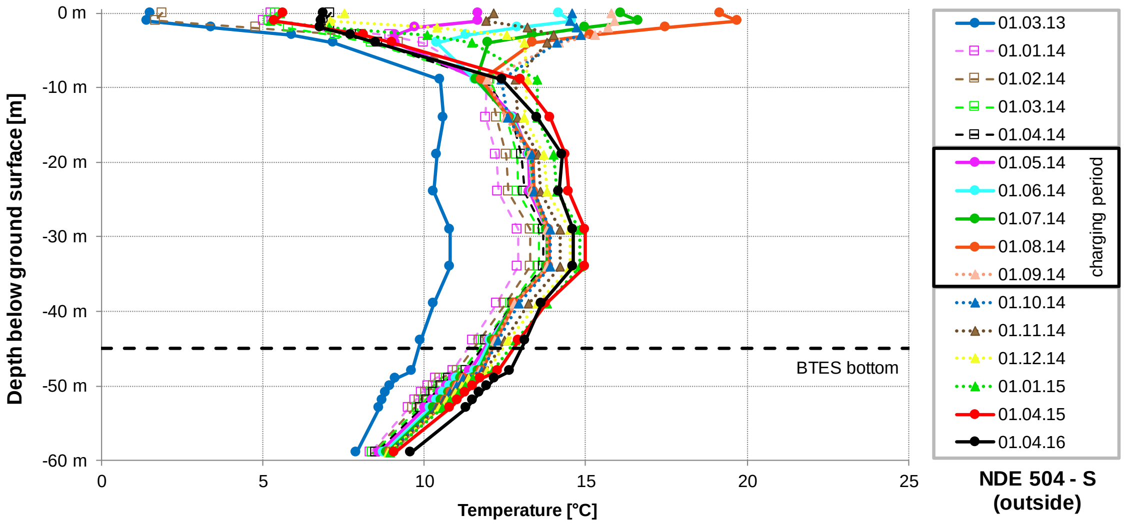


Figure 9. *Monthly ground temperature development outside the BTES in Brædstrup at position NDE 504 (see* ***Figure 5****) in 2014.*

When comparing **Figure 7**, **Figure 8** and **Figure 9**, in total a horizontal temperature stratification from the centre to the sides can be identified in the core part of the storage horizon.

4.1.2 Marstal

This section gives a summary of the monitoring data evaluations for the Marstal Fjernvarme solar district heating plant for the years 2015 to 2017. The summary starts with a system concept, an overview of the system heat balance values and performance indicators for the considered evaluation period. At next the summary focuses on the seasonal pit thermal energy storage. For the PTES an exemplary energy flow diagram is discussed and data on the utilization and the development of the storage temperatures is presented.
More evaluations are documented in a separate evaluation report for the period covered by this project [Schmidt, 2018-2].

Figure 10 show the system concept of the plant.

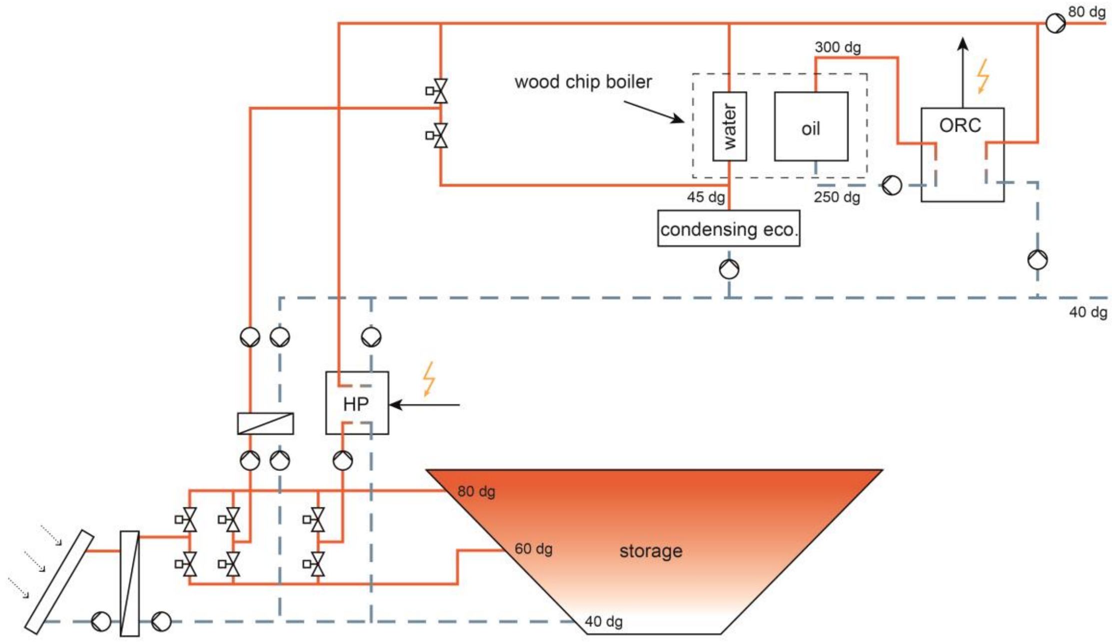


Figure 10. *Marstal SDH system concept.*

The 75,000 m³ water-filled PTES in Marstal went into operation in June 2012. **Table 2** gives the main heat balance values as well as a number of performance indicators.

Table 2. *Overview of evaluation results for the considered evaluation period in Marstal.*

		2015	**2016**	**2017**
solar irradiation on solar collectors	*MWh*	-	36978	34533
heat from solar collectors	*MWh*	12990	11848	11759
solar heat direct to system	*MWh*	5177	4743	4992
heat charged into PTES	*MWh*	7813	7104	6768
heat discharged from PTES	*MWh*	5758	5322	3471
PTES internal energy change	*MWh*	-569	-642	-858
PTES thermal losses	*MWh*	2624	2424	4155
heat pump heat delivery	*MWh*	2199	3468	3595
heat pump electricity demand	*MWh*	671	1045	1117
heat from biomass boiler and ORC	*MWh*	16500	15445	17169
ORC electricity production	*MWh*	2854	2543	1243
heat from oilboiler plant	*MWh*	35	2193	3823
heat delivery to DH	*MWh*	29043	30143	30868
key performance indicators				
solar collector field efficiency	*%*	-	32	34
PTES storage efficiency	*%*	66	66	39
PTES no. of storage cycles	-	1.1	1.0	0.7
PTES maximum temperature	*°C*	84	82	69
PTES minimum temperature	*°C*	20	20	13
PTES used heat capacity	*MWh*	5430	5320	4830
heat pump COP	-	3.3	3.3	3.2
solar fraction	*%*	39	35	28
biomass fraction	*%*	59	54	56
oil boiler fraction	*%*	0	8	13
heat pump electricity fraction	*%*	2	4	4

Figure 11 exemplarily shows an energy flow diagram for the plant for 2015. With the presented numbers a solar fraction of 39% can be calculated for the considered year. As additional heat sources are based on biomass and bio-oil the plant was supplied to 100% from renewable energy sources (RES).

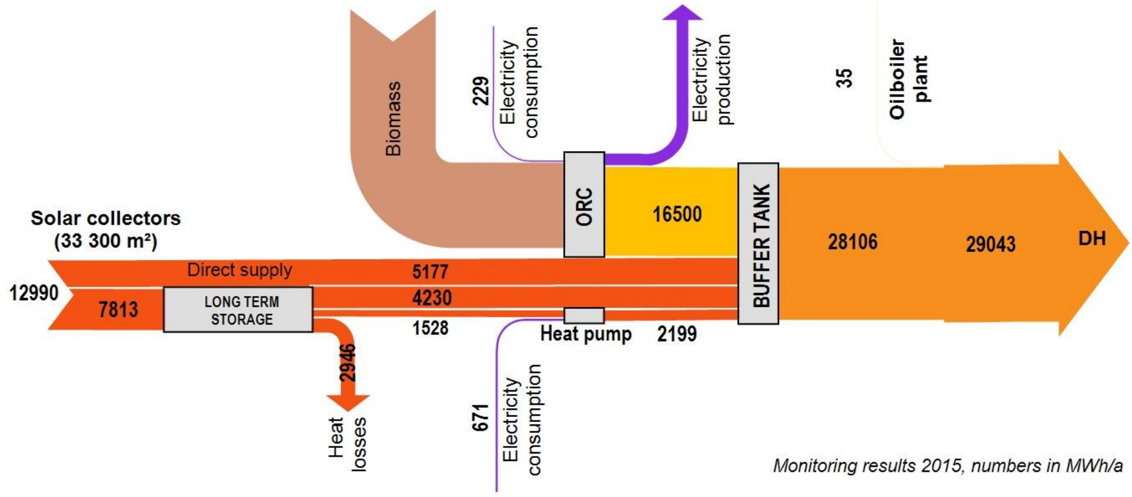


Figure 11. *Marstal SDH heat flow diagram according to monitoring data for 2015.*

In **Figure 12** the yearly energy balance for the PTES is shown for 2015. 7813 MWh of solar heat were charged into the storage and 5758 MWh were discharged to the system. The internal energy content of the storage is calculated based on temperature sensors that are installed in the water volume every 0.5 m in vertical direction. In 2015 the energy content in the storage at the end of the year was 569 MWh below the one at the beginning of the year. According to the storage heat balance, the thermal losses that were transferred to the surrounding ground and the ambient air summed up to 2624 MWh. The maximum and minimum temperatures in the storage volume in 2015 were 84 °C and 20 °C respectively.

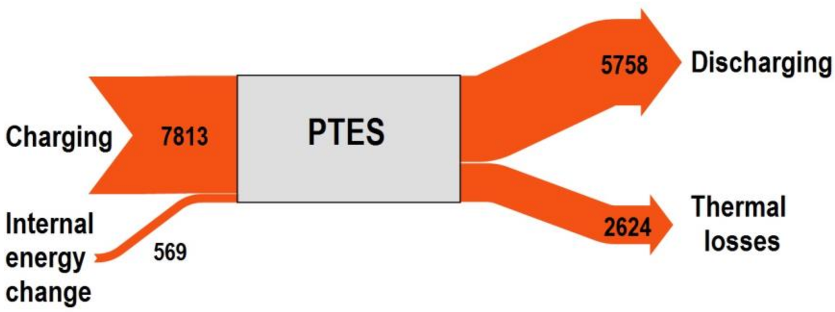


Figure 12. *Heat balance for the PTES in Marstal for 2015, numbers in MWh.*

The evaluated storage efficiency of 66% is a little higher than the design value of 61%. A storage cycle number of 1.1 means that the heat capacity of the storage was used 1.1 times in 2015, representing a pure seasonal operation. The latter can also be seen in the monthly charged and discharged amounts of heat presented in **Figure 13**. The main charging processes are in summer and the main discharging processes in winter.

In 2017 the thermal losses of the PTES were higher than in the years before. This also led to a lower storage efficiency in this year. The reason for this is most probably a humidification of the cover insulation by rain water entering the cover construction through a leakage.

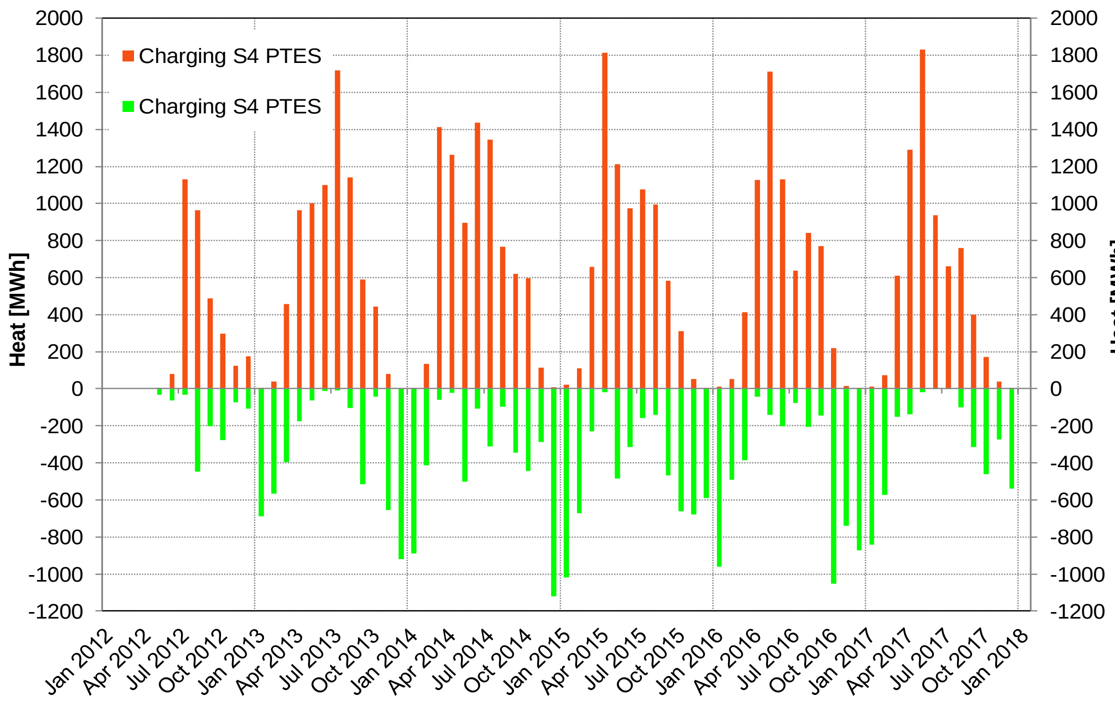


Figure 13. *Monthly heat balance for the PTES in Marstal for the period 2012-2017.*

In **Figure 14** the temperature development in the storage is illustrated from 2013 to 2017. Again the seasonal operation is clearly visible with a charging period from around March to September and a discharging period from around September to March. Minimum temperatures in March are around 30 °C at the top of the storage and 15-20 °C at the bottom. Maximum temperatures in September reach some 85 °C at the top and around 70 °C at the bottom. In 2017 the temperatures in summer were lower compared to the years before. The highest thermal stratification, that means the largest temperature differences between the top and the bottom of the storage, of around 30 K can be seen in spring and autumn.

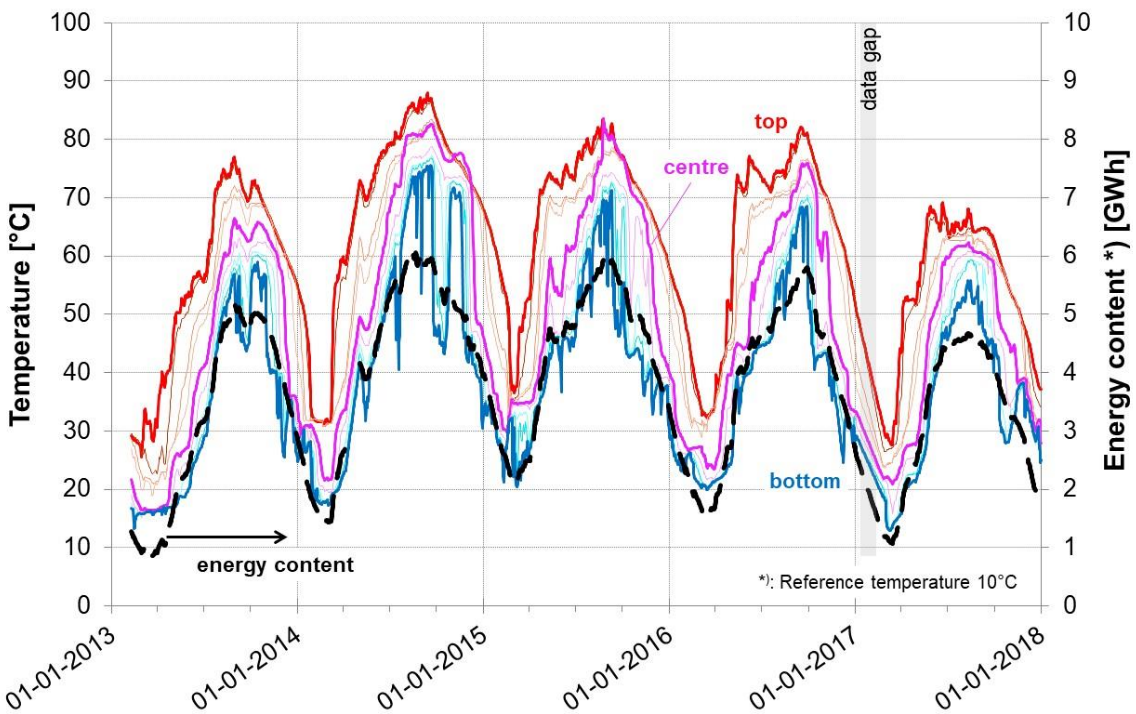


Figure 14. *Development of the temperatures inside the Marstal PTES and internal energy content for the period 2013-2017.*

85 temperature sensors are installed inside and around the storage volume in order to allow for an observation of the long-term temperature development in the storage volume and in the surrounding ground. **Figure 15** shows the locations where temperature sensors are placed in different horizontal and vertical positions.
The temperatures shown in **Figure 14** are from the storage internal position A1. The vertical positions inside the storage range from below the floating liner (0 m) down to the bottom liner at -16 m. The sensors in the locations B to G are installed in the surrounding ground. C and B go down 2 m below the bottom of the PTES to a level of -18 m. The horizontal distance between B and C is 10 m.

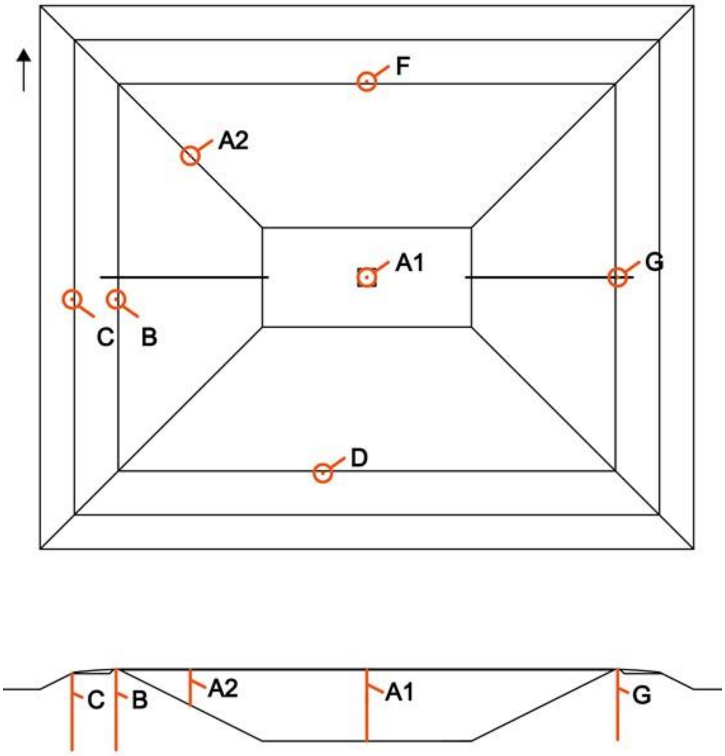


Figure 15. *Positions of temperature sensors inside and outside the PTES in Marstal (above: top view, below: side view).*

Figure 16 and **Figure** 17 show ground temperatures at the positions B and C since 2013. The temperatures at the upper part of B and C show a seasonal variation with decreasing temperature levels and amplitudes with deeper locations and larger distances from the PTES side wall. The temperatures below approximately 10 m show steady temperature increases that are heading towards their long-term limits at the end of the presented period.

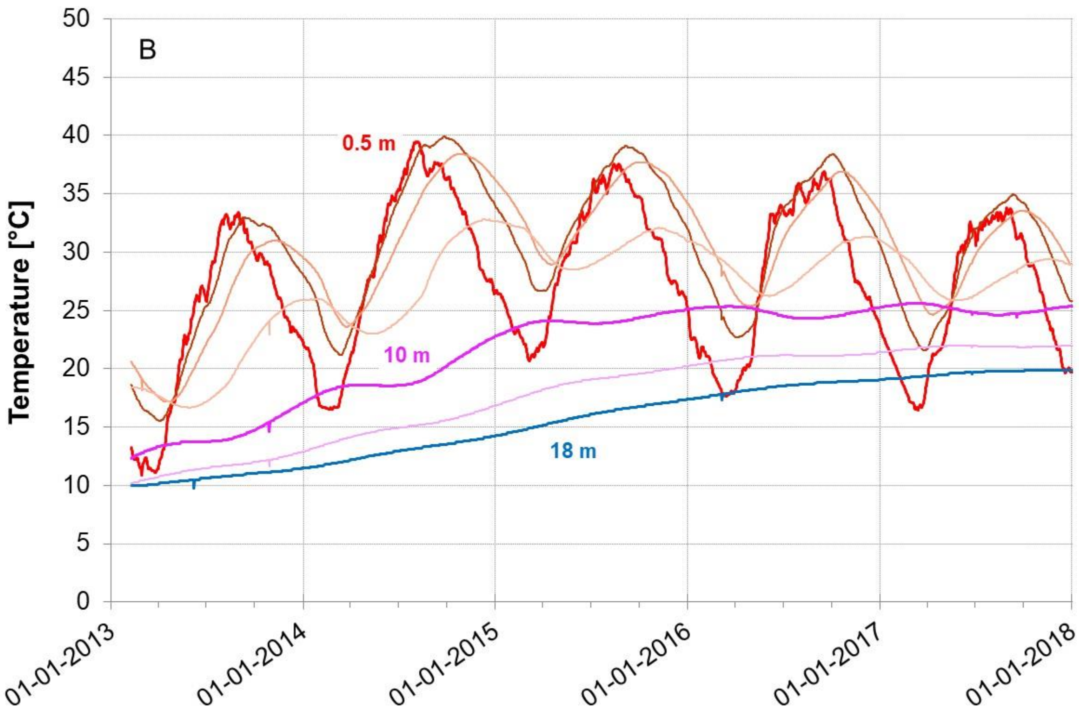


Figure 16. *Long-term ground temperature development around the Marstal PTES at position "B", see **Figure 15** (depth levels 0.5, 1.5, 3, 6, 10, 14, 18 m below water surface).*

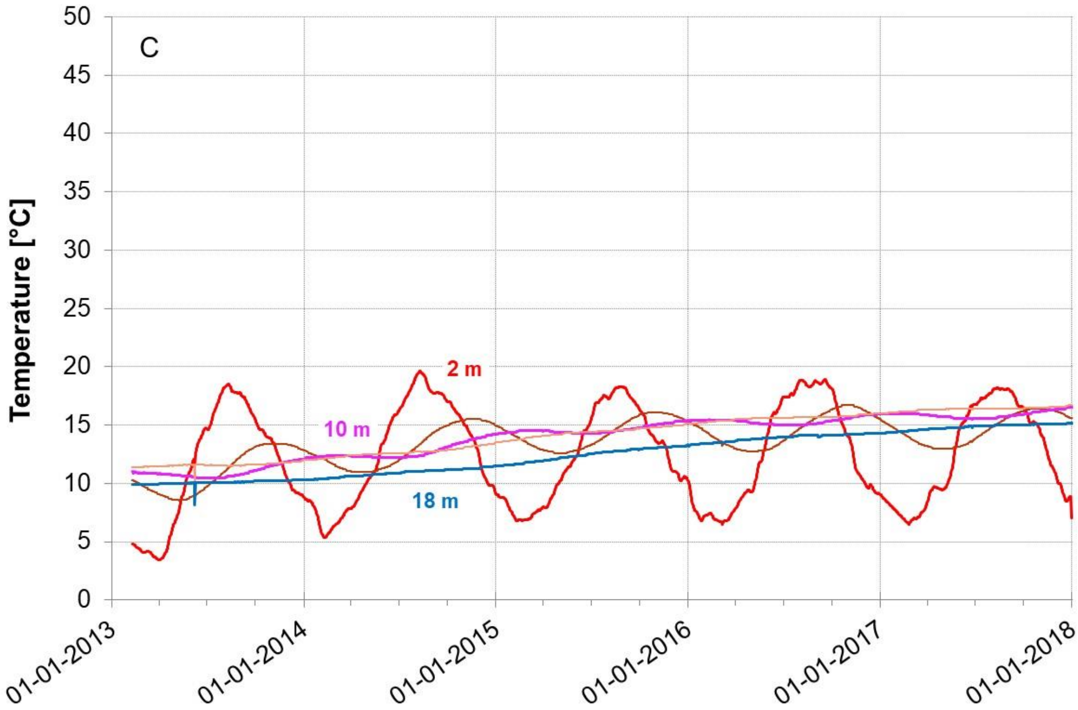


Figure 17. *Long-term ground temperature development of the PTES in Marstal at position "C", see Figure **15** (depth levels 2, 6, 10, 14, 18 m below water surface).*

4.1.3 Dronninglund

This section gives a summary of the monitoring data evaluations for the Dronninglund Fjernvarme solar district heating plant for the years 2015 to 2017. The summary starts with a system concept and an overview of the overall system heat balance values and performance indicators for the considered evaluation period. At next, the summary focuses on the seasonal pit thermal energy storage. For the PTES an exemplary energy flow diagram is discussed and data on the utilization and the development of storage temperatures is presented.
More evaluations are documented in a separate evaluation report for the period covered by this project, see [Winterscheid et. al., 2018].

The pit heat storage, the solar collectors and the absorption heat pump was in operation from March 2014 as part of the project "Sunstore 3", supported by the national Danish EUDP-program. The project enables Dronninglund district heating to deliver heating to the consumers from 70% renewable energy sources where app. 40% is solar heat. **Figure 18** shows the system concept of the plant.

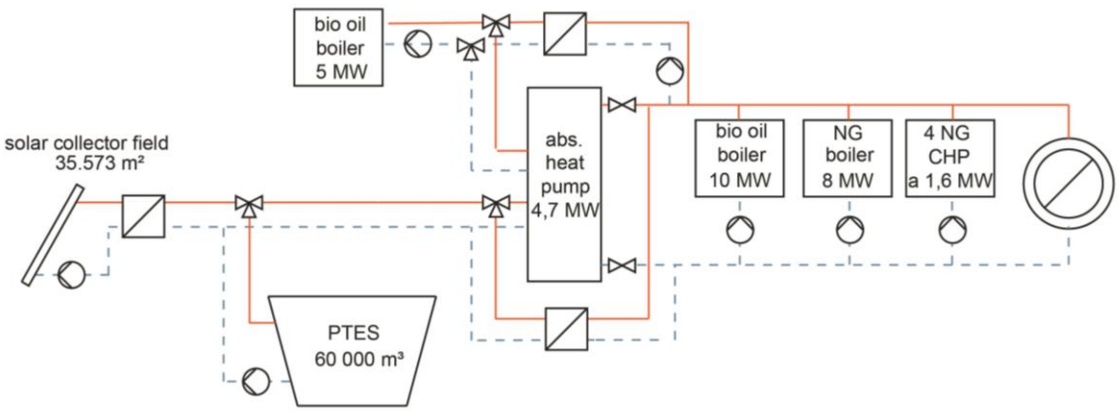


Figure 18. *Dronninglund SDH system concept.*

Table 3. *Overview of evaluation results for the considered evaluation period in Dronninglund.*

system heat balance		**2015**	**2016**	**2017**
solar irradiation on collectors	*MWh*	40631	40327	38674
heat from solar collectors	*MWh*	16793	16071	15121
heat charged into PTES	*MWh*	12760	11855	11120
heat discharged from PTES	*MWh*	11983	10716	11315
PTES internal energy change	*MWh*	-497	93	-583
PTES thermal losses	*MWh*	1275	1046	388
abs heat pump heat delivery	*MWh*	10300	9446	12194
heat pump driving heat demand	*MWh*	5934	5228	9216
heat pump source heat demand	*MWh*	4375	4019	5398
heat from high temperature biooil boiler 5MW	*MWh*	9894	10187	14350
heat from biooil boiler 10MW	*MWh*	2498	1078	209
heat from gas engines 4*1.6MW heat from gas boiler 8MW	*MWh*	8011	11456	8160
heat delivery to DH	*MWh*	35447	36994	36869
key performance indicators				
solar collector field efficiency	*%*	41	40	39
PTES storage efficiency	*%*	90	91	96
PTES no. of storage cycles	-	2.2	1.9	2.2
PTES maximum temperature	*°C*	89	87	84
PTES minimum temperature	*°C*	10	12	9
PTES used heat capacity	*MWh*	5500	5200	5202
heat pump COP	-	1.7	1.8	1.6
solar fraction	*%*	40.9	41.1	40.2

In **Figure 19** the energy flow diagram of the energy production according to monitoring data for the year 2017 is illustrated. With the data of **Figure 19** a solar fraction of 40% can be calculated for the year 2017 (design value: 41%).

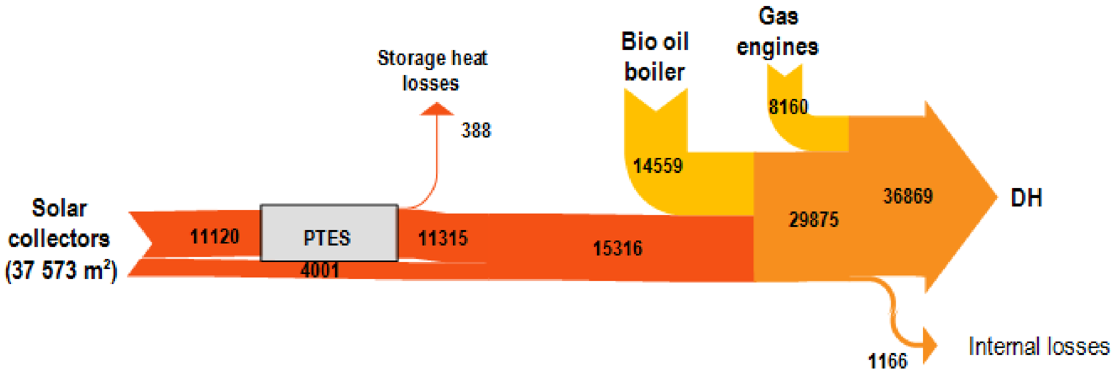


Figure 19. *Dronninglund SDH heat flow diagram according to monitoring data for 2017, numbers in MWh.*

The energy balance of the PTES in the year 2016 is presented in **Figure 20**. **Table 3** (column '2016') shows the corresponding key figures that can be calculated from the energy values in **Figure 20**. The internal energy content of the storage is calculated based on temperature sensors that are installed in the water volume every 0.5 m in vertical direction. The thermal losses can be derived from the energy balance around the PTES.

Figure 21 shows the energy figures for the PTES since start of operation until 2017. The yearly numbers in general show only minor variations, which is an indicator for a rather stable and similar yearly operation of the storage.

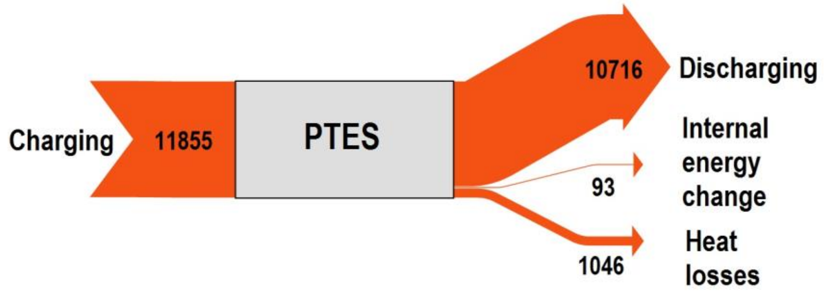


Figure 20. *Heat balance diagram for the Dronninglund PTES in the year 2016, numbers in MWh.*

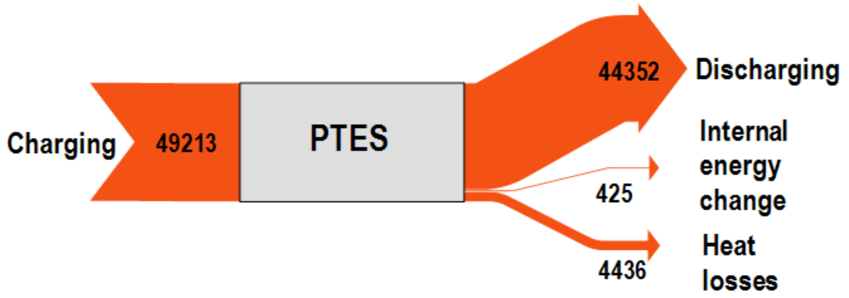


Figure 21. *Heat balance diagram for the Dronninglund PTES for the period 2014-2017, numbers in MWh.*

The evaluated mean storage efficiency of around 90% in 2015 and 2016 is according to design expectations. Compared to the PTES in Marstal the higher efficiency is on the one hand result of lower thermal losses of the PTES in Dronninglund. On the other hand also the energy turnover of the Dronninglund PTES is twice as much as in Marstal, what is indicated by a mean storage cycle number of 2 instead of only 1 in Marstal. As the thermal losses of the storage are mainly depending on the surface temperatures and not on the energy turnover, a higher energy turnover reduces the effect of the thermal losses on the efficiency number. In addition, the minimum storage temperatures in winter are lower than the surrounding ground temperatures in some parts of the storage, see **Figure 22**. This means that in these periods there are negative heat losses in the bottom areas.
A storage efficiency of 96% in 2017 seems unrealistic high. However, when looking into the numbers given in **Table 3** more in detail one can see that the amount of heat discharged from the storage is higher than the amount of heat charged into the storage in 2017. This is only possible because of the heat pump, that was used more extensively in 2017 compared to the years before. In 2017 the energy used as source heat from the PTES for the heat pump accounted for about 5400 MWh, which is more than 1000 MWh more compared to 2015 and 2016 (see **Table 3**). As a consequence of this the temperatures in the storage are lower for longer periods of the year. An analysis of the temperatures in the storage in a depth of 8 m e.g. shows, that in 2016 the lower part of the storage had temperatures below 15 °C for about 940 hours whereas in 2017 this number was more than 2200 hours. In these periods the temperatures in the surrounding ground are higher than the temperatures inside the storage. This leads to a heat transfer from the underground into the storage in the lower parts of the storage and thus to negative heat losses. This also explains the low overall thermal losses of the storage in 2017. The effect of negative heat losses cannot be confirmed directly from the monitoring data, as no suitable monitoring sensors for this are available, but has been verified in a recent simulation study that was done for the Dronninglund PTES based on monitoring data for 2015.

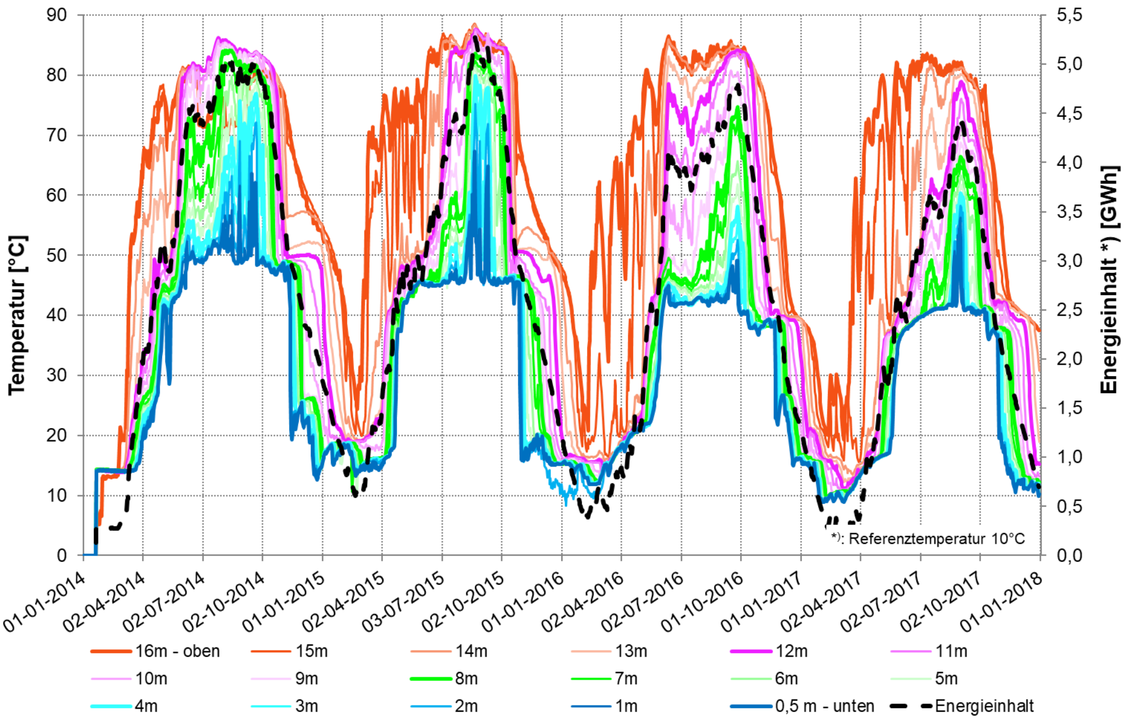


Figure 22. *Temperature distribution and energy content in the storage from 2014 to 2017.*

In **Figure 22**, where the temperature development inside the storage volume can be seen, a similar behaviour of the storage can be observed for the four presented years. Maximum temperatures at the top of the storage in summer are a little more than 85 °C, minimum temperatures go down to 10-15 °C at the bottom and around 20 °C at the top in winter. Temperature differences between top and bottom reach almost 50 K in spring and 40 K in autumn.

In the discharging periods clear steps can be seen in the bottom temperatures (blue lines) in October / November. At this time the connected heat pump starts operation and allows for a discharging of the storage far below the return temperature level of the DH network.

Figure 23 shows the monthly heat amounts that were charged into and discharged from the PTES for the years 2014 to 2017. Compared to the same illustration for the Marstal PTES in **Figure 13**, a more uniform discharging behaviour is clearly visible. This indicates that the storage is also used for short-term storage processes in the summer period besides the seasonal storage process from summer to winter. These additional short-term storage processes lead to the larger energy turnover in comparison with the Marstal PTES that was already discussed above in conjunction with the storage cycle number.

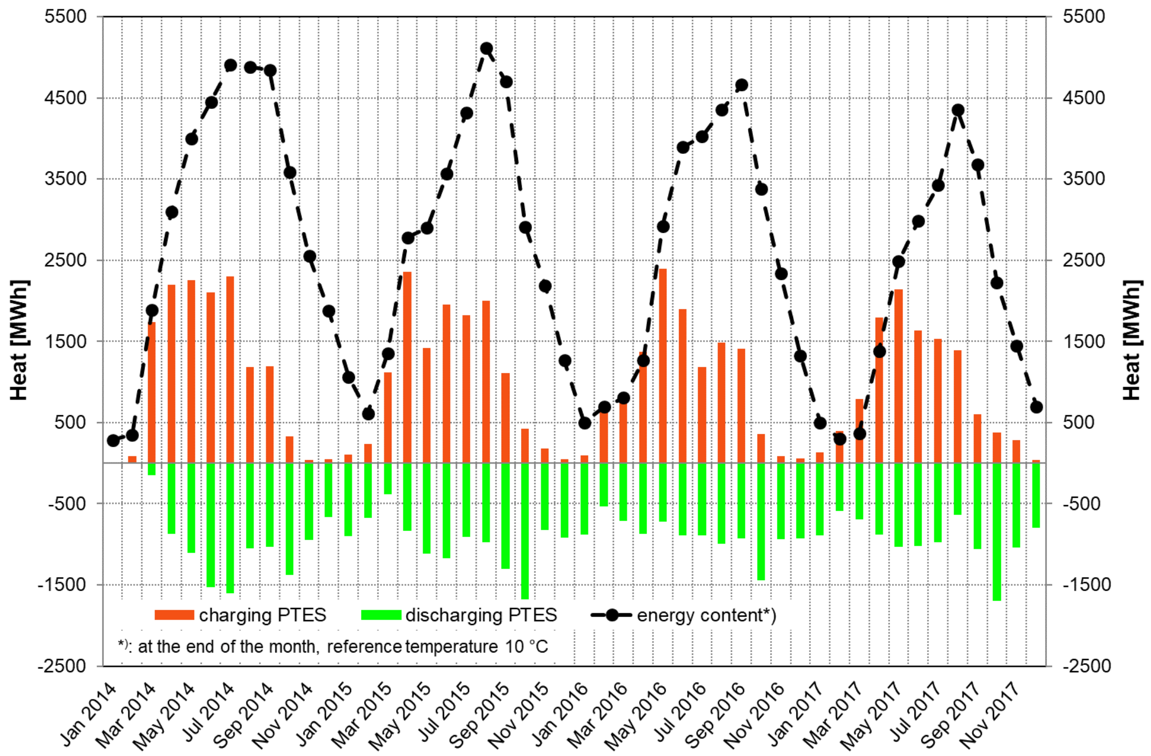


Figure 23. *Monthly overview of charging and discharging of the PTES in Dronninglund from 2014 till 2017.*

The temperature distribution in the storage is shown in **Figure 24**. For each month in 2017 the temperature can be read out depending on the depth below water surface, which is shown on the y axis. From June to September higher temperatures can be seen in the top and bottom of the storage. When comparing these lines one can see that the storage is charged from the top. The top warms up first and deeper layers at a later point. One can also see, that the temperatures in the bottom are higher in summer and fall than in spring and winter.

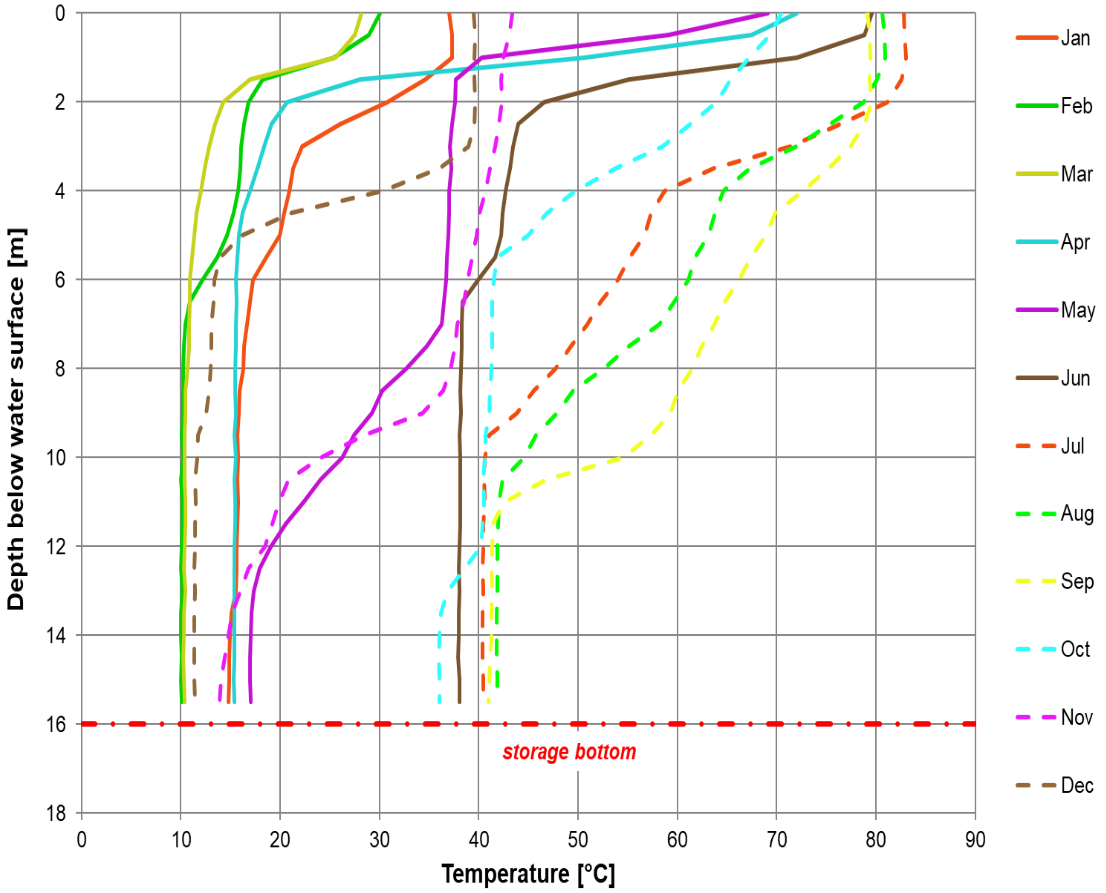


Figure 24. *Temperature in the storage depending on depth and month in the year 2017.*

Ground temperatures outside the PTES are presented in **Figure 25**. The sensor in 10 m depth shows fluctuating temperatures as it is close to the top of the PTES with stronger seasonal temperature variations. The sensors further down show less pronounced variations. In 20 m and 25 m depth, a slow but steady temperature increase can be observed. Measurements from the upper 2 sensors had to be taken out of consideration after a certain time as the sensors were broken.

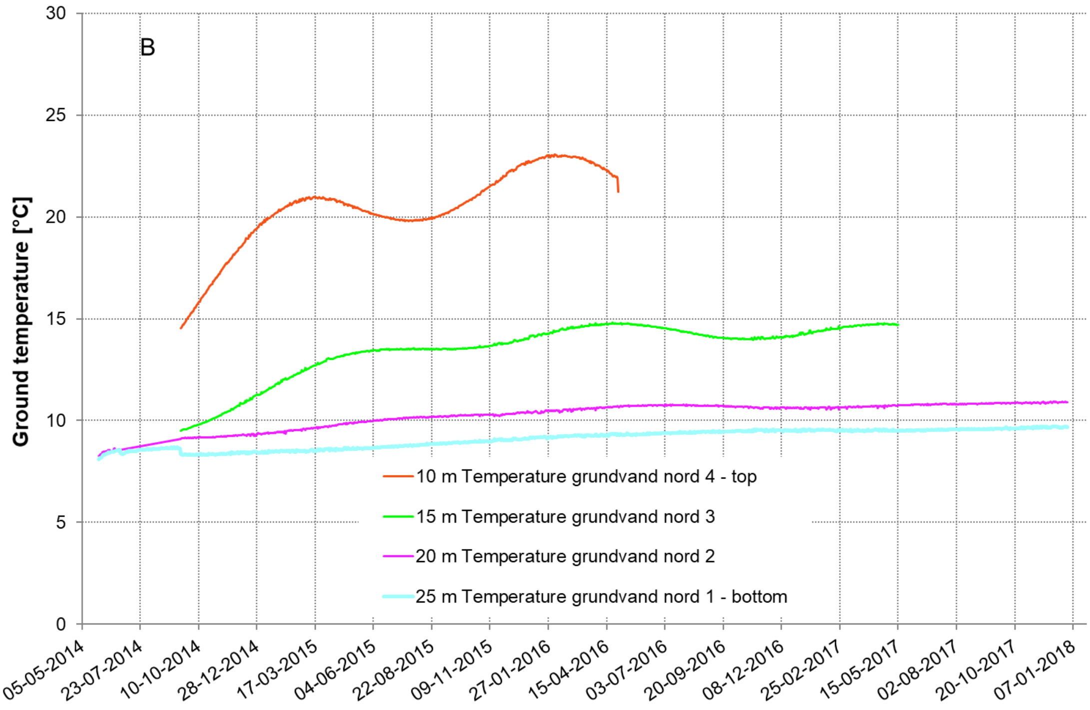


Figure 25. *Temperature measurements in the ground close to the storage.*

4.2 Export of data to varmelagre.dk

Though the storage monitoring was originally planned to be part of the solvarmedata.dk website, a dedicated website has been developed for the heat storages: http://varmelagre.dk This has been done to promote the storages separately and avoid that a mix with solar heating plant data confuses users. The website has been created with a similar design and setup as solvarmedata.dk to make the connection intuitive for users familiar with that website. Direct links between the websites enforces the connection.

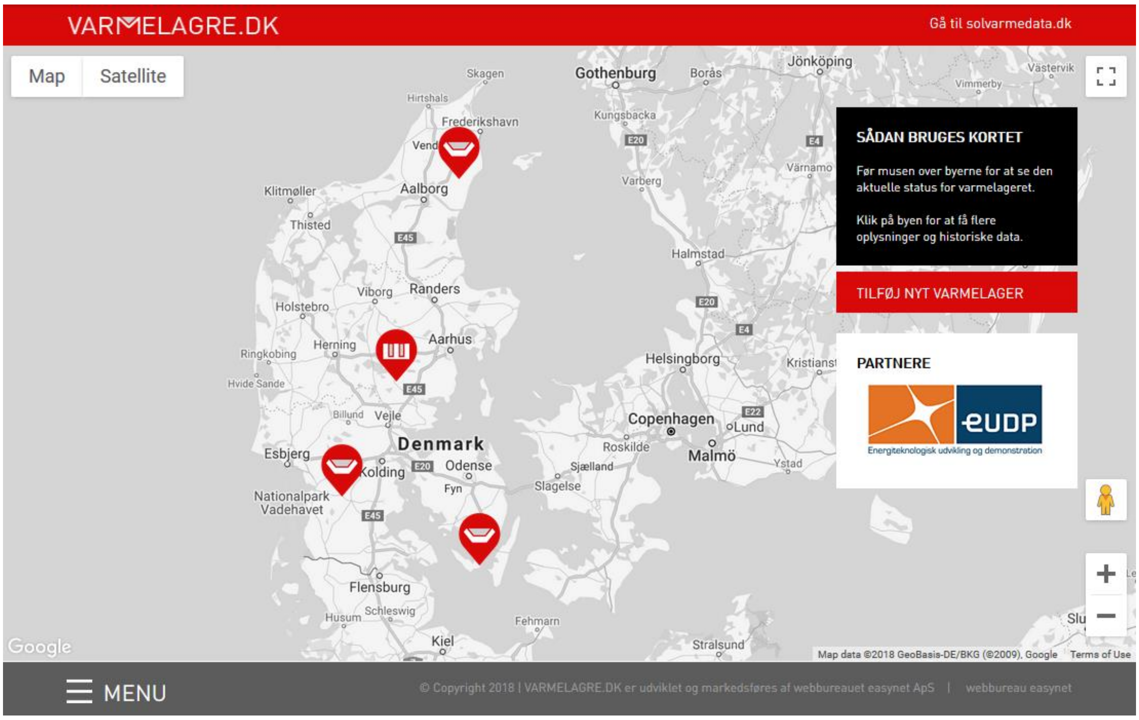


Figure 26. *Screen shot of varmelagre.dk.*

4.2.1 The key features of varmelagre.dk

The front page gives an overview map of the storages with icons showing the type of storage (see **Figure 26**). With a mouseover the present status of the storage is shown including

- Charging
- Discharging
- Energy content in MWh
- State of charge in percent (of "full")

These values are based on a continuous monitoring of the storages and shown in real time (updates every 5 minutes).

Figure 27. *Icons used at varmelagre.dk. From left to right are seen icons for pit heat storage, borehole storage and indication of several overlaying icons (i.e. two or more storages located close to each other for the chosen zoom level).*

By clicking on one of the storage icons the user is presented with the "subpage" for the chosen storage which includes a top menu including three sections

a) present and historical monitoring data
b) information about the storage and district heating plant
c) access to monitoring results from previous periods

Besides the real-time monitoring data in menu section a) above, each subpage includes optio for graphical presentation and historical data download of

- charged energy
- discharged energy
- energy content
- charging temperature
- discharging temperature
- temperature levels in the storage

The graphics are divided in two charts: One for energy and one for temperatures. In **Figure 28** is seen an example of the energy chart.

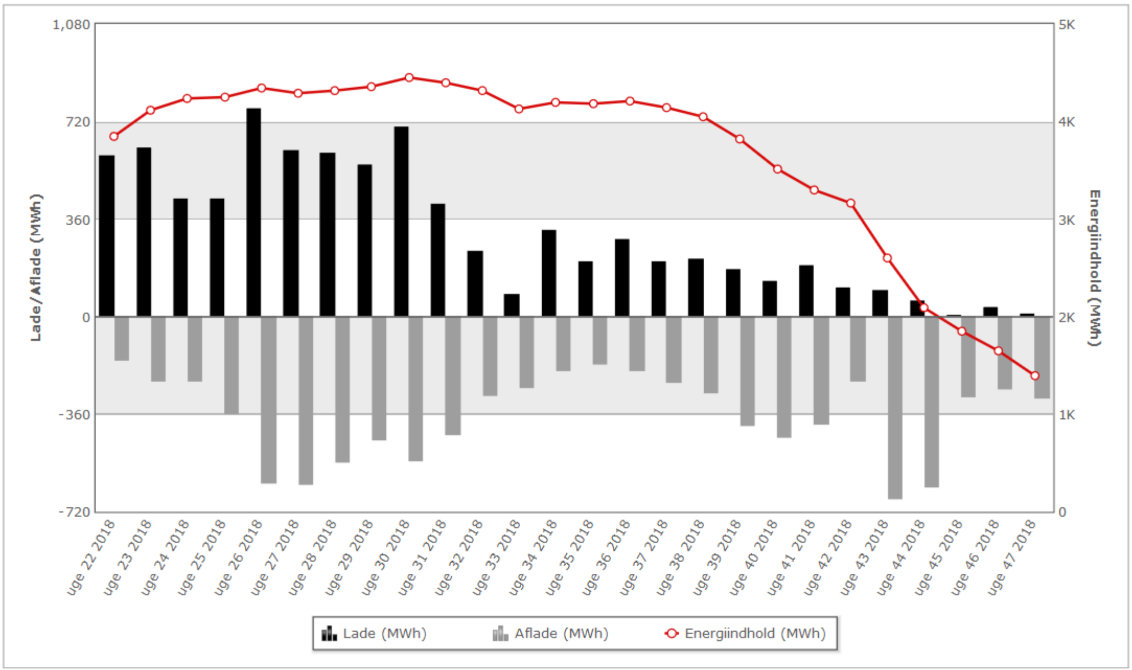


Figure 28. *Example of the energy chart for half a year with a chosen timestep of one week. Black and grey bars represent charging and discharging energy respectively (left axis, both in MWh). These are paired so that each timestep includes one charging and one discharging bar. The red line shows the energy content (right axis) which in this example stays between 1,000 and 5,000 MWh.*

In the top menu (point b above) general information about the plant is found (e.g. storage type, volume etc.) besides a download option to access a short introduction to the district heating plant and storage in question.
The last top menu (point c above) enables users to download presentations of annual monitoring data overview from previous years developed by SOLITES.

4.2.2 Data details

Regarding temperature levels it has been decided that mean temperature is not included for pit heat storages since it could lead to confusion if it represents the temperature in the mean height of the storage or the average water temperature. A mean temperature is only included for borehole storages.
Correspondingly the storage top and bottom temperature – which for pit storages represent high and low temperatures respectively due to the stratification in the storage – are not included for borehole storages since a similar stratification is not present.

Energy content is provided as the value at the end of the given time step. If hourly values are chosen, a value provided for the period 13:00-14:00 represents the energy content at 14:00.

4.2.3 General information available in bottom menu

In a bottom menu which can be hidden or not the user can access further, general information:

- About the website (who is behind it, how to use the website)
- Sources of further information on heat storages in general
- How to get a heat storage connected to the website and contact information in case of technical issues.

4.2.4 The future for the website

Other storages can be connected to the website. With the button "Tilføj nyt varmelager" the user is presented with what is required to connect a new storage.

It is expected that the financing of the website after funding from the EUDP project no. 64014-0121 ends can be handled by sponsors which in turn are presented at the website. To secure such financing a folder has been created to present the sponsor option. This is available from the project website at http://varmelagre.dk/files/files/Varmelagre-folder_web.pdf .

4.3 Corrosion problems and how they are solved

Diver inspection in Marstal showed corrosion on in- and outlet pipes. The corrosion was expected to be both bacterial caused by organic material coming into the water during November 2011 to April 2012 when the storage was filled up with water, and galvanic corrosion caused by the combination of black steel and galvanised steel in the in- and outlet pipe system.
It was decided to raise pH from 7.4 to 9.6 be adding NaOH to prevent organic corrosion and to place sacrificial zinc anodes to prevent galvanic corrosion. Furthermore, water tests has been taken four times/year. Diver inspections in 2016 and 2017 showed that the corrosion did not develop further.

Figure 29. *Left: zinc anodes are placed. Right: zinc anodes on in- and outlet pipes. Source: Marstal Fjernvarme*

4.4 Test of the liner

The liner used in Dronninglund was tested during the monitoring program. It was an accelerated test carried out at Teknologisk Institut in Copenhagen. Test temperature was 110 °C and the test was carried out with drinking water on one side and air on the other side. The test was 50% co-financed by the liner supplier, GSE (now SOLMAX GSE). From the test Teknologisk Institut concluded that the liner life time would be app. 5 years if the water temperature is 90 °C constantly.
The same liner type is tested by RISE in Sweden where the test result was 25 years by 90 °C constant water temperature. The main difference between the test methodologies is the content of oxygen in air and water.

4.5 Test of insulation material

The insulation material used in Marstal and Dronninglund was tested during the monitoring program. The test was carried out by temperatures below melting point of the material. The test was 50% co-financed by the supplier of the insulation material, Termonova.
The test result was, that the insulation material will last only in few years if humidity is 100% and temperature is 90 °C.
Termonova has now developed a new type of insulation with higher melting point. This type will be tested by Teknologisk Institut after finalization of the monitoring program.

4.6 Other operation experiences

The lid in Marstal and Dronninglund is floating on the water and rain water is supposed to end in the middle of the lid and pumped away. Bud puddles of rain water near the edge has to be emptied manually. Also in Marstal the insulation material moves into the ditches made for the weight pipes on the lid.
In Dronninglund these problems are minor since the weight pipes are heavier (and the slope to the middle larger) and steel anchors are used to fix the insulation.

Figure 30. *Water puddles on the lid in Marstal. Source: Marstal Fjernvarme*

The storage had in 2012 a loss of water of 30-40 m^3/day. During the diver inspection was found a leakage of 7 cm in the bottom of the storage (a welding mistake). The leakage was preliminary repaired in February 2013 and permanently repaired by the diver in February 2015.

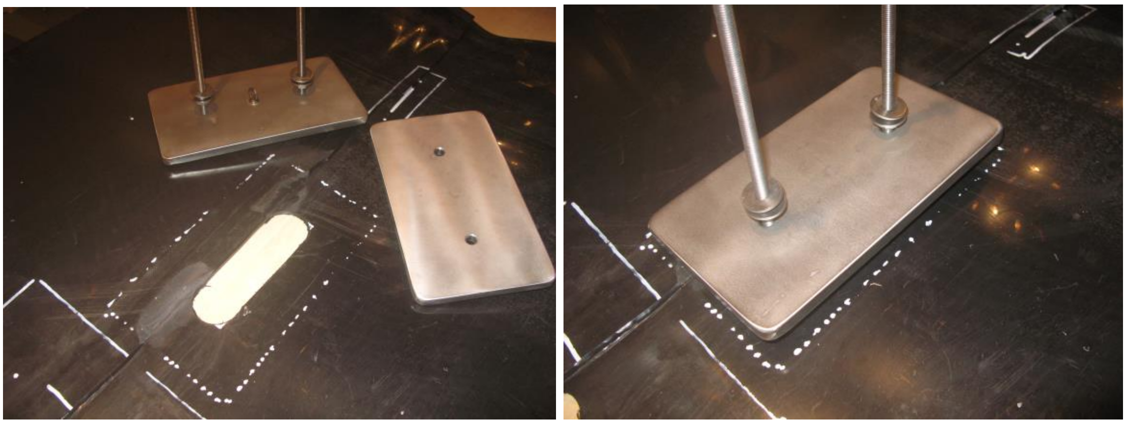


Figure 31. *Leakage located (left) and repaired by pressing metal plates around the leakage. Source: Marstal Fjernvarme*

4.7 Dissemination of project results

PlanEnergi dissemination:

1. Sørensen, P.A., Miedaner, O., Mangold, D.: Large scale sensible storages (up to 100 °C) in Germany and Denmark. Paper and oral presentation at "Greenstock 2015", 21.05.2015, Beijing, China
2. SDH Conference 2016. PlanEnergi and Kristensen Consult arranged the conference. There were 170 participants. Program is annexed.
3. Trier, D.: Presentation of the project results at Solvarme-ERFA meeting 20th September 2016
4. Brochure. Long term storage and solar district heating. Distributed at SDH Conference 2016 and at conferences and workshops during 2016, 2017 and 2018. www.planenergi.dk/arbejdsområder/fjernvarme/saesonvarmelagre/
5. Sørensen, P.A.: Danish examples of large scale SDH. Presentation at workshop in Warsaw, Poland, 16.03.2017
6. Sørensen, P.A.: Large scale heat storages. Presentation at workshop in Varna, Bulgaria, 21.06.2017
7. Trier, D.: ProgRESsHEAT-webinar 26th June 2017. https://energy-cities.adobeconnect.com/p2ofnw0aihwy/
8. Nielsen, J.E.: Presentation of the project results at Solvarme-ERFA meeting September 2017.
9. Schmidt, T., Sørensen, P.A.: Monitoring Results from Large Scale Heat storages for District Heating in Denmark, 14th International Conference on Energy Storage, 25-28 April 2018, Adana, Turkey. Paper and presentation
10. Sørensen, P.A., Schmidt T.: Design and Construction of Large Scale Heat Storages for District Heating in Denmark, 14th International Conference on Energy Storage, 25-28 April 2018, Adana, Turkey. Paper and presentation
11. Sørensen, P.A.: Siver varmen ud af damvarmelagrene? House of Energy, Aalborg Energidag 12.09.2018
12. Sørensen, P.A.: Driftserfaringer fra storskala varmelagre i Danmark. Dansk Fjernvarmes temadag om geotermi og varmelagring. 20.11.2018

Brædstrup dissemination:

Visits from among others participants in IEA ECES Annex 27 and Geological Institute in Finland. Beside that at least 15 scientific delegations.

Marstal dissemination:

Marstal has several visitors every year

Dronninglund dissemination:

Visits from among others SDHp2m stakeholders from Styria, three Japanese delegations (municipalities), delegations from China and participants in 4DH Conference 2016 in Aalborg. Beside that several Danish DH utilities

Solites dissemination:

1. Schmidt, T.: Monitoring results from the SUNSTORE 4 smart district heating plant in Marstal, Denmark, presentation at 2nd International Solar District Heating Conference, 3-4 June 2014, Hamburg, Germany
2. Schmidt, T.: Monitoring results from large-scale solar thermal plants with long term storage in Marstal, Brædstrup and Dronninglund, Denmark, presentation at 3rd International Solar District Heating Conference, 17-18 June 2015, Toulouse, France
3. Schmidt, T.: Resultate und Erfahrungen aus der Betriebsoptimierung von solaren Fernwärmeanlagen, presentation at "Forum Solare Wärmenetze", 11-12 May 2016, Stuttgart, Germany
4. Schmidt, T.: Monitoring results from large-scale solar thermal plants with long term storage in Marstal, Brædstrup and Dronninglund, Denmark, presentation at 4th International Solar District Heating Conference, 21-22 September 2016, Billund, Denmark

5. Schmidt, T.: Monitoring results and performance of seasonal heat storage, presentation at SolarThermalWorld webinar "Think Big – Design Rules and Monitoring Results of Solar District Heating Systems", 16.12.2016
6. Pauschinger, T.: Wärmenetze 4.0 – eine schlüssige Lösung für die Energiewende, Fachkongress Nahwärme (DH congress), 11. April 2017, Kupferzell, Germany
7. Pauschinger, T.: SDH for Tübingen – pre-selection of potential land areas for solar thermal, presentation for the city of Tübingen, Tübingen city utilities and Regionalverband Neckar-Alb, 17. August 2017, Tübingen, Germany
8. Pauschinger, T.: Solare Nah- und Fernwärme – Wie erschließen wir den Markt der solaren Wärmenetze? General assembly Austria Solar, 20. December 2017, Salzburg, Austria
9. Pauschinger, T.: Solare Fernwärme, 23rd International fair for heat, cold and CHP, 18 April 2018, AGFW, Frankfurt, Germany
10. Schmidt, T., Sørensen, P.A.: Monitoring Results from Large Scale Heat storages for District Heating in Denmark, 14th International Conference on Energy Storage, 25-28 April 2018, Adana, Turkey
11. Sørensen P.A., Schmidt T.: Design and Construction of Large Scale Heat Storages for District Heating in Denmark, 14th International Conference on Energy Storage, 25-28 April 2018, Adana, Turkey
12. Schmidt, T.: Solar District Heating in Dronninglund, Denmark, presentation, company internal training workshop, 01.08.2018, Transsolar Energietechnik GmbH, Stuttgart

VIA dissemination:

1. K.W. Tordrup, S.E. Poulsen, H. Bjørn,: An improved method for upscaling borehole thermal energy storage using inverse finite element modelling. Renewable Energy 105 (2017) 13e21
2. Presentation for participants in IEA ECES Annex 27.

DTU Byg dissemination:

Fan, J., Junpeng, H., Chatzidiakos, A., Furbo, S.: Experimental and theoretic investigations of thermal behaviour of a seasonal water pit heat storage. ISES Solar World Congress 2017, Abu Dhabi, United Arab Emirates.

5. Utilization of project results

PlanEnergi utilization of results:

Experiences from the PTES in Dronninglund and Marstal have been used within the IEA DHC Annex XII Project 03 "Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and Cooling" (https://www.iea-dhc.org/index.php?id=528) for the deliverable "Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling".
PlanEnergi has utilized the project results in design projects in Austria, Germany, Bulgaria and Denmark (Høje Taastrup and Aalborg).
Experiences from the project are brought into the European HEATSTORE project.

Solites utilization of results:

Monitoring data from the PTES in Dronninglund and Marstal have been used within the IEA DHC Annex XII Project 03 "Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and Cooling" (https://www.iea-dhc.org/index.php?id=528) for validation of TRNSYS simulation models for PTES.

Project results and monitoring data are furthermore used within the ongoing Austrian research project "giga-TES - Giga-scale thermal energy storage for renewable districts", supported by the Austrian Climate and Energy Fund.

VIA utilization

Experiences from the project is utilized when educating students in "Shallow Geothermal Systems" and "Sustainable Energy".

DTU Byg utilization of results

The project results have been presented for students following the solar energy courses at the Technical University of Denmark. Measurements from the project on the heat storages have been used in connection with Master Thesis projects on water pit storages carried out at the Technical University of Denmark.

6. Project conclusion and perspective

The Results from the evaluations of the monitoring data of two large-scale pit thermal energy storages in Marstal and Dronninglund and one borehole thermal energy storage in Brædstrup prove the efficiency and reliability of the presented storage technologies. The results show good agreements with the design figures in terms of storage efficiency, usable temperature ranges and contributions to the heat supply of the connected district heating networks. Deviations are explainable by different operational conditions or other site specific effects.

Especially the example of the PTES in Dronninglund shows a high storage efficiency, which is on the one hand a result of the good technical quality of the storage construction that leads to low thermal losses, on the other hand the storage has a large energy turnover as it is used for seasonal storage and for short-term storage simultaneously. In addition, the low temperatures in the storage in the winter period result in negative thermal losses in the bottom parts of the storage.

All of the considered systems have a heat pump included in the system concept that enables a discharging of the storages below the temperature levels of the district heating return lines. This allows for a nameable increase of the usable temperature differences of the storages and by this smaller storage volumes with the same usable heat capacities than without heat pumps.

Furthermore, all of the three presented plants are so-called Smart District Heating Systems that connect the heat sector with the electricity sector. Their main components are large solar thermal systems, seasonal thermal energy storages (STES), combined heat and power units (CHP) and heat pumps. The system concepts in principle also allow for a storage of surplus heat from the connected CHP units, even though this option has not been used in real operation up to now. The system flexibility nevertheless offers potential for an optimisation of the system and storage economy by e.g. a storage of CHP surplus heat in periods with high electricity prices and low heat demand.

Experiences from operation of the storages has been that operation of the borehole storage in Brædstrup has caused nearly no problems and it seems that the storage type will have the expected lifetime of >40 years.

Operation of the storages in Marstal and Dronninglund has showed minor problems, that have been or can be solved. Liner leakages can be repaired under water, water puddles on the lid must be emptied, insulation mats moves and can be replaced, and water chemistry must be controlled regularly. Still the lifetime of the PE/PEX insulation mats can be a problem if the expected lifetime of >20 years shall be reached. A new type with higher melting point is under development.

In the future thermal storages can be a key element in smart district heating and cooling systems because it opens for utilization of excess heat from power production, industries and waste incineration, and provides flexibility in the total energy system [Sørensen 2018]. For PTES this will require materials that can stand 20 years of operation by 90 °C.

This project has identified key issues, that Have to be be solved before operation at 90 °C constantly throughout 20 years is possible

- liner solution has to be changed or oxygen must be removed from storage water
- insulation material must be changed
- water chemistry must be controlled intensely to prevent corrosion or in- and outlet must be changed to non-corrosive materials

If these problems can be solved the market potential is huge since for instance the amount of excess heat in EU exceeds the heating demands in buildings according to the Heat Roadmap Europe project (www.heatroadmap.eu) – and thermal storages opens for utilization of this resource.

7. References

Schmidt, 2018 Schmidt, T.: Brædstrup monitoring district heating monitoring data evaluation report for the years 2014-2017, report within EUDP project 'Follow up on large scale heat storages in Denmark' (project no. 64014-0121), Solites, 2018

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