14th International Conference on Energy Storage
25-28 April 2018, Adana, TURKEY

Monitoring Results from Large Scale Heat storages for District Heating in Denmark

Thomas Schmidt [a] and Per Alex Sørensen [b]

[a] *Solites – Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems, Meitnerstraße 8, 70563 Stuttgart, Germany, Tel.: +49 711 67320000, E-Mail: info@solites.de*

b) PlanEnergi, Jyllandsgade 1, 9520 Skørping, Denmark, Tel.: +45 9682 0400, E-Mail: pas@planenergi.dk

Abstract

District energy is one of the main technologies for the transition of existing buildings in cities to be heated and cooled without using fossil fuels. Many heat sources as solar thermal energy, geothermal energy and excess heat from industry are available only with strong fluctuation or constantly during the year. Large-scale thermal energy storages make it possible to utilize these sources, replace peak fossil-based heat production and integrate fluctuating surplus electricity from PV and wind.

Since the 80'ties large-scale thermal energy storages have been developed and tested in the Danish energy system. From 2011 five full-scale pit thermal energy storages and one pilot borehole thermal energy storage have been built. The evaluation of the first two real-scale water-filled pit storages in Marstal (75,000 m³) and Dronninglund (60,000 m³) and the first pilot borehole storage in Brædstrup (19,000 m³ soil volume) is funded by a national Danish monitoring project.

The paper presents results from evaluation periods of three to five years for the mentioned storage projects including storage efficiencies, energy balances and temperature developments inside the storages and in the surrounding ground. A comparison of relevant key figures with design data proves the efficiency of the plants and the storage components.

Keywords:

Sensible heat storage; pit thermal energy storage (PTES); borehole thermal energy storage (BTES); underground thermal energy storage (UTES); district heating; integrated district energy production

1. Introduction

This paper presents monitoring results of three large-scale seasonal underground thermal energy storages (UTES). The storages are integrated into solar district heating systems (SDH) and allow for high solar fractions due to the seasonal storage of solar heat from the summer period to the winter heating season. Two of the presented storages are pit thermal energy storages (PTES, in Marstal with 75,000 m³ and Dronninglund with 60,000 m³). The third one is a pilot borehole thermal energy storage (BTES, in Brædstrup with 19,000 m³ ground volume). A detailed description of the plants and storages is given in (Sørensen and Schmidt, 2018).

The SDH projects are part of a national Danish monitoring project that is coordinated by PlanEnergi. Solites is responsible for the evaluation of monitoring data. The project is ongoing and will end in spring 2018.

2. Definitions

In the following sections some key figures are presented. They are defined as follows:

Solar fraction: $$f_{sol} = \frac{Q_{sol}}{Q_{DH}} \quad (1)$$

Storage efficiency: $$\eta_{TES} = \frac{Q_{DC} + dQ_{\text{int}}}{Q_{CH}} \quad (2)$$

Storage cycle number: $$CN = \frac{Q_{DC}}{Q_{CAP}} \quad (3)$$

Heat capacity: $$Q_{CAP} = V_{TES} \cdot \rho \cdot c_p \cdot (T_{\max} - T_{\min}) \quad (4)$$

Storage energy balance: $$0 = Q_{CH} - Q_{DC} - Q_{loss} + dQ_{\text{int}} \quad (5)$$

With Q_{sol} : solar heat delivered to the district heating (DH) network
Q_{DH} : total heat delivered to the DH network
Q_{DC} : heat discharged from the storage
Q_{CH} : heat charged into the storage
Q_{loss} : thermal losses of the storage
dQ_{int} : internal energy change of the storage within the considered period
($dQ_{int} < 0$ if energy content is lost within the period)
Q_{CAP} : heat capacity of the storage
V_{TES} : Volume of the thermal energy storage (TES)
ρ : density of the storage medium
c_p : specific heat capacity of the storage medium
T_{max} / T_{min} : maximum / minimum temperatures in the storage

3. The Marstal 75,000 m³ PTES

The 75,000 m³ water-filled PTES in Marstal went into operation in June 2012. Figure 1 shows an energy flow diagram for the energy production with design figures in blue and figures from monitoring data of 2016 in black. With the presented numbers a solar fraction of 41 % can be calculated for the plant. As additional heat sources are based on biomass and bio-oil the plant is supplied to 100 % from renewable energy sources (RES).

In Figure 2 the yearly energy balance for the PTES is shown for the year 2015. 7813 MWh of solar heat were charged into the storage and 5435 MWh were discharged to the system. The internal energy content of the storage was 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 567 MWh below the one at the beginning of the year. According to (5) the thermal losses that were transferred to the surrounding ground and the ambient air summed up to 2946 MWh. The maximum and minimum temperatures in the storage volume in 2015 were 84 °C and 20 °C respectively.

With the data of Figure 2 the following key figures can be calculated for 2015 with (2) to (4):

- Storage efficiency: 62 %
- Storage cycle number: 1.0
- Heat capacity: 5,430 MWh

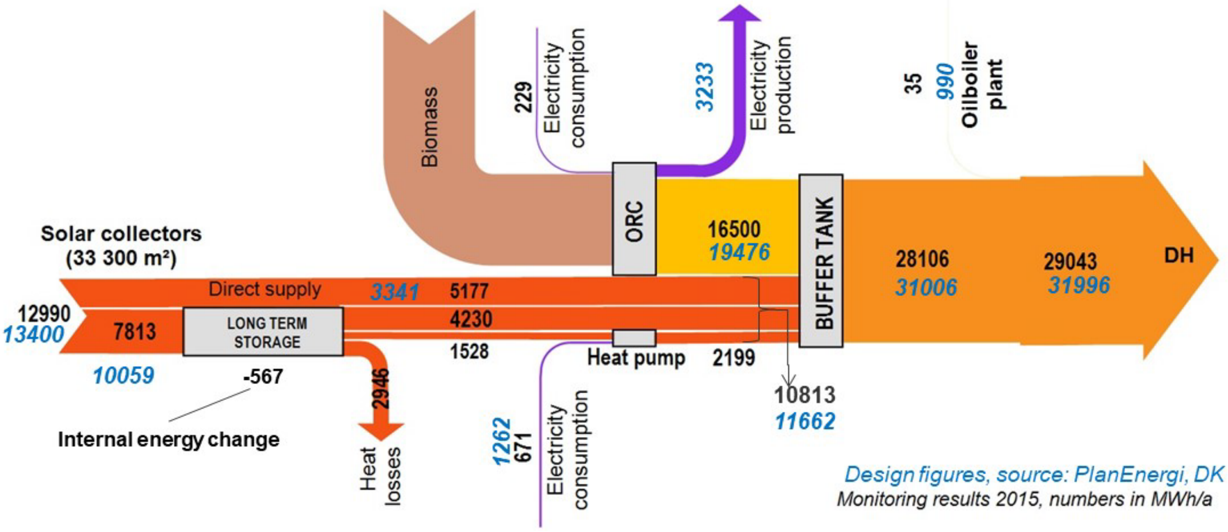

Figure 1: Energy flow diagram for the SDH plant in Marstal, DK

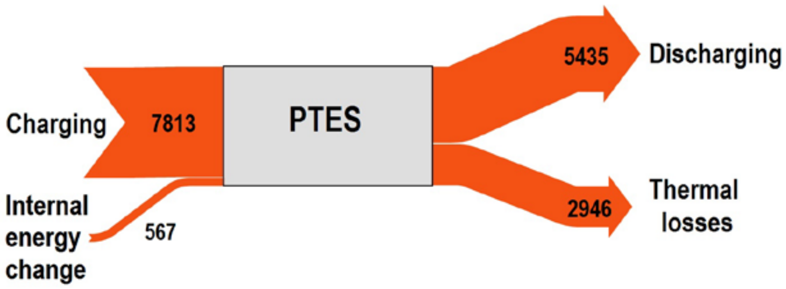

Figure 2: Energy flow diagram for the PTES in Marstal according to monitoring data for the year 2015, numbers in MWh/a

The evaluated storage efficiency of 62 % is a little higher than the design value of 61 %. A storage cycle number of 1 means that the heat capacity of the storage was used once in 2015, representing a pure seasonal operation. This can also be seen in the monthly charged and discharged amounts of heat presented in Figure 3. The main charging processes are in summer and the main discharging processes in winter.

In Table 1 the key figures for the PTES are listed since start of operation until 2015.

Table 1: Key figures for the PTES in Marstal from start of operation until 2015

		2012	2013	2014	2015
storage efficiency	%	-	65	66	62
storage cycle number	-	-	0.8	0.8	1.0
charged heat	MWh	3261	7538	8598	7813
discharged heat	MWh	1202	4141	4597	5435
internal energy change	MWh	-	776	1093	-567
thermal losses	MWh	-	2621	2908	2946
maximum temperature	°C	-	77	88	84
minimum temperature	°C	-	13	17	20
storage heat capacity	MWh	-	5500	6000	5430

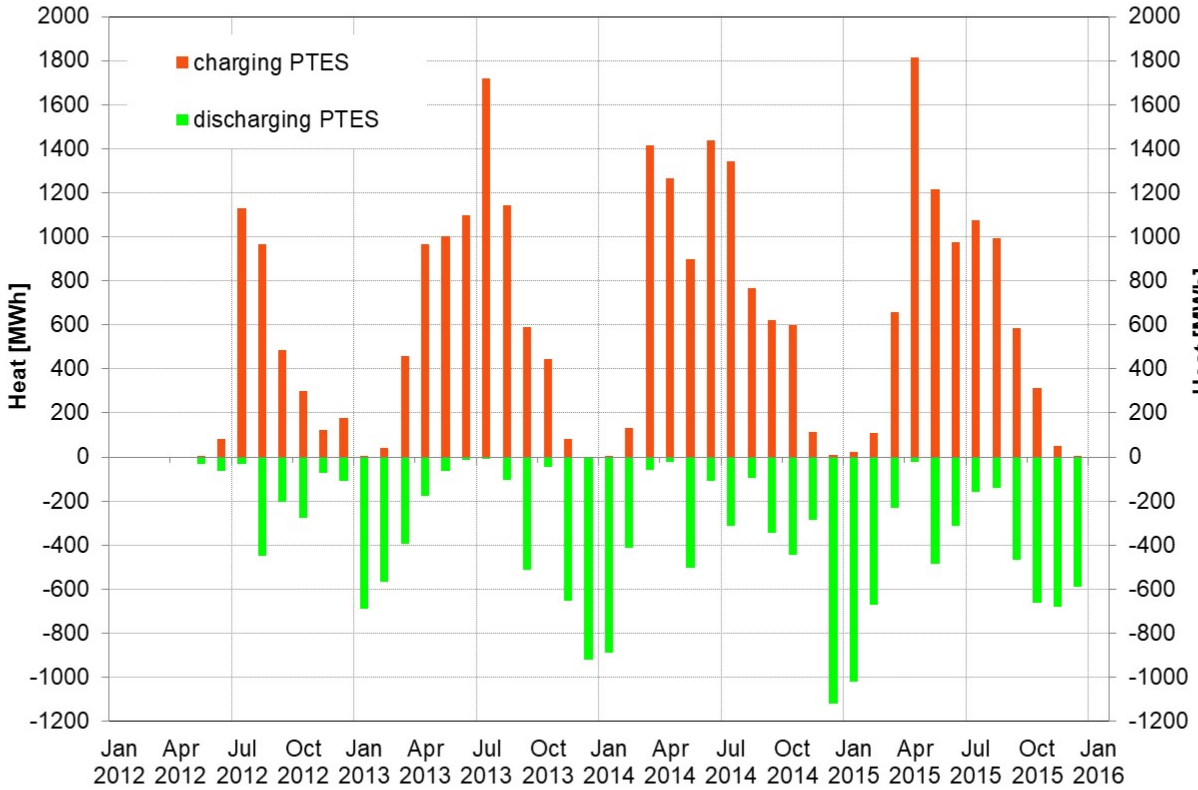

Figure 3: Monthly charging and discharging heat balance of the Marstal PTES between start of operation and end of 2015

In Figure 4 the temperature development in the storage is illustrated from 2013 to 2016. 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 slightly above 30 °C at the top of the storage and some 20 °C at the bottom.

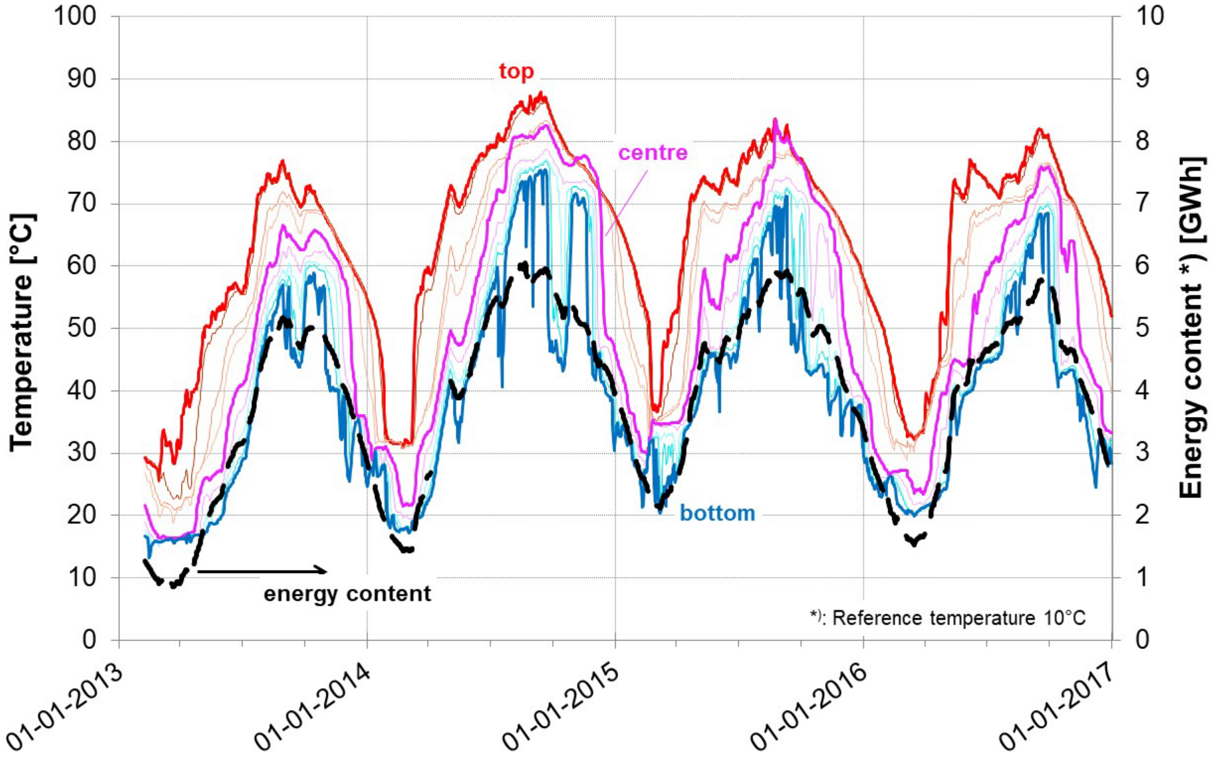

Figure 4: Temperature development in the PTES in Marstal between start of operation and end of 2016

Maximum temperatures in September reach some 85 °C at the top and around 70 °C at the bottom. 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.

85 temperature sensors were 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 5 shows the locations where temperature sensors are placed in different horizontal and vertical positions.

The temperatures shown in Figure 4 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 ground. C and B go down 2 m below the bottom of the PTES to 18 m. The horizontal distance between B and C is 10 m.

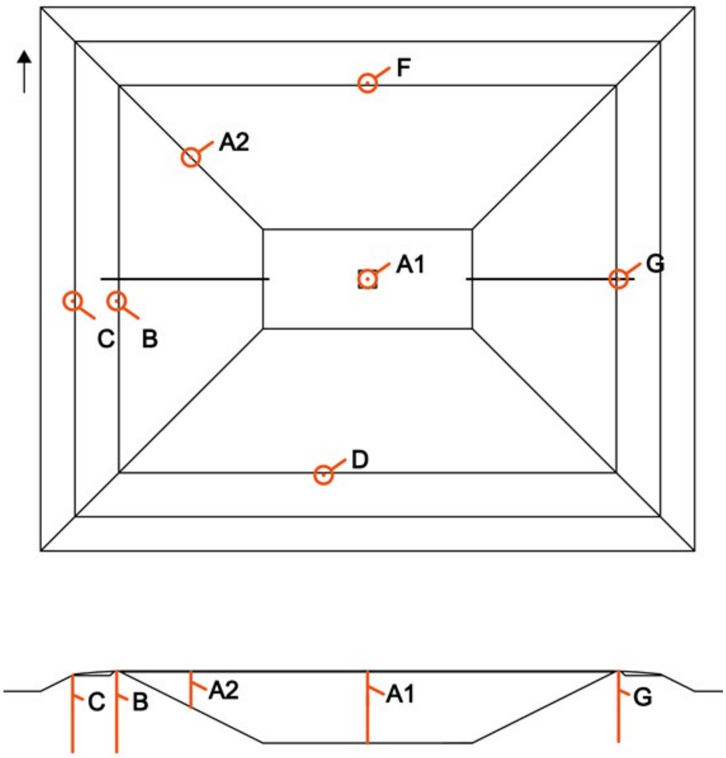

Figure 5: Positions of temperature sensors inside and outside the PTES in Marstal (above: top view, below: side view)

Figure 6 and Figure 7 show ground temperatures at the positions B and C. 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.

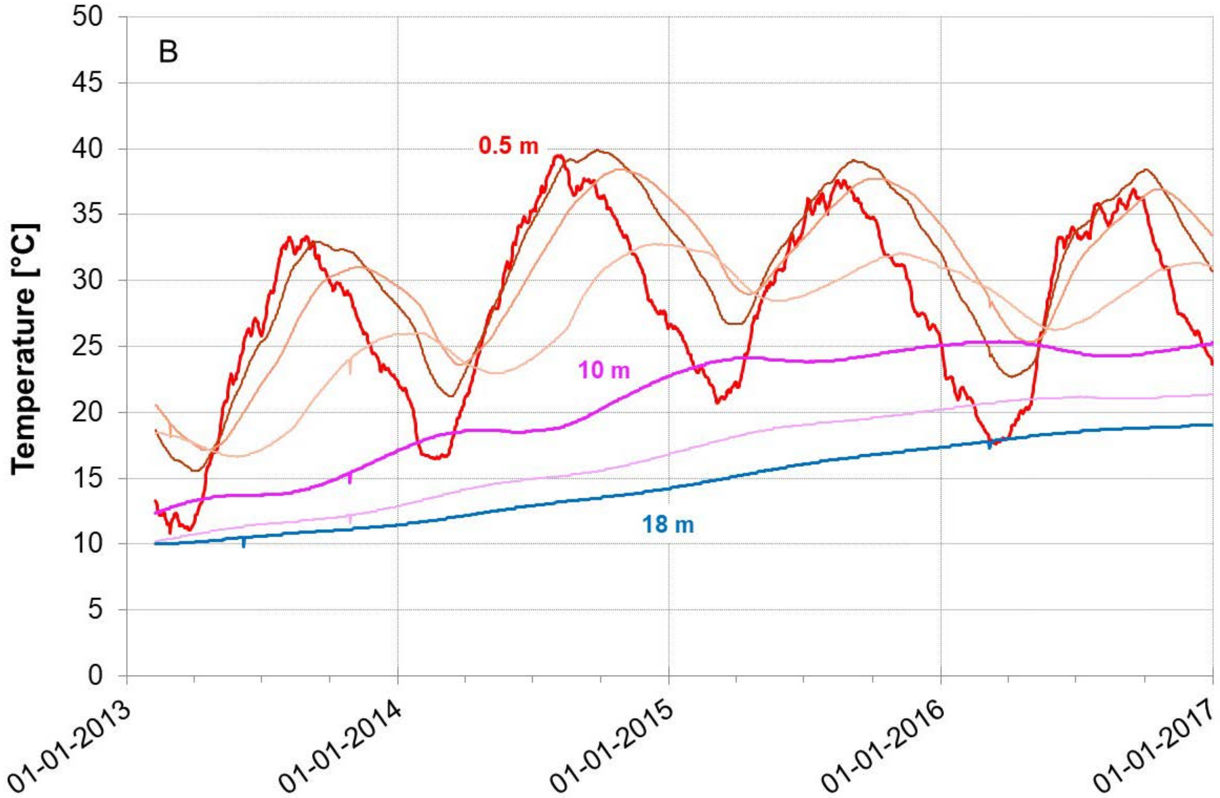

Figure 6: Long-term ground temperature development of the PTES in Marstal at position "B", see Figure 5 (depth levels 0.5, 1.5, 3, 6, 10, 14, 18 m below water surface)

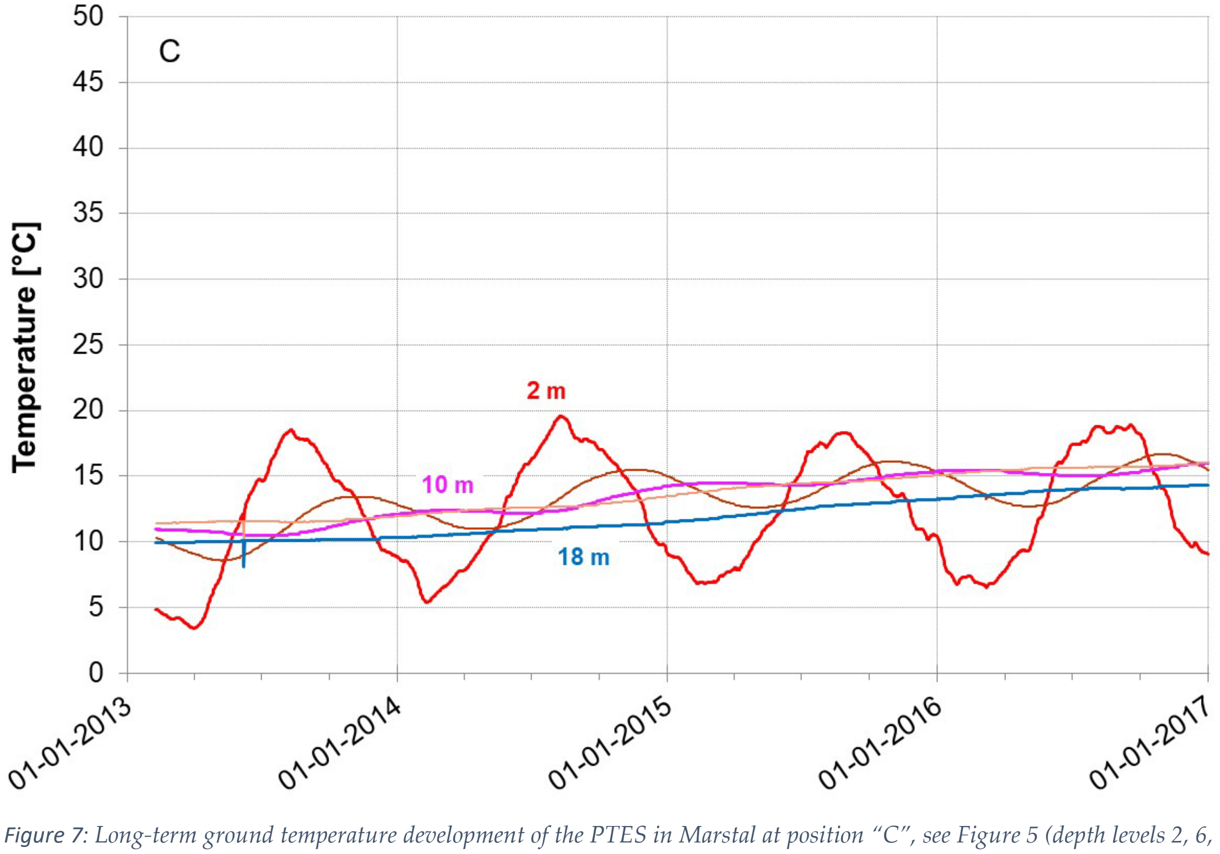

Figure 7: Long-term ground temperature development of the PTES in Marstal at position "C", see Figure 5 (depth levels 2, 6, 10, 14, 18 m below water surface)

4. The Dronninglund 60,000 m³ PTES

The 60,000 m³ water-filled PTES in Dronninglund was built in 2013 and went into operation in the beginning of 2014. In Figure 8 the energy flow diagram of the energy production according to monitoring data for the year 2016 (black figures) is illustrated. For comparison the design figures are given in blue. With the data of Figure 8 a solar fraction of 41 % can be calculated for the year 2016 (design value: 41 %).

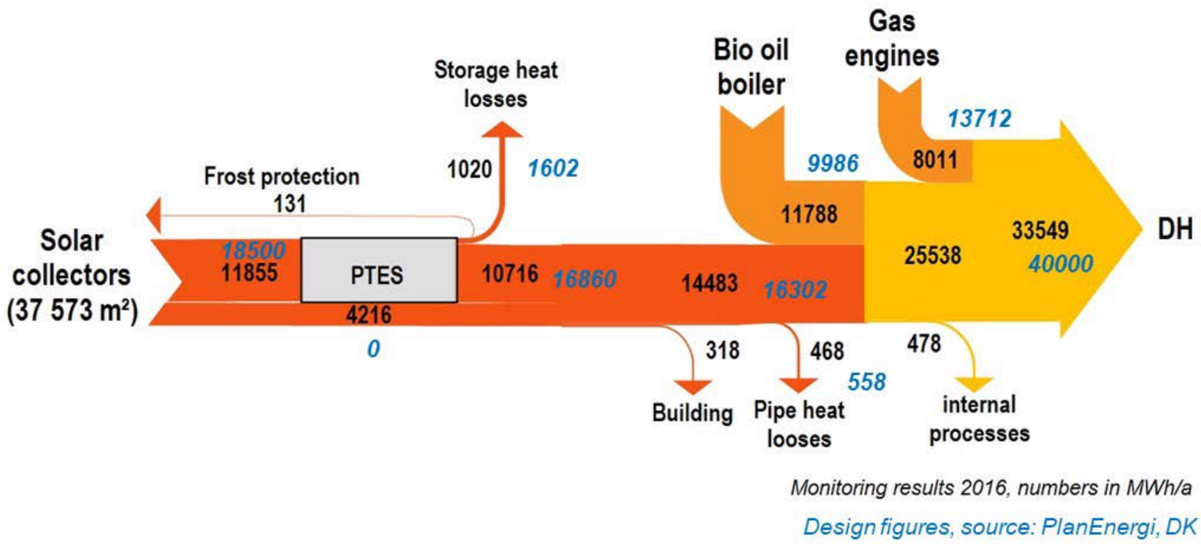

Figure 8: Energy flow diagram for the SDH plant in Dronninglund, DK, a fuel change from bio-oil to natural gas in October 2016 is not considered

The energy balance of the PTES in the year 2016 is presented in Figure 9. Table 2 (column '2016') shows the corresponding key figures that can be calculated from the energy values in Figure 9. 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 (5).

Table 2 shows the key figures for the PTES since start of operation until 2016. The numbers show only minor variations, which is an indicator for a rather stable and similar yearly operation of the storage.

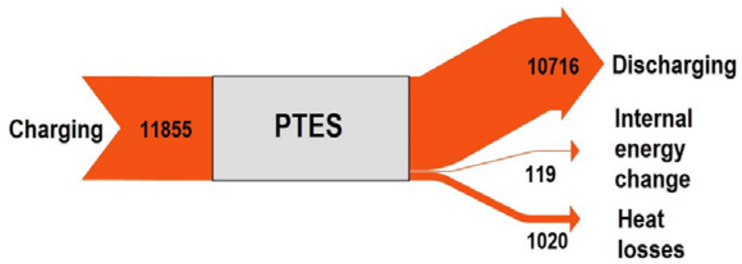

Figure 9: Energy flow diagram for the PTES in Dronninglund according to monitoring data for the year 2016, numbers in MWh/a

Table 2: Key figures for the PTES in Dronninglund since start of operation until 2016

		2014	2015	2016
storage efficiency	%	78	90	91
storage cycle number	-	2	2.2	1.9
charged heat	MWh	13176	12760	11855
discharged heat	MWh	10338	11983	10716
internal energy change	MWh	1663	-497	119
thermal losses	MWh	1175	1275	1020
maximum temperature	°C	86	89	87
minimum temperature	°C	12	10	12
storage heat capacity	MWh	5100	5500	5200

The evaluated storage efficiency of 91 % for 2016 is according to the design figures (compare Figure 8). 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 Figure 10, where the temperature development inside the storage volume can be seen, a similar behaviour of the storage can be observed for the three 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 11 shows the monthly heat amounts that were charged into and discharged from the PTES from 2014 to 2016. Compared to the same illustration for the Marstal PTES in Figure 3, 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.

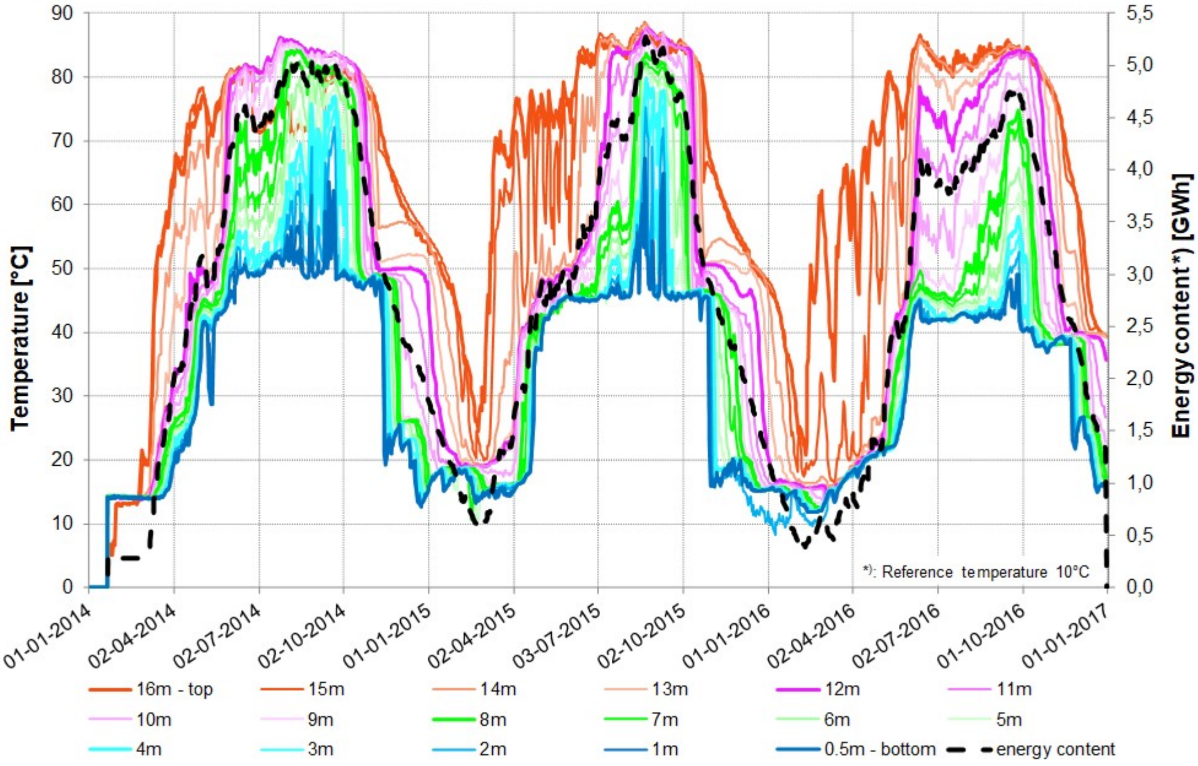

Figure 10: Temperature development inside the PTES in Dronninglund since start of operation until end of 2016

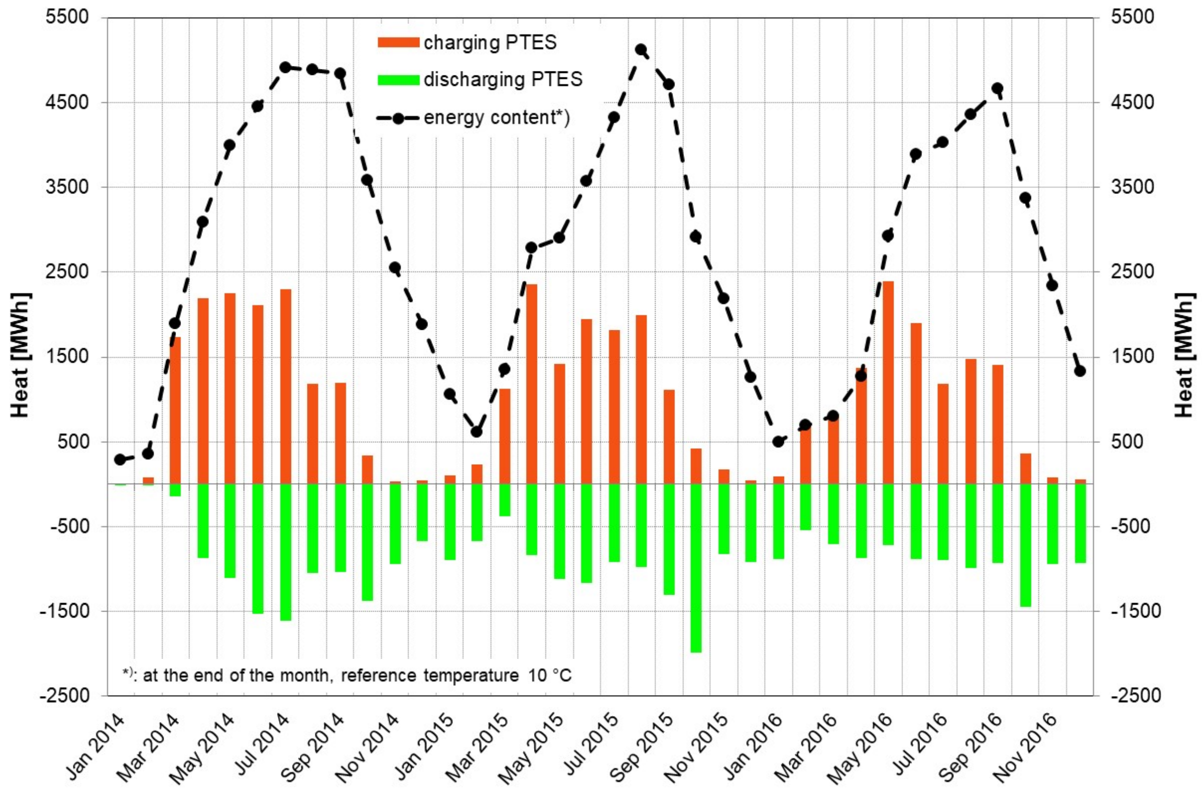

Figure 11: Monthly charging and discharging heat balance according to monitoring data for the PTES in Dronninglund from 2014 to 2016

5. The Brædstrup 19,000 m³ BTES

The Brædstrup borehole thermal energy storage (BTES) with 19,000 m³ soil volume was set into operation in spring 2012. It was built as a pilot storage to gain experiences for a real-scale BTES that shall be built as a follow-up at a later stage. Figure 12 shows the energy flow diagram for the energy production according to monitoring data for the year 2014 (black figures) and the corresponding design figures (in blue). With these numbers a solar fraction of 22 % can be calculated (design: 18 %) for the plant.

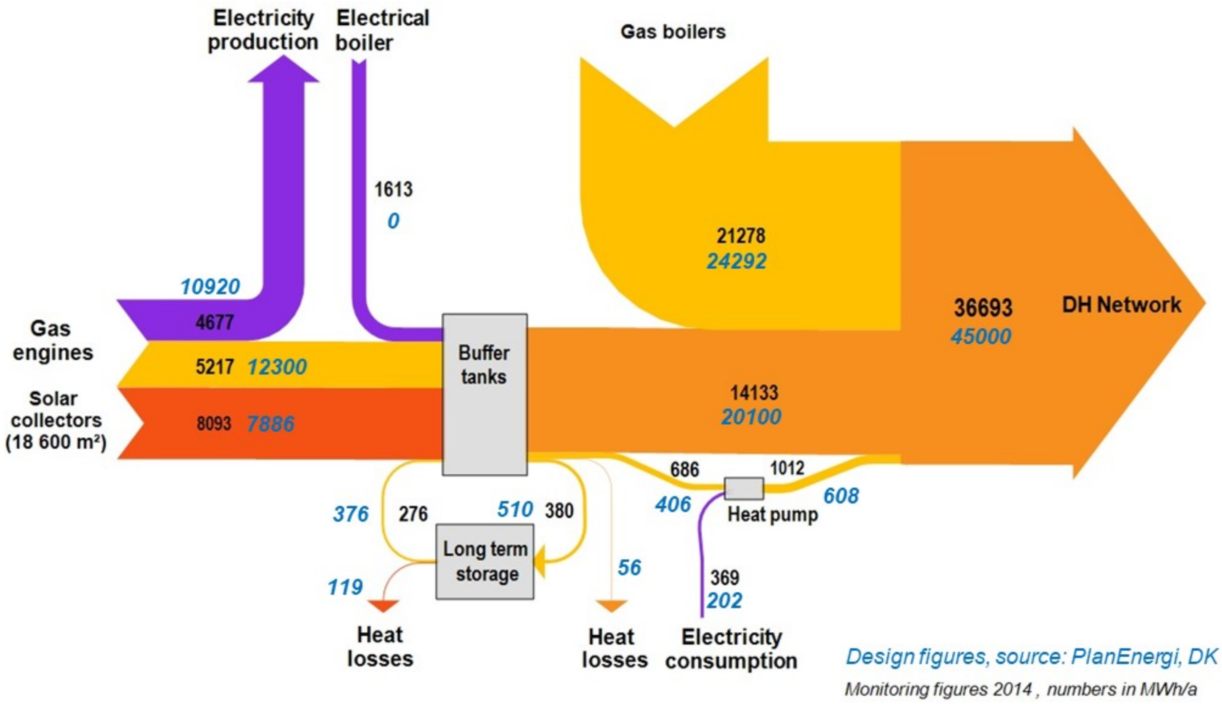

Figure 12: Energy flow diagram for the SDH plant in Brædstrup, DK in 2014

For the three years from the beginning of 2014 to the end of 2016, the heat flows as presented in Figure 13 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 calculated according to (5).

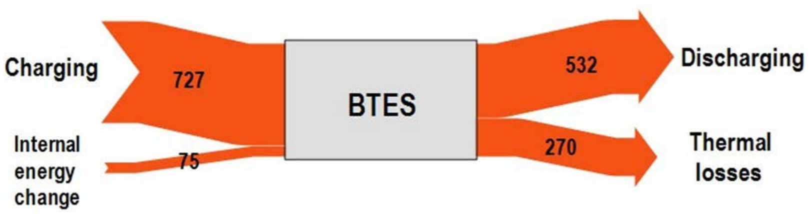

Figure 13: Energy flow diagram for the BTES in Brædstrup according to monitoring data for the three-year period from 2014 to 2016, numbers in MWh

With the data of Figure 13 the following key figures were calculated for 2014 to 2016:

- Storage efficiency: 63 %
- Storage cycle number: 1.3
- T_{max} / T_{min}: 50 / 12 °C
- Heat capacity: 400 MWh

The storage efficiency of 63 % is lower than the design value of 74 % 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 in 2014 as assumed in the simulations - and even less in 2015 and 2016, see Figure 12 and Figure 14.

The storage cycle number of 1.3 for the three-year period indicates a small utilization of the storage. The low maximum temperature of 50 °C is 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.

Because of its pilot character the operation of the BTES in Brædstrup was not as extensive as in the two plants described before. The monthly amounts of charged and discharged heat as shown in Figure 14 furthermore indicate a decreasing usage of the storage from 2014 to 2016.

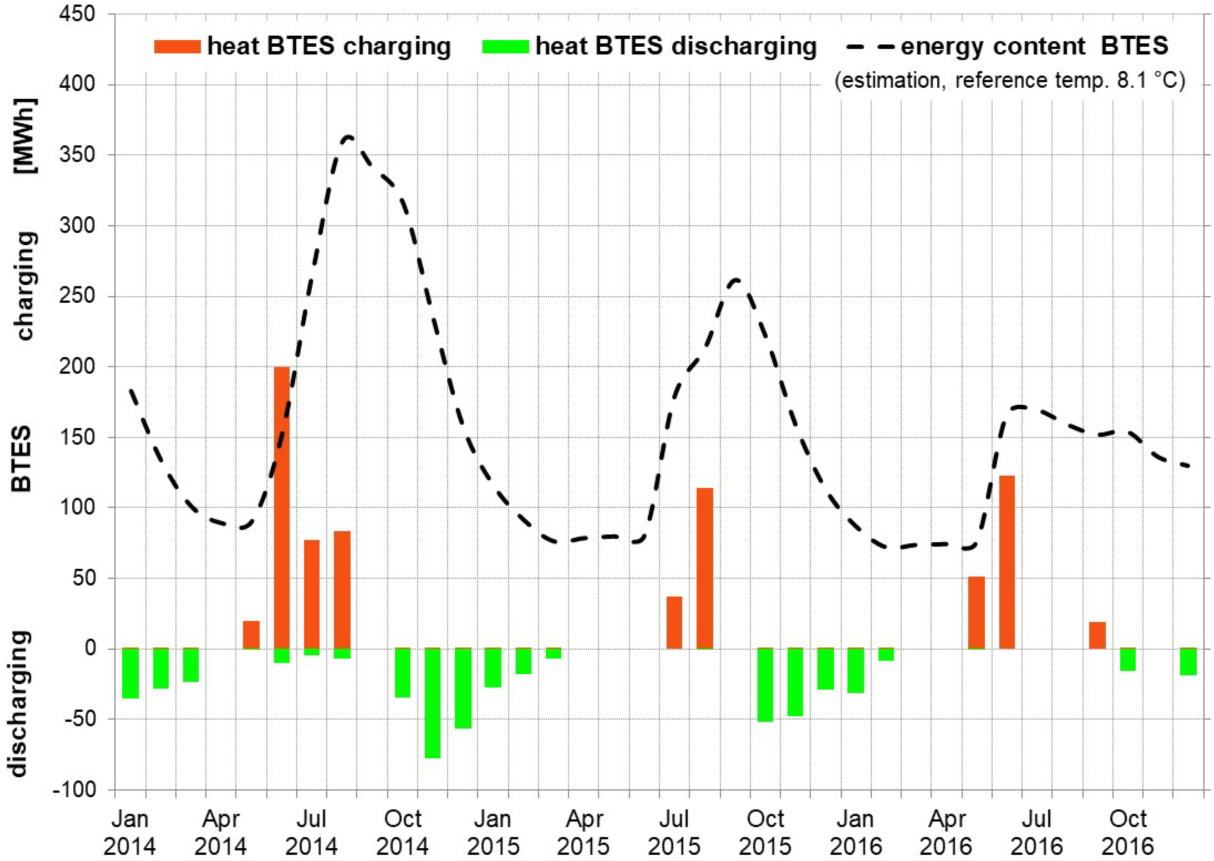

Figure 14: Monthly energy flow diagram according to monitoring data for the BTES in Brædstrup from 2014 to 2016

For observation purposes 100 temperature sensors were installed in the ground between, below and in the surroundings of the borehole heat exchangers, see Figure 15. In each of the five horizontal 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 16 shows the ground temperature development at the central position NDE 505 for the years 2014 to 2016. Inside the storage volume (depths range 0 to 45 m) a rather uniform 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 the two PTES storages, no vertical thermal stratification is existent. The ground area below the storage (-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.

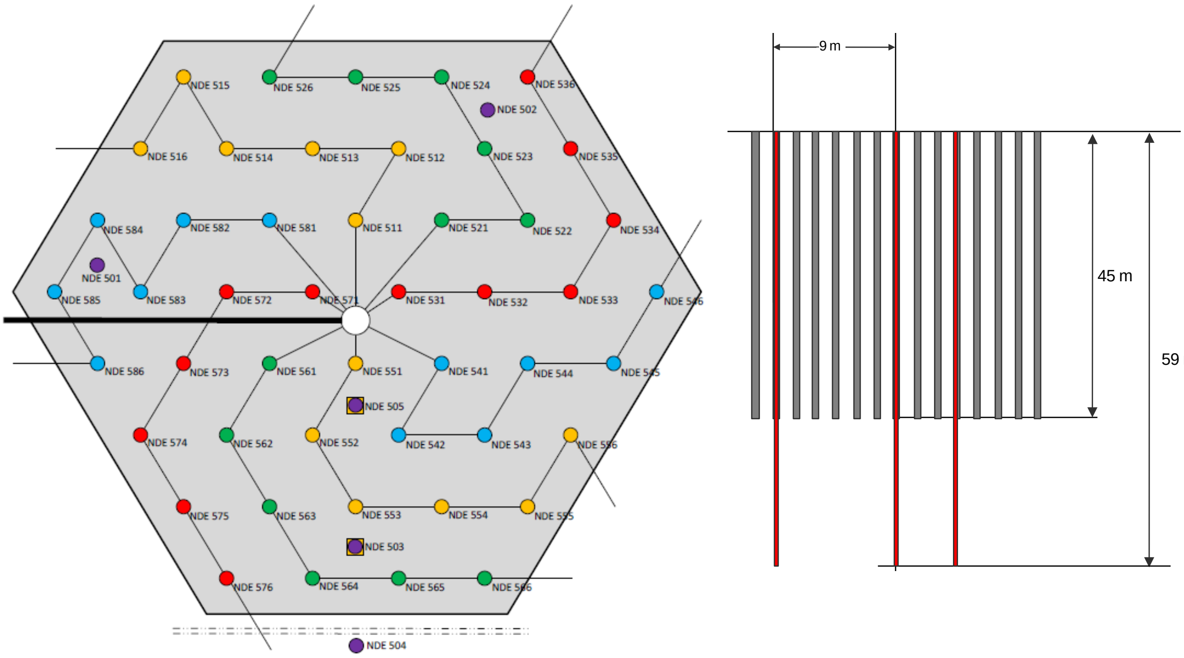

Figure 15: Positions of borehole heat exchangers and temperature sensors inside and outside the Brædstrup BTES (left: top view, NDE 501 to NDE 505: positions of temperature sensors, NDE 504 is located 11 m outside the BTES boundary, right: side view, red lines: positions of temperature sensors, grey lines: borehole heat exchangers, source: (Sørensen et. al 2013))

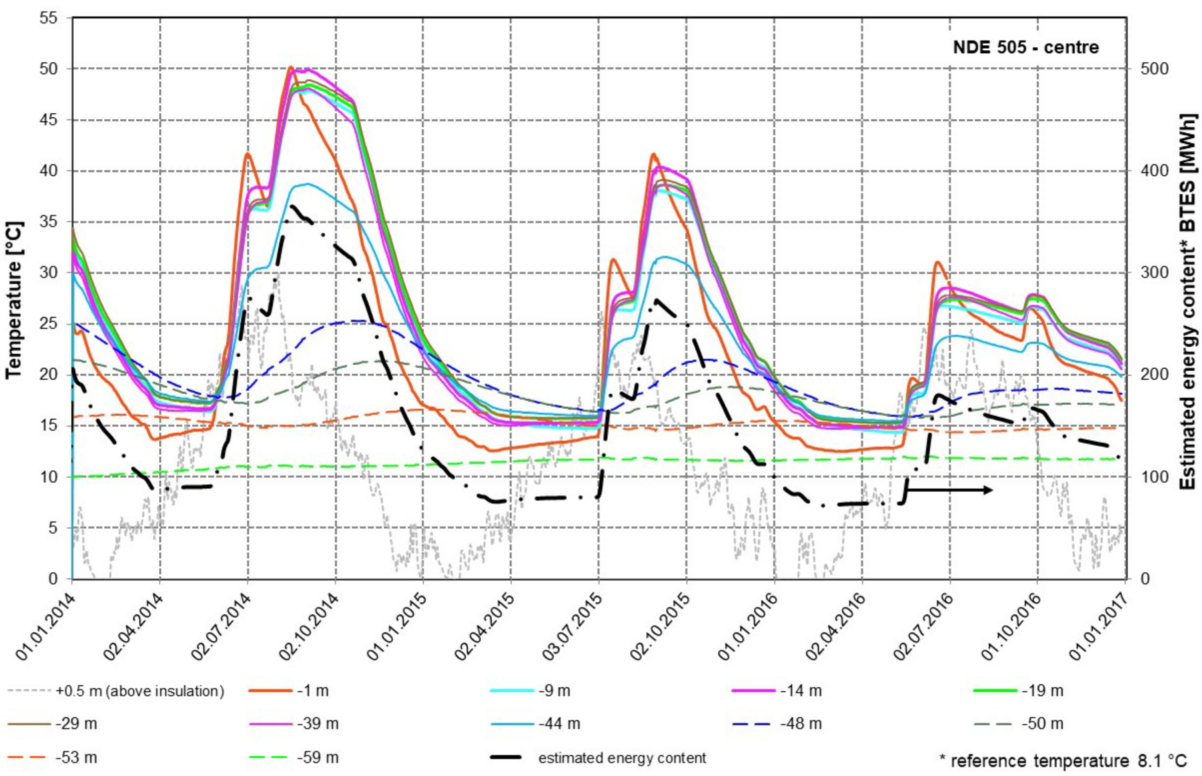

Figure 16: Ground temperature development in the centre of the Brædstrup BTES at position NDE 505 (see Figure 15) from 2014 to 2016, labels give vertical sensor positions below ground surface (0 m corresponds to the bottom of the insulation layer)

Figure 17 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 14.

Figure 18 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 17) but on a lower temperature level. Temperature developments at positions NDE 501 and NDE 502 show a similar behaviour (not illustrated here).

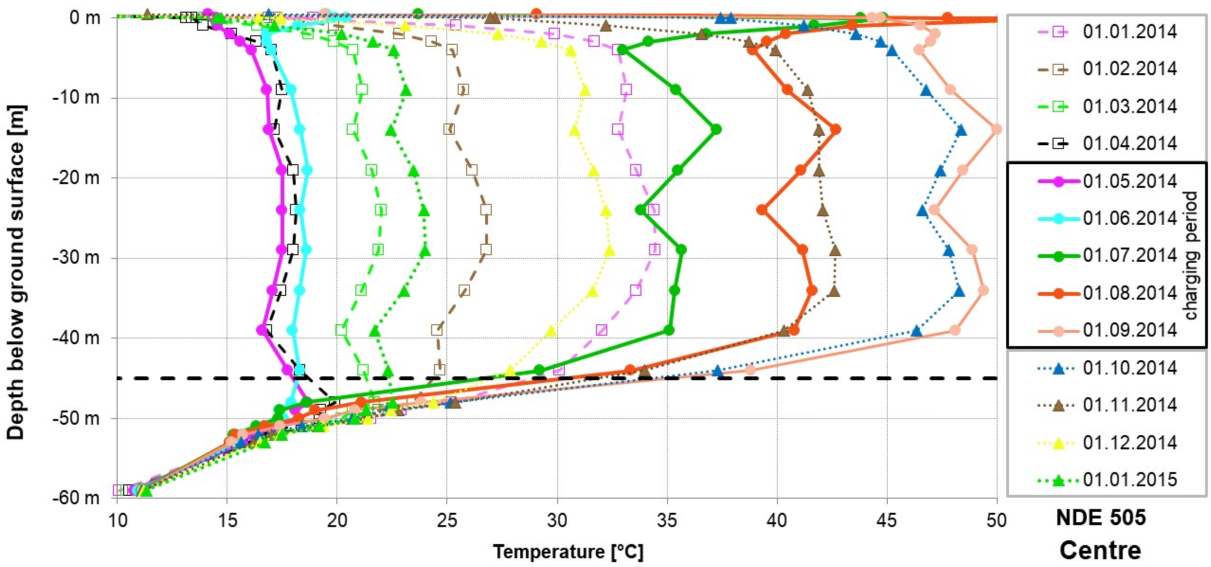

Figure 17: Monthly ground temperature development in the centre of the BTES in Brædstrup at position NDE 505 (see Figure 15) in 2014

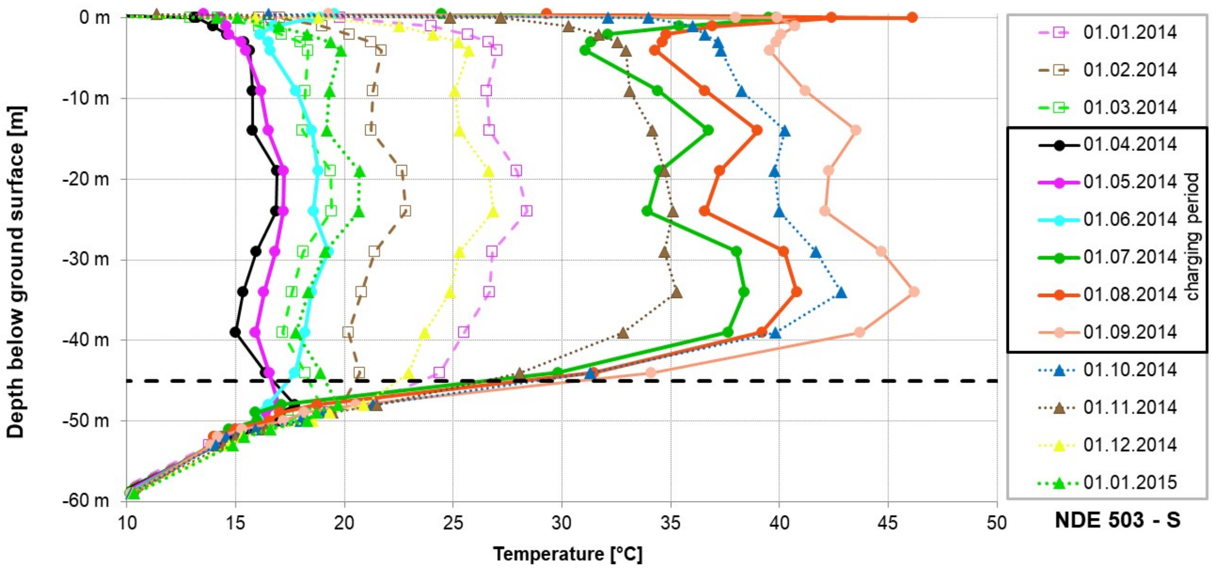

Figure 18: Monthly ground temperature development in the BTES in Brædstrup at position NDE 503 (see Figure 15) in 2014

Figure 19 illustrates the situation outside the storage volume in a distance of 11 m from the most southern 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 16) with a certain time delay.

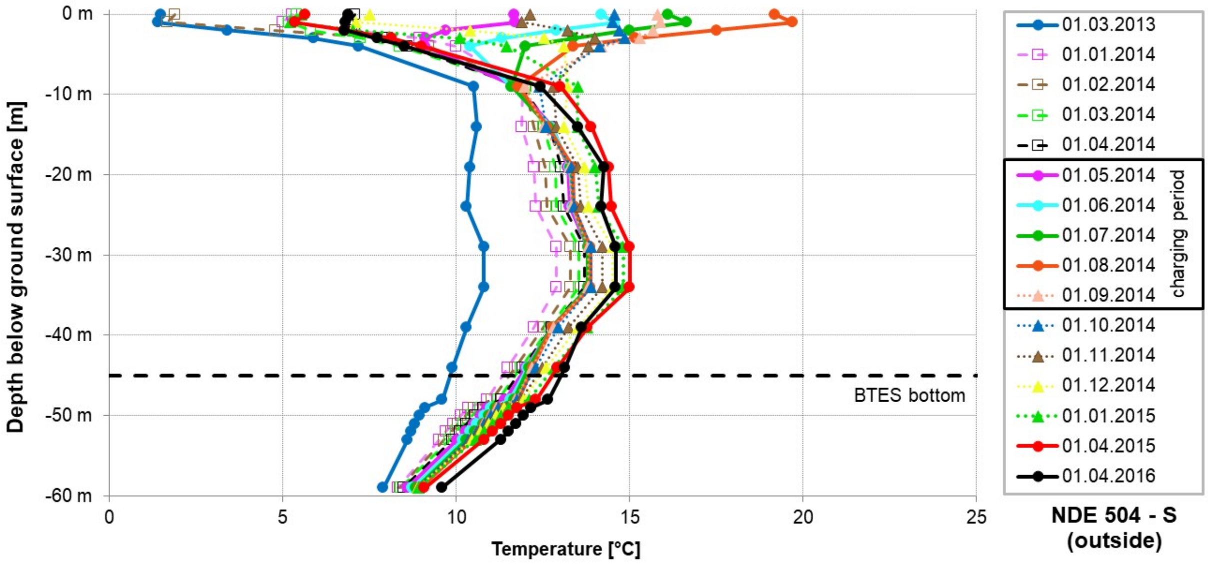

Figure 19: Monthly ground temperature development in the BTES in Brædstrup at position NDE 504 (see Figure 15) in 2014

When comparing Figure 17, Figure 18 and Figure 19, in total a horizontal temperature stratification from the centre to the sides can be identified in the core part of the storage horizon.

6. Conclusions

The Results from the evaluation 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.

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.

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.

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 so far. 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.

Aknowledgement

The R&D work described in this paper was carried out with the support of the European Commission and the Danish Ministry for Climate, Energy and Building through the EUDP program.

The authors gratefully acknowledge this support. Neither the supporting authorities nor the authors are responsible for any use that may be made in the information contained herein.

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