DRONNINGLUND DISTRICT HEATING MONITORING DATA EVALUATION FOR THE YEARS 2015-2017





ON BEHALF OF

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1. INTRODUCTION

This report documents the evaluation of monitoring data for the Dronninglund solar district heating plant for the years 2014-2017. This work was done within the Danish EUDP project "Follow up on large scale heat storages in Denmark" (project no. 64014-0121). Evaluations for the year 2014 can also be found in [Sørensen et.al, 2015].

The report starts with an overview of the overall system heat balance followed by evaluations focused on the parts of the solar system: solar collector fields, thermal energy storage and heat pump. Minor deviations in heat balances are due to rounding, measurement errors or not measured energy flow streams (e.g. thermal losses of storages).

The pit heat storage, the solar collectors were in operation from March 2014 as part of the project "Sunstore 3", supported by the national Danish EUDP-program, see [Sørensen et.al, 2015]. The project enables Dronninglund district heating to deliver heating to the consumers from 70 % renewable energy sources where app. 40 % is solar heat. Figure 1 shows the system concept of the plant.



Figure 1: Hydraulic schematic of the plant in Dronninglund (NG: Natural Gas)

2. MONITORING CONCEPT

This section gives a summary of the monitoring concept for the Dronninglund solar district heating energy system.

2.1. Monitoring sensors

Figure 2 illustrates the positioning of different sensors in the PTES. At position "A", water temperature sensors are installed each 0.5 m vertically to qualify the stratification in the PTES. At position "B", a water level sensor is mounted on top of the diffusor. A heat flux sensor in the middle of the insulation, as well as temperature and humidity sensors above and below the insulation are installed at position "C". Finally, position "D" is the location of the rain water pump.



2. MONITORING CONCEPT



Figure 2: Placement of sensors (source: PlanEnergi)

In addition to the sensors directly in the PTES, four temperature sensors were placed in a depth of 10 m, 15 m, 20 m and 25 m below the water level of the storage on the northern side of the storage. The distance to the storage on water level is between 1 and 2 m. These sensors are used to show the temperature development from the storage to the surrounding soil.



3. SYSTEM HEAT BALANCE

All monitoring sensors are connected to the SCADA¹ system of the plant, all data is stored in a database in 10-minute time steps.

2.2. Evaluation

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

Solar fraction:

$$\mathsf{F}_{\mathsf{Sol}} = \frac{\mathsf{Q}_{\mathsf{Load}} - \mathsf{Q}_{\mathsf{Aux}}}{\mathsf{Q}_{\mathsf{Load}}} = \left(1 - \frac{\mathsf{Q}_{\mathsf{Aux}}}{\mathsf{Q}_{\mathsf{Load}}}\right)$$

Q_{Load}: heat supply to the district heating (DH) network

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

Solar collector field efficiency

$$\eta_{Coll} = \frac{Q_{Coll}}{G_{sol}}$$

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

G_{Sol}: global irradiation in solar collector pane

Storage efficiency

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

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 during the period

No. of storage cycles

 $N_{cyc} = \frac{Q_{STES,out}}{Q_{STES,max}}$

QSTES,max: maximum heat capacity of the STES

3. SYSTEM HEAT BALANCE

Table 1 gives an overview with relevant performance indicators for the years 2015 to 2017 for the solar collector array, the PTES and the heat pump as well as other heat production facilities.

¹ SCADA: Supervisory Control and Data Acquisition

3. SYSTEM HEAT BALANCE

		2015	2016	2017
solar irradation on solar 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
absorption heat pump heat delivery	MWh	10300	9446	12194
heat pump driving heat	MWh	5934	5228	9216
heat pump source heat	MWh	4375	4019	5398
heat from HT ^{**)} bio-oil boiler 5 MW	MWh	10474	10701	14350
heat from bio-oil boiler 10 MW	MWh	2498	1078	209
heat from gas engines 4*1.6 MW _{th}	0.010/1-	8161	11456	8160
heat from natural gas boiler 8 MW	1010011			
heat delivery to the DH network	MWh	35447	37184	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
absorption heat pump COP	-	1.7	1.8	1.6
solar fraction	%	41	38	40

Table 1: Overview of evaluation results for the considered evaluation period in Dronninglund

*) positive values indicate energy increase, negative values indicate energy decrease in the PTES

**) HT: high-temperature

Figure 3 shows the measured results for the year 2017 in a heat flow diagram. Compared to the first two years, 2017 has had less irradiation and therefore lower gains in solar heat, while the consumption remained rather constant. In 2017 a solar fraction of 40 % was reached, which is slightly below the expected design value of 41 %. The energy from the absorption heat pump, which uses heat from the storage as well as from the high temperature bio oil boiler, increased in 2017.

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3. SYSTEM HEAT BALANCE



Figure 3: Heat flow diagram according to monitoring data from 2017 (numbers in MWh; dQ_{STES}: internal energy change in the storage, positive value for energy increase)



Figure 4: Heat flow diagram according to monitoring data from 2016 (numbers in MWh; dQ_{STES}: internal energy change in the storage, positive value for energy increase)



Figure 5: Heat flow diagram according to monitoring data from 2015 (numbers in MWh; dQ_{STES}: internal energy change in the storage, positive value for energy increase)



3. SYSTEM HEAT BALANCE



Figure 6: Heat flow diagram of the Dronninglund design figures

Figure 4 and Figure 5 are the corresponding annual heat flow diagrams to Figure 3, for the years 2016 and 2015. Additionally, Figure 6 illustrates the design figures for the plant. One can see that frost protection was only needed in the year 2016 and that the storage heat losses have decrease from 2015 until 2017.

The following Figure 7, Figure 8 and Figure 9 show the monthly energy productions and consumptions for 2017 to 2015. The consumption is visualized as thin bars in the centre of each thick bar. The consumption is based on the load of the DH network, the energy that is stored in the PTES and the transmission line losses.

The production (thick) bars are set up from the bio oil boilers, heat from gas engines and gas boilers, discharging from the PTES, heat from the solar collectors and if applicable frost protection for the collector field.

When the three figures are compared one can always see the base curve of the solar heat input, mainly in the summer months. The charging of the PTES is to the largest extend in late spring and summer. Production and consumption are usually lower in the late summer months. A clearly visible change in the application of a production facility can only be seen for the bio oil boiler. The production by this boiler has decreased over the three years of monitoring.



3. SYSTEM HEAT BALANCE

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Figure 7: Monthly system heat balance for 2017



Figure 8: Monthly system heat balance for 2016



4. SOLAR COLLECTORS



Figure 9: Monthly system heat balance for 2015

4. SOLAR COLLECTORS

Figure 10 to Figure 12 give an impression of the solar heat production by the solar collector fields in the different years. The production of the two collector fields is stacked on top of each other and the solar irradiation and solar collector field efficiency is shown as connected points. Additionally, the total produced heat and the total area-related produced heat are shown in the top right of the figures.

The solar collector field efficiency is based on the temperatures in the solar heating plant. In winter, at times of lower solar irradiation, higher system temperatures and lower ambient temperatures, the efficiency decreases.

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4. SOLAR COLLECTORS



Figure 10: Solar collector heat production in 2017



Figure 11: Solar collector heat production in 2016

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4. SOLAR COLLECTORS



Figure 12: Solar collector heat production in 2015

In Figure 13 to Figure 15, the temperatures on the water side of the heat exchanger of the first solar collector field can be seen. For the year 2017, one can see that from April to October the solar collectors supplied the temperatures required by the DH network. During the other months, lower temperatures were produced. Two different temperature levels can also be observed for the return temperatures. During the winter months, the water from the bottom of the storage is provided to the solar collectors. In summer by contrast, the DH network return temperature level is used.

Figure 16 and Figure 17 show the daily solar gains as a function of the daily solar irradiation. It is visible that the marks for solar field 1 are on average a little bit more left compared to solar field 2. This means, that solar field 1 has slightly higher gains at the same radiation compared to solar field 2.



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Figure 13: Operating conditions of the solar collector field 1 in 2017 (flow weighted daily mean values at the water side of the solar heat exchanger (HX))



Figure 14: Operating conditions of the solar collector field 1 in 2016 (flow weighted daily mean values at the water side of the solar heat exchanger (HX))

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Figure 15: Operating conditions of the solar collector field 1 in 2015 (flow weighted daily mean values at the water side of the solar heat exchanger (HX))



Figure 16: Heat production of the two solar collector fields as a function of the solar irradiation into corresponding solar collector aperture area per day in 2017



5. PIT THERMAL ENERGY STORAGE



Figure 17: Heat production of the two solar collector fields as a function of the solar irradiation into corresponding solar collector aperture area per day in 2016

5. PIT THERMAL ENERGY STORAGE

5.1. PTES energy balances

The energy balance of the PTES in the year 2017 is presented in Figure 18. Table 1 (column '2017') shows the corresponding key figures that can be calculated from the energy values in Figure 18. 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 of the PTES for the period from 2015 to 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. The only exception are the storage losses, which declined since the beginning. The year 2017 had especially low values for the thermal losses, which can be explained by lower storage temperatures, which also allowed recovering energy from the surrounding soil. Furthermore, a large amount of discharged heat was used by an extensive operation of the heat pump.



5. PIT THERMAL ENERGY STORAGE



Figure 18: Yearly heat balance for the PIT thermal energy storage for 2017 (numbers in MWh; dQ_{STES}: internal energy change in the storage, positive value for energy increase)



Figure 19: Yearly heat balance for the PIT thermal energy storage for 2016 (numbers in MWh; dQ_{STES}: internal energy change in the storage, positive value for energy increase)



Figure 20: Yearly heat balance for the PIT thermal energy storage for 2015 (numbers in MWh; dQ_{STES}: internal energy change in the storage, positive value for energy increase)



Figure 21: Heat balance for the PIT thermal energy storage for the period 2015 to 2017 (numbers in MWh; dQ_{STES}: internal energy change in the storage, positive value for energy increase)



5. PIT THERMAL ENERGY STORAGE

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 26. 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 1, 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 1).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 shows, that in 2016 the lower part of the storage had temperatures below 15 °C for about 940 hours, whereas in 2017 the duration was higher 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. Negative heat losses cannot be confirmed directly from the monitoring data, as no suitable monitoring sensors for this are available, but have been verified in a recent simulation study that was done for the Dronninglund PTES based on monitoring data for 2015.

Figure 22 shows the monthly heat amounts that were charged into and discharged from the PTES since start of operation in 2014 until 2017. It can be seen that besides the seasonal storage process from summer to winter the storage is also used for short-term storage processes in the summer period. 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.



5. PIT THERMAL ENERGY STORAGE



Figure 22: Monthly overview of charging and discharging of the PTES in Dronninglund from 2014 - 2017

5.2. PTES temperature development

The temperature development inside the storage volume can be seen in Figure 23 for the year 2017. Similarly, the behaviour of the storage can be observed since start of storage operation in Figure 24. Generally, the maximum temperatures at the top of the storage in summer are a little higher than 85 °C, minimum temperatures go down to 10 – 15 °C at the bottom. The minimum temperature at the top is around 20 °C 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. During 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.



5. PIT THERMAL ENERGY STORAGE



Figure 23: Temperature distribution in the PTES during the year 2017



Figure 24: Temperature distribution and energy content in the PTES from 2014 to 2017

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5. PIT THERMAL ENERGY STORAGE

Figure 25 shows the water temperatures in the PTES depending on the depth for each month in 2017. (The temperature can be read out depending on the depth below the 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 follow at a later point. One can also see that the temperatures in the bottom are higher in summer and autumn than in spring and winter. The largest stratification in the storage can be seen in April and May with more than 50 K.



Figure 25: Water temperature development in the PTES in 2017 (measured on the 15th day of each month)

Four sensors at different depths measure the ground temperatures outside the storage. Figure 26 shows a graph with the temperatures since the beginning of the PTES operation. One can see the influence of depth by the variance of the temperatures throughout the seasons. The lower sensors measure rather steady temperatures, which are slowly increasing. Since the beginning of operation, the temperatures in a depth of 20 m and 25 m have risen about 2 to 3 K. The temperatures at 10 m and 15 m depth have increased more than 5 K between the start of measurement and their collapse in 2016 and 2017. Clearly visible in the upper temperature developments are seasonal changes.



5. PIT THERMAL ENERGY STORAGE



Figure 26: Temperature measurements in the ground in a distance of about 1-2 m to the storage water surface centrally on the northern side of the storage



Figure 27: Temperature and heat flux in the storage lid in 2016 and 2017



Figure 27 visualizes measurements from sensors at a central position in the PTES lid. For this location the inside and outside temperatures in the insulated floating lid are measured. Additionally, the heat flux and the humidity in the lid insulation are measured. When comparing the year 2016 and 2017, one can see lower maximum temperatures in 2017 and a lower cover heat flux, especially during autumn time.

6. HEAT PUMP

The following three graphs show the performance of the absorption heat pump from 2015 to 2017. The total heat production found its maximum in 2017 with 14,852 MWh, which is considerable higher than in the previous years where it has been around 10,000 MWh. The heat pump is used to extract heat from the storage, when the temperature is too low for direct use. Therefore, the main operation of the heat pump is in winter and spring.



Figure 28: Monthly heat balance of the heat pump in 2017





6. HEAT PUMP



Figure 29: Monthly heat balance of the heat pump in 2016



Figure 30: Monthly heat balance of the heat pump in 2015



Figure 31 to Figure 33 show the temperatures and the COPs of the heat pump for the years 2015 to 2017. As the COP is highly influenced by the temperature difference that has to be overcome, a larger temperature lift results in a lower COP. In Figure 31 this is clearly visible in the beginning of 2017. The decrease of the source side temperature of the heat pump, combined with the temperature increase on the condenser side leads to a drop in the COPs. In all three figures, the summer time without operation can be seen as a gap of operation points. In Figure 31 one can also observe a higher source temperature in April, which is caused by the increase in storage temperatures.



Figure 31: Heat pump operation conditions (weighted daily mean values) of the year 2017





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7. SUMMARY

7. SUMMARY

The results from the monitoring data evaluations of the large-scale pit thermal energy storage in Dronninglund prove the efficiency and reliability of the storage technology. The results show good agreements with the design figures in terms of storage efficiency, usable temperature ranges and contribution to the heat supply of the connected district heating networks. Deviations are explainable by different operational conditions or other site specific effects. The evaluated solar fractions are according to design expectations. The losses of the storage turned out to be lower than expected for all years. One positive impact in this sense are the low temperatures in the storage in the winter period, which result in negative thermal losses in the bottom parts of the storage.

These low temperatures were only possible due to the operation of the heat pump. This allows a nameable increase of the usable temperature differences of the storage and therefore smaller storage volumes are required compared to systems without heat pumps. In Dronninglund the temperatures in the bottom of the storage were about 10 °C in winter and spring, which means below the soil temperatures in that region. The highest temperatures decreased from 89 °C in 2015 to 84 °C in 2017. As the majority of heat losses occur at the top of the storage, this reduction has also had a positive impact on the storage losses.

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