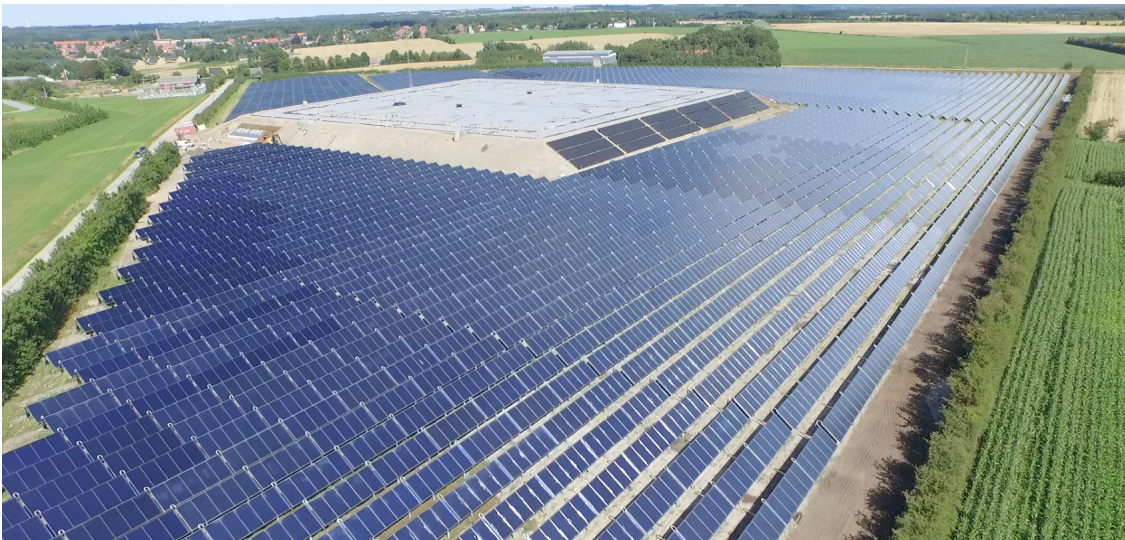


GRAM DISTRICT HEATING MONITORING DATA EVALUATION FOR THE YEARS 2016-2017



ON BEHALF OF

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Cover photo: source Gram Fjernvarme

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GRAM MONITORING DATA EVALUATION 2016-2017

TABLE OF CONTENTS

1. Introduction.....	1
2. Monitoring concept.....	1
3. System heat balance.....	3
4. Solar collectors.....	7
5. PIT Thermal Energy Storage	10
6. Heat pump.....	12
7. Summary.....	15
8. References	16
9. Additional sources of information	16
10. Annex 1: Monthly PTES ground temperature development.....	17
11. Annex 2: Storage water level and PH-level	18

1. INTRODUCTION

This report documents the evaluation of the monitoring data for the Gram solar district heating plant for the years 2016 and 2017. This work was done within the Danish EUDP2015 project “Follow up on large scale heat storages in Denmark, Gram” (project no. 64015-0567).

The report starts with an overview of the overall system heat balance followed by evaluations focused on the renewable parts of the system: solar collector fields, pit 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 following figure shows the hydraulic schematic of the heat supplying facilities in Gram. On the left side, the pit storage is visible, followed by three collector fields, which are separated from the pit storage circuit by heat exchangers. Another heat exchanger separates the storage circuit from the main system. A buffer storage tank and additional heat producers are integrated: a heat pump, a gas engine, a gas boiler, a combined gas and oil boiler, an electric boiler and excess heat from a carpet factory. On the right end, the district heating network is symbolized.

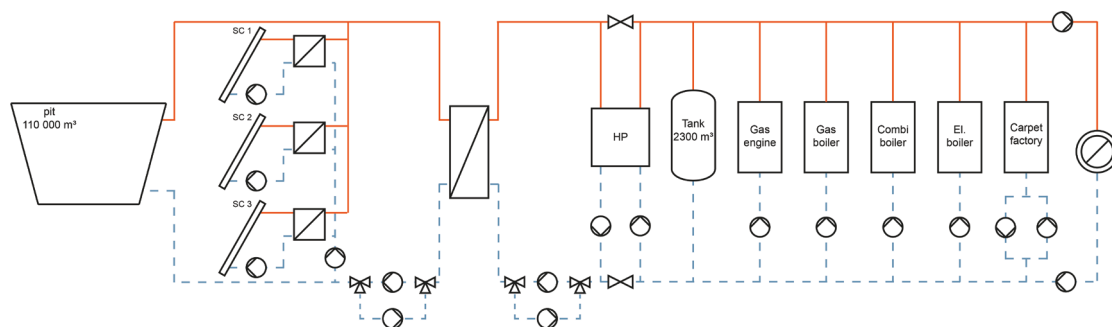


Fig. 1: Schematic of the production facilities at the SDH plant in Gram (SC: Solar Collectors; HP: Heat Pump)

2. MONITORING CONCEPT

This section gives a summary of the monitoring concept for the Gram Fjernvarme energy system. Fig. 2 shows an overview of monitoring sensors available in the system.

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

¹ SCADA: Supervisory Control and Data Acquisition

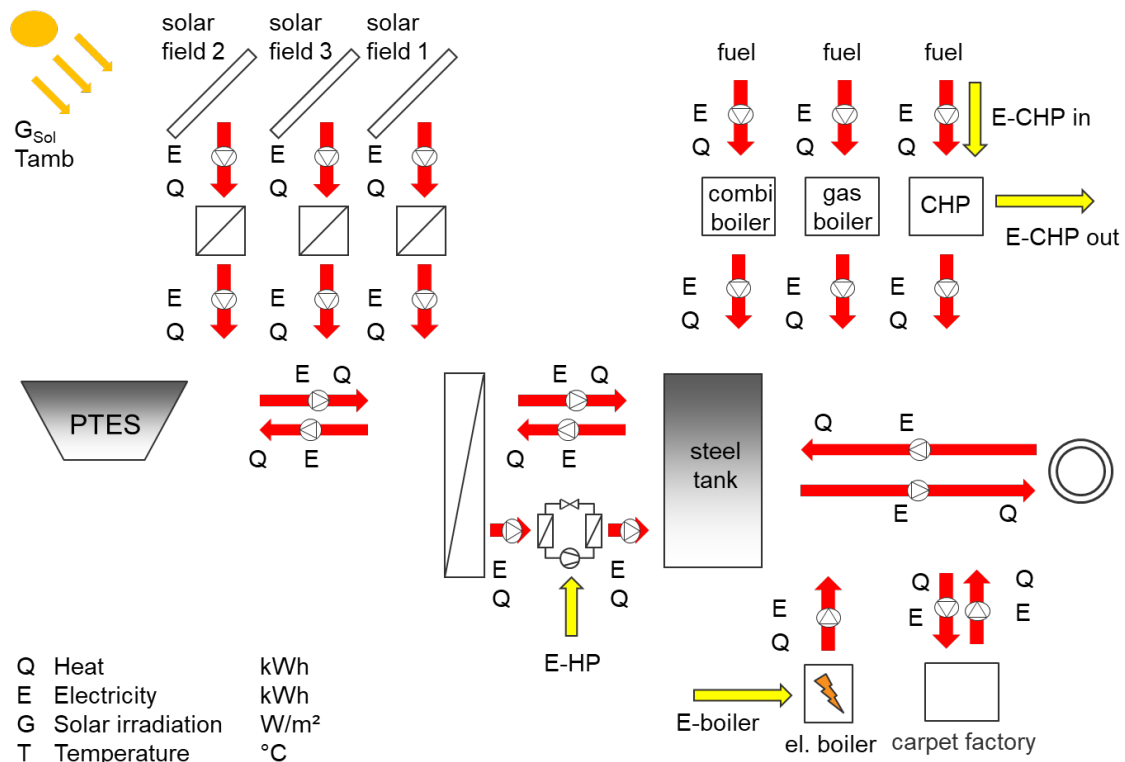


Fig. 2: Monitoring concept of the SDH plant in Gram

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

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

G_{Sol} : global irradiation in solar collector pane

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

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

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

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

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

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

3. SYSTEM HEAT BALANCE

In this chapter, the key performance indicators for the plant are presented. Furthermore, the system energy balances will be shown and elaborated for the two years of measurement.

Table 1 shows the major energy values for the plant and the key performance indicators for the two years of measurement and analysis. One can see a decrease of the solar fraction from 42 % to 37 %. This can be explained by less energy input from the collector field in comparison to the first year. Therefore, also the charging and discharging of the storage decreased, which in turn results in a lower number of storage cycles. The lowered temperatures in the storage can by contrast be seen as an improvement, because it explains lower losses.

Fig. 3 shows the yearly heat balance of the entire system for 2016. About 27.3 GWh of heat were delivered to the district heating (DH) network. The calculated solar fraction in that period is 42 %. 4 % of the heat was produced as surplus heat from two gas engines, 37 % were produced by two natural gas boilers. The electrical boiler was responsible for 15 % and the electricity demand of the heat pump accounted for 2 % of the total heat delivery. The energy from the collector arrays is either used directly (in 2016 it was 2920 MWh) or fed into the PTES. From the storage heat may be used as direct feed-in to the DH network or be used as source heat for the heat pump. The internal energy change of the PTES is the difference between the energy content of the storage at the end of the year compared to the beginning of the year.

GRAM MONITORING DATA EVALUATION 2016-2017

3. SYSTEM HEAT BALANCE

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

		2016	2017
solar irradiation on solar collectors	MWh	50943	48905
heat from solar collectors	MWh	18120	16041
heat charged into PTES	MWh	15200	12997
heat discharged from PTES	MWh	7946	5951
PTES internal energy change ^{*)}	MWh	-397	583
PTES thermal losses	MWh	7650	6463
heat pump heat delivery	MWh	2726	2614
heat pump electricity demand	MWh	564	531
heat from natural gas CHP engine	MWh	1052	125
heat from natural gas boiler	MWh	10112	10460
heat from combi boiler	MWh	61	138
heat from electrical boiler	MWh	4074	6132
heat from carpet factory	MWh	Unknown	932
heat delivery to DH	MWh	27352	27617
key performance indicators			
solar collector field efficiency	%	36	33
PTES storage efficiency	%	50	50
PTES no. of storage cycles	-	0.9	0.7
PTES maximum temperature	°C	84	79
PTES minimum temperature	°C	23	21
PTES used heat capacity	MWh	8628	8126
heat pump COP	-	4.8	4.9
solar fraction	%	42	37
aperture area-related solar heat production	kWh/(m ² *a)	404	358

^{*)} Positive values indicate energy increase, negative values indicate energy decrease in the PTES

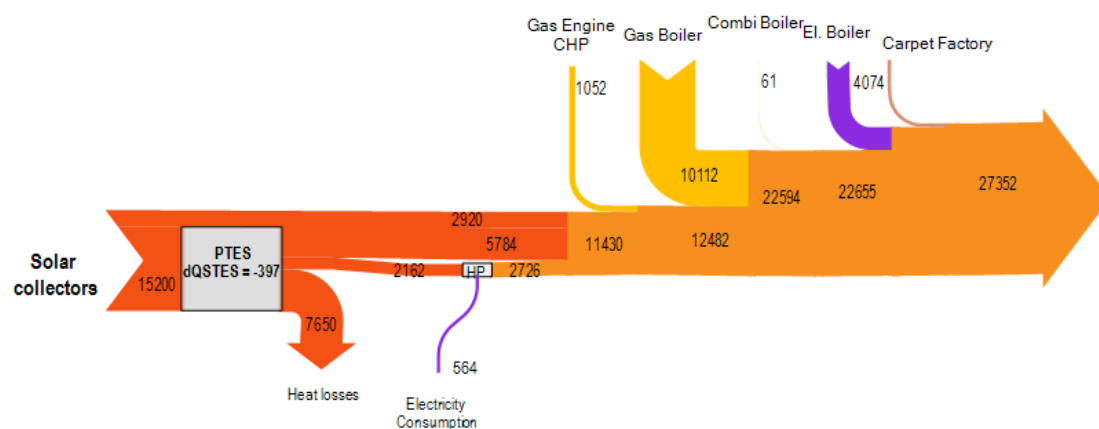


Fig. 3: Heat flow diagram according to monitoring data for 2016 (numbers in MWh; dQ_{STES}: internal energy change in the storage, positive value for energy increase)

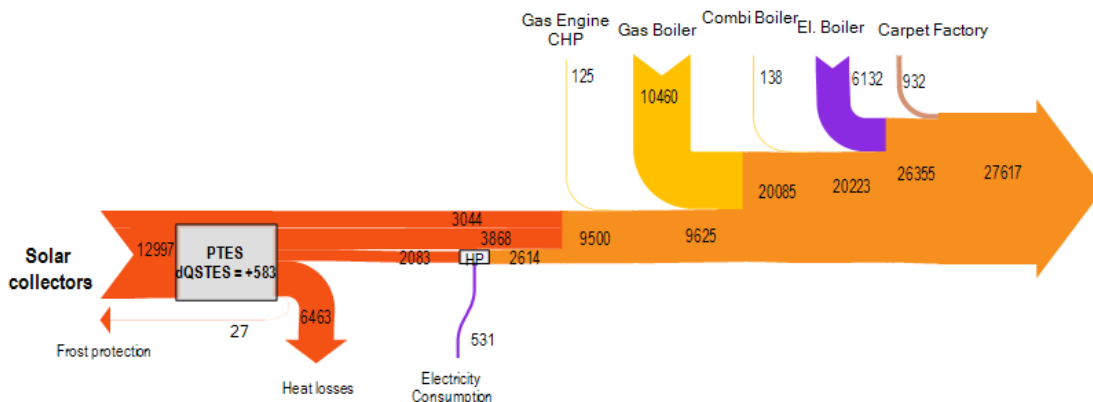


Fig. 4: Heat flow diagram according to monitoring data for 2017 (numbers in MWh; dQ_{STES} : internal energy change in the storage, positive value for energy increase)

Fig. 4 shows the corresponding figure for the year 2017. In that year the solar fraction is 37 %. In 2017, 27 MWh were used for frost protection of the collector arrays. The internal energy increased in contrast to the year 2016 by 583 MWh. The losses of the PTES were with about 6463 MWh slightly lower than in the year before. The energy that was used for the heat pump remained with 2083 MWh nearly as much as in 2016. The amount of energy that was used directly from the storage for the DH network decreased from 5784 MWh to 3868 MWh. The energy that was used from the collectors directly for the DH system remained with about 3000 MWh quite steady. The gas engine CHP usage reduced drastically from 2016 to 2017. While it was 1052 MWh in the first year, it decreased to 125 MWh in the second year. The natural gas boiler and the combi boiler remained rather steady in their annual energy supply. They accounted for about 10000 MWh in case of the gas boiler and about 100 MWh in case of the combi boiler. The electricity consumed for direct heating increased by 2058 MWh from 4074 MWh to 6132 MWh. In 2017, data was also received for the excess heat from a carpet factory. It accounted for 932 MWh of supplied heat in 2017.

In Fig. 5, the monthly heat balance of the overall system is illustrated for the year 2016. The same data is visualized for the year 2017 in Fig. 6. The narrow bars in the front show the heat consumption as well as the charging of the storage. The wide bars in the background represent the different heat producers as well as discharging of storages. Differences in the heat balances may appear due to errors or gaps in the sensor measurement or thermal losses, which are not measured.

In both figures it is visible, that the heat supplied by the collector arrays is largest in summer and is used for charging the PTES and for direct supply of the DH network. The storage is discharged throughout the year, but to a larger extend in autumn. This is especially visible in a large discharge from the PTES in October 2016. During the winter months, the natural gas boiler and the electrical boiler supply the majority of the consumed heat. It has to be remarked, that the CHP engine is used in 2016 during the winter months, but hardly in the year after, in 2017.

GRAM MONITORING DATA EVALUATION 2016-2017

3. SYSTEM HEAT BALANCE

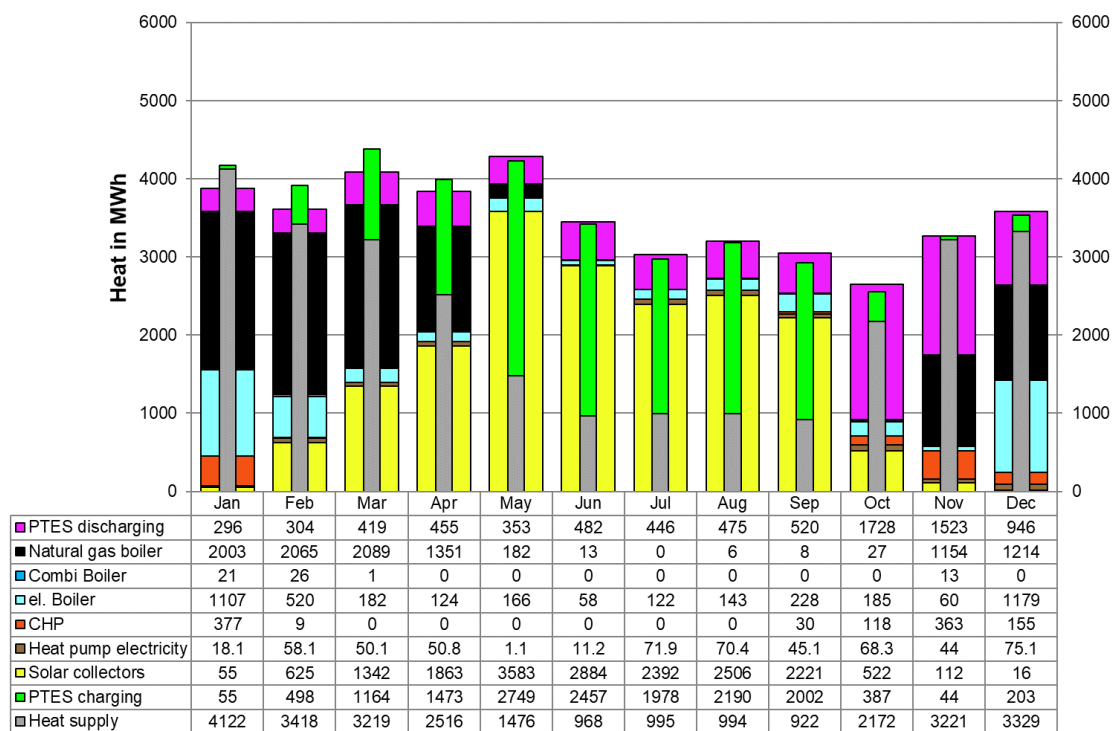


Fig. 5: Monthly system heat balance for 2016

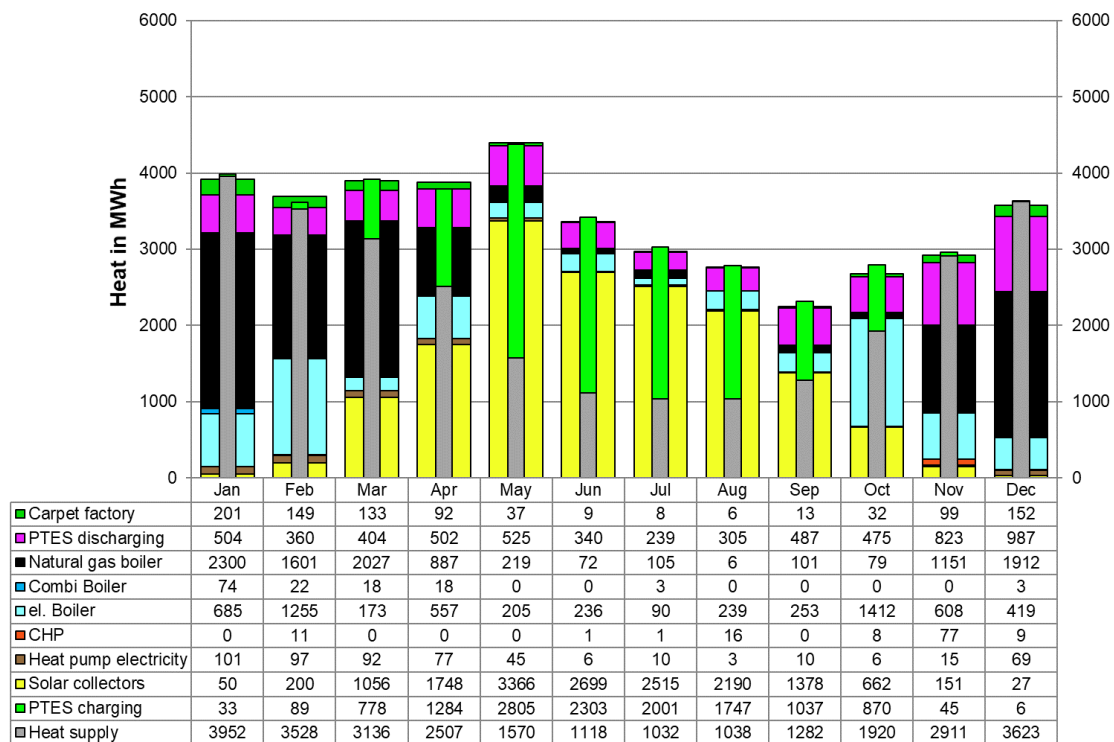


Fig. 6: Monthly system heat balance for 2017

Fig. 7 exemplarily visualizes the DH network temperatures and the load development for the year 2017.

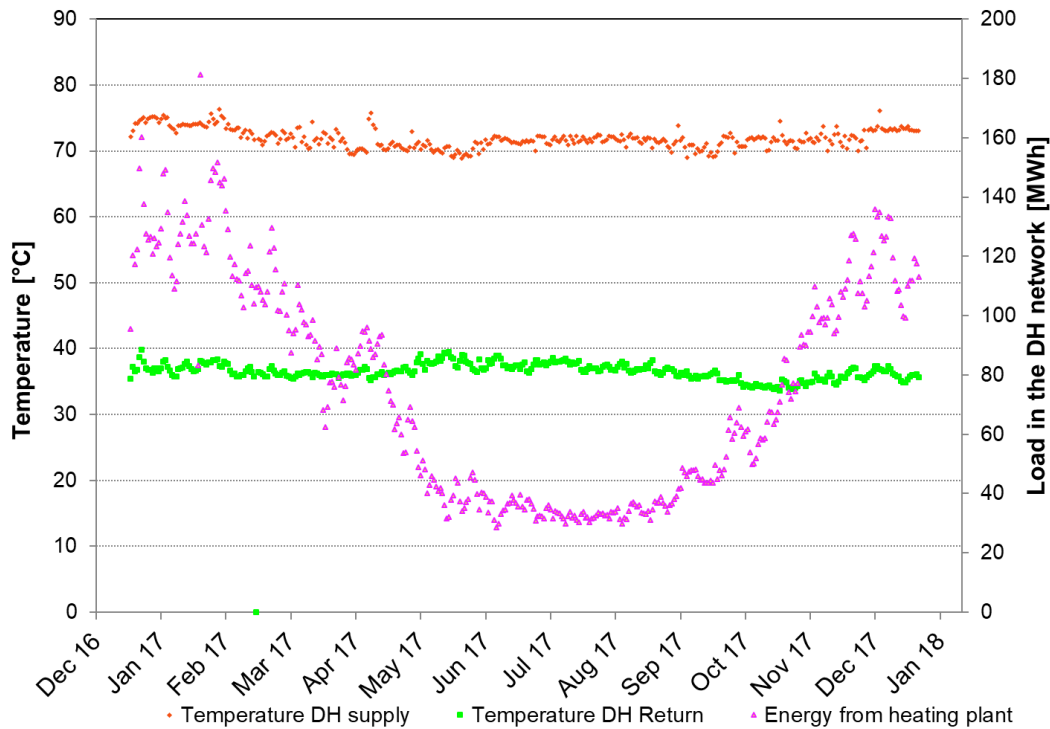


Fig. 7: Temperatures and load of the DH network in 2017 (daily values)

4. SOLAR COLLECTORS

Fig. 8 presents the heat production of the solar collector fields in 2016. In total 18120 MWh of heat were delivered to the system in 2016. The heat production per m^2 of solar collector aperture area was $404 \text{ kWh}/(\text{m}^2_{\text{aperture}} \cdot \text{a})$. Due to worse weather in 2017, the yield has reduced to 16041 MWh. Specifically, this results in $358 \text{ kWh}/(\text{m}^2_{\text{aperture}} \cdot \text{a})$. The line together with the second y-axis shows the measured radiation per m^2 per month. It can be seen that the yield of the collector arrays corresponds to the solar radiation per month. Furthermore, a lower yield of the collector field 1 can be spotted in both years. The lower yield is based on the smaller collector area of the older collector field 1.

Fig. 10 and Fig. 11 show on the primary axis the solar heat production in MWh/day as a function of the irradiation on the solar collector field in MWh/day. The secondary axis is used to show the daily solar collector field efficiency, again depending on the irradiation on the collector field. It is in both years visible, that collector field 1 experiences lower radiation, due to its smaller size. When comparing the two years one can also realize that the measurement points in the year 2016 have fewer extremes.

GRAM MONITORING DATA EVALUATION 2016-2017

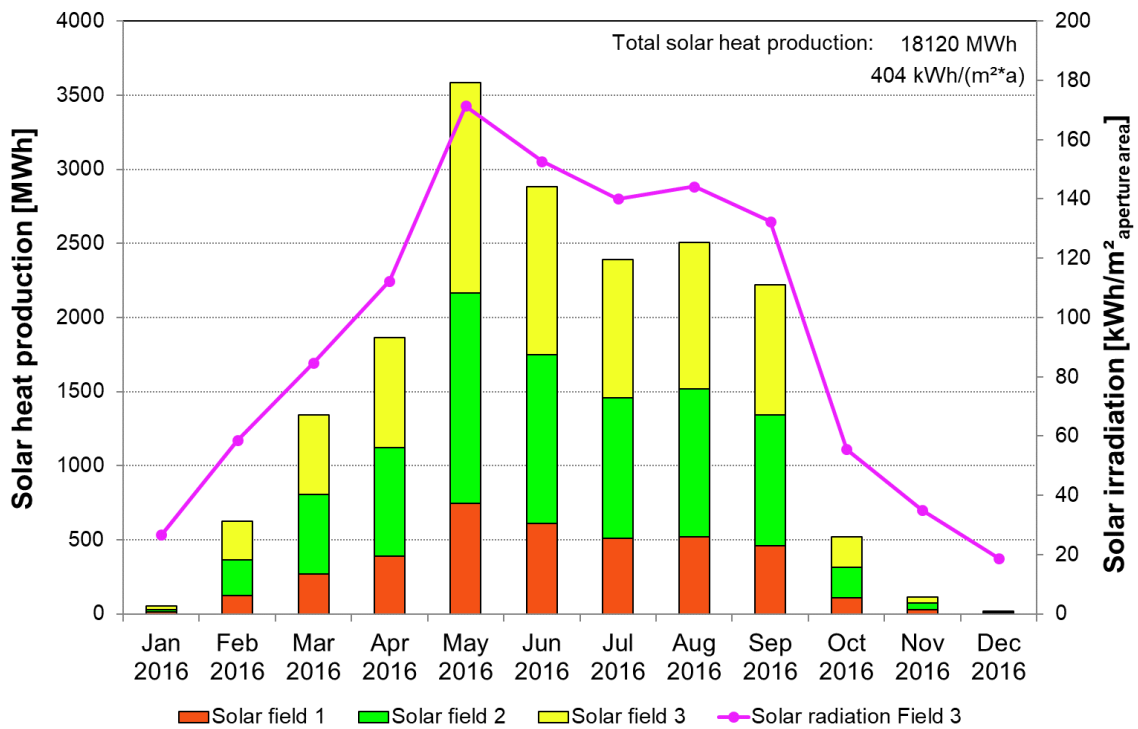


Fig. 8: Solar collector heat production in 2016

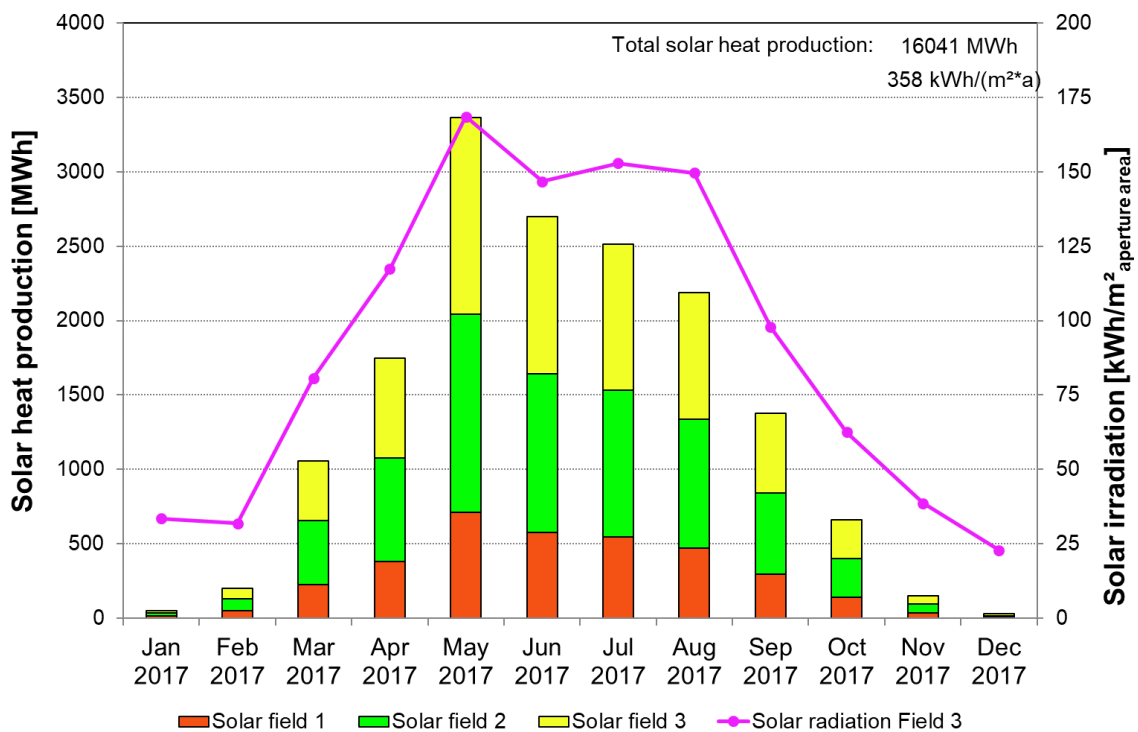


Fig. 9: Solar collector heat production in 2017

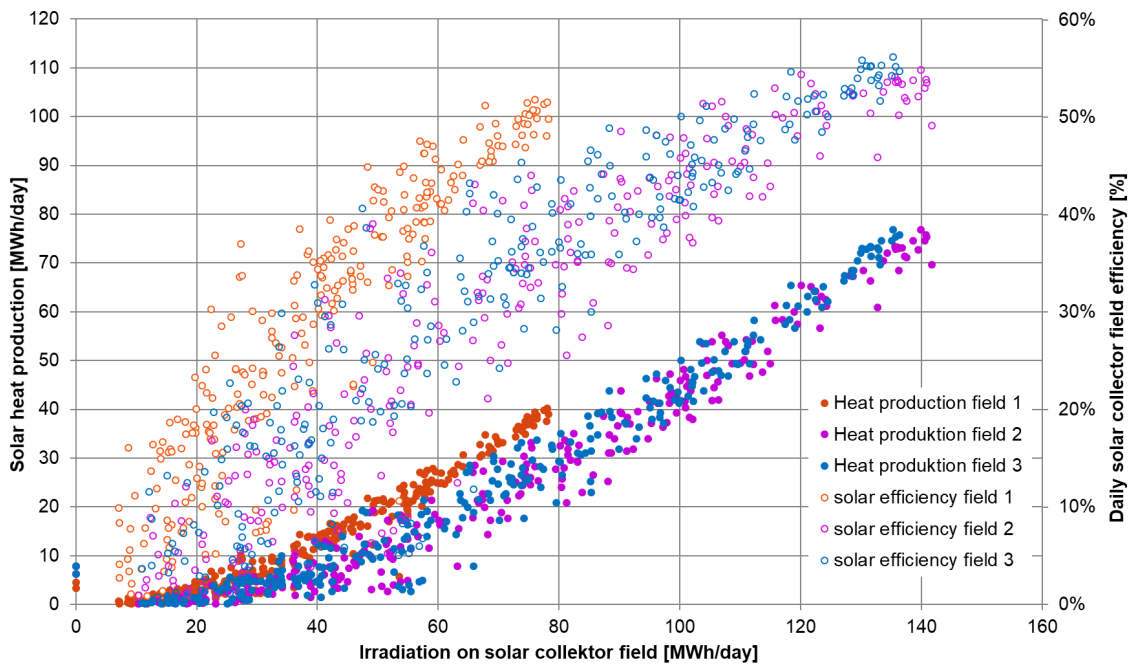


Fig. 10: Heat production and daily solar collector field efficiency of the three solar collector fields as a function of the solar irradiation on the corresponding solar collector area in 2016.

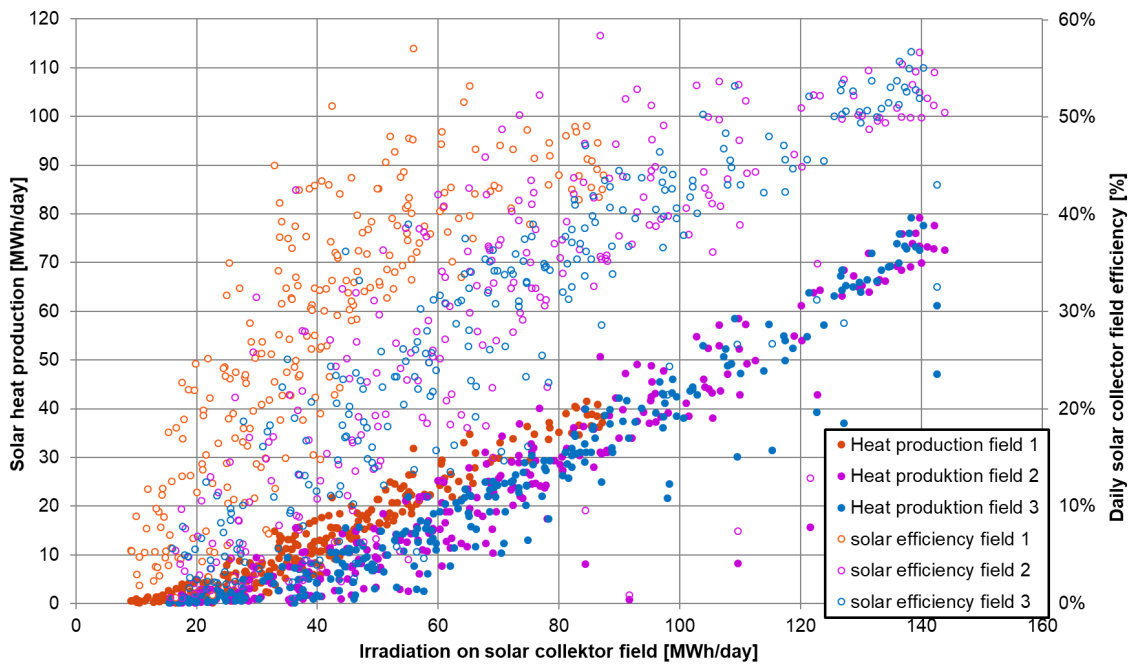


Fig. 11: Heat production and daily solar collector field efficiency of the three solar collector fields as a function of the solar irradiation on the corresponding solar collector area in 2017.

5. PIT THERMAL ENERGY STORAGE

Fig. 12 and Fig. 13 show the heat flow diagrams for the pit storage in the years 2016 and 2017 respectively. Due to the lower solar yield of the collectors in 2017 the PTES was also charged less in the year 2017 compared to 2016. The energy discharged to the heat pump remained in both years steady at about 2100 MWh. The heat pump was used when the storage temperature level was not sufficiently high and electricity prices were moderate enough for operation. The energy discharged directly to the DH network reduced from about 5800 MWh in 2016 to about 3900 MWh in 2017. The internal energy of the storage decreased in 2016 whereas it increased in 2017. It is calculated based on the vertical temperature distribution inside the storage. The storage losses decreased slightly from 7650 MWh in 2016 to 6463 MWh in 2017. The losses are calculated based on an annual balance, comparing the amount of charged and discharged heat taking into account the internal energy change.

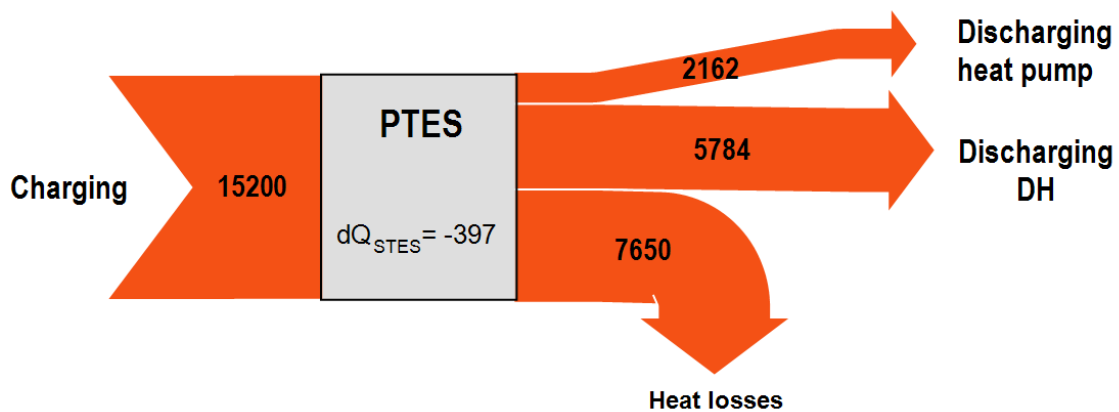


Fig. 12: Heat flow diagram for the PTES in the year 2016 (numbers in MWh; dQ_{STES} : internal energy change in the storage, negative value for energy decrease)

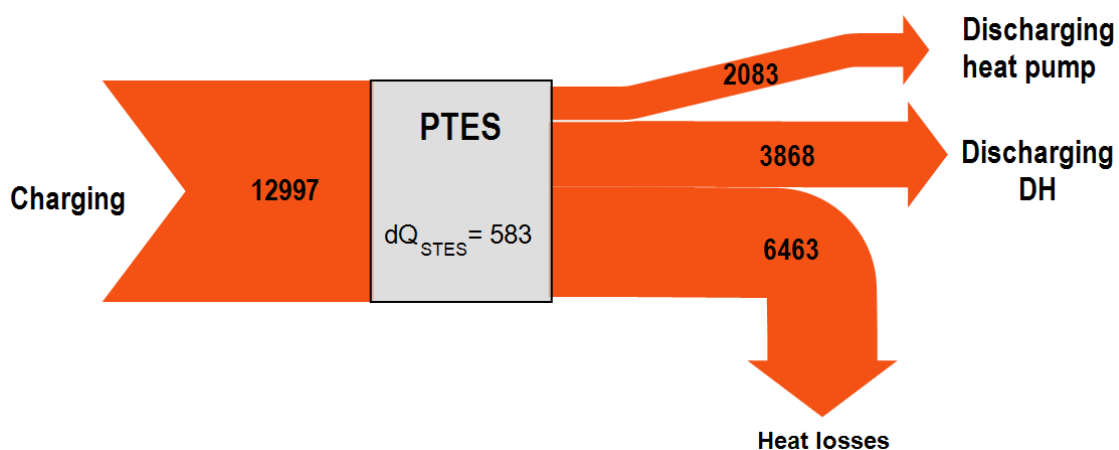


Fig. 13: Heat flow diagram for the PTES in the year 2017 (numbers in MWh; dQ_{STES} : internal energy change in the storage, positive value for energy increase)

The evaluated storage efficiency was 50 % in 2016 and 2017, see Table 1. A storage cycle number of 0.7 indicates that the heat capacity of the storage was not used to its full extend in 2017. This shows a purely seasonal operation. This can also be seen in the monthly charged and discharged amounts of heat presented in Fig. 14. The main charging processes are in summer and the main discharging processes in winter. As the storage temperatures are high in summer, it can additionally serve as a short term storage, which explains the discharge also during summer. According to the charged and discharged amounts of heat, the energy content of the storage is illustrated as a dashed line.

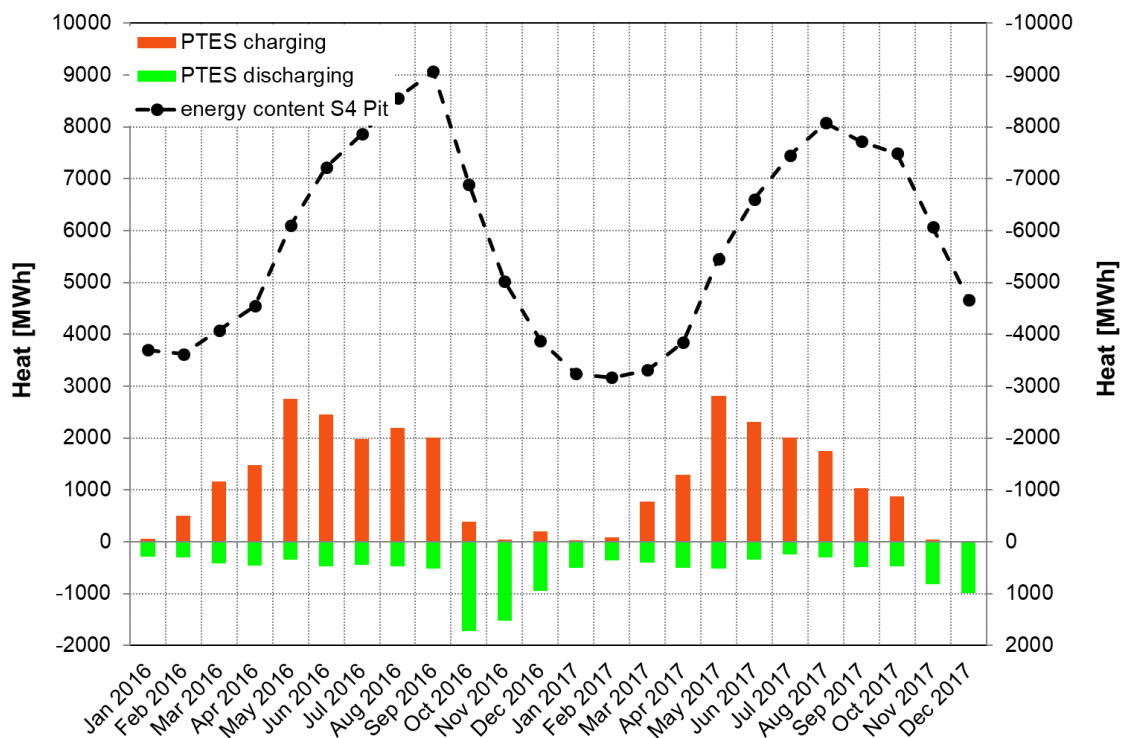


Fig. 14: Monthly heat balance for the Gram PTES for 2016 and 2017

PTES GROUND TEMPERATURES

The PTES is equipped with a range of sensors to monitor the temperatures in different horizontal layers. Fig. 15 shows the years 2016 and 2017 with the temperature levels in different depths on the primary axis and the energy content on the secondary axis. The temperatures in the upper layer close to the lid are always highest and are varying to a larger extend. In addition, the temperatures in the bottom of the storage are fluctuating faster due to the inlet of water. Minimum temperatures in February are around 40 °C at the top of the storage and 20 to 25 °C at the bottom. Maximum temperatures in September reached about 85 °C at the top and around 65 °C at the bottom in 2016. In 2017, the temperatures in summer were somewhat lower. The highest thermal stratification that means the largest temperature differences between the top and the

bottom of the storage, of around 40 K can be seen in spring and autumn. The development of the thermal stratification throughout the years is visible more clearly in Fig. 20 and Fig. 21 in Annex 1.

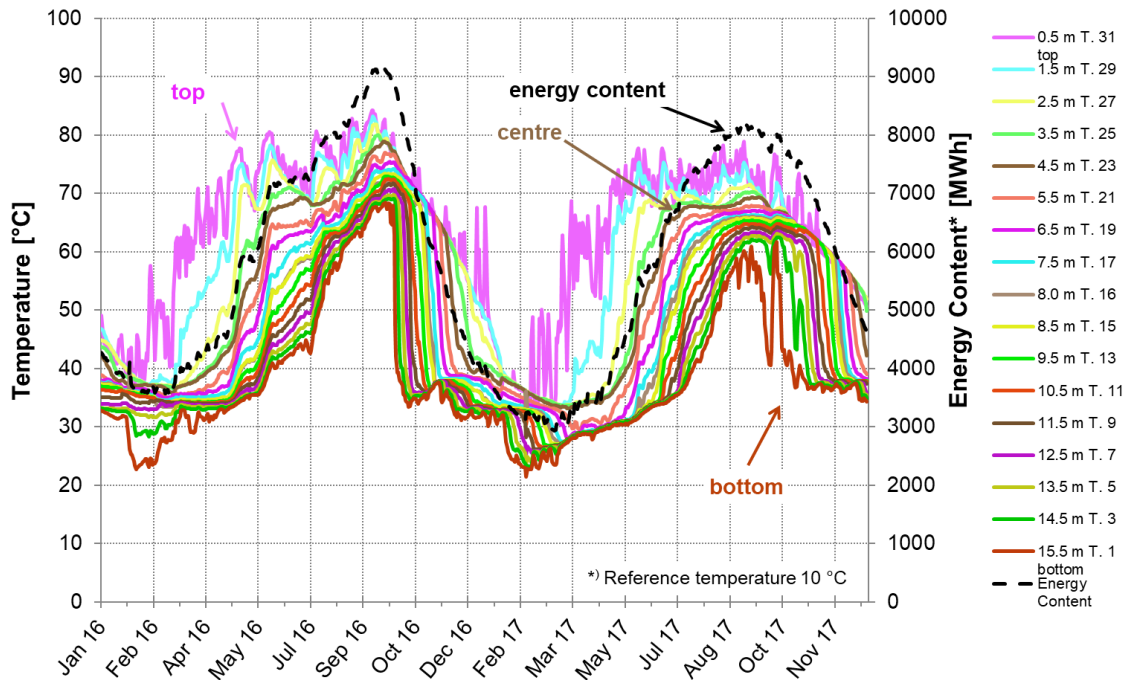


Fig. 15: Recorded temperatures at different depth below the water surface in the PTES.

6. HEAT PUMP

In Fig. 16 and Fig. 17, the monthly heat balance for the heat pump can be seen. In 2016 the annual COP was 4.8 and 2726 MWh of condenser heat were supplied to the system. A clear operation trend in 2016 is not visible. In 2017 by contrast, the heat pump operated to a large extent in the heating period in spring. The operation hours decline until summer and remain low until they rise again in November and December. The discharge of the storage by the heat pump in November and December can be explained by lower PTES temperatures, which are not sufficient for direct use in the DH network. In 2017 the COP increased to 4.9 but the overall energy supplied to the system decreased slightly to 2614 MWh.

GRAM MONITORING DATA EVALUATION 2016-2017

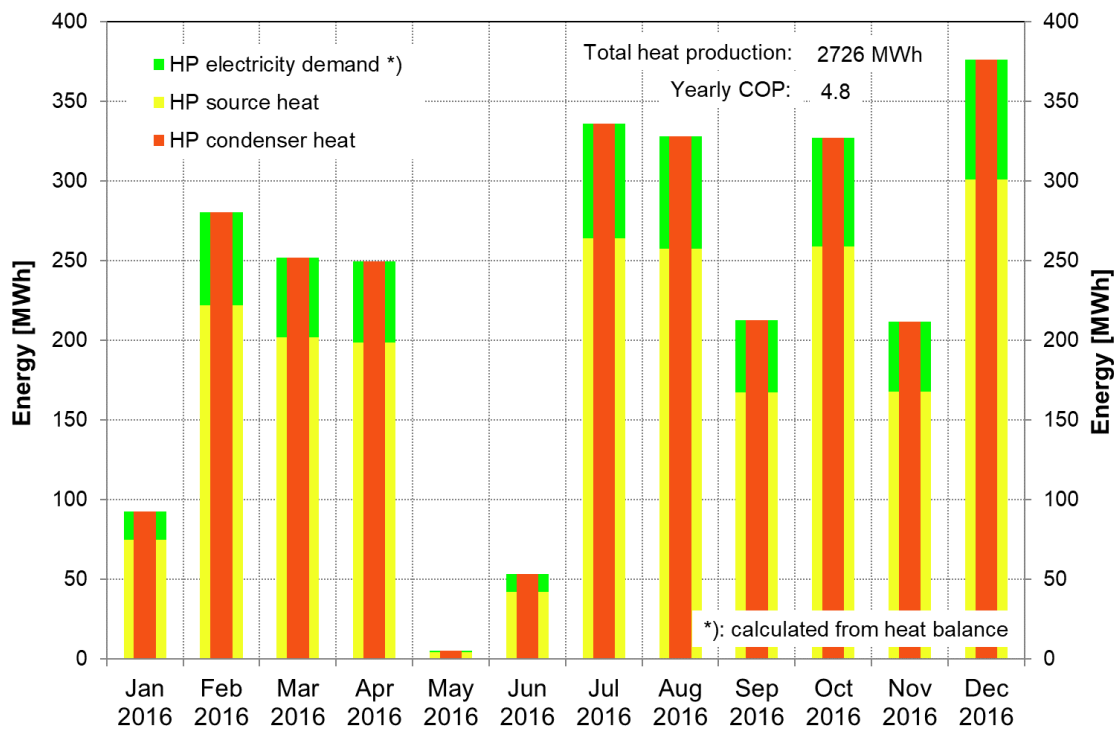


Fig. 16: Monthly heat balance of the heat pump in 2016

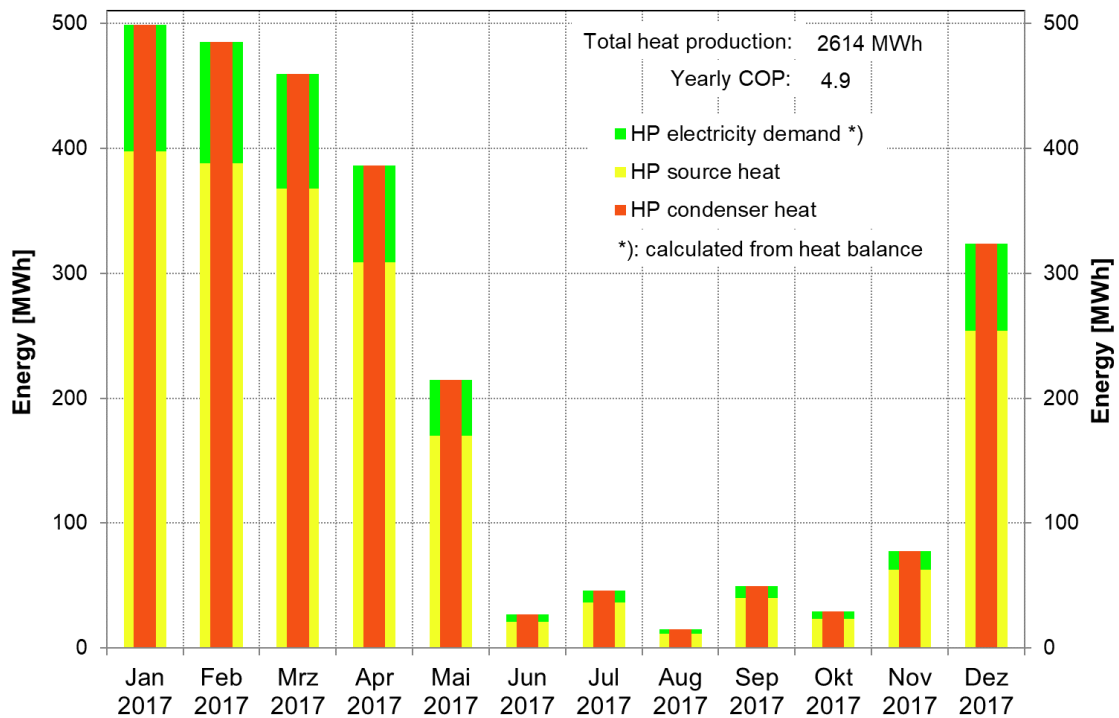


Fig. 17: Monthly heat balance of the heat pump in 2017

The following Fig. 18 and Fig. 19 show the operation of the heat pump. On the primary axis the daily mean temperatures are shown, while the corresponding COP is shown on the secondary axis. In Fig. 18 one can see the supply gap in May 2016 which is also visible in Fig. 16. Similarly, but not as strong, fewer operation hours can be spotted in January 2016. For the rest of the year a rather constant operation can be seen. The evaporator inlet temperature rests between 30 and 40 °C and the condenser outlet temperature remains about 70 °C.

In 2017 (Fig. 19), sensor data are very stable during the beginning of the year, when the heat pump is operating with little interruptions. The fluctuations are higher during the rest of the year.

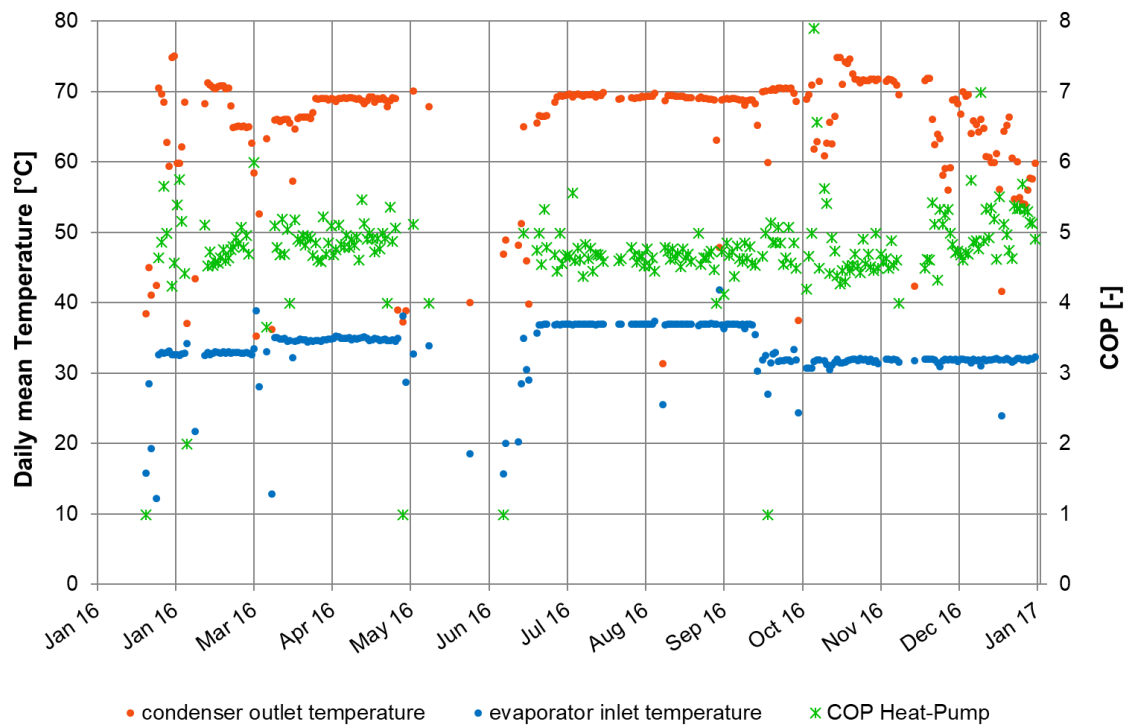


Fig. 18: Heat pump operation conditions 2016 (weighted daily mean values)

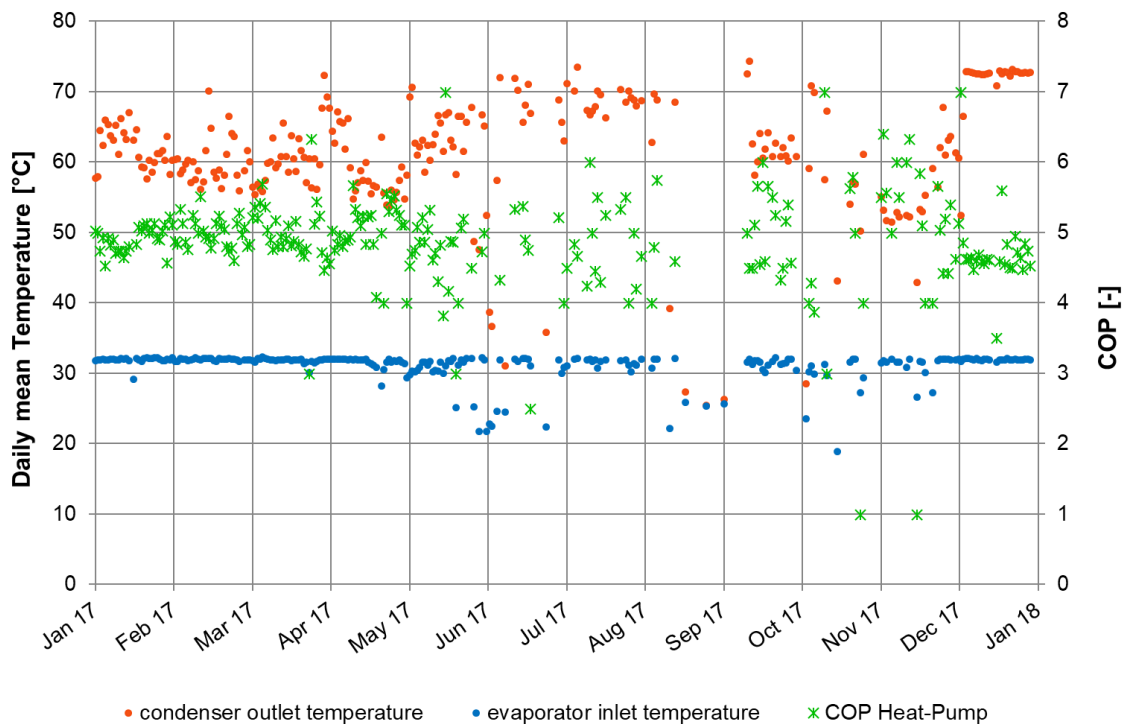


Fig. 19: Heat pump operation conditions 2017 (weighted daily mean values)

7. SUMMARY

The results from the evaluation of the Gram monitoring data in 2016 and 2017 show good agreements with the design figures in terms of usable temperature ranges. The contributions of solar heat to the heat supply of the connected district heating network turned out to be lower than expected. Instead of 51 % solar fraction, the plant arrived on 42 % and 37 % for 2016 and 2017 respectively. This result may also be influenced by higher storage losses than design values were showing. In 2016, the PTES losses were about 2 % higher than design values and in 2017 the losses were 14 % higher than design values that were communicated by Mr. Flemming Ulbjerg from Ramboll.

The storage losses can partly be explained by increasingly wet insulation in the lid. Resolving this issue is likely to reduce the losses mentionable.

When comparing the results from Gram with similar PTES systems, a lower amount of heat discharged by operation of the heat pump can be seen. Generally, the heat pump supports a larger energy extraction from the storage, even if the storage temperatures are below the level of the DH network. In the case of the plants in Marstal and Dronninglund, the heat pump helps to decrease the storage temperatures in the bottom of the storage below the surrounding soil temperature. This results in energy recovery of the thermal losses of the summer season.

Solving the issue of wet insulation is likely to improve the performance of the PTES and the overall system as well as the comparability of the system in Gram with other systems that are part of the EUDP Monitoring projects.

8. REFERENCES

- Sørensen, P.A. 2018: "Best practice" for implementation and operation of the Large Scale Borehole and Pit Heat Thermal Storages (BTES and PTES) in Brædstrup, Marstal, Dronninglund and Gram, Denmark, PlanEnergi 2018.
- Sørensen et.al. 2018: Sørensen P.A., Larsen J., Larsen L., Frey J., Schmidt T., Bjørn H., Furbo S.: Follow up on large scale heat storages in Denmark, final report to EUDP project 64014-0121, PlanEnergi 2018

9. ADDITIONAL SOURCES OF INFORMATION

- Ulbjerg, F. 2018: Ulbjerg F., (Rambøll), personal communication about design values, 13.12.2018

10. ANNEX 1: MONTHLY PTES GROUND TEMPERATURE DEVELOPMENT

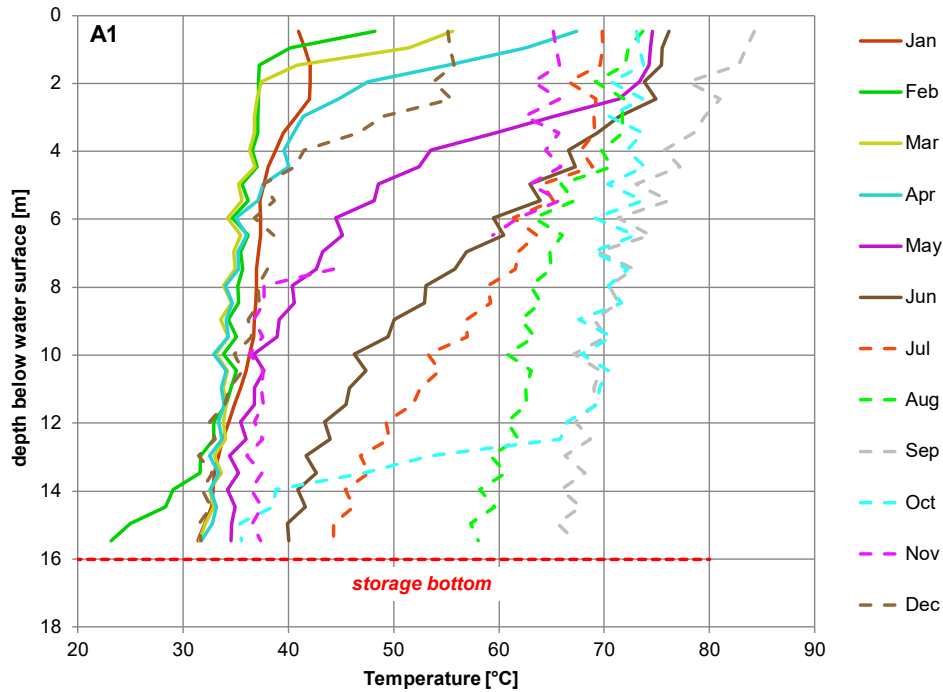


Fig. 20: Monthly PTES temperatures in 2016 (based on the 15th of each month)

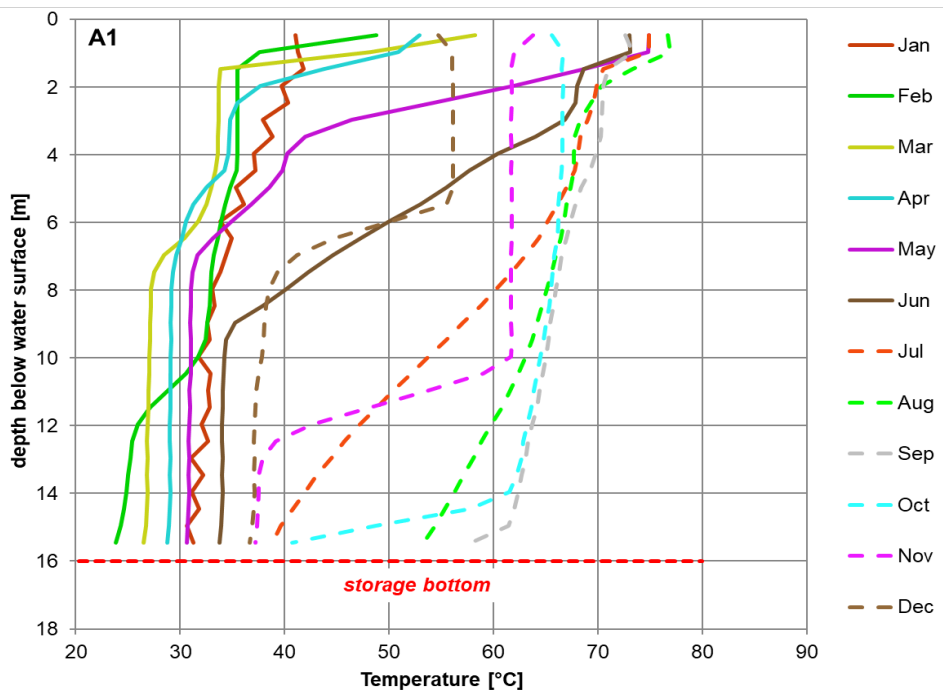


Fig. 21: Monthly PTES temperatures in 2017 (based on the 15th of each month)

GRAM MONITORING DATA EVALUATION 2016-2017

11. ANNEX 2: STORAGE WATER LEVEL AND PH-LEVEL

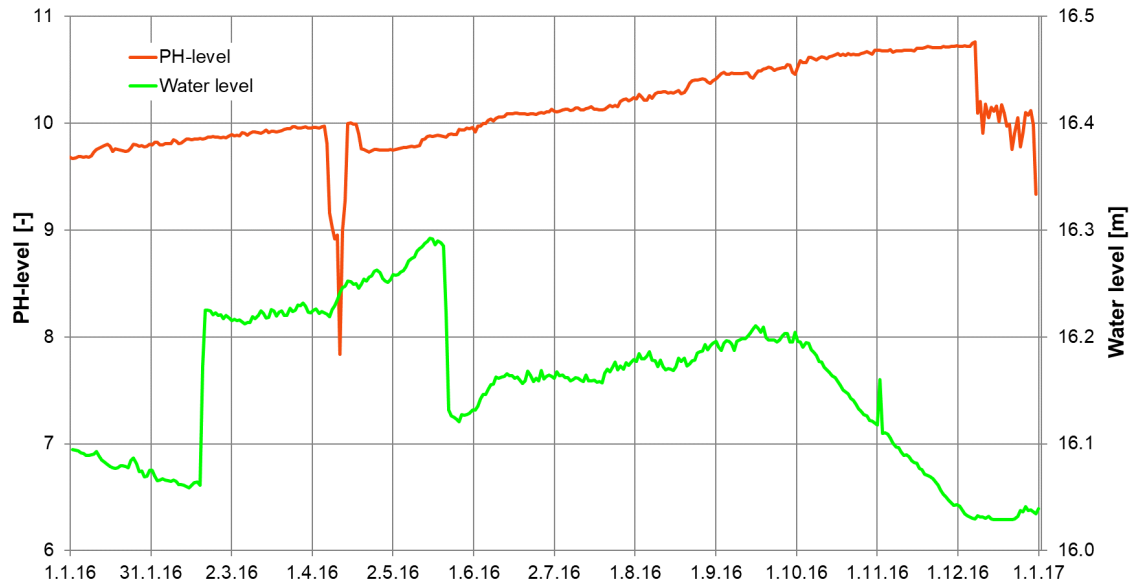


Fig. 22: PTES water level and PH-level 2016

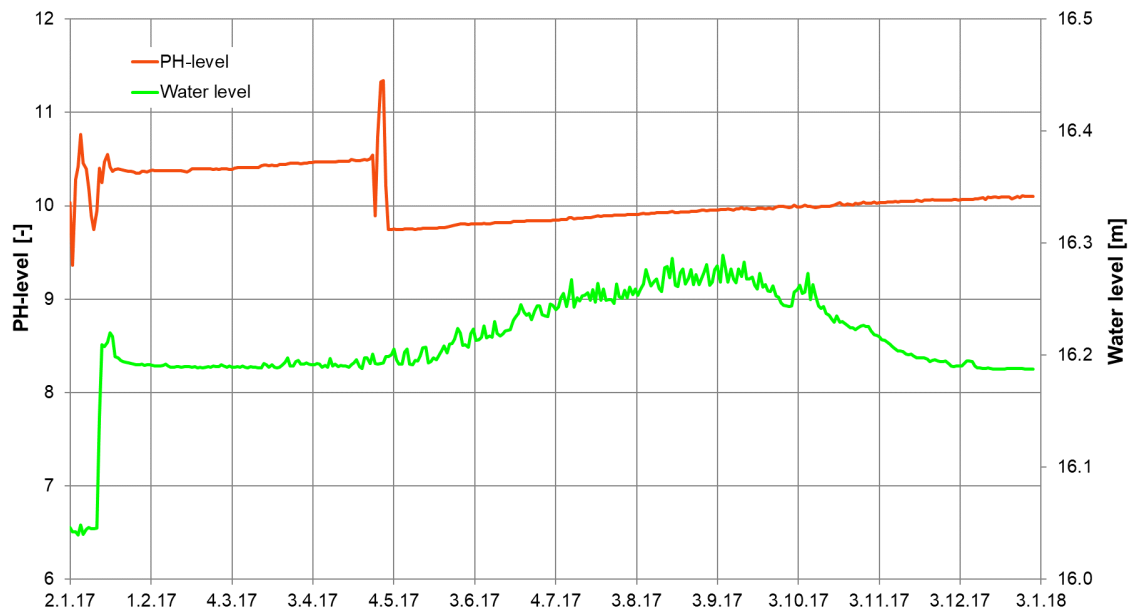


Fig. 23: PTES water level and PH level 2017