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DOCUMENTATION OF AN INTEGRATED THERMAL ENERGY SYSTEM FOR A BUILDING COMPLEX

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ABSTRACT

In large buildings and building complexes, energy use can be reduced by efficient interaction between heating and cooling demands and thermal storage (short and long term storage). This work describes an integrated energy system in Norway which supplied several commercial and residential buildings with heating and cooling. The integrated thermal energy system consisted of heat pumps (~1 MW total cooling capacity), solar thermal collectors (290 m^2), district heating connection as well as water tanks (15000 l) and boreholes (62 x 300 m) for thermal energy storage. The water tanks acted as buffer and balanced the mismatch of supply and demand during a day. The seasonal operation modes were chosen depending on the outdoor conditions. In summer, the condenser heat from the cooling systems and the solar collectors was sent to the boreholes. In winter, the heat pumps used the boreholes and the surplus heat from the cooling systems as heat source and delivered heat to the buildings for space heating and domestic hot water. In spring, certain cooling demands could be covered by free-cooling as long as the borehole temperature was low enough. District heating was utilized to lift the temperature for the domestic hot water and also served as backup system. In this work, the system is described in detail and operational data is presented. Improvement suggestions are made which could cut operational costs.

1. INTRODUCTION

There is an extensive focus on reducing the energy use of buildings as the buildings sector accounts for a large share of the world's energy use (around 40% in the European Union (European Union, 2010)). The main part of this energy is used for heating, ventilation, and air conditioning (HVAC), and domestic hot water (DHW) production (Pérez-Lombard et al., 2008). The DHW demand is relatively constant throughout the year, while the demand of the HVAC system highly depends on the outdoor temperature (Pedersen, 2007). Both heating and cooling load vary greatly between different buildings or building complexes as they are influenced by the building construction, type, use, size, and the climatic conditions (Guo, 2011). Thermal storage at high or low temperature can be used for heating and cooling, respectively. This allows, to a certain extent, to decouple the current thermal load of a building from the current energy demand which can reduce expensive peak demands. Common storage components of building energy systems are water tanks for short-term storage and underground thermal energy storage (UTES) for long-term (seasonal) storage. Examples of UTES are aquifer storage and borehole thermal energy storage (BTES). Both allow storing surplus heat during the summer period which can be used as heat source during the winter period (Heier et al., 2015). BTES is often combined with a heat pump system (Nord et al., 2012) and such combined systems are especially suited for colder climate countries (Hesaraki et al., 2015). The heat loss from a BTES depends significantly on the ground conditions, especially the amount and/or flow of ground water (Reuss, 2015).

An old industrial area (size roughly 100 x 200 m) in the Norwegian capital Oslo has recently been renewed with several buildings and an integrated thermal energy system (construction started in 2009). Various building types were built, namely apartments, shops, event locations, restaurants, food court, hotels, sport facilities, offices, and a university. Almost all of these were connected to the main integrated thermal energy system described in this paper. Each connected building had an individual distribution system which exchanged heat with the main system by a designated heat exchanger in the corresponding substation. The complete system has been in operation since the end of 2013 and was subject to efficiency improvement measures. The aim of this study was to document the system's operation during the year 2014 and give improvement suggestions.

2. INTEGRATED THERMAL ENERGY SYSTEM AND ITS CONTROL MODES

2.1. System and Component Description

A simplified scheme of the integrated thermal energy system can be seen in Figure 1. It also shows the fluids that were used for energy transport in the different closed circuits as well as the thermal energy users and their corresponding temperatures that were covered by the system. Product cooling was needed for the display cabinets in the food court.

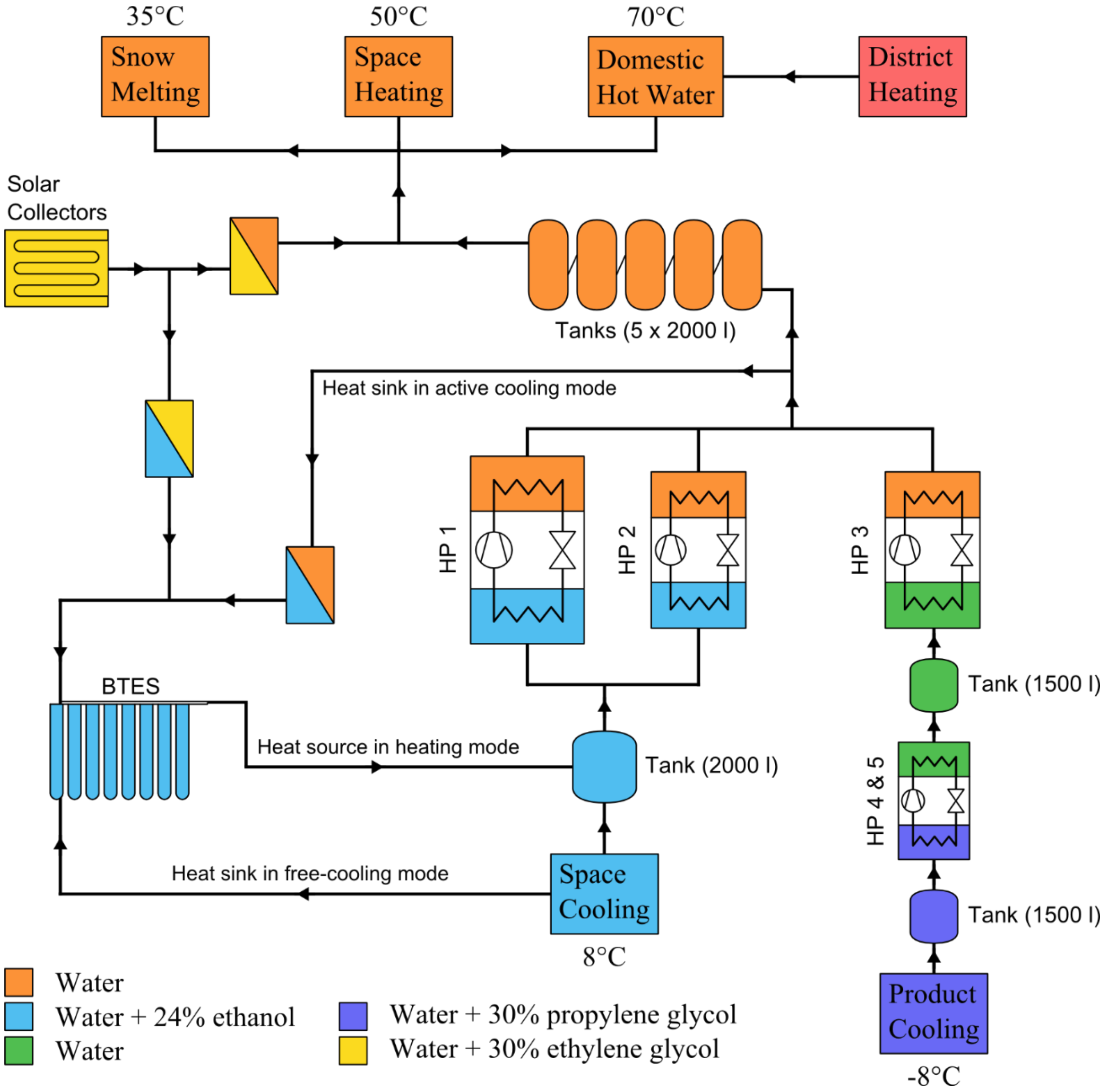

Figure 1. Simplified system overview.

The main parts of the integrated energy supply system were five heat pumps (HP), tanks and boreholes for thermal energy storage, and solar thermal collectors as shown in Figure 1. The specifications of the five heat pumps are listed in Table 1. The BTES consisted of U-pipes, 300 m deep, where the design flow rate was 0.81 l/s per pipe. 14 boreholes were drilled in the southern part of the area (hereafter called BTES South) and 48 boreholes were drilled in the northern part (hereafter called BTES North). However, they are shown as one unit in Figure 1 for simplicity. The solar thermal collectors consisted of 290 m² flat plate collector panels, integrated in the south-facing facade of an office building.

It can be seen from Table 1 that the heat pumps were designed to deliver heat at 50°C, so they could only cover parts of the DHW demand by preheating the DHW up to ~50°C. District heating was then employed to lift the temperature to the required 70°C. The space heating circuits were also connected to the district heating network (not shown in Figure 1) as backup system in case of very high space heating demands or heat pump failure.

Table 1: Heat pump specifications

	HP 1	HP 2	HP 3	HP 4 & 5
Type	WSA2802X	WSA1602X	WSA0701X	NXW0600X
Working fluid	R134a	R134a	R134a	R410a
Compressor	Screw (2)	Screw (2)	Screw	Scroll
Design data cooling (evap./cond.)				
Temperatures	4.5°C / 48°C	4.5°C / 48°C	20°C / 55°C	-8°C / 25°C
Capacities	595 / 772 kW	334 / 436 kW	224 / 283 kW	87 / 110 kW
COP	4.36	4.27	4.80	4.78
Design data heating (evap./cond.)				
Temperatures	0°C / 50°C	0°C / 50°C		
Capacities	473 / 652 kW	264 / 365 kW		
COP	3.64	3.61		

2.2. Control Modes

The system had several closed circuits for energy transfer and different operation modes were developed to cover the various energy demands throughout the year. Specifically, heating, free-cooling, and active cooling mode were developed and are described below. For all control modes, the tanks could be used to ensure even supply and return temperatures during operation.

Heating mode was developed for the winter period with typically high space heating demand. In this mode, the BTES as well as the surplus heat from space cooling and product cooling were used as heat sources for the heat pumps. The condenser heat from HP 1, 2, and 3 was then sent to the substations for space heating, DHW preheating, and snow melting when necessary. The solar collectors were not used during heating mode due to the very low solar irradiation in Oslo during winter. The ground temperature around the boreholes decreased during heating mode.

Free-cooling mode was implied during spring. In this mode, the ground temperature was at its minimum due to the heat extraction during winter. If the fluid’s return temperature from the boreholes was lower than 8°C, it could directly be sent to the space cooling substation. This mode was called free-cooling because the surplus heat from space cooling did not need to be upgraded to a higher temperature level to be released (as usually done with the help of a heat pump). The ground temperature increased during heating mode. The surplus heat from product cooling was still used as heat source for the heating demands like in heating mode. The solar collectors and snow melting circuits were activated depending on the outdoor conditions.

Active cooling mode was used during summer. Due to the typically high space cooling demand, a lot of surplus heat needed to be released from HP 1 and 2. In addition, the solar collectors and HP 3 also delivered heat and only a part of this was needed for space heating and DHW preheating. Therefore, the main part was sent to the BTES and led to an increase in the ground temperature.

3. OPERATION EXPERIENCE

3.1. Data Acquisition and Quality

Measurement data for 2014 was received from the operator’s server. Due to different logging intervals of the sensors, all data points were averaged for each hour of the year before being analyzed. Due to the slow thermal response of some of the components (especially the BTES), this could lead to errors in the hourly values during transient operation. The monthly values were less affected by this averaging. Short periods of missing data due to sensor problems and/or server errors were not long enough to influence the results significantly.

3.2. Performance of the Integrated Thermal Energy System

Monthly values for energy use and the system’s coefficient of performance (COP) are shown in Figure 2.

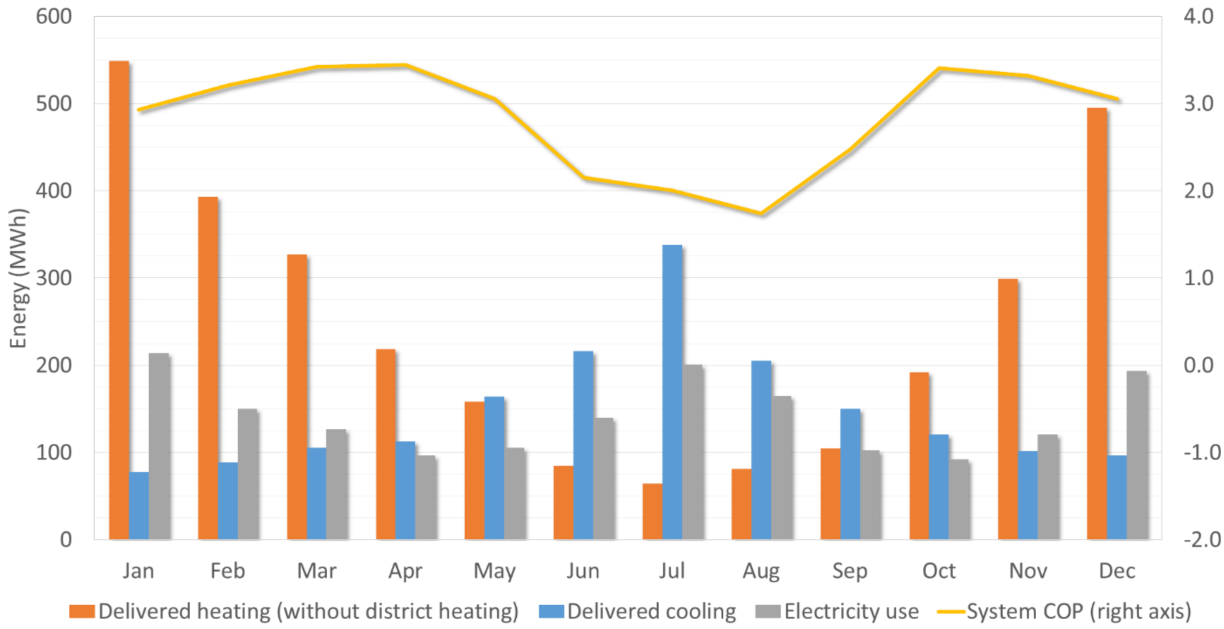

Figure 2. Monthly energy amounts and average system COP for 2014.

The variation of heating and cooling demand throughout the year can clearly be seen in Figure 2. This is mostly due to space heating and cooling. DHW preheating and product cooling were relatively constant demands. The electricity use in Figure 2 was the amount used by the whole system, including all pumps, control system, safety systems, etc. It also varied throughout the year and was highest during the peak load months in summer and winter. The COP of the system shown in Figure 2 was calculated as:

$$COP = \frac{\text{Delivered heating} + \text{Delivered cooling}}{\text{Electricity use}} \tag{1}$$

The system COP ranged from 1.7 to 3.4 in 2014. In total, 1 707 MWh of electricity were used to deliver 384 MWh for product cooling, 1 393 MWh for space cooling, 309 MWh for snow melting, and 2 658 MWh for space heating and DHW preheating.

District heating was not included in the COP calculation. The daily use of district heating compared to the delivered heat from the energy system is shown in Figure 3. The outdoor temperature is also shown, but the measured values were too high. This is explained afterwards and shown in Figure 4.

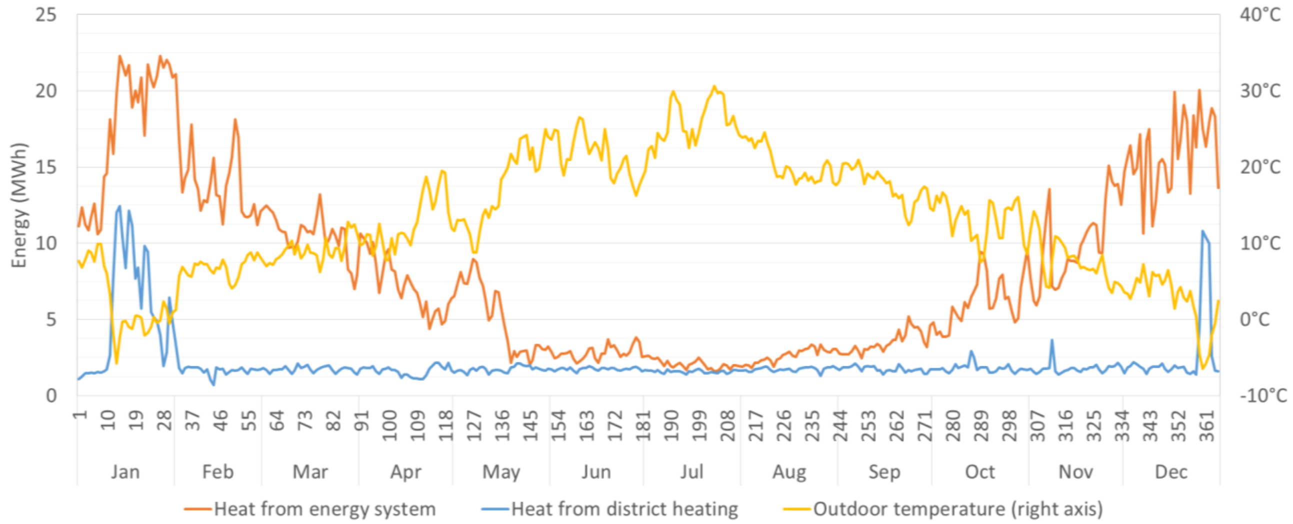

Figure 3. Daily heat amounts and average outdoor temperature for 2014.

It can be seen from Figure 3 that the district heating load was almost constant for most of the year. This was due to the typically low variation in DHW use which was the only recipient of district heating during normal operation. However, when the outdoor temperatures were very low in the middle of January and the end of December, a significant increase in district heating use could be observed. The district heating network then also delivered heat to the buildings for space heating.

The system's outdoor temperature measurements seemed high and were compared to data from a weather station 20 km away (Bioforsk, 2015). The comparison in Figure 4 shows that the suspected offset was about 6°C.

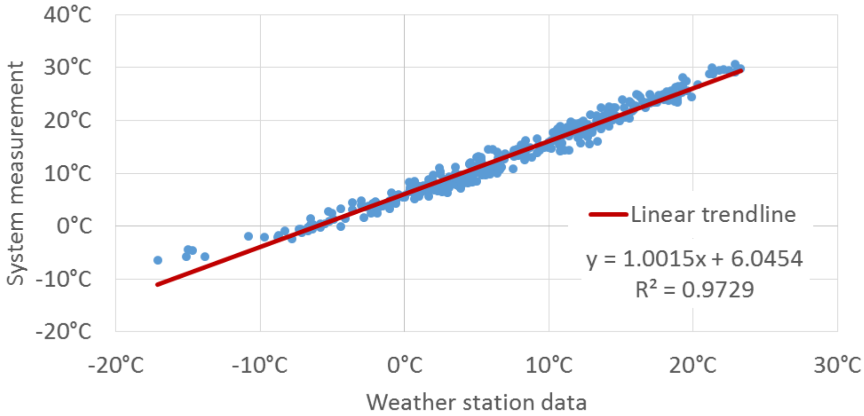

Figure 4: Comparison of daily average outdoor temperatures.

The monthly heat exchange with the boreholes is shown in Figure 5. It can be seen that the boreholes were loaded during summer and unloaded during winter, as intended. However, the amount of energy stored in summer (1 190 MWh) was a lot higher than the amount taken out during winter (734 MWh) in 2014. If this tendency continues over the next years, the ground around the boreholes will heat up making it increasingly difficult to use the BTES as heat sink in summer. However, 2014 was a very warm year with the average temperature in Oslo being almost 2°C higher in 2014 compared to the ten previous years (Bioforsk, 2015). This is a possible reason for the deviation as higher outdoor temperatures lead to decreased heating load during winter and increased cooling load during summer. Still, the energy balance should be analyzed each year to avoid operational difficulties in the future.

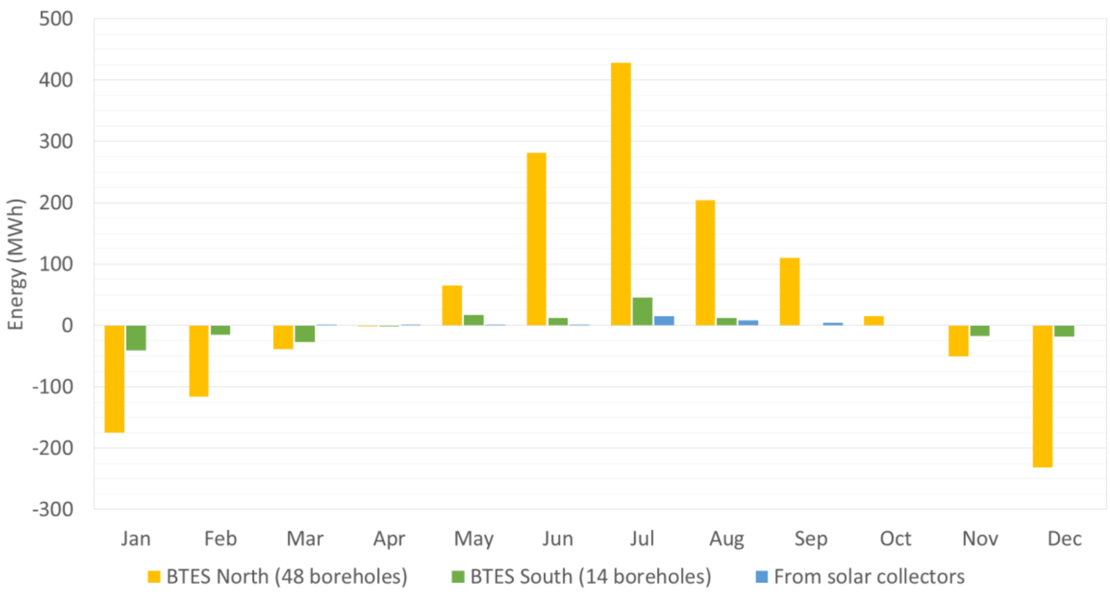

Figure 5. Monthly energy amounts for borehole storages for 2014.

The in- and outflow temperatures of the two borehole-arrays are shown in Figure 6. Gaps in the data indicate periods with no flow circulation.

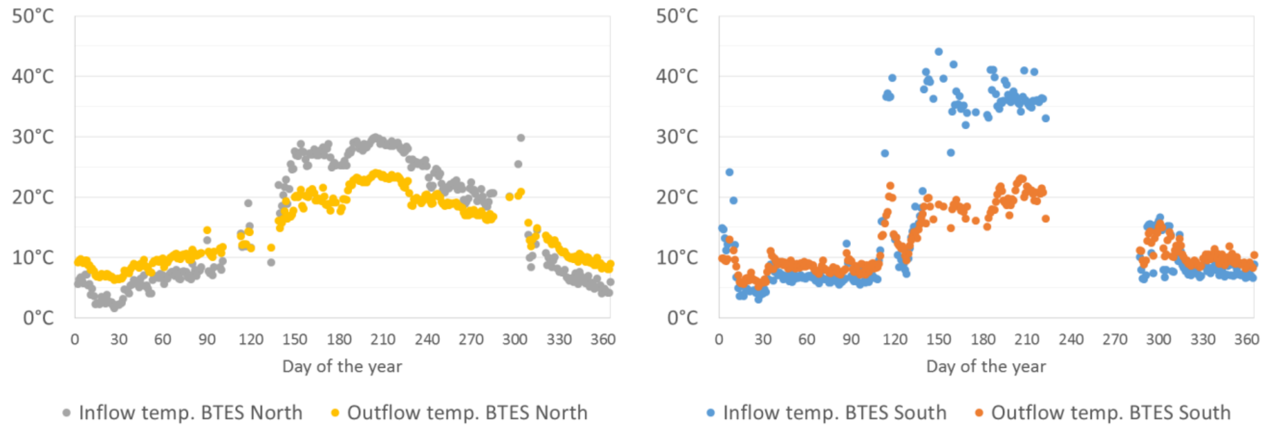

Figure 6. Daily average in- and outflow temperatures of the borehole-arrays for 2014 (gap = no flow).

The supply and return temperatures in Figure 6 confirm that the BTES were loaded during summer and unloaded during winter. However, it is difficult to identify periods of free-cooling mode. Such periods would be characterized by inflow temperatures of 10-15°C and outflow temperatures around 6°C which cannot be seen in Figure 6. This suggests that this operation mode is not used as planned.

4. IMPROVEMENT SUGGESTIONS

The integrated thermal energy system operated successfully in 2014. No failures occurred and the user demands could be satisfied by the system apart from short periods where the district heating backup was active. The system COP was acceptable but could be improved with the following measures. An economic evaluation of the different options has not been performed.

4.1. Heat Pump Performance

HP 4 & 5 (see Figure 1) were two identical heat pumps in parallel that could be operated independently (a third heat pump was originally planned as backup but has not been installed). They were used for product cooling which required constant operation of at least one of the heat pumps. They are each designed for a cooling load of 87 kW (see Table 1) which shows that the predicted product cooling load was around 1 500 MWh per year. However, the actual load for 2014 was 384 MWh which is only around 25% of the predicted load. HP 4 & 5 were therefore running in part load for most of 2014 with the associated decrease in efficiency. The same holds true for HP 3 which was also designed based on the predicted product cooling load.

4.2. Solar Collectors

The solar collectors were integrated in the facade of an office-building which they supplied with heating energy directly (not shown in Figure 1). The surplus heat was sent to the BTES, the monthly amounts can be seen in Figure 5. As the solar collectors can deliver higher temperatures than the heat pumps, they could be used to lift the temperature of the DHW after it has been preheated by the heat pumps. However, office buildings have relatively low DHW demands and the other buildings were not connected so a main part of the high temperature heat was not used optimally. The surplus heat sent to the BTES played a minor role in the system in 2014.

4.3. Different Fluid for Cold Circuit

The properties of the water/ethanol mixture are worse than those of pure water in terms of performance. The higher viscosity of ethanol increases pressure drops and the lower heat capacity requires larger mass flows both leading to increased pumping power for the same heat transfer. The ethanol was added to lower the freezing point as even local freezing of the working fluid could impede the system's functionality. However, the minimum temperature in the water/ethanol circuit was 1.5°C in 2014. This means that water or at least a lower ethanol concentration mixture could be used in the circuit instead. This would reduce the parasitic losses in this circuit and increase the overall system COP.

4.4. Buffer Tank on Cold Side

Figure 7 shows the buffer tank on the cold side of the system and the flows in heating mode.

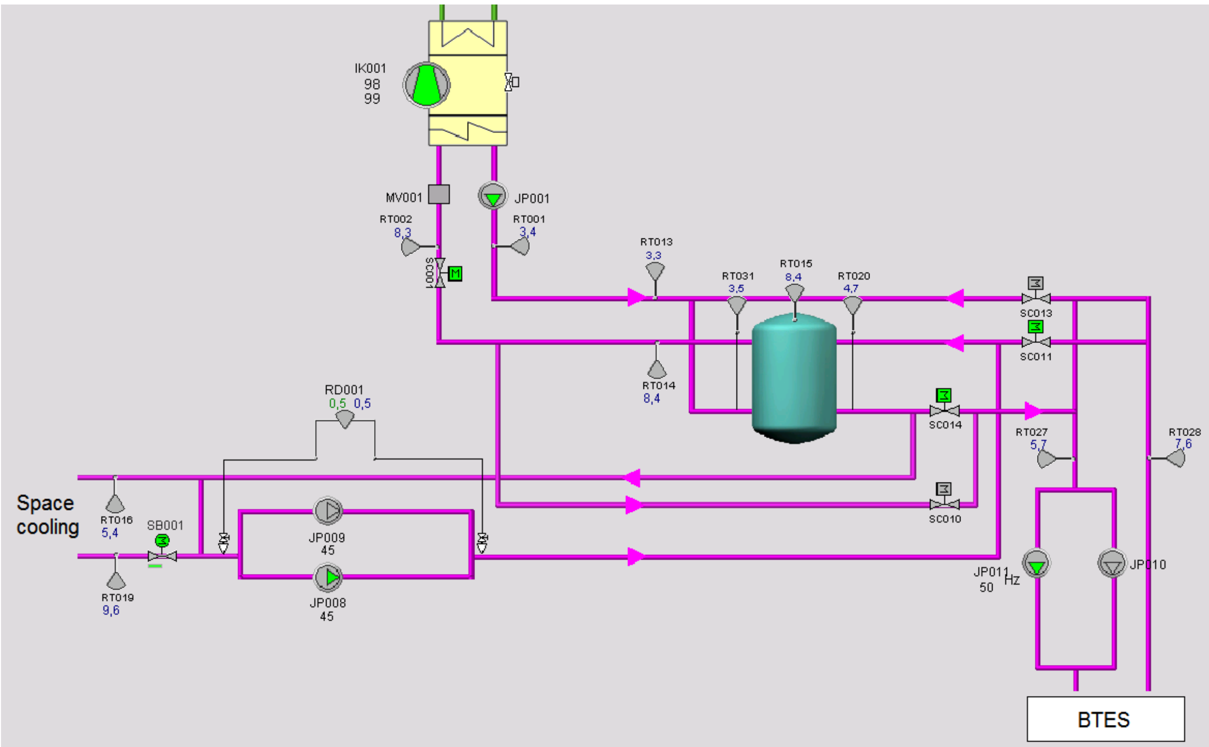

Figure 7. Detail of cold buffer tank in heating mode (green components are active).

The evaporator of HP 2 takes up heat from the water/ethanol mixture and cools it from 8.3°C to 3.4°C. It is then sent to the space cooling and BTES heat exchangers to be heated up again. On its way there, it passes through the lower (colder) end of the buffer tank where it is preheated from 3.5 to 4.7°C. This preheating reduces the amount of heat that the fluid will take up in the following heat exchangers and should thus be avoided. On the return side, after the flows from space cooling (9.6°C) and BTES (7.6°C) are joined, the fluid passes through the same tank again. It is not significantly cooled with the current flows in Figure 7, but mixing with the (usually lower) tank content is possible. This could easily be avoided by installing a separate buffer tank for supply and return flow and would reduce mixing losses.

5. CONCLUSIONS

An integrated thermal energy system was presented in this work. This energy system delivered heating and cooling energy to several buildings and employed boreholes as seasonal thermal energy storage. Operational data from 2014 showed that the BTES was successfully used to store heat during summer and recover it during winter. All heating and cooling demands could be covered, but district heating was needed as backup system during very cold periods. Also, the product cooling load was overestimated during the design phase which led to the installation of oversized heat pumps. Still, the system COP ranged from 1.7 to 3.4 which is satisfactory. However, it could be improved by replacement of the unsuitable heat pumps, better utilization of the high temperature heat from the solar collectors, installation of an extra buffer tank in the space cooling circuit, or using pure water instead of a water/ethanol mixture.

6. ACKNOWLEDGEMENTS

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