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Solar District Heating and Heat Pump at Rye Kraftvarmeværk (Rye CHP)

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Abstract – This paper describes the design and implementation of a solar heat and heat pump plant at an existing natural gas fired CHP plant. The purpose of the project was to decrease the dependency of natural gas remarkably, and to demonstrate the ability to help the electricity system in a market heavily influenced by wind power, by using electricity for heat production primarily when prices are lowest. The demonstration part of the project was supported by funding from EUDP (Danish national support program for Energy Technology Development and Demonstration). The solar plant was designed to cover 12% of the yearly heat demand and the heat pump was designed to cover 67% of the yearly heat demand by extracting heat from groundwater. The heat production from natural gas is then reduced by app. 80%. The heat pump is driven by electricity and was designed with a COP (Coefficient Of Performance) of 4.0, meaning that 75% of the heat production from the heat pump is renewable energy from the ground water, and 25% is from the electrical input to the compressors. A high share of the electrical input is also renewable because the heat pump is operated in the hours with lowest electricity prices where the share of wind power is usually highest. To maximize the performance of the overall plant and reduce the natural gas consumption as much as possible the control strategies are important. The control strategies are also covered in the paper as well as the monitoring results for the first year of operation. The monitoring results shows that the expected reduction of natural gas was obtained.

1. INTRODUCTION

"Rye Kraftvarmeværk" is a small CHP plant in the village: "Gl. Rye". The CHP plant was built in 1995 and consisted of two natural gas fired CHP engines (renewed in 2006) a natural gas fired boiler and a heat storage. In 2014-2015 the plant was expanded with a solar plant and an electrical driven heat pump. The solar plant has a collector area of 2 444 m^2 and the heat pump has a thermal capacity of 2.05 MW and uses ground water as heat source. The heat, app. 33 570 GJ/year (9 325 MWh/year), is supplied to 365 consumers, which are primarily individual households in Gl. Rye. This paper covers the solar heat and heat pump project with an emphasis on design, implementation, control strategies and monitoring results.

2. DESIGN OF THE PLANT

2.1 Functional diagram

A functional diagram of the plant is shown in figure 1. The existing plant consisted of two natural gas CHP engines delivering 1 MW heat each, a 3.2 MW natural gas boiler delivering 3.2 MW heat and a 500 m^3 hot water tank. The CHP plant was designed to operate only when the electricity prices were high by using the water tank as heat storage.

The new plant consist of app. 2 400 m^2 solar collectors and a heat pump of app. 2 MW heat. The solar collectors use the existing heat storage tank when the solar production is larger than the consumption (typically during summer days). The heat pump uses the heat storage tank when the heat pump production is bigger than the consumption (typically during fall, winter, and spring nights when electricity prices are low). In addition to this the heat pump uses a cold water storage for ground water to even out the water consumption from the ground water drillings and the water treatment system. The heat pump retracts energy from the ground water by cooling it from 9°C. to 2°C. before it is returned to the ground through a drain system in the soil.

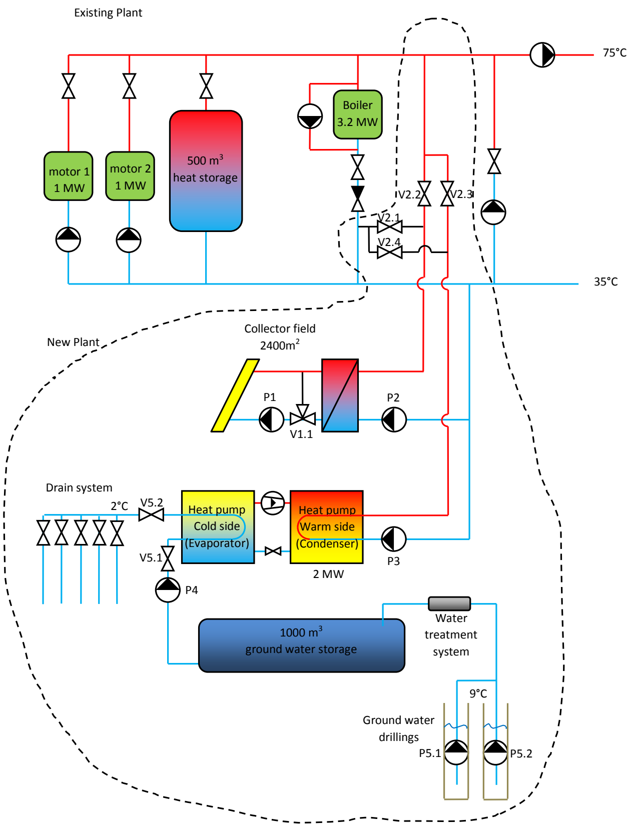

Figure 1: Functional diagram of the plant

2.2 Dimensioning

The size of the solar plant was defined from the available land space nearby the CHP plant and the size of the existing storage tank. The aim was a solar plant that could produce around 20% of the yearly heat demand but this would require an extra storage tank and longer transmission pipes to an available land area. Therefore it would be economical unfeasible to extend the solar area to more than 2 400 m^2.

The size of the heat pump was from an economical perspective found to be ideally 1-1.2 MW_{heat} running 6 000 h yearly by the present conditions regarding electricity prices and taxes. However to demonstrate the ability to help the electricity system, funding was given from EUDP for a bigger heat pump. A 2.4 MW heat pump would be able to produce the same amount of heat running only the 2 000 h with lowest electricity prices (most wind), and thereby help to use excess electricity in the Danish electricity system that would otherwise be exported to neighbour countries. For technical reasons regarding the specific size and composition of compressors, the size of the heat pump ended up being 2.05 MW. The electricity connection from the heat pump to the electricity grid was established through the existing transformer at the plant that also connects the CHP engines to the grid. The heat pump is connected on so called interruptible conditions meaning that the electricity company has the possibility to shut down the heat pump if the load in the distribution system is too high. In return the connection fee to the electricity grid company is avoided.

The number of ground water wells and the size of the ground water storage was found from an economical optimisation. When the heat pump is in operation it demands a ground water flow of 200 m^3/h. From the first test well it was concluded that it would be possible with up to 50 m^3/h from each well in the area. Without a ground water storage it would be necessary with 4 wells and a water treatment system capable of handling 200 m^3/h. The ground water storage is a relatively cheap storage made as an uninsulated concrete tank buried in the ground. The optimal size of the tank was found to be 1000 m^3 meaning that the number of wells could be reduced to two delivering 100 m^3/h in total and allowing the heat pump to operate continuously for 10 hours before the storage has to be filled up again.

The water treatment system was designed to clean the ground water (100 m^3/h) for iron and manganese to a level corresponding to drinking water. This is necessary due to a high level of iron in the ground water at the location of Gl. Rye. A high level of iron in the water combined with exposure of atmospheric air (oxygen) would result in deposits in the heat exchangers of the heat pump requiring unwanted frequent cleaning. It was planned to make a simple aeration of the water followed by a sedimentation of iron at the bottom of the storage tank, but experiments showed that it was not possible to establish an effective sedimentation. The solution ended up being a large pressurized sand filter as known from water supply facilities.

The purpose of the drain system is to return the water to the ground water reservoir. This is done by drainage pipes buried horizontally in the field with solar collectors 2 m below the surface. The drainage system is dimensioned from the local soil conditions. The total pipe length of the drainage system is 1 830 m.

2.3 Environmental issues and authority permits

To get the necessary authority permits for the project it was necessary to document the environmental risks of the project. To document the impact on the local ground water reservoir and eventual impacts on surrounding wells for irrigation or drinking water purpose geologists created a hydrogeological numerical model. From model simulations, the geologists carried out impact analyses, which was examined by the authorities. The local drinking water facility has its production wells less than 300 m from the production wells for the district heating company. The impact analysis showed only minor impact on the ground water level in the drinking water wells. Therefore the necessary authority permits were given.

3. IMPLEMENTATION OF THE PLANT

3.1 Layout of the plant

The overall layout of the plant is shown in

figure 2. The two ground water wells are placed northwest and northeast of the existing heating plant. The wells are connected to the water treatment system through underground pipes and further to the ground water storage. The ground water storage is connected to inlet of the heat pump inside the new building and the outlet is connected to the drain system below the solar collectors south of the buildings. Inside and around the drain system is placed 5 monitoring drillings to monitor the water level in the drain area and stop the heat pump and ground water flow if the water level reach a critical level. The heat exchanger for the solar collectors is also placed inside the new building. The heat pump and solar plant is connected to the existing plant inside the building.

3.2 Ground water drillings

The first thing in the implementation process was to drill the first ground water well as a test well to investigate the water potential in the area. The test well was test pumped with quite disappointing results at first sight. Only around 30-35 m^3/h could be pumped from the well, and with a demand of 200 m^3/h for the heat pump it would require too many drillings for a feasible project. It was though possible to flush and clean the well with hexametaphosphate which increased the performance of the well to 50 m^3/h. From these results it was decided to make two ground water drillings and use a ground water storage as mentioned.

Figure 2: Layout of the plant

3.3 Heat pump

The heat pump consist of 4 compressors and several heat exchangers. The two low pressure compressors can be seen in figure 3 and the two high pressure compressors can be seen in figure 4. The heat pump was site build and tested after implementation to check the guaranteed performance of the heat pump.

Figure 3: Heat pump low pressure compressors.

Figure 4: Heat pump high pressure compressors

3.4 Drain system

The drain system was established in the solar field before the solar collectors. A drawing view of the cross section of the drain system is shown in figure 5 and a picture from the implementation is shown in figure 6

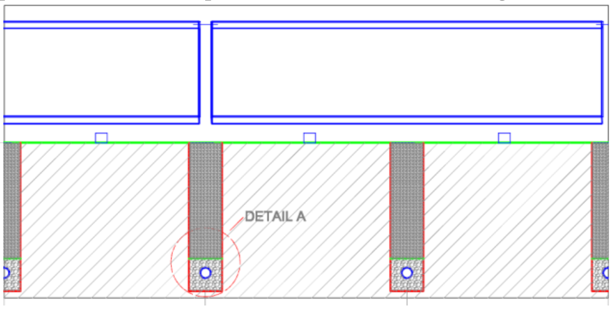

Figure 5: section view of drain system

Figure 6: Implementation of drain system.

3.5 Solar Plant

After implementation of the drain system the transmission pipes for the solar collector field was buried and the field was prepared for solar collectors. The solar collectors were mounted on concrete foundation blocks as seen in figure 7. Around the solar field an embankment of earth was build up to minimize the visibility of the plant.

Figure 7: Mounting of solar collectors.

4. CONTROL STRATEGIES

The overall control strategy is to minimize the production costs. This is done by choosing the cheapest production unit at all time taking into account hour by hour the expected spot prices for electricity and natural gas, the expected heat consumption, the expected solar radiation and the storage capacities. The overall production strategy is planned each day by the operator using a software tool from the electricity balance responsible party.

In addition to the overall control strategy it is important that each production unit is operated at its maximum possible performance. For both the solar plant and the heat pump the performance is highly dependent of the production temperatures. The production temperatures should be kept as low as possible. Therefore it is important that the forward and return temperatures in the district heating network are kept as low as possible. This is done by a control system that monitors the flow and temperatures in the system and automatically adjust the setpoint forward temperature to reach the desired flow. If the flow is lower than desired the forward temperature will be lowered gradually resulting in a higher flow. If the flow is too high the forward temperature will gradually be raised resulting in a lower flow in the system.

When the solar plant and heat pump delivers more heat than the heat demand some of the heat will be stored in the storage tank. In this case it is possible to produce at a temperature slightly higher than the required forward temperature to maximize the performance or at a higher temperature to increase the storage capacity if desired. When the solar plant and heat pump delivers less heat than the heat demand, it is possible to produce at even lower temperatures than the district heating forward temperature. This is because they will be supplemented by either another unit (CHP engines or boiler) with higher temperature or heat from the storage tank which is eventually at a higher temperature than the required forward temperature.

To make sure that the solar plant and heat pump can produce at as low a temperature as possible the required production temperature is calculated at all time from the calculated available heat production from the solar plant and heat pump, the required district heating forward temperature and the available temperature and capacity from the supplementing unit.

Below is an example of the calculation of the setpoint temperature from the solar plant when the solar plant is supplemented by the storage tank.

The lowest possible production temperature for the solar plant to achieve the desired district heating forward temperature can be calculated as:

$$T_{sol} = \frac{p_{sol}(T_F - T_R)(T_R - T_{akku})}{(Q - p_{sol})(T_F - T_{akku}) + p_{sol}(T_R - T_{akku})} + T_R \ [°C]$$

where: P_{sol} = Current solarproduction [kW]
T_{akku} = Top temperature in tank [°C]
Q = District heat power [kW]
T_F = District heat forward temp. [°C]
T_R = District heat return temp. [°C]

The solar plant forward temperature has to be between the district heating return temperature and the maximum allowable solar plant forward temperature T_{max} (set point). Otherwise the solar plant forward temperature is set to the maximum allowable solar plant forward temperature:

$T_{sol}=T_{max}$ if T_{sol}(calculated) $>T_{max}$ or T_{sol}(calculated) $<T_R$

Similar calculations are done for other possible combinations of the production units.

5. MONITORING RESULTS

5.1 Monitoring period

The monitoring results presented here are from 2015: **February 23rd 2015 to December 31st 2015**. The reason for this is that the heat pump is first put into service around this time, and the relevant data does not exist before this point. The monitoring results are retracted and analysed by the Danish Technological Institute. Results from 2016 are not retracted or analysed yet.

5.1 Total heat production of CHP-plant

The measured and calculated heat production of the individual units for the measured period is presented in table 1. The calculations are carried out in the calculation tool "EnergyPRO" for a complete year and adjusted to a period of 312 days (0,855 years) The annual values are multiplied by a factor 0,855 to get values corresponding to the measured time period. This gives some inaccuracies in the comparison because the heat consumption, the heat pump production and the solar production is not evenly distributed throughout the year.

	Measured and restored data		Theoretically calculated data	
Unit	MWh	%	MWh	%
Heat pump	4,168	59.4%	5,312	66.6%
Solar heat plant	1,063	15.2%	937	11.8%
Combustion engine 1	90	1.3%	121	1.5%
Combustion engine 2	88	1.2%	100	1.3%
Boiler	1,602	22.9%	1,500	18.8%
Sum	7,012	100%	7,971	100%
Heat delivery from plant	7,278		7,971	

Table 1: Measured and calculated heat production

The measured data shows in general a good agreement with the calculated data with the heat pump and solar plant contributing with the major part of the heat production (75% - 78%). This indicates that the overall control of the plant is in line with the control strategy. The solar plant has produced slightly higher than expected and the heat pump lower than expected. This can partly be explained by the adjustment of the time period and for the heat pump partly by difficulties and adjustments in the start-up period. The overall heat production also seems to be smaller than the calculated values, but this is again partly due to the adjustment of the time period.

The Measured results are shown graphically in figure 8 and the calculated results are shown in figure 9.

5.2 Heat pump

The heat pump is evaluated in terms of the hot side heat pump COP (COPh) and in- and output power. COPh is calculated from the electric power consumption of the compressors and the output power in terms of heat.

If all data points with COPh < 0.2 are ignored the average COPh is 4.54.

However, start-up and shutdown is a part of the realistic heat performance so all values related to this cannot be ignored altogether. If the data for COPh is filtered so that values lower than 0.2 and higher than 10 are discarded, the most extreme values are avoided and the realistic operation of the heat pump is reflected. When doing so the COPh is 3.74, which is meant as being a realistic average across the time period. This filtering of data with both a lower and an upper bound is showed in figure 10 along with the average COPh of 3.74. Here it is also evident that the variation in COPh during operation is of minor magnitude as there is a clear locus of data points.

The consumption of electric power for the compressors and the output power are presented in figure 11

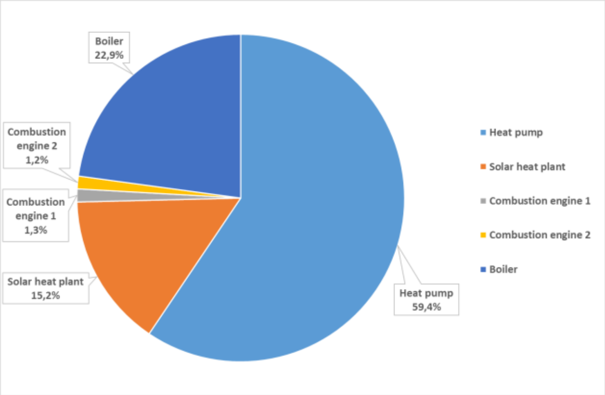

Figure 8: Graphical representation of the measured heat production of the CHP-plant.

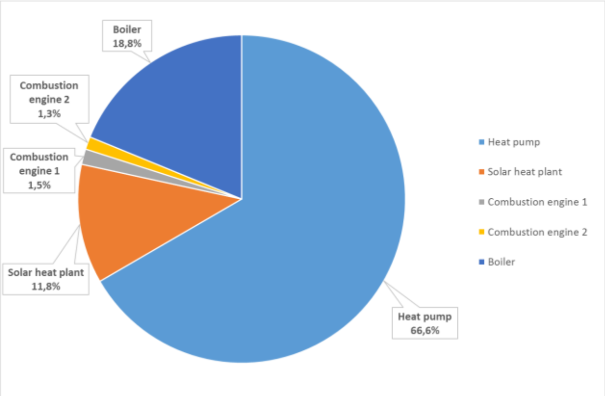

Figure 9: Graphical representation of the theoretically calculated heat production of the CHP-plant.

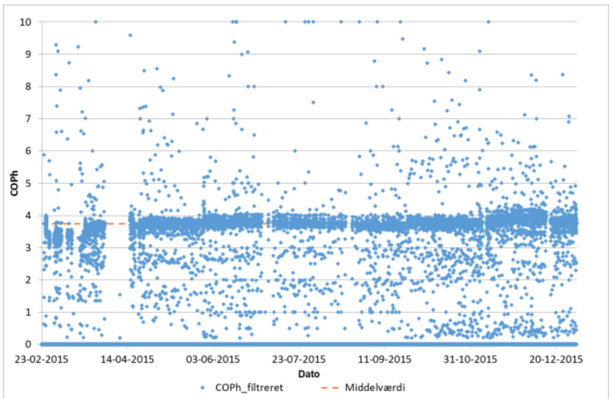

Figure 10: COPh for the heat pump calculated with filtered data: 0.2< COPh >10. Average value showed through the locus of data points.

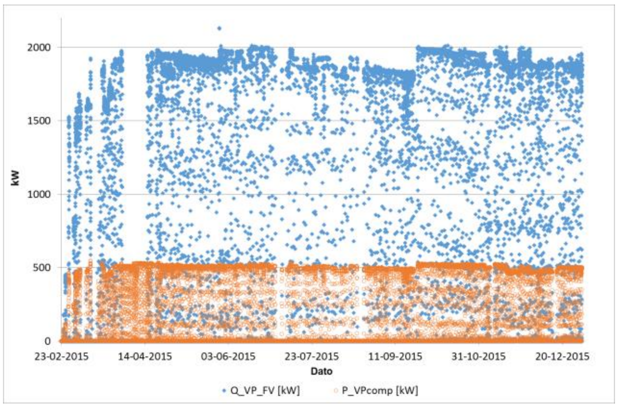

Figure 11: Power consumption by the compressors of the heat pump depicted along with the output power on the water side.

5.2 Solar plant

In the following, the output power in terms of heat, in- and output temperatures, and flow are presented for the water side of the solar heat plant.

The input and output temperatures are shown in figure 12. Quite high output temperatures are seen especially in the beginning of the period. The control strategy of the solar plant is expected to contribute to lower output temperatures in larger periods of operation but this can not be identified in the figures. The initial period of operation has been affected by start-up challenges and better results are expected for the second year of operation.

The heat output and the flowrate of the solar plant is shown in figure 13. The maximum output is between 1.5 and 2.0 MW.

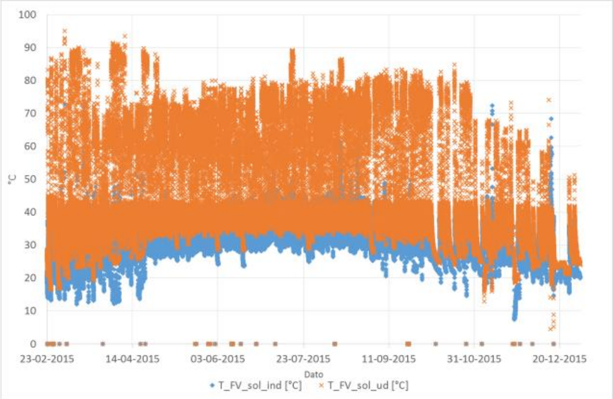

Figure 12: Input and output temperatures of the water side of the heat exchanger connected to the solar heat plant.

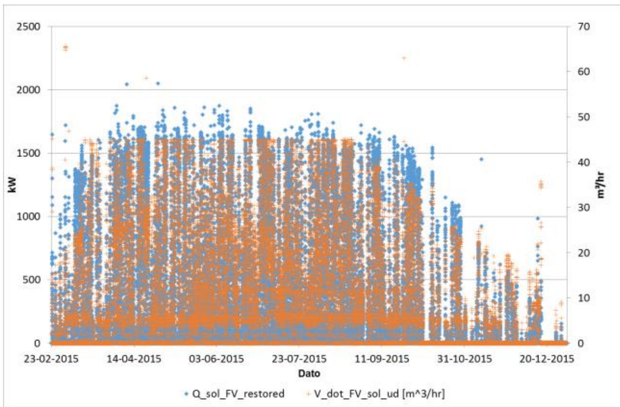

Figure 13: Heat output and the flow rate of the water side of the solar heat plant.

6. CONCLUSIONS

The solar heat and heat pump plant implemented and put into operation at “Rye Kraftvarmeværk” during 2014-2015 has met the expectations of a reduction in natural gas consumption by almost 80%. 2015 was not a complete year of operation and it has been influenced by start-up challenges, as the plant was not in operation until the 23rd of February.

The design and implementation of the plant has been successful and caused no major problems during the first year of operation.

The overall control of the plant seems to be very much in line with the control strategy when comparing the measured and calculated distribution of the heat production. The ability to act on the electricity market and operate the heat pump during the cheapest hours regarding electricity is demonstrated. The efforts however for reducing the output temperatures for the solar plant and heat pump does not seem to have a significant impact on the measured temperatures during the initial period of operation. This is expected to be better in the second year of operation.