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Flexibility of Large-Scale Solar Heating Plant with Heat Pump and Thermal Energy Storage

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Abstract

In the future energy system, based wholly on renewable energy sources, biomass is likely to become a scarce resource because of high demand especially by the transport sector. The current paper investigates, what is the possibility of utilizing excess electrical energy from renewable generation to decrease biomass use in a district heating system. The paper focuses on the renewable energy-based district heating system in Marstal, Denmark, with heat produced in central solar heating plant, wood pellet boiler, heat pump and bio-oil boiler. The plant has been the object of research and developments since its construction in 1996 and its operation is well documented. In the first part of the paper, the background of the current study is explained and the system in question is presented. Subsequently, the methodology of the study is explained and the model used in the study is described. Due to lack of widely accepted definition of a metrics for comparing system flexibility the paper proposes such an indicator. It was concluded, that cheap electricity can partially replace scarce biomass for heat production for district heating system.

Keywords: *Central Solar Heating Plant, District Heating, Heat Pump, Integrated Energy System*

1. Introduction

1.1. Background

The goal of the Danish energy system, including electricity, heating, industry and transport, is to wholly transition to renewable energy resources by 2050. In contrast to fluctuating renewable energy sources such as solar and wind energy, biomass offers generation flexibility on similar level as traditionally used fossil fuels. However, there is a number of considerations that need to be taken into account in case of evaluating environmental impact of biomass use for energy purposes. Removal of biomass can impact soil, hydrology and water quality, and habitat resources (Abbas et al., 2011). Reijnders (2006) lists a number of conditions that are required for sustainable biomass-for-energy production: levels of soil, organic matter and nutrients should not decrease over time, erosion and water usage should not exceed additions to soil and water stocks and the use of virtually non-renewable phosphate ores and fossil fuels should be significantly reduced. The author states also, that meeting such conditions requires major effort and most likely leads to relatively low productivity per hectare (estimated for around 3 metric tons per hectare per year of woody biomass, both in the temperate and tropical areas (Pimentel et al., 2008)). In Denmark, realistic biomass potential for energy purposes was estimated supply by Danish Energy Agency to be 20-25% of current total energy supply (Lund, 2007). Additionally, in the future energy system based wholly on renewable energy sources, in some development scenarios biomass is expected to be in high demand by the transport sector (Lund, 2007). Thus, its availability for heat production is going to decrease. It is also expected, that with increasing share of wind in electricity sector, periods when electricity generation exceeds the demand will occur more and more often. Thus, utilizing this excess electrical energy can provide an opportunity to simultaneously decrease biomass use for heating purposes and provide cost-effective heat generation.

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1.2. *Aim of the study*

The aim of the study was to investigate, to what degree the biomass use in the a large-scale solar heating plant with seasonal storage could be reduced through the use of heat pump during the periods with excess electrical energy generation from the fluctuating renewable sources. It was expected, that the central solar heating plant remains the main heat source for the system.

2. Methodology

2.1. *Investigated system*

The system investigated in the study is the district heating system in Marstal, Denmark. The system supplies heat to around 1,600 consumers. 50-55% of heat production comes from solar energy, 40% from a wood pellet boiler, 2-3% from a heat pump and the rest from a bio-oil boiler (Marstal Fjernvarme). Three solar collector fields sizing respectively, 9,000 m^2, 9,300 m^2 and 15,000 m^2. The plant has the thermal capacity of 23,300 kW_{th} and is equipped with water thermal energy storages of the size of 2,100 m^3 (steel tank), 10,000 m^3 and 75,000 m^3 (pit heat storages). The storage can act both as diurnal storage and seasonal storage. The plant runs with an adjustable flow both on the primary and secondary side. Thanks to this, it is possible to ensure requested outlet temperature through regulating the flow, using the efficiency curve for the solar collectors and taking into account sun radiation and return temperature to the collectors (PlanEnergi, 2013a). The first heat pump uses R290 as refrigerant and has the power use of 100 kW. The second heat pump uses CO_2 as a refrigerant and has the power use of 475 kW and thermal output of 1.5 MW_{th}. The 4 MW wood chip boiler includes thermal oil boiler for ORC and has a heat output of 3.25 MW (PlanEnergi, 2013a). The diagram of the existing system is shown in Figure 1.

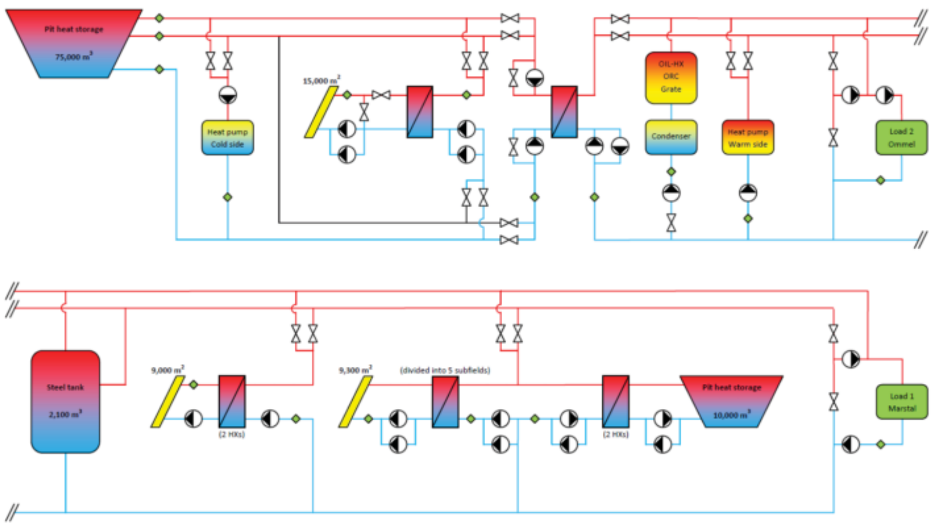

Figure 1. System diagram of the Solar District Heating plant in Marstal (PlanEnergi, 2013b)

The system was chosen as the subject of investigation, as has been the object of research and developments since its construction in 1996 and its operation is well documented (Fan et al., 2009; Heller, 2000; Heller and Dahm, 1999; Sørensen et al., 2012). Moreover, it is entirely based on renewable energy sources and therefore it is interesting in the context of developing such systems in the future.

2.2. *Model*

2.2.1. *Model with simple electric heater*

The model of the energy system in question was created by the Danish consultant company PlanEnergi in the TRNSYS software (Solar Energy Laboratory, 2014). The system was modelled in a simplified way, with the demand side represented in an aggregated way and certain simplifications on the supply side. The collector fields were modelled by using three separate 2nd-Order Incidence Angle Modifier (Type 1b) components representing the three collector fields. The largest pit heat storage was modelled in TRNSYS using the non-standard XST- Seasonal Ground Heat Storage component (Type 342) (Mazzarella and Holst, 1992). Two smaller storages were modelled as non-standard Type 340 (Multi-port water storage) (Drück, 2006). The heat pumps were modelled by a set of equation, not with the use of an existing TRNSYS heat pump component. The annual heat load was set at 32,000 MWh/year, the number of degree-days at 81834.3936 and the GAF ratio at 0.709. GAF is the part of heat demand dependent on the weather conditions (degree days) and the ratio expresses the share of heat demand dependent on the number of degree days in the total heat demand. The electricity prices used in the simulation were Elspot prices for DK-Vest for year 2009 ("Nord Pool Spot," 2016). Elspot is the day-ahead market for electrical energy operated by Nord Pool Spot. Nord Pool Spot is the market for electrical energy that operates in Denmark, Finland, Norway, Sweden, Estonia, Latvia, Lithuania, Germany and the UK ("Nord Pool Spot," 2016). Supply and return temperatures were set based on the measurements in the system. The supply temperatures are between 72 and 77 °C and the return temperatures between 33 and 41 °C. Bio oil boiler was modelled in a simplified way as an Auxiliary heater (Type 6) with the maximum heating rate of 10 MW. The ORC was set to operate from October 7th (280th day of the year) to June 6th (160th day of the year), to avoid using it in the summer period. Both heat pumps already existing in the system were set to operate from September 30th to April 1st (91st day of the year).

The reference model, was then validated by PlanEnergi (PlanEnergi, 2013a) by comparing the results from the model with the measurements taken in the year 2009. The new parts of the installation were disabled in the simulation (thus, no heat pumps or wood chip boiler were taken into account), as it was done before the expansion of the heating plant. The system in its current form and resulting mix of heat production technologies were taken as the reference.

The heat pumps or a potential electric boiler were identified as the elements of the systems that can be used to connect electrical and thermal energy systems. To investigate the possibility of decreasing the biomass use in favour of heat pumps during the low electricity price periods, the above model of the existing system was then modified to simulate the future application.

In an initial phase of the investigation, the system was expanded by a simple electrical heater placed before the wood chip boiler. This was done just to investigate how an additional heating source influences operation of the plant without introducing additional "disturbances" to the simulations. The efficiency of the heater was set to 1 and heat losses in this component were not accounted for. The electrical heater was set to operate during the periods, when the electricity price was below a certain set point. The same way as the ORC, additional electric heater was set to operate from October, 7th to June, 6th, to avoid using it in the summer.

A parameter variation on a) the size of the electric heater b) limit electricity price for the heater operation was carried out by simulation with the above TRNSYS model. The initial investigation for the data from 2009 was performed for electric heater sizes between 0.01 MW and 10 MW and for the price limit for electric heater operation between 0 and 300 DKK/MWh. Then, the range of analyzed electric heater sizes was limited to the range between 0.1 MW and 7.5 MW. This was done, as the smallest of the investigated heat sources did not have any significant influence on the system's operation. On the upper end of the parameter scale, the largest value is chosen to be able to supply the max demand of the whole district heating system. Results showed that values the 10 MW additional heater had power overshooting the largest observed load. Moreover, no significant increase in energy delivered by electrical heater was observed after increasing the heater size from 7.5 MW to 10 MW.

Then, influence of different price levels on the energy delivered by electrical heater (and subsequent reduction in biomass use by ORC unit) was investigated by running the simulations with the Nordic Elspot electricity prices from four different years (Energinet.dk, 2015). This was done to investigate sensitivity of the results concerning the amounts of biomass saved to the electricity prices, with respect to the variation in prices during the last years. Data from 2009 were used for the reference case. For the other three cases, data from 2006 (to represent a year with very high electricity prices), 2013 (a year with high electricity prices) and 2015 (a year with relatively low electricity prices) were used. Price curves for the years between 2000 and 2015 are shown below in Figure 2. The highest prices were not shown in the graph, as they occur for a very short period and do not influence the results of the investigation. It was assumed, that the heat demand was independent from the electricity prices and was the same in all analyzed cases.

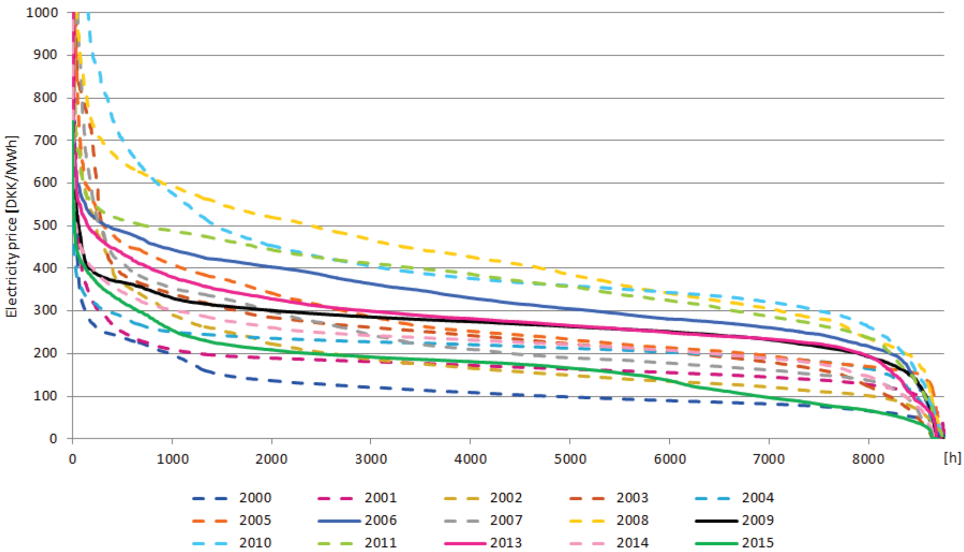

Figure 2. Elspot price curves for the period from 2000 to 2015 (Energinet.dk, 2015)

2.2.1. Model with heat pump

In the above simulation a simplified model with idealizes electrical heater was applied to find the overall potential for substituting part of the biomass use by the excess electricity. In the second model the heat pump was placed in the same spot in the system as the heater. Two sizes of the heat pump were investigated – the first one was chosen to correspond to the 1.25 MW electric heater, the second one to 3.25 MW electric heater. The absorbed power rating for the first heat pump was set at 350 kW and for the second one at 1050 kW.

The general control system in the modified model was not changed compared to the original model applied by PlanEnergy in 2013. The same way as the electric heater before, the heat pump was set to operate from October 7th to June 6th, to avoid using it in the summer period and so its operation substitutes the operation of ORC unit. As the data used is in 1-hour resolution, the concerns about the heat pump compressor turning on and off frequently for very short periods was not considered to be relevant. It was assumed the heat pump is a ground source heat pump. However, as the TRNSYS heat pump component (Type 927) requires more detailed input than the one that could be provided based on the model used, the heat pump was modelled using a set of equations, as two other heat pumps in the system. The equations used were based on the ones used for the propane heat pump. The investigation, due to its general character, was not aimed at optimizing the heat pump operation. It was assumed, that the mass flow through the warm side of the heat pump stays the same as the mass flow directed to boiler. To prevent circular reference, caused by making COP depend on the outlet temperature that at the same time can depend on the COP, the outlet temperature from the previous step was used, the same way it was done for CO_2 heat pump. The resulting COP levels correspond to the ones indicated in “Technology Data for Energy Plants” from Energinet.dk (Energinet.dk, 2012).

$$Q_{warm} = P_{HP} \cdot 3600 \cdot COP_{AHP\ warm} \cdot HP_{ON?} \qquad \text{(eq. 1)}$$

$$T_{WS\ out} = min(T_{setpoint} + 5, T_{WS\ in} + \frac{Q_{warm}}{c_{p\ water} \cdot m_{WS\ out}}) \qquad \text{(eq. 2)}$$

$$COP_{AHP\ warm} = 0.6 \frac{T_{WS\ out} + 273.15}{T_{WS\ out} - T_{CS\ in}} \qquad \text{(eq. 3)}$$

where: Q_{warm} – heat output of a heat pump [kWh], P_{HP} – electrical power used [kW], $COP_{AHP\ warm}$ - Coefficient of Performance of the heat pump operating as a heat source, $HP_{ON?}$ - is the heat pump on (1 if yes, 0 if no), $T_{WS\ out}$ – output temperature on the warm side [°C], $T_{setpoint}$ – setpoint temperature [°C], $T_{WS\ in}$ – input temperature on the warm side [°C], $m_{WS\ out}$ – mass flow on the warm side of the heat pump [kg/h], $T_{CS\ in}$ – input temperature on the cold side [°C].

The TRNSYS model of the modified system with a heat pump can be seen in Figure 3. The figure shows only the water loops of the model – layers with control systems, weather files and outputs were switched off to make the schematics clearer.

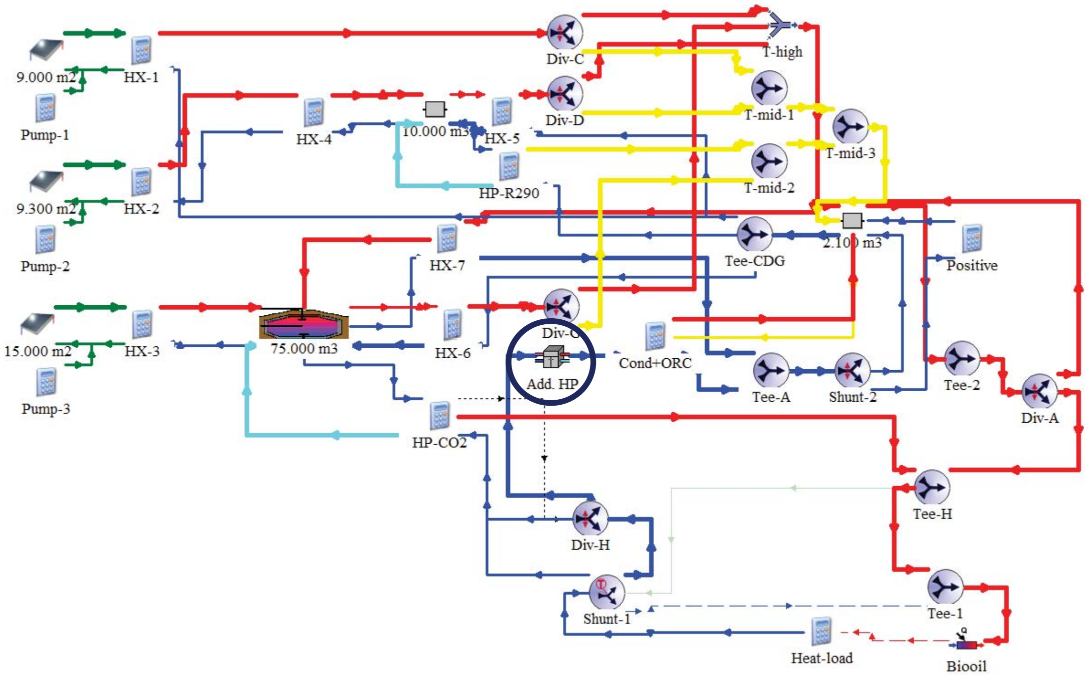

Figure 3. Model of the water loops in TRNSYS after modification. Left side of the model represents solar collector fields, connected to the rest of the system with the use of heat exchangers; followed by the storages (labeled "75..000 m3" and "2.100 m3" and "10.000 m3"); the black circle indicates additional heat source in the system added in the current investigation, "Cond+ORC" represents the woodchip boiler and ORC unit

2.3. Biomass use

The biomass savings were calculated in a simplified way, to estimate the amount of biomass saved thanks to substitution of ORC unit by the heat pump. First, the biomass burned to generate 1 MWh of heat was calculated. The fuel efficiency of the wood chip boiler in the ORC unit depends on the temperature of the cooling water, which is the return temperature from the district heating system. The return temperatures in the district heating system are between 33 and 41 °C, with the average return temperature of 36 °C. So, based on the information from the report by PlanEnergi (2013a), it was assumed the efficiency of the boiler is η = 108%. The heating value of the wood chips at 45% of moisture content was estimated as LHV = 2.63 kWh/kg, using the information from (WoodEnergy.ie, 2015). The amount of biomass saved, $m_{biomass\ saved}$, was calculated using eq. 4.

$$m_{biomass\ saved} = \frac{Q_{boiler\ ref} - Q_{boiler}}{\eta \cdot LHV} \qquad \text{(eq. 4)}$$

where: $m_{biomass\ saved}$ – mass of biomass saved [kg], $Q_{boiler\ ref}$ – heat output of the boiler in the reference scenario [kWh], Q_{boiler} – heat output of the boiler [kWh], η – efficiency of the boiler, LHV - lower heating value of the wood chips [kWh/kg]

2.4. Flexibility indicator

There is no one single, universal way of defining flexibility in literature (Alizadeh et al., 2016; Lund et al., 2015). Cochran et al. (2014) used the definition of flexibility as "the ability of a power system to respond to change in demand and supply". While flexibility is often defined as the ability of the system to shift the use of certain amount of energy in time (Nuytten et al., 2013; Six et al., 2011), it can relate to its ability to utilize different energy sources.

Based on the definitions from literature, in the context of this study, the energy flexibility of the system in question was defined as its ability to utilize different energy sources, also called fuel shifting. So, the energy in MWh that can be shifted over a year in an analysed scenario was used as an indicator of system's flexibility.

3. Results

3.1. Results for the model with electric heater

3.1.1. Change in production distribution and in biomass use

Results of the initial simulations done with the data for 2009 can be seen in Figure 4. The graph shows annual energy production by the biomass boiler in the Organic Rankine Cycle (ORC) unit and electric heater (added to the existing system) in MWh for different electric heater sizes and limit price set-points. It can be seen, that there is a significant increase in energy generation from the electric heater between the limit price of 200 DKK/MWh and 250 DKK/MWh. This is related to the shape of the electricity price curve and elaborated on in the further in the Discussion chapter. It should be noted, that for the heaters greater than 1.5 MW for limit price higher than 225 DKK/MWh temperature in one of the storages exceeded 100 °C. Heat delivered by the ORC and electric heater for these cases was not shown in the graph.

Additionally, the ratios between annual energy generation and heater size were compared for heaters of different sizes at different price limit levels. The results of this comparison indicated, that for the heaters up to 1.25 MW, this ratio remained constant and above that size gradually decreases. However, the smaller heaters were not able to replace significant part of the heat generation from the ORC unit – for the limit price of 225 DKK/MWh, electric heater of the size of 1.25 MW delivered 5.6% of energy generation of ORC unit (1,018 compared to 1,8087 MWh). Hence these sizes are excluded from further analysis.

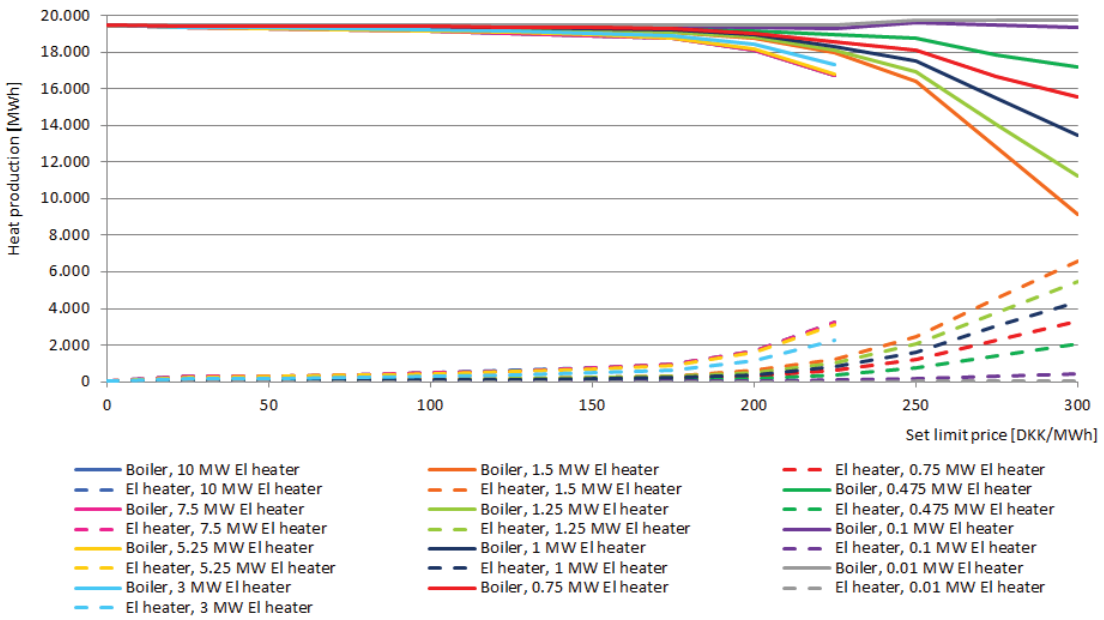

Figure 4. Heat generation by ORC unit and electric heater for different sizes of the heater and different levels of limit price for electricity prices from 2009

Subsequently, the following simulations were run for identical range of limit prices as above, but for the reduced range of heat source sizes 0.1 - 7.5 MW, using the electricity prices for year 2006, 2013 and 2015. Figure 5 shows how much heat can be delivered to the system by 1.25 MW electric heater for different limit price levels for electricity prices from different years. It can be seen that for 2015, a year with relatively low prices (Figure 2), energy delivered increases significantly at much lower limit price than in case of three other years. It can be seen that, as expected, electricity prices during the year have significant impact on the level of substituting biomass by electricity. For example, for the prices from 2006, for the limit price of 225 DKK/MWh, 1.25 MW electric heater delivered 948 MWh, and for the prices from 2013 - 928 MWh.

However, for the price levels from 2015, a heater of the same size delivered 5,981 MWh, so significantly more than both in 2006 and 2013. Additionally, small changes in the limit price may have significant influence on the substitution level, also due to the shape of the price curve. This can be seen for example for the data from 2015, where the energy delivered to the system by electrical heater at the limit price of 200 DKK/MWh is 201% of the energy delivered at the limit price of 175 DKK/MWh for the heaters between 0.1 MW and 1.5 MW.

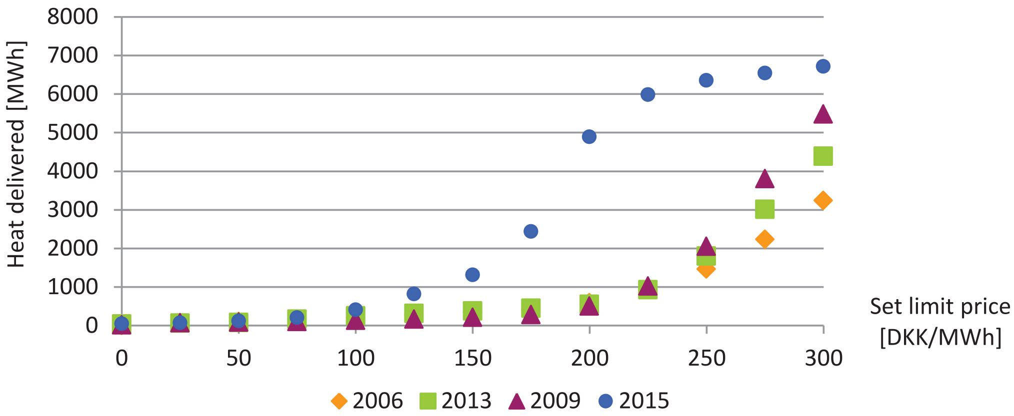

Figure 5. Heat delivered to the system by 1.25 MW electric heater for different limit price levels for electricity prices from different years

Figure 6 shows duration curves for the load, the ORC unit, the oil boiler and electrical heater (in case of the modified systems). All curves are based on results of simulations run with the electricity prices from 2009. Three cases of the systems with additional heater installed were shown: 1.25 MW heater with limit price of 225 DKK/MWh, 1.25 MW heater with limit price of 250 DKK/MWh and 3 MW heater with limit price of 225 DKK/MWh. It can be seen again that the slight increase in limit price resulted in significantly greater number of operation hours for the electric heater. Reduction in ORC unit operation occurred for all three shown cases, the greatest for the case with 1.25 MW heater and limit price of 250 DKK/MWh. The differences between cases with 1.25 MW heater and different limit prices is greater than between the case with 3 MW and 1.25 MW at the same limit price. However, it should also be noticed that the use of bio oil boiler is greatest for the case with highest degree of ORC unit substitution. This is caused by the fact that the operation of the electric heater prevents ORC unit from turning on, but the heat supplied is not sufficient to cover the system demand.

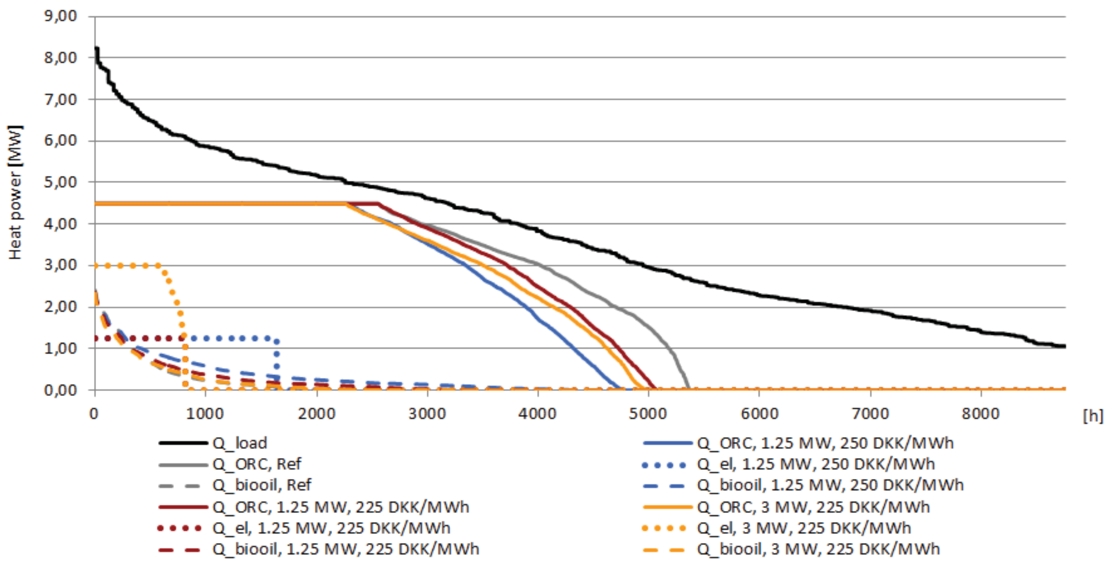

Figure 6. Duration curves for the load, the ORC unit and the oil boiler for the reference system

It was observed, that heater size at which the heat delivered by bio oil boiler changes the least between 2.70 - 3.25 MW. Thermal output of the ORC unit is 3.25 MW. This is caused by the fact that the operation of the electric heater prevents ORC unit from turning on, but the heat supplied is not sufficient to cover the system demand. Another problem at the investigated system configuration is the injection of the heated up water to the cold part of the 2,100 m^3 storage tank. This is also the reason of the overheating in 10,000 m^3 tank that occurs in systems with large supplementary electric heater at high limit prices, so if the heater operates for many hours during a year (exact level of the limit price depends on the price levels in a given year). Table 1 shows more detailed information about heat delivered by different technologies in the system and about calculated heat losses from heat storages. All the results presented in the table were calculated using electricity prices from 2009.

Table 1. Heat delivered by different technologies and thermal losses from heat storages

	Reference	**5.25 MW, 100 DKK/MWh**	**5.25 MW, 175 DKK/MWh**	**1.5 MW, 100 DKK/MWh**
	MWh/year	**MWh/year**	**MWh/year**	**MWh/year**
9,000 m^2 collector field	3.341	3.339	3.337	3.341
9,300 m^2 collector field	3.647	3.644	3.637	3.656
15,000 m^2 collector field	6.412	6.411	6.410	6.412
Collectors total	13.400	13.394	13.384	13.409
Propane heat pump	219	219	218	219
CO_2 heat pump	1.043	1.043	1.043	1.043
Heat pump total	1.262	1.261	1.261	1.262
2,100 m^3	-132	-132	-132	-131
10,000 m^3	-525	-525	-527	-524
75,000 m^3	-2.475	-2.476	-2.483	-2.475
Storage losses total	-3.132	-3.133	-3.142	-3.130
ORC	19.476	19.166	18.778	19.328
Electrical heater	-	438	903	158
Bio oil	996	873	816	973
Total	32.002	32.000	32.000	32.000

	1.5 MW, 225 DKK/MWh	**1.25 MW, 100 DKK/MWh**	**1.25 MW, 225 DKK/MWh**	**0.75 MW, 275 DKK/MWh**
	MWh/year	**MWh/year**	**MWh/year**	**MWh/year**
9,000 m^2 collector field	3.325	3.342	3.321	3.293
9,300 m^2 collector field	3.742	3.656	3.736	3.795
15,000 m^2 collector field	6.421	6.412	6.416	6.464
Collectors total	13.489	13.410	13.473	13.552
Propane heat pump	217	219	218	210
CO_2 heat pump	1.043	1.043	1.043	1.043
Heat pump total	1.260	1.262	1.260	1.253
2,100 m^3	-130	-131	-130	-128
10,000 m^3	-515	-524	-513	-513
75,000 m^3	-2.434	-2.475	-2.502	-2.315
Storage losses total	-3.079	-3.130	-3.144	-2.956
ORC	18.087	19.349	17.954	16.188
Electrical heater	1.018	133	1.219	2.282
Bio oil	1.224	976	1.236	1.679
Total	31.997	32.000	31.998	31.999

After this initial observation, additional simulations were run with the electric heaters at sizes between 1.5 and 5.25 MW. It was observed, that heater size at which the heat delivered by bio oil boiler changes the least between 2.70 - 3.25 MW. Thermal output of the ORC unit is 3.25 MW. This is caused by the fact that the operation of the electric heater prevents ORC unit from turning on, but the heat supplied is not sufficient to cover the system demand. Another problem at the investigated system configuration is the injection of the heated up water to the cold part of the 2,100 m^3 storage tank. This is also the reason of the overheating in 10,000 m^3 tank that occurs in systems with large supplementary electric heater at high limit prices, so if the heater operates for many hours during a year (exact level of the limit price depends on the price levels in a given year).

It was decided that for the needs of this study, the configuration of the system will not be modified. However, if the additional heat source is to be installed in the suggested place in the system, modification of the system and adjustment of the control scheme is necessary. This is further elaborated on the in the Discussion section.

3.1.3. Sizing of the supplementary heat source

Based on the initial investigation, two sizes of the heat pump were proposed 1.25 MW and 3.25 MW. The 1.25 MW heat pump was chosen, as it was the largest electric heater size for which the ratio between annual energy generation and heater size remained the same as for all smaller heaters. The 3.25 MW heat pump was chosen to investigate the situation where the supplementary heat pump has the same thermal output as the ORC unit.

3.2. Results of the simplified heat pump investigation

Schematic of the system with heat pump in question is shown in Figure 3. Results of the performed simulations can be seen in Figure 7. Heat generation by ORC unit and additional heat pump for different sizes of the heat pump and different levels of limit price for electricity prices from 2009 The graph shows annual energy production by the biomass boiler in the Organic Rankine Cycle (ORC) unit and heat pump in MWh for two heat pump sizes and different limit price set-points. It can be seen, that there is a significant increase in energy generation from the heat pump between the limit price of 200 DKK/MWh and 250 DKK/MWh, similarly as it was for the simplified electric heaters. It should be noted, that for the larger heat pump 250 DKK/MWh temperature in one of the storages exceeded 100 °C, similarly as it was in case of the electric heater. Energy delivered by the ORC and electric heater for these cases was not shown in the graph.

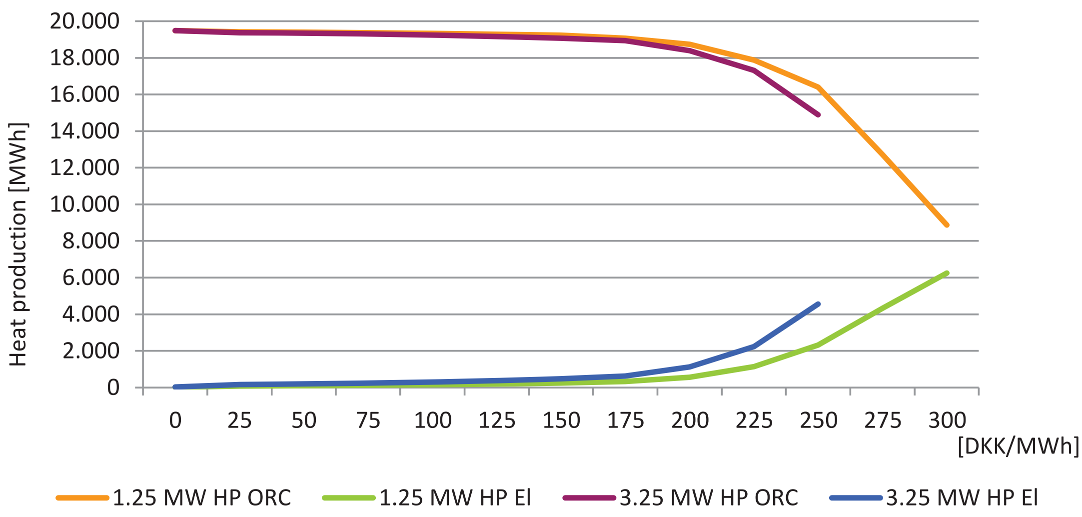

Figure 7. Heat generation by ORC unit and additional heat pump for different sizes of the heat pump and different levels of limit price for electricity prices from 2009

3.2.1. Change in production distribution and in biomass use

Figure 8 shows the energy production in each month both for the reference case and for two heat pump cases, with the share coming from bio oil use and delivered by heat pump highlighted (yellow parts). It can be seen, that they do not constitute significant part of the production. However, introducing the heat pump to the system leads to the decrease in heat production from biomass boiler in the ORC unit that is directly substituted by the heat pump. This shows the potential for biomass savings due to a combination of low electricity prizes and the potential of the heat pump installed. It can be seen, that this potential in the proposed setup is not significant compared to the energy output of the whole system.

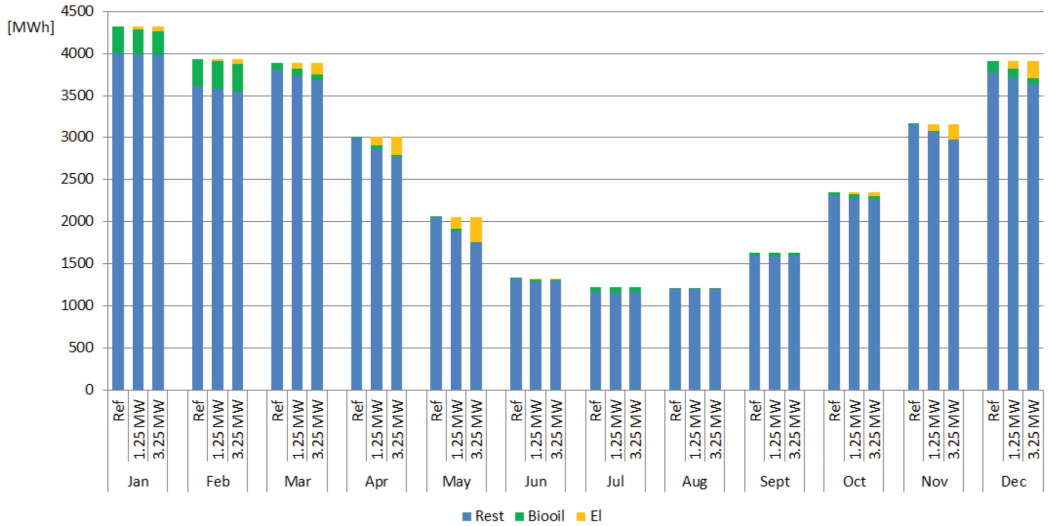

Figure 8. Monthly heat production for the reference case and two heat pump cases with the production from bio oil boiler and additional heat pump highlighted

Amount of biomass saved annually thanks to the use of heat pump for two investigated heat pump sizes at different limit prices is presented in

Table 2.

Table 2. Biomass saved for two investigated heat pump sizes at different limit price levels

Limit price [DKK/MWh]		**25**	**50**	**75**	**100**	**125**	**150**	**175**	**200**	**225**	**250**	**275**	**300**
Biomass replaced by electricity [tonne]	**1.25 MW HP**	18	26	35	47	64	84	145	260	563	1080	2381	3734
	3.25 MW HP	36	46	62	82	110	143	189	381	759	1613		

3.3. Flexibility of the system

Finally, the flexibility of different systems was compared. We decided to use the energy in MWh that can be shifted over a year as an indicator of system's flexibility under chosen control conditions. System's flexibility understood that way increases with the increase in the size of additional heat source. For the system with 1.25 MW heat pump was calculated to be 153 MWh annually for the set limit price of 100 DKK/MWh, 320 MWh for 175 DKK/MWh and 2324 MWh for 250 DKK/MWh. For the system with 3.25 MW heat pump it was calculated to be 301 MWh annually for the set limit price of 100 DKK/MWh, 630 MWh for 175 DKK/MWh and 4552 MWh for 250 DKK/MWh. After adjusting the system control to cope with additional large heat source, the flexibility indicators independent of the control scheme and set limit price should be established. This is further elaborated on in the Discussion.

4. Discussion

One of the assumptions made in the analysis is related to the use of electricity prices as an input for control system. In the study, electricity prices from Nordic Elspot market were used as a control signal for the additional electricity-based heat source, with a constant price limit indicating whether the electric heater / heat pump should turn on or not. Low electricity prices occur in periods when expected demand is relatively low compared to the expected supply. Very low electricity prices in Denmark are frequently associated with periods of high electricity production by wind turbines. However, middle-sized district heating utilities are not participating in trade at Nord Pool. So, in the current conditions, proposed solution brings no economic benefit for the district heating plant and is beneficial only from the perspective of energy system as a whole.

It was assumed, that the heat demand was identical for all analyzed cases for different electricity prices and thus, indirectly, that heat demand and electricity prices are fully independent. This is a simplification. However, it was decided that electricity market prices are influenced by numerous factors not connected to the local heat demand and that such an assumption provides a good way of investigating the influence of electricity prices during a year on the analysis' results.

Another factor that significantly influences the results is the set limit price and market electricity prices. As it was discussed in section 3.1, the exact energy delivered to the system by additional electricity-based heat source during a year is very sensitive to the set limit price and price levels on the electricity market. This causes trouble in case of a potential economic analysis, when estimating e.g. Net Present Value of the system's modification. Additionally, results of such analysis would be also heavily influenced by assumptions on future energy market and taxation.

In the proposed system setup, operation of the additional heat source competes with the operation of ORC unit. So, if the district heating utility benefits from selling electricity generated by the ORC unit, adding additional heat source in proposed configuration decreases this profit. However, it can be argued, that generating electricity during the low-price periods does not benefit energy system as a whole and should be avoided.

As it was mentioned in section 3.1.1, it was decided that for the needs of this study, the configuration of the system will not be modified. However, if the additional heat source is going to be installed in the system, adjustment of the setup and control strategy would be necessary. Such an adjustment would have to include connections between the electric heater / heat pump, boiler and ORC unit and heat storages. Moreover, it should be assured that the operation of the additional heat source does not result in increase in energy delivered by the bio oil boiler – both for economic and for environmental reasons. After this adjustment, also the flexibility indicator for a given system configuration should be estimated, by calculating theoretically possible heat production by the additional electrical heat source when the set limit price is higher than highest electricity price during a year.

5. Conclusions

We showed in the paper that cheap electrical energy can replace scarce biomass in a large-scale solar heating plant with large storage capacities. However, location of the additional heat source in the system and control scheme for the new setup need to be carefully considered, as there is a risk the new heat source will destabilize system's operation, as it was shown. Increasing the size of additional heat source increases also system's flexibility, understood as the ability to utilize different energy sources, but makes incorporating in the existing system more difficult and results in high investment costs. Results of the performed study indicate, that for the system in question the potential for such a replacement is not significant. Additionally, results are characterized by large uncertainties due to the significant influence of the level of electricity prices on the results in the proposed control strategy. While the investigation was made based on the solar district heating plant and renewable-based district heating system in Marstal, Denmark, we believe that such solution can also be applicable for other similar systems, where biomass is used as supplementary heat source.

In further work, we will investigate the possibility of replacing biomass that may become a scarce resource, by cheap electricity from renewable sources for a district heating system with seasonal storage based on different energy sources than solar energy. This will be done for a generic model also with that will be applied on concrete city districts.

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