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Heat Pumps for Domestic Hot Water Preparation in Connection with Low Temperature District Heating

Appendix 4: Calculations on Different Concepts for LTDH HP

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Work Package 03

Calculation on different concepts for LTDHHP

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Introduction:

In the project at hand, heat pumps have been proposed to increase water temperature on either primary or secondary side of the district heating network heat exchanger. Several concepts are briefly presented in a separate note. The focus of this note is to evaluate the most promising candidates in terms of energy efficiency for the tap water heat exchanger, heat pump and storage system with variable temperature of forward and return of district heating system. Not all of the different candidates are evaluated, as some could be disregarded due to practical constraints. The evaluation is considering both first- and second law of thermodynamics, as the systems will be part of a major calculation of efficiency.

Two basic concepts are considered: primary side (District heating water heated in condenser and stored in the tank) and secondary side (Tap-water heated in condenser and stored in tank - requires a set minimum temperature to avoid legionella). Additionally, the most promising concept is changed, in order to evaluate the effect of using district heating return to supply the source heat for the evaporator. The concepts are:

- A1 - Variant primary 1
- A2 - Variant primary 4 (with/without preheating)
- B1 - Variant secondary 1 (with/without preheating)
- B2 - Variant secondary 2
- C1 - Variant primary 1 (source heat from District heat return line)

The results presented in this note is intended for further analysis, as the impact of reducing supply temperature will influence both space heating and hot tap water efficiencies, cost and dimensioning. It is important to note, that that tap-water only corresponds to between half and one third of the combined heat consumption in the house. Losses in the district heating system may be significant compared to the losses and additional consumption from introducing a decentralised heat pump in the system.

Assumptions:

The calculations are based on the assumptions presented in figure 1. Assumptions are made based on best guesses for a small decentralized heat pump producing hot tap water by use of low temperature district heating network.

Table 1 - Assumptions for low temperature district heating network heat pump

Variable	Assumption
Pinch temperature in Tap-water HEX (Q=32 kW)	8 [K]
District heating Network forward	40 [C]
District heating Network Return	22 [C]
Refrigerant	R134a
Isentropic efficiency of compressor	0,5 [/]
Pinch in condenser and Evaporator	2,5 [K]
Tap water out (at both types of load)	45 [C]
Tap water in	10 [C]
Minimum temperature in secondary tank	58 [C]

Of particular interest is the fixation of both forward and return temperature, as changes in both temperature levels will have major impact on the performance results. The temperatures chosen represent a best guess on steady state performance of the district heating network. As individual concepts may differ in performance from changes in forward and return temperatures, an evaluation of the effects is presented for the most promising configurations.

As the system is comprised in a novel district heating network, where reasonable temperatures on especially return side is based on assumptions, several factors may influence the results. When approaching a return temperature close to ambient (in this work represented by the cold tap water) several constraints appear, as heat exchangers are finite sizes in application.

In the conducted calculations heat exchange between district heating water and tapping water is assumed with a constant pinch temperature of 8 [K], as high flow rates occur in the tap water system. The pinch temperature corresponds to the highest flow of tap water, but is assumed constant across the entire range of tap water flows (worst case).

Regarding heat storage and heat pump on either primary or secondary side, some assumptions are introduced:

- With heat pump and storage on primary side of the network, only the tapping temperature dictates the temperature of the storage in the calculations.
- Employing the Heat pump on the secondary side of the system, the tap water is stored at high temperatures. Concern must be regarded towards legionella, which the heat pump system must be able to prevent and even remove the bacteria. Taking into account some of the heat losses that may emerge in a real system, the heat pump must deliver the tap water at minimum 58 [C]. With higher temperatures in the storage, the volume of water required for the dynamic operation is lowered.

In order to dimension the different heat pumps and storage tank sizes, a heat demand profile from Danish building standards is used. As the recovery time for the system (storage empty -> storage full) is not expected to exceed 3 hours, only the time interval between 6.00 AM and 7.05 AM has been considered in these calculations, as the time until next tap is almost 2 hours according to the standard. Only for the tapping sequence from 6.00 AM to 7.05 AM a full heat storage will be needed. For this period it is assumed, that there is no tapping in the preceding hours. In the calculations presented below, the interaction between heat pump and storage tank is dimensioned to always accommodate a “refilling” (heating of water in tank – all cold -> all hot) in two hours.

The profile presented in figure 1, correspond to the tapping and refilling profile considered. The concept considered in the figure corresponds to configuration A1, but identical profiles are experienced in the four remaining configurations. Some assumptions correspond to the profile:

- Second law observations (exergetic efficiencies) are based on fuel and product for the combined period considered in figure 1 - corresponding to 185 minutes of heat pump operation.
- The tapping sequence is assumed to correspond to 45 [C] tapping temperatures during the entire profile (small setoff from standard – where some are 40[C]).

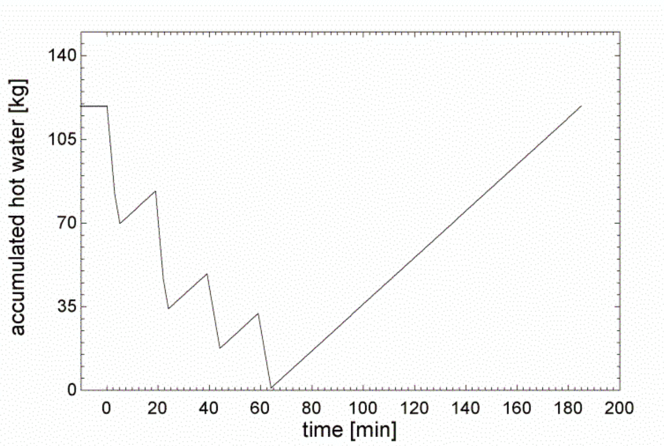

Figure 1 - Tapping and refilling sequence considered.

As can be seen on Figure 1, the heat pump is working continuously during the taping procedure, thereby reducing the required amount of stored hot water. With a larger heat pump capacity, this can be reduced even further. At the same time the heat pump capacity influences the "recovery time" of the hot water storage. In this way, proper dimensioning of the heat pump capacity can reduce the required volume of storage. Heat loss from the stored hot water has not been considered, as an almost equivalent amount of stored hot water is required in all the configurations. Figure 2 presents the relation between volume of storage tank and the heat pump capacity defined by the "Recovery time"

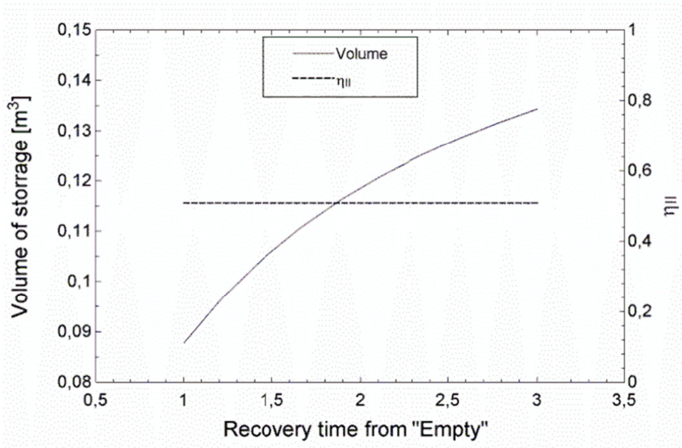

Figure 2 - Influence of "Recovery time from Empty"

In some of the considered configurations direct heat exchange between the tap water and the district heating forward stream can be beneficial ("preheating"), both in terms of exergetic efficiency and to reducing the amount of electricity required in the heat pump. In these cases the dimensions of the district heating network will be challenged, as higher volume flows of DH will be needed. "Preheating" is not beneficial in all cases, as the required temperature of the heat pump may increase correspondingly.

Calculation of individual concepts:

A1 - Variant primary 1:

The heat pump is modeled according to the simplified PI-diagram presented in Figure 3. The forward stream supplies DH water for both the evaporator and the condenser. The two streams are mixed in the return flow, combining the residue heat from the evaporator and storage/ tap water HEX.

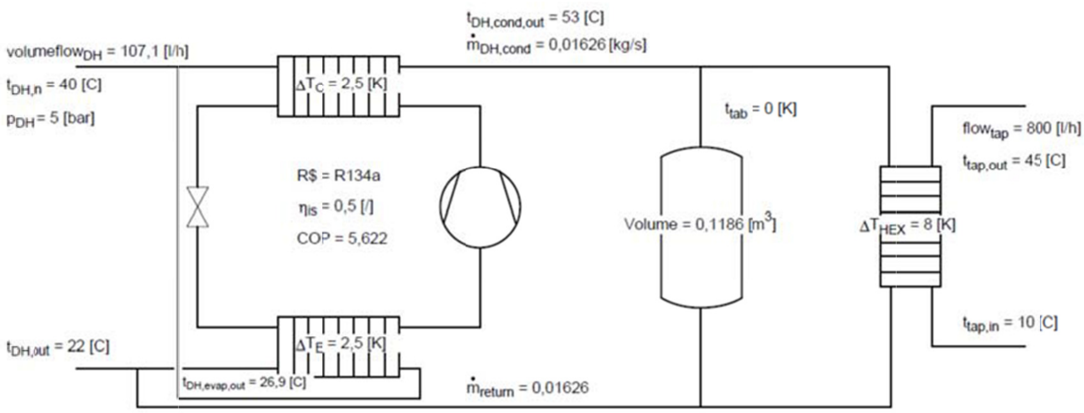

Figure 3 – Simplified diagram of A1

Variant	DH [l/h]	DH (max) [kW]	Condenser [kW]	P [kW]	Heat pump COP [/]	Water Volume [L]	Exergetic eff. [/]
A1	107,1	2,22	0,88	0,157	5,62	118,6	0,44

Due to the build of 'variant 1', preheating of the tap water is not possible, as the return temperature is set for 22 [C] (as the cold tap water dictates the temperature of DH-water leaving the tap water HEX . With the set pinch temperature in the heat exchanger, preheating may (likely) be beneficial with higher return temperatures in the network).

The forward temperature of the DH has a high impact on the system performance.
Figure 4 shows the performance variation with variation in forward temperatures of the district heating network. Power consumption and the district heating load are presented as a function of the product - this is to represent how much power and heat load is required in order for the system to produce one [kWh] of hot tap water at 45 [C]. Furthermore the second law efficiency is presented on the figure at the right hand side along with COP of the heat pump pack. Approaching the temperature required for tap water heating (53 [C] when considering a pinch temperature of 8 [K]), the consumption of electricity is reduced significantly; while a higher flow rate is required from the district heating network. With increase in forward temperature the second law efficiency is increased as the power consumption decreases.

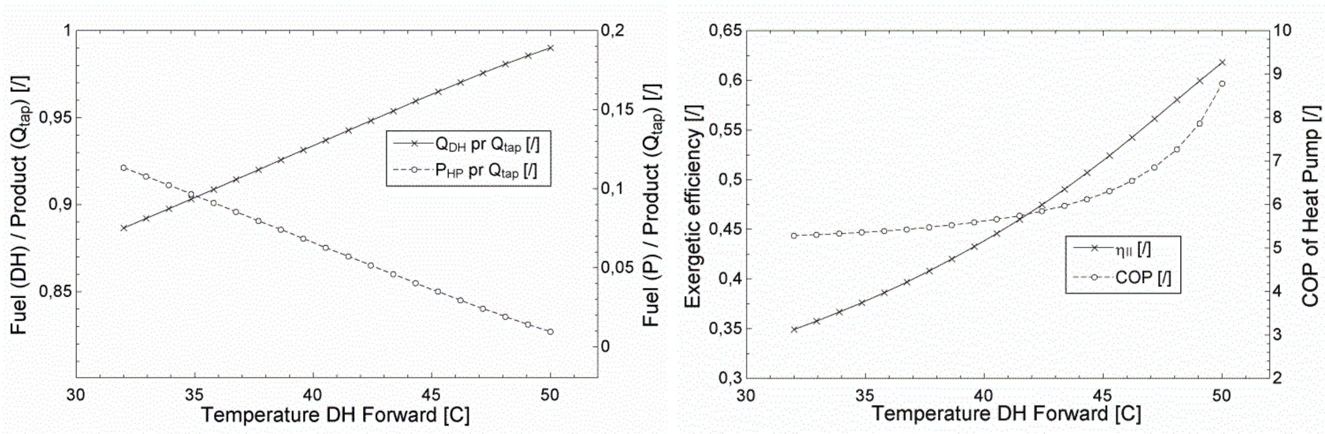

Figure 4 - Changes in forward temperature of the DH-network with the A1 configuration

As discussed in the introduction, the return temperature is a significant parameter for the dimensioning of the district heating network, as the temperature level will have a significant effect on the piping dimensions and pressure losses. An evaluation of the heat pump characteristics with a change in return temperature is considered in Figure 5.

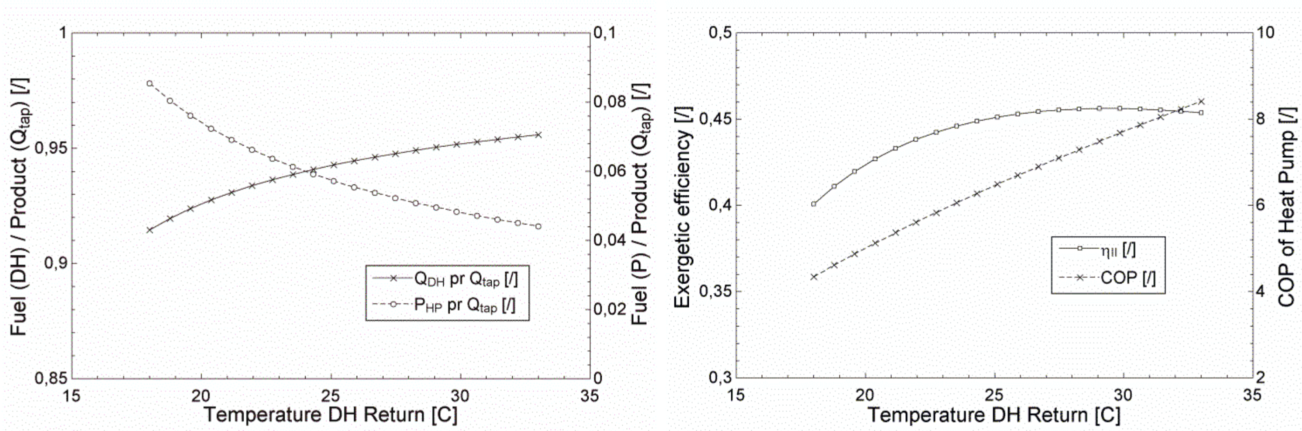

Figure 5 - Changes in return temperature of the DH-network with the A1 configuration

Assuming tap water at 10 [C], and a finite heat exchanger (8 [K]), 18 [C] is the lowest reachable temperature for the return water in the district heat system by direct heat exchange. Lower temperatures can only be achieved by using the heat pump evaporator to cool the stream further.

A2 - Variant primary 4:

The heat pump is modeled according to Figure 6. Without using preheating, district heating is only supplied to the evaporator. The condenser and storage tank is a closed loop of DH-water.

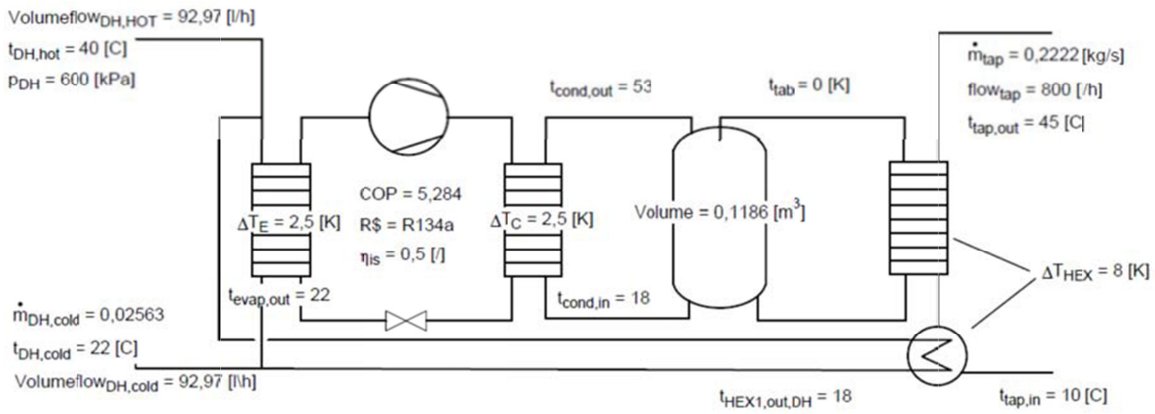

Figure 6 - Simplified diagram of A2

	DH [l/h]	DH (max) [kW]	Condenser [kW]	P [kW]	Heat pump COP [/]	Water Volume [L]	Exergetic eff. [/]
A2	92,97	1,93	2,38	0,450	5,28	118,6	0,23
1 kW preheat	147,8	3,06	2,25	0,403	5,57	116,4	0,24
5 kW preheat	364,9	7,57	1,72	0,259	6,64	105,7	0,25

Based on assumptions from table 1, the result from this configuration is presented in the table above. Using preheat to heat the tap water has a limited effect on the second law effectiveness of the system. According to Figure 7, the optimum preheat (without consideration to the DH-network) is around 5 [kW]. Second law efficiency of 'Variant 4' will never reach the reference 'Variant 1'.

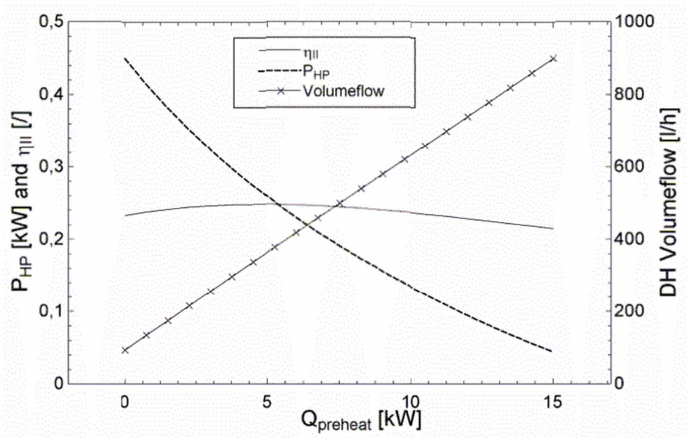

Figure 7 - Efficiency of 'Variant primary 4' with variable Preheat

Similar reduction of exergetic efficiencies are found for variation of district heat forward and return temperatures compared to A1. The significantly higher heat pump load in A2, introduces increased losses to the system. No further work is done to characterise this configuration.

B1 - Variant secondary 1:

B1 is alike A2, but with condenser and storage tank on the secondary side. Without considering preheating, only the evaporator is feed with district heating water. The flow diagram is presented in Figure 8.

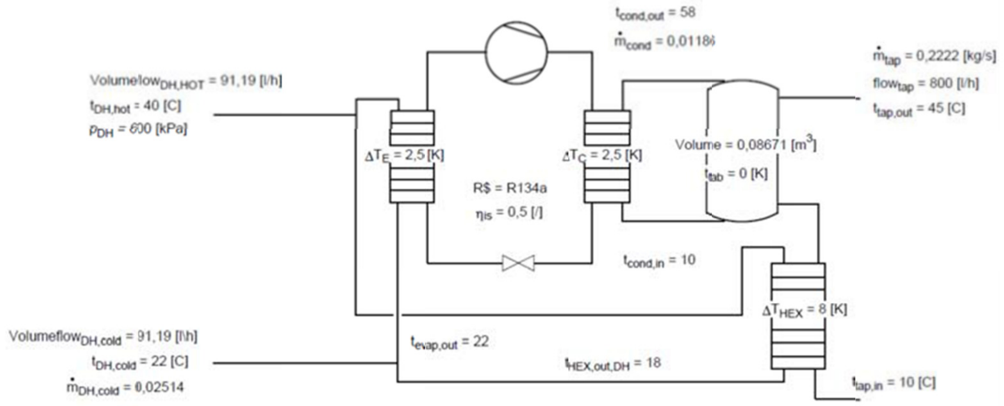

Figure 8 - Simplified diagram of B1

	DH [l/h]	DH (max) [kW]	Condenser [kW]	P [kW]	Heat pump COP [/]	Water Volume [L]	Exergetic eff. [/]
Variant 1	91,2	1,89	2,38	0,487	4,88	86,7	0,22
1 kW preheat	147,4	3,06	2,29	0,448	5,11	86,7	0,22
5 kW preheat	371,5	7,70	1,93	0,331	5,82	86,7	0,22

Results from evaluation of configuration B1 is listed in the table above. In Figure 9 both the power consumption and the exergetic efficiency is plotted with increasing use of preheating of the tap water. As can be seen, power consumption can be reduced by utilizing additional preheat, but the exergetic efficiency of the combined operation is not increasing accordingly. This is due to the very high volume flow of district heating water.

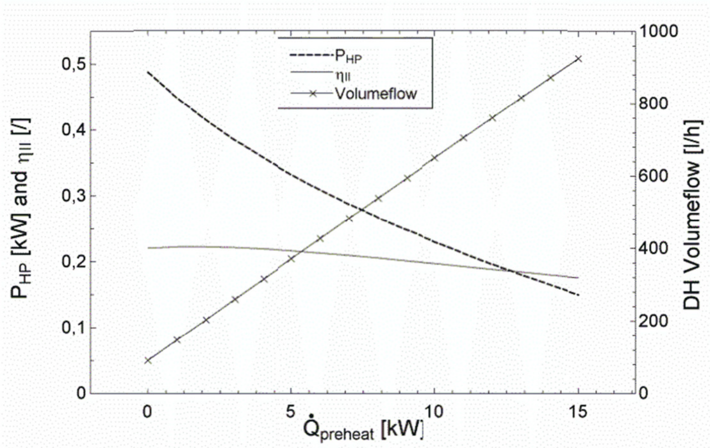

Figure 9 - Effects of preheating with heat pump on secondary side '(variant secondary 1')

The configuration B1 cannot be increased to levels matching either A1 or B2 (next) in terms of exergetic efficiency. No further work is done to characterise this configuration.

B2 - Variant secondary 2:

The configuration of this system allows only one set amount of preheating to be utilized. The setup is much alike the setup from B1, but where the DH-water preheats the small stream of tap water between the condenser and the storage tank. As the preheat is only a limited stream of tap water at a time, the pinch temperature difference in the preheater has been chosen to correspond to the pinch temperature in the condenser. Preheating reduces the thermal load of the condenser. The simple diagram of B2 is presented below in Figure 10:

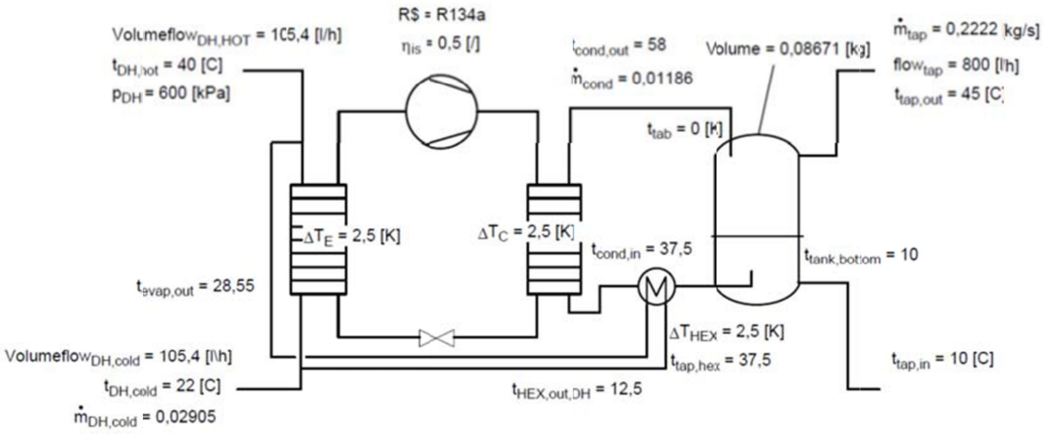

Figure 10 – Simple diagram of B2 (set preheating)

	DH [l/h]	DH (max) [kW]	Condenser [kW]	P [kW]	Heat pump COP [/]	Water Volume [L]	Exergetic eff. [/]
Variant 1	105,2	2,19	1,02	0,193	5,26	86,7	0,39

Variation of forward temperature in the district heating network is presented in Figure 11, with similar setup as in Figure 4. As the heat pump has a higher condenser load in B2 (as in A1), the electricity consumption for the heat pump is increased correspondingly, and thus lowering the exergetic efficiency. The requirements towards the district heating network are comparable between B2 and A1.

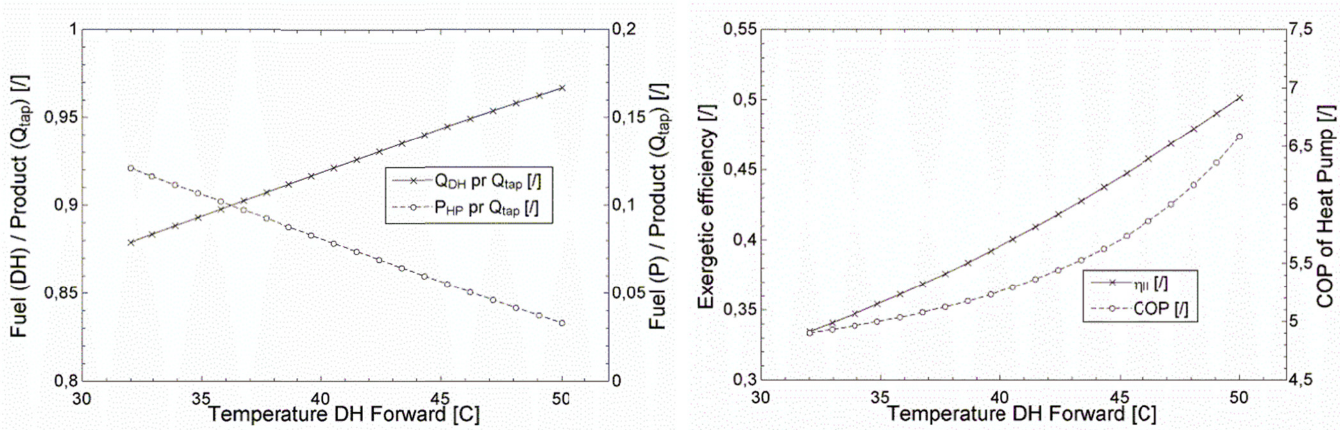

Figure 11 - Changes in forward temperature of the DH-network with the B1 configuration.

Similar variations have been done to the return temperature of the district heating network in Figure 12. Comparing with Figure 5, the tendencies are similar, although the consumption of electricity is increased due to higher heat pump load, lowering the exergetic efficiency. The higher load is due to the higher temperatures in the storage tank and mixing of tap-water after the tank.

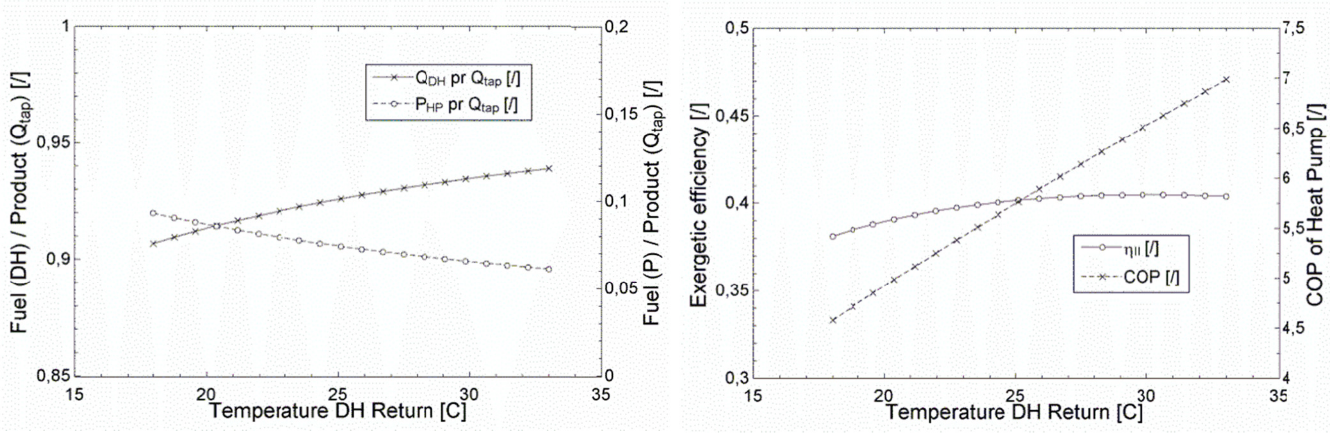

Figure 12 - Changes in return temperature of the DH-network with the B1 configuration.

Additional subtraction of source heat from district heating return water:

Correct implementation of heat pumps ensures the needed relationship between heat and power consumption. In this project, another possible solution is to supply configuration A1 with "waste" heat instead of district heat. Return temperatures are often just as constant as forward temperatures in the district heating network, and as such just as suited for heat extraction.

C1 - Variant primary 1 (heat source on Return):

Heat can be extracted from space heating return flow, or even from the system return line. High temperatures in the heat supply for the evaporator is of cause an advantage, in order to minimize the temperature lift between condenser and evaporator.

- 'Flow x0' is only using the return stream from either the tap water heat exchanger or the storage tank.
- 'Flow x1' is an equivalent additional amount of return flow (most likely from space heating) with temperature 22 [C] and mass flow equivalent to the return from "flow x0"
- 'Flow x2' and 'Flow x3' is increasing the amount of return district heat from space heating or equivalent.

Figure 13 presents the simple flow diagram. The concept is quite similar to A1, except for the extraction of waste heat.

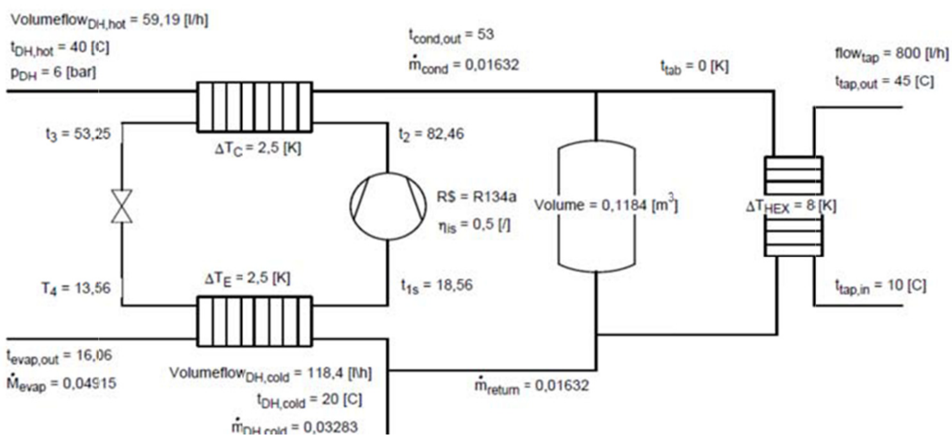

Figure 13 - Simple diagram of C1 (heat source on Return)

Variant	DH [l/h]	DH hot (max) [kW]	DH cold [kW]	Condenser [kW]	P [kW]	Heat pump COP [/]	Water Volume [L]	Exergetic eff. [/]
Flow x0	59,19	1,50	0	0,89	0,252	3,52	118,4	0,40
Flow x1	59,19	1,50	0,47	0,89	0,219	4,05	118,4	0,45
Flow x2	59,19	1,50	0,64	0,89	0,207	4,27	118,4	0,47
Flow x3	59,19	1,50	0,72	0,89	0,201	4,40	118,4	0,48

In the calculation of exergetic efficiency for this system, the exergetic content of district heating water is only accounted between supply temperature and 22 [C] corresponding to Table 1. This is done to produce a fair comparison with the remaining systems considered in this note, as the different flow-configurations does not give directly comparable results. Accounting the waste heat in the calculation would require a specification on the effects to heat and electricity production in Denmark. As potential improvements in power production is possible the use of waste heat is considered of no additional cost for the consumer.

With no adjacent heat requirement in the house, the heat pump unit will operate on only the return stream from the tap water heat exchanger. As the return temperature in this system is an output, only an evaluation of the forward temperature is interesting. It is clear that the configuration will allow for a significantly lower DH-flow requirement - compared to the variant A1 and B2 - as expected.

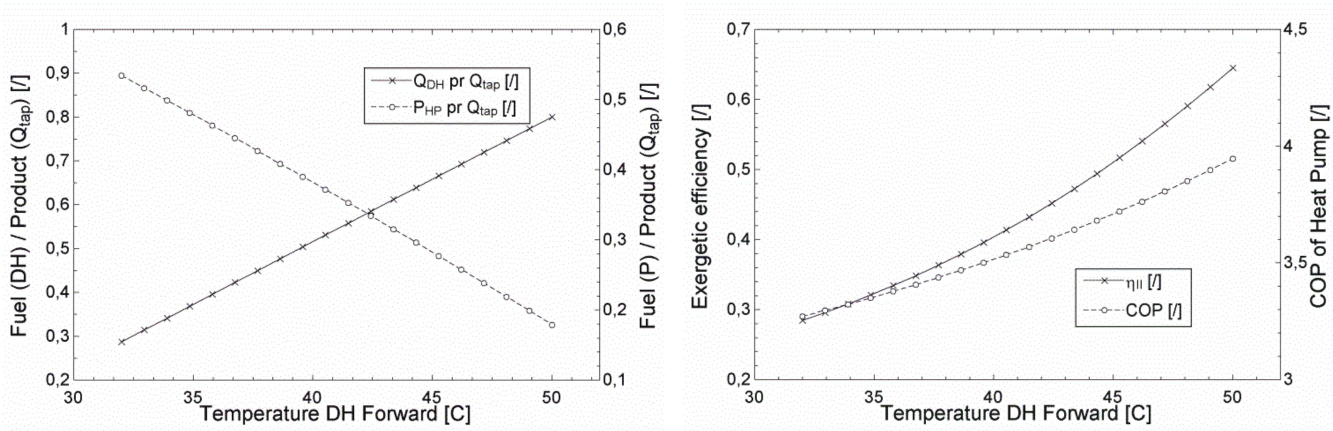

Figure 14 – Evaluation of heat and power demand for the DH-network with the C1 configuration without surplus heat addition

Considering available surplus heat, the system efficiency improves, as higher evaporation temperature lowers the temperature lift of the heat pump. These effects can be seen in Figure 16 and Figure 16.

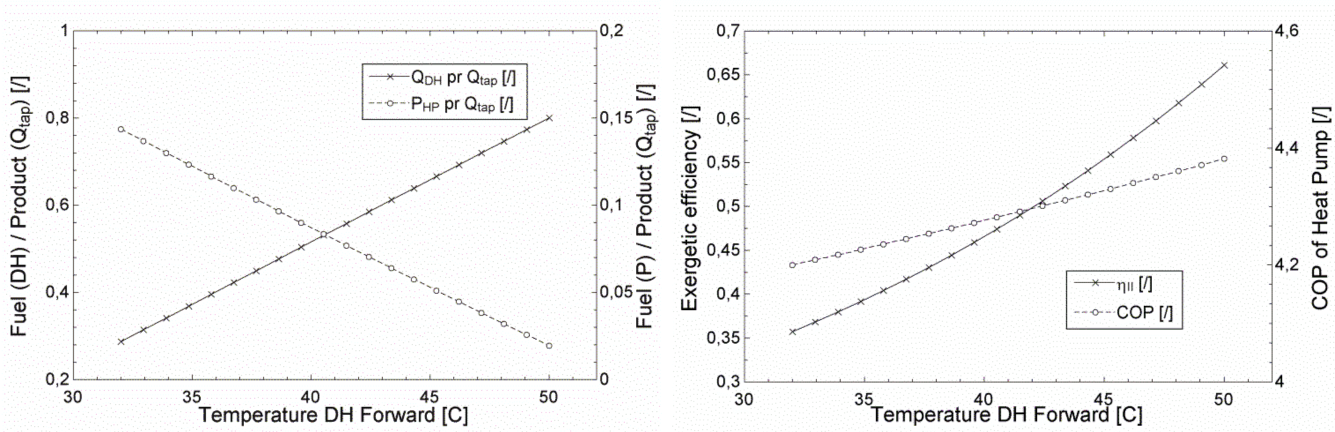

Figure 15 - Changes in forward temperature of the DH-network with the C1 configuration.

Figure 15 present the Fuel / Product relation from varying the forward temperature and variation of the return flow is presented in Figure 16. The two figures are comparable with Figures 4-5 and 11-12.

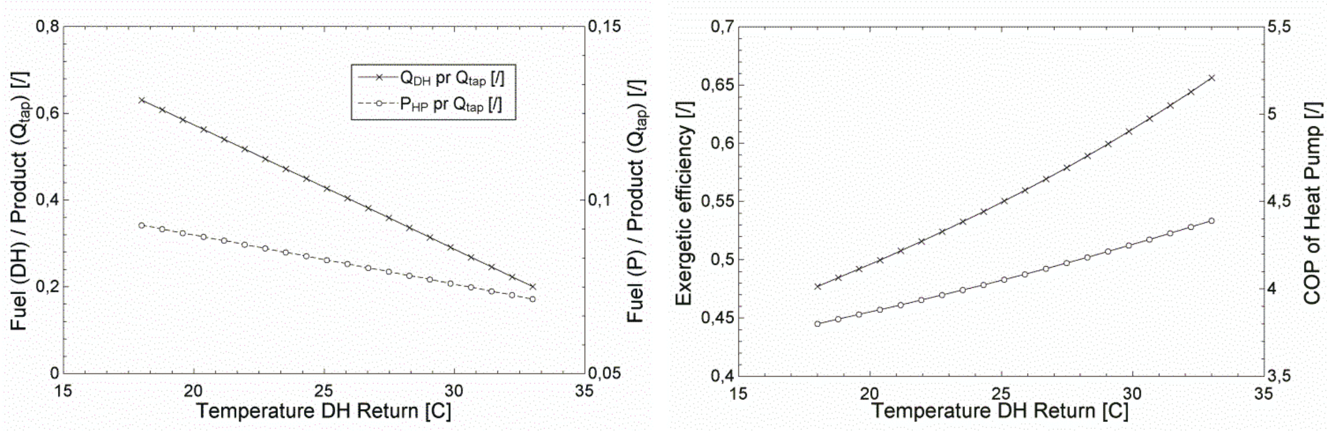

Figure 16 - Changes in return temperature of the DH-network with the C1 configuration

Final outline:

Out of the different heat pump configurations in the note "advantages/disadvantages heat pump", five different systems have been evaluated. Out of the five different variants, three different configurations were singled out for further analysis

A1 – Lowest power consumption of the investigated configurations independent of the district heating forward and return temperatures.

B2 – Most efficient "secondary" solution. Lower second law efficiency due to the increased temperature level of the storage tank, and mixture after storage tank. Close to the performance of A1

C1 – Possibility to reduce return temperatures significantly (2-5 K dependent on configuration). With space heating, this variant has the highest second law efficiencies.