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

Appendix 3: Basic Concepts of Hot Water Supply in Low Temperature District Heating

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Work Package 02

Basic Concepts of Hot Water Supply in Low Temperature District Heating EUDP project

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1 Introduction

Comparison of basic concepts for space heating and domestic hot water in conventional district heating and low temperature district heating networks based on time-averaged calculations. The basis is an annual consumption of 4010 kWh for space heating and 3200 kWh for hot water.

This results in that averages of 365 W hot water and 458 W space heating are consumed. Space heating is provided at 30/22°C and hot water at 50/10°C. Hot water is supplied from a tank which may be located on the primary (district heating) side or on the secondary (consumer) side in the system. In the cases where the hot water storage is located on the secondary a temperature of 60°C is required in the tank.

Heat loss is based on an estimated heat loss coefficient per unit pipe length of 65 W/km°C. The length of forward and return pipes in the network is 3.6 km. The ground temperature is assumed to be 10°C. Heat loss is only considered in the distribution network.

The following cases have been studied:

- Conventional system 80/40°C
- Conventional system 65/55°C
- Conventional system 60/30°C
- Low temperature system with electric heating 45/25°C
- Low temperature system with heat pump and secondary side tank 45/25°C
- Low temperature system with heat pump and secondary side tank and preheating 45/25°C
- Low temperature system with heat pump and primary side tank 45/25°C

The heat pump systems are calculated for both a conventional R134a heat pump cycle and a transcritical CO₂ cycle.

The transmission system operates at 85/60°C to cover all cases.

The following parameters are used throughout the calculations:

Minimum temperature difference in heat exchangers	2.5	K
Minimum temperature difference in heat exchangers in network	5	K
Minimum temperature difference in tank coil	5	K
Isentropic efficiency of heat pump compressor	50	%
Pressure loss	0	Pa

The consumer cost of the energy supply is calculated by estimated electricity and district heating prices of 2.20 DKK/kWh and 0.56 DKK/kWh, respectively, in a conventional system. Benefits of decreased heat loss are assigned to the consumer prices in low-temperature scenarios.

2 Method

2.1 Energy and Exergy

The results of the calculations are the required heat supply from the transmission system, the electricity demand and the total heat loss.

The results are quantified in terms of energy and exergy. For energy a unit energy from district heat and electricity are equal, which makes it ambiguous to define a meaningful efficiency. Contrary, exergy not only measures the energy content, but also takes the “quality” of the energy into account. In thermodynamics exergy is defined as the maximum work that may be extracted from a given amount of energy. This theoretical measure may, however, be described in several ways that show the value of exergy as a measure of quantity and quality of energy. Exergy may namely also be stated to be the part of an amount of energy that can be converted into any other energy form by a thermodynamically reversible process. For, e.g., electric, mechanical, kinetic and potential energy this fraction is 1, whereas for heat and substances at finite temperature the fraction is less than unity.

Exergy will due to irreversible energy conversion be destroyed and is closely related to entropy that is generated, due to the Guoy-Stodola theorem. It states that exergy destruction and entropy generation are proportional:

$$E_{dest} = T_0 S_{gen} \quad (1)$$

The two quantities are related by the reference temperature. This shows that exergy is a state variable when the reference conditions p_0 , T_0 are decided. In the present case they are set to 1 bar and 10°C, respectively.

Primary energy sources as fuel, solar, and wind can all be found to be exergy within 5% accuracy. This shows that exergy destruction is also a quantification of the primary energy supply to a system.

Primary energy utilization in the system may thus be evaluated by the exergetic efficiency:

$$\eta_x = \frac{\dot{E}_{prod}}{\dot{E}_{cons}} \quad (2)$$

In the present case the exergy consumption is electricity and district heat, exergetic product is the space heating and domestic hot water.

$$\eta_x = \frac{\dot{E}_{dhw} + \dot{E}_{sh}}{\dot{E}_{dh} + \dot{E}_{el}} \quad (3)$$

As changes in kinetic and potential energy are neglected and chemical reactions do not occur, only the physical exergy of the flows is calculated. It is given as:

$$\dot{E} = \dot{m}(h - h_0 - T_0(s - s_0)), \text{ where } h_0 \text{ and } s_0 \text{ are found at } (p_0, T_0) \quad (4)$$

In the present case the exergy input to the heat supply system is defined to be the transmission network. This means that it is assumed that the heat in the transmission system is assumed to have

been produced by a reversibly (Carnot) engine driving a reversible (Carnot) heat pump that produces the heat in the system at 85°C/60°C. Similarly, the consumed electricity is assumed to be produced by a reversible engine. This is naturally not the case, so in order to quantify the primary energy utilization the calculated exergetic efficiencies should be multiplied by the exergetic efficiency of the CHP production to the transmission system. In the Danish energy system, this efficiency is about 45%, presently.

Stating exergy to be a measure of quality, is correct in the thermodynamic sense. Monetary value does not reflect this completely, heat usually has a higher price than what would be determined by adding economy to the exergy analysis, termed a *thermoeconomic* analysis. We thus do not intend to give information about market prices, but only to indicate to what extent primary energy is utilized in the different cases.

The exergy content of the energy supply to the consumers is 1 kWh exergy/kWh electricity and 0.18 kWh exergy per unit district heat from the transmission grid.

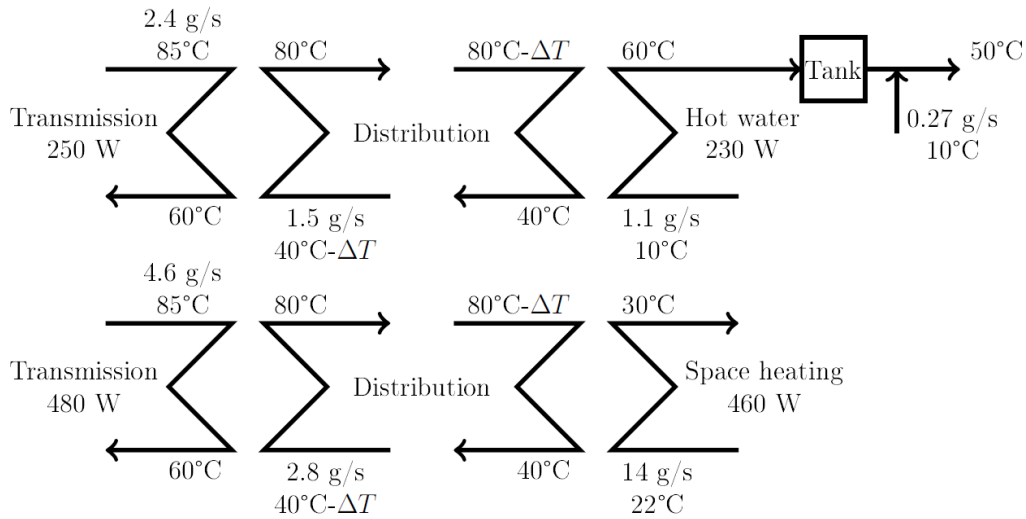
The exergy cost per unit of electricity supply is equal to the electricity price, 2.2 DKK/kWh. For heat the cost per unit exergy is 2.6 kr/kWh.

This shows that even though exergy is a common measure of any energy supply, the price of an exergy unit is not the same in practice. In this case heat has an 18% higher cost than it should have based on the exergy content.

3 Results

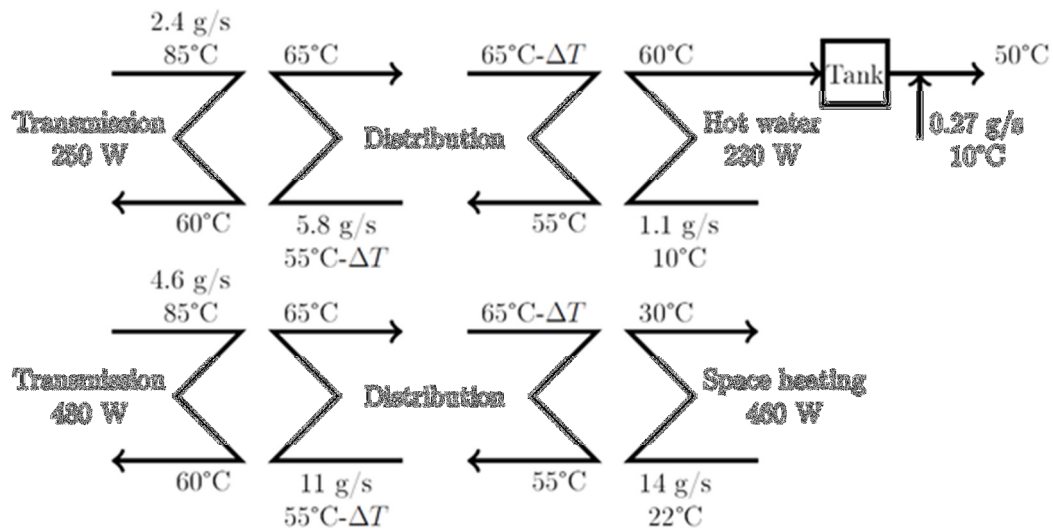
3.1 Conventional District Heating

3.1.1 80/40°C



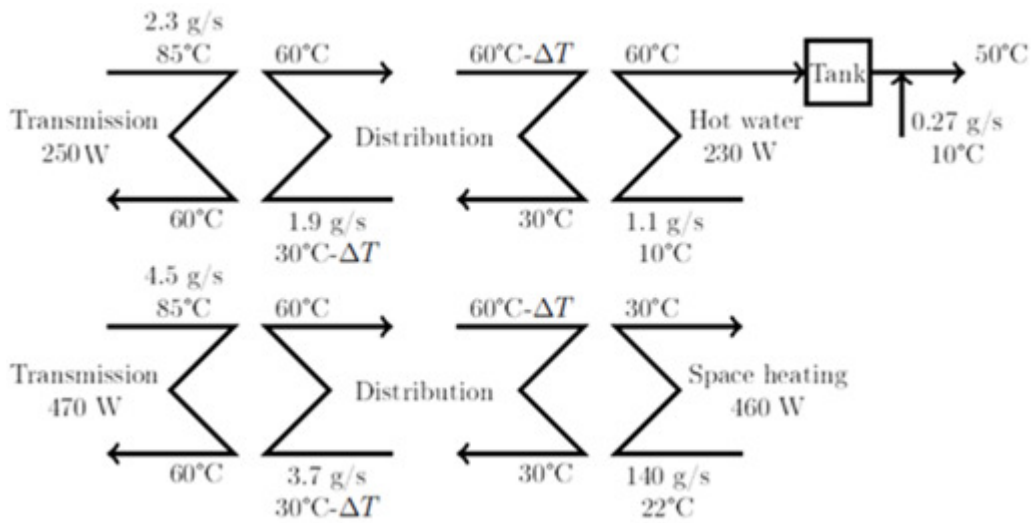
	Energy [W]	Exergy [W]	Exergetic efficiency [%]
Hot water			32
Hot water supply	230,	15,	
Heat loss	24,	4,0	
District heat consumption	250,	46,	
Space heating			28
Heat supply	460,	25,	
Heat loss	25,	4,1	
District heat consumption	480,	87,	
Total			30
Heat supply	690,	40,	
Heat loss	49,	8,1	
Heat consumption	730,	133,	
Power consumption	0,0		

3.1.2 65/55°C



	Energy [W]	Exergy [W]	Exergetic efficiency [%]
Hot water			32
Hot water supply	230,	15,	
Heat loss	24,	3,8	
District heat consumption	250,	46,	
Space heating			28
Heat supply	460,	25,	
Heat loss	25,	3,8	
District heat consumption	480,	87,	
Total			30
Heat supply	690,	40,	
Heat loss	49,	7,6	
Heat consumption	730,	133,	
Power consumption	0,0		

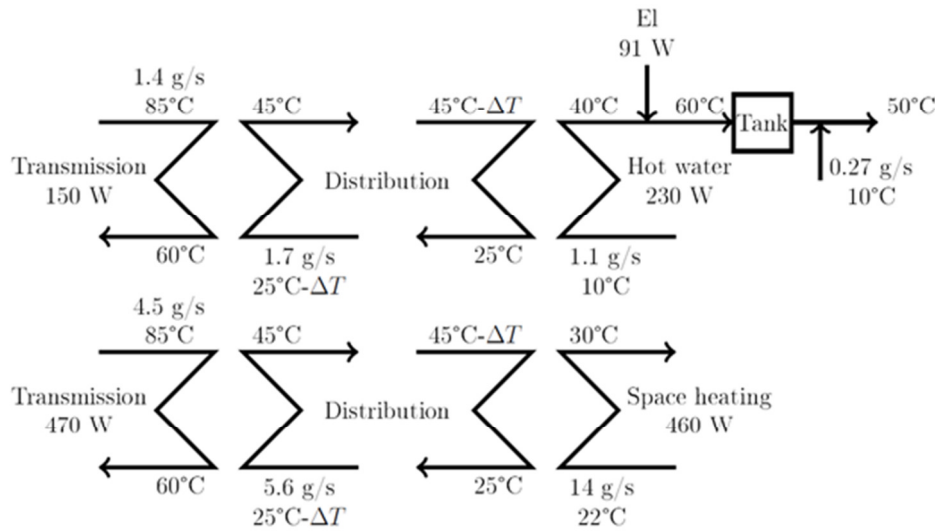
3.1.3 60/30°C



	Energy [W]	Exergy [W]	Exergetic efficiency [%]
Hot water			33
Hot water supply	230,	15,	
Heat loss	13,	2,1	
District heat consumption	250,	44,	
Space heating			29
Heat supply	460,	25,	
Heat loss	17,	2,2	
District heat consumption	470,	86,	
Total			31
Heat supply	690,	40,	
Heat loss	30,	4,3	
Heat consumption	720,	130,	
Power consumption	0,0		

Notice violation of temperature constraints in domestic hot water heat exchanger

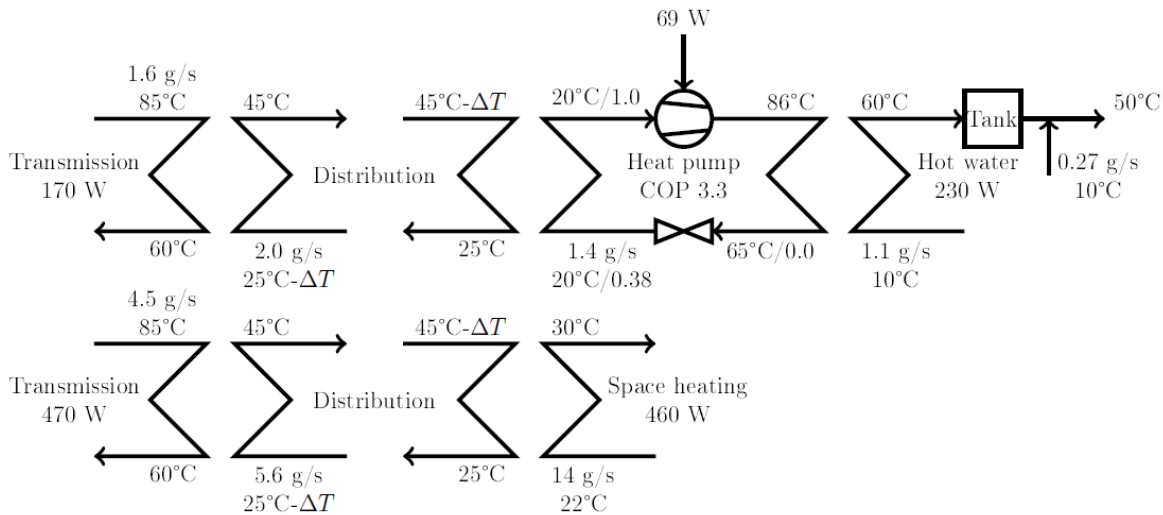
3.2 Low Temperature District Heating 45/25°C with Electric Heating



	Energy [W]	Exergy [W]	Exergetic efficiency [%]
Hot water			12
Hot water supply	230,	15,	
Heat loss	12,	1,1	
District heat consumption	150,	27,	
Electricity consumption	91,	91,	
Space heating			29
Heat supply	460,	25,	
Heat loss	12,	1,1	
District heat consumption	470,	84,	
Total			20
Heat supply	690,	40,	
Heat loss	24,	2,2	
Heat consumption	620,	111,	
Power consumption	91,	91,	

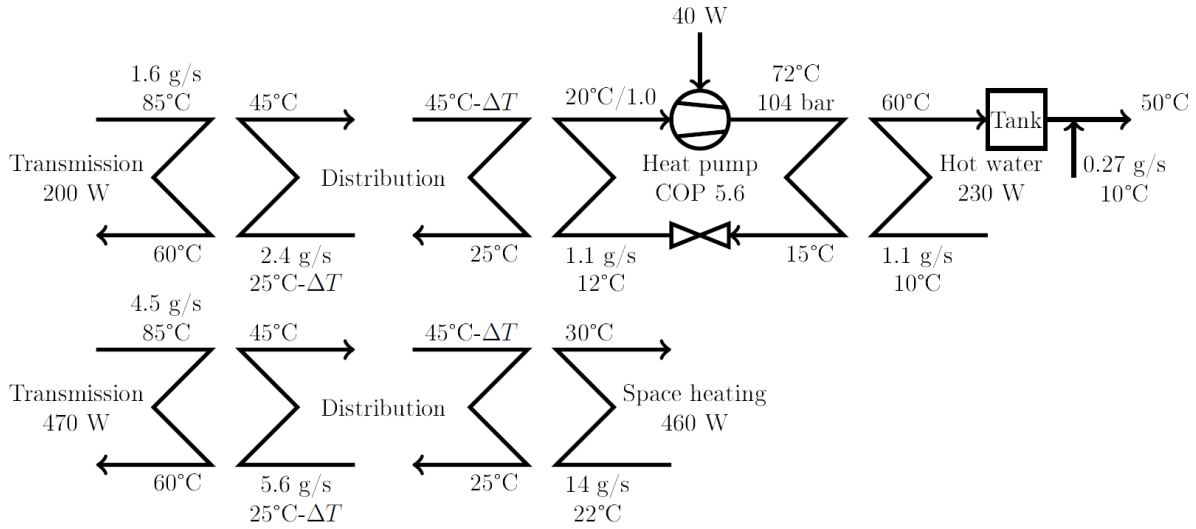
3.3 Low Temperature District Heating with Heat Pump and Secondary Side Tank

3.3.1 R134a



	Energy [W]	Exergy [W]	Exergetic efficiency [%]
Hot water			15
Hot water supply	230,	15,	
Heat loss	12,	1,1	
District heat consumption	170,	31,	
Electricity consumption	69,	69,	
Space heating			29
Heat supply	460,	25,	
Heat loss	12,	1,1	
District heat consumption	470,	84,	
Total			21
Heat supply	690,	40,	
Heat loss	12,	2,2	
Heat consumption	640,	120,	
Power consumption	69,	69,	

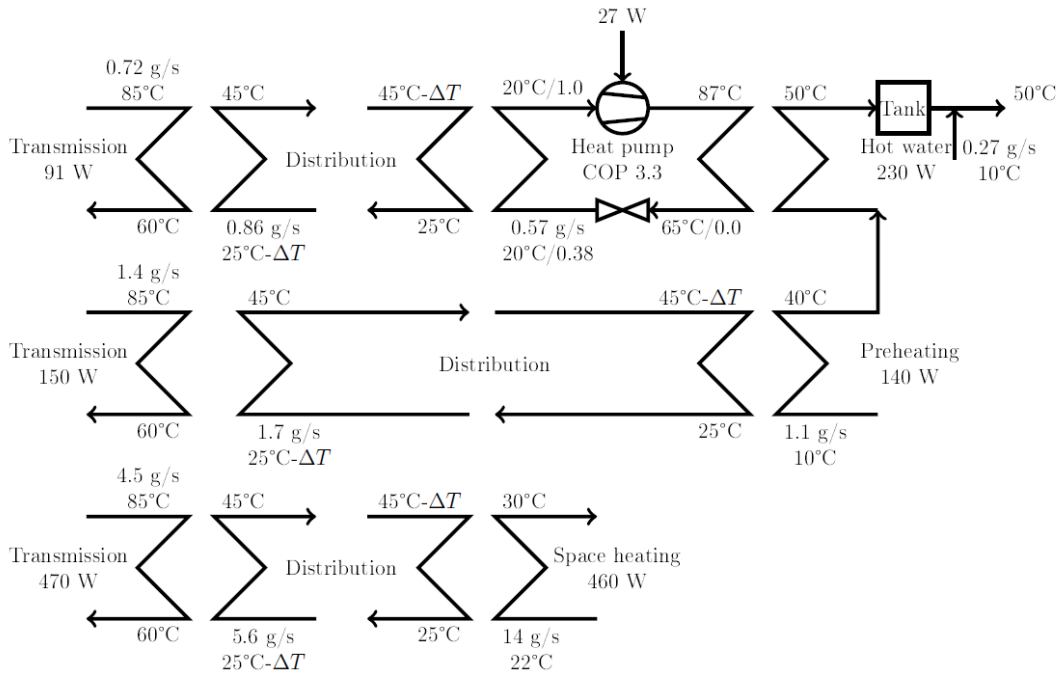
3.3.2 R744



	Energy [W]	Exergy [W]	Exergetic efficiency [%]
Hot water			19
Hot water supply	230,	15,	
Heat loss	12,	1,0	
District heat consumption	200,	36,	
Electricity consumption	40,	40,	
Space heating			29
Heat supply	460,	25,	
Heat loss	12,	1,1	
District heat consumption	470,	84,	
Total			25
Heat supply	690,	40,	
Heat loss	12,	2,2	
Heat consumption	640,	120,	
Power consumption	40,	40,	

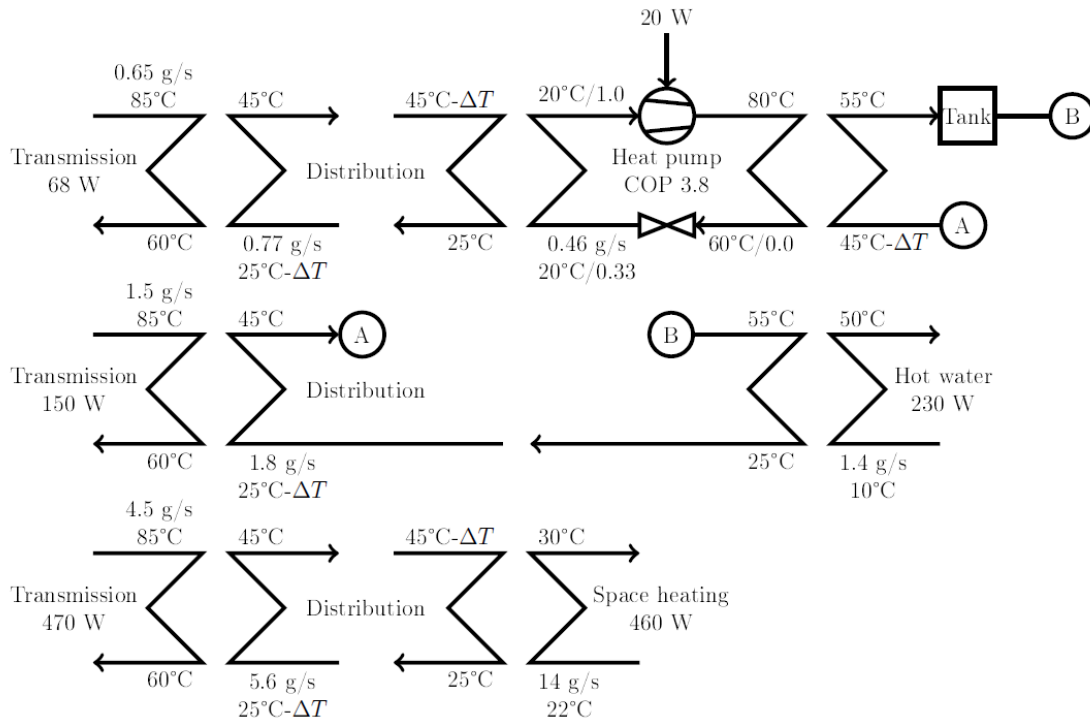
Notice that the supercritical refrigerant is cooled to below the heat source temperatures in the gas cooler.

3.4 Low Temperature District Heating with Heat Pump and Secondary Side Tank – Preheat configuration



	Energy [W]	Exergy [W]	Exergetic efficiency [%]
Hot water			22
Hot water supply	230,	15,	
<i>Evaporator side</i>			
Heat loss	4,2	0,39	
District heat consumption	76,	14,	
<i>Preheating</i>			
Heat loss	7,8	0,71	
District heat consumption	140,	25,	
<i>Heat Pump</i>			
Electricity consumption	27,	27,	
Space heating			29
Heat supply	460,	25,	
Heat loss	12,	1,1	
District heat consumption	470,	84,	
Total			27
Heat supply	690,	40,	
Heat loss	24,	2,2	
Heat consumption	670,	123,	
Power consumption	27,	27,	

3.5 Low Temperature District Heating with Heat Pump and Primary Side Tank



	Energy [W]	Exergy [W]	Exergetic efficiency [%]
Hot water			24
Hot water supply	230,0	15,	
<i>Evaporator side</i>			
Heat loss	12,	1,1	
District heat consumption	68,	12,	
<i>Condenser side</i>			
Heat loss	0,25		
District heat consumption	150,	27,	
<i>Heat pump</i>			
Electricity consumption	20,	20,	
Space heating			29
Heat supply	460,	25,	
Heat loss	12,	1,1	
District heat consumption	470,	84,	
Total			28
Heat supply	690,	40,	
Heat loss	12,	2,2	
Heat consumption	680,	123,	
Power consumption	20,	20,	

3.6 Overall Results

In summary the results of the above calculations are:

System	Distribution temperatures [°C]	Refrigerant	Heat pump COP [-]	Tank location	Preheating	Heat consumption [W]	Electricity consumption [W]	Exergetic Efficiency [%]
Conv. 1 (sec. 3.1.1)	80/40	–	–	Secondary		730	0	30
Conv. 2 (3.1.2)	65/55	–	–	Secondary		730	0	30
Conv. 3 (3.1.3)	60/30	–	–	Secondary		720	0	31
LT EL (3.2)	45/25	–	1.0	Secondary		620	91	20
LT HP 1 (3.3.1)	45/25	R134a	3.3	Secondary		640	69	21
LT HP 2 (3.3.2)	45/25	R744	5.6	Secondary		640	40	25
LT HP 3 (3.4)	45/25	R134a	3.3	Secondary	×	670	27	27
LT HP 4 (3.5)	45/25	R134a	3.8	Primary		680	20	28

The results show that the exergetic efficiency of the conventional system configurations is higher than in the low temperature cases. This is caused by the low exergy content of heat at the relatively low temperatures in the system. However, the difference in efficiency is low if compared to the best low temperature solutions which are R134a heat pump with primary side tank and with secondary side tank and preheating. The former is considered to be the best solution and it will reach exergetic efficiency of the same values as the conventional system if the minimum temperature differences in the heat pump evaporator and condenser are lowered to 2.5 K.

It should also be noted that the best solution with a 60/30°C distribution network actually involves a temperature crossover, which means that it is not a realistic solution as is.

The three latter heat pump solutions are close in performance. The R744 system may be competitive even though the efficiency is lower than for the R134a solutions. R744 has several advantages such as being a natural refrigerant with very low global warming potential (GWP), a low safety classification and a low price. Other refrigerants that do not operate in a transcritical cycle may have similar performance as R134a and may thus also be competitive.

5 Conclusion

Eight configurations for supply of heat for tap water and space heating in a district heating system have been studied to determine the demands for heat and electricity supply. It is found that the systems all have a primary energy utilization, i.e., exergetic efficiency, of 20-30%, and thus that significant potential for improvement theoretically exists. The exergy utilization in the presented systems does not include the CHP production, so the primary energy utilization is only about half of the presented values.

Conventional systems with higher temperatures in the network have a better utilization than low temperature solutions, as the decrease in heat loss does not compensate the electricity demand to cover the energy consumption. However, district heating will probably in general be converted to lower temperature and thus a heat pump solution is required.

The results show that a solution with R134a, or other subcritical systems, with heat storage on the primary side, will have lowest primary energy consumption. A transcritical R744 solution or a R134a solution with preheating both with heat storage on the primary side may also be considered as they have similar performance.