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# LOW TEMPERATURE DISTRICT HEATING CONSUMER UNIT WITH MICRO HEAT PUMP FOR DOMESTIC HOT WATER PREPARATION

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*Keywords: Low temperature District Heating, DH consumer unit, Domestic hot water, Micro booster heat pump*

## ABSTRACT

In this paper we present and analyse the feasibility of a district heating (DH) consumer unit with micro heat pump for domestic hot water (DHW) preparation in a low temperature (40 °C) DH network.

We propose a micro booster heat pump of high efficiency (COP equal to 5,3) in a consumer DH unit in order to boost the temperature of the district heating water for heating the DHW. The paper presents the main designs of the suggested system and different alternative micro booster heat pump concepts. Energy efficiency and thermodynamic performance of these concepts are calculated and compared. The results show that the proposed system has the highest efficiency. Furthermore, we compare thermodynamic and economic performance of the suggested heat pump-based concept with different solutions, using electric water heater. The micro booster heat pump system has the highest annualised investment (390 EUR/year) and the lowest operation (320 EUR/year) expenditures. Electric heater-based concepts consume 5-14 times more electricity, which leads to relatively high annual operation costs (530-970 EUR/year); while investment costs are lower (326-76 EUR/year). The suggested DHW heat pump-based system is cost-efficient for private consumers already today. Furthermore, application of the micro booster heat pump in low energy houses complies with the energy consumption requirements, set by the recent Danish Building Regulations. The use of electrical heater variants would exceed this limit.

## INTRODUCTION

District heat in Denmark is mainly produced in heat boilers or combined heat and power plants [1]. The average yearly district heating supply and return temperatures in distribution networks are 80 °C and 40 °C respectively [2]. Clearly, lower DH temperatures are desired in order to reduce energy losses in the district heating networks. Reducing district heating supply temperature becomes possible with increasing focus on energy efficiency improvements in energy supply systems and in the buildings. In Denmark energy performance requirements for new buildings set progressively lower limits on energy consumption for space heating and hot water preparation. At the same time renovations of the existing buildings are required to include certain minimum energy saving measures, such as insulation of roofs and walls and replacement of windows with more efficient ones etc. Consequently, with decreasing heat demand, low temperature heating becomes feasible in the increasing share of the building stock.

According to the proposal by the Danish Government [3] for future energy, heat and power supply and transport systems should solely rely on renewable energy (RE) resources by 2050. An important milestone is in 2035 where the entire heat and power supply should be 100 % renewable. Clearly, energy efficiency plays an important role in achieving these targets – reducing energy resource consumption and additional capacity investments. In the district heating sector biomass will play an important role in the 100 % renewable energy system. However, both national and global biomass resources are scarce. Therefore, other energy resources and technologies will have to be used in addition to biomass plants. For district heating production alternative sources are solar, geothermal, ambient and waste heat resources. The utilisation efficiency of energy resources depends on the required district heating water temperature and increases with decreasing DH temperatures

In this context the benefits of low temperature district heating (LTDH) are multiple. First, heat losses from the district heating network can be reduced. For example, by reducing DH supply temperature from 80 to 40-45 °C, heat losses in a DH system can be lowered by approximately 37 % or even more [4]. Second, low temperature DH in local networks opens for possibilities to connect new users to existing DH systems without necessarily requiring additional capacity investments[1]. Moreover, LTDH enables efficient use of low temperature renewable energy resources, such as solar, geothermal, industrial waste heat.

[1] Depends on a specific DH system and generation technology

The viability of a LTDH consumer substation with DH supply at just above 50 °C has been proven and demonstrated in Denmark [7]. Here it is possible to prepare domestic hot water of 45 °C without any additional energy source. Further lowering DH supply temperature could for example enable use of the DH return water (40 °C) in the traditional networks (and connect more consumers without significant increase in capacity). However, while district heating supply at 40-45 °C is in principle sufficient for space heating, it cannot be used for domestic hot water preparation.

In this paper possibilities for preparation of domestic hot water, when DH supply temperature is as low as 40 °C are discussed. We analyse different heat pump and electric heater concepts for utilising additional energy source – electricity for heating DHW. The concepts are compared on the basis of thermodynamic and economic calculations, described in the article. We recommend using a small heat pump for boosting DH water to 53 °C. As it was mentioned earlier, such temperature is sufficient for DHW preparation.

## ENERGY CONSUMPTION FOR SPACE HEATING AND DOMESTIC HOT WATER

We assume that low temperature district heating is supplied to a low energy detached single family house. The house is built according to the requirements of the recent Danish Building Regulations (BR10) for low energy buildings of class 2015. The total yearly energy demand for space heating, domestic hot water preparation, operation of ventilators and pumps should not exceed the maximum annual energy demand set by the BR10 – the energy frame ($E_{frame}$, kWh/m$^2$), calculated by the following equation (1):

$$E_{frame} = 30 + \frac{1000}{A} \qquad (1)$$

Here $A$ is gross heated floor area (m$^2$).

Different weight coefficients are applied for consumed district heat and electricity – 0,8 and 2,5 respectively – when comparing the calculated energy consumption of a designed building with the energy frame.

Table 1 Energy consumption in the low energy house

| | |
|---|---|
| Space heating demand, kWh/year | 2570 |
| DHW demand (250l/m2 per year at 55 °C (BR10)), kWh/year | 2083 |
| Electricity in pumps and ventilators, kWh/year | 525 |
| Total energy consumption, kWh/year | 5178 |
| Total allowed energy consumption by energy frame, kWh/year | 5771 |

The analysed single family house has a heated area of 159 m$^2$, thus the energy frame is 36,3 kWh/m$^2$. The calculated energy demand is presented in Table 1. The energy consumption for domestic hot water heating accounts for a considerable share (40 %) of the total energy demand in the low energy house according to Table 1.

The single family house is heated by under floor heating. Consequently, with low energy demand and under floor heating systems the house is well suited for low temperature (40°C) district heating supply.

Different hot water consumption rates are assumed by various literature sources. For comparison of energy consumption in the building when different domestic hot water preparation alternatives are applied with the energy frame, hot water consumption calculated according to BR10 (Table 1), is used. For energy and economic cost calculations a more conservative and higher DHW [4] demand of 3200 kWh/year has been assumed (800 kWh per person per year and 4 occupants), which is 54 % higher than according to BR10.

## DOMESTIC HOT WATER SYSTEM AND LOW TEMPERATURE DISTRICT HEATING

When considering domestic hot water preparation systems, three main aspects/requirements need to be taken into account:

- The required temperature of DHW is 40 - 45 °C, depending on the tapping place (kitchen or bathroom);
- The risk of bacterium 'Legionella' (especially if storing the hot tap water), which can be avoided either by increasing temperature of the DHW to around 55 °C or by avoiding storing it;
- The Danish water standard DS 439, which includes hot water tapping profile, has to be met when dimensioning DHW system, meaning that the peak load of 32,3 kW has to be satisfied and the hot water storage tank has to be large enough to cover the most critical DHW tapping profile during morning hours.

Previously a low temperature DH network and consumer substations have been developed and demonstrated, when district heating supply temperature was lowered to around 50 °C [7]. The Danish full-scale demonstration project of the low-temperature DH supply to low-energy buildings has proven that the concept works – both space heating and hot water demand can be satisfied.

In this article we take a step further and reduce DH supply temperature to 40 °C. Clearly this temperature is too low for heating the tap water up to 45 °C, thus additional energy is needed for domestic hot water preparation. This energy could come from electricity – in a heat pump or electric heater. For evaluation of energy systems with multiple fuels and products, the thermodynamic quantity *Exergy* is commonly used [5]. The exergy level of a stream expresses the availability to do technical work, as temperature, pressure and chemical composition of the stream reaches equilibrium with the ambient. Electricity has a very high availability to do work, normally considered to be 100 %. If the ambient is represented by the cold tap water, the exergy of district heating water at 40 °C is very low (10 %) compared to electricity. Exergy expresses the minimum demand of primary energy supply theoretically needed to fulfil the DHW demand and should thus be minimized. The total energy demand for DHW supply may thus be quantified by the total exergy consumption of electricity and DH. From this viewpoint it will be advantageous to substitute one unit of electricity by up to ten units of DH. The further lowering of the district heating supply temperature is from a thermodynamic point of view more beneficial if the share of electricity in total energy, consumed for DHW, is small. Compared to an electric heater, where one unit (kW) of electricity input results in one unit (kW) of heat output, heat pumps can reduce this consumption by several units. To optimise the DHW production we have designed a small heat pump-based unit for hot tap water preparation in the low temperature DH system – a *microbooster heat pump unit*. Clearly, such DHW unit has to fulfil also the 2 latter requirements regarding legionella and sufficient capacity. This has been also taking into account when designing different DHW system concepts.

## CONSUMER DHW UNIT WITH MICROBOOSTER HEAT PUMP

The additional energy, needed for DHW can be added either on the secondary side, directly to the tap water, or to the district heating water on the primary side, which is then used to heat the tap water. Different system configurations regarding hot source for the heat pump (DH supply or return water), pre-heating of tap or return water, configuration of the heat pump and storage tank type are possible for the two options. We have selected the three most promising concepts for further analysis (see Figure 1).

In variant **A** the district heating water entering the hot water system is divided into two flows. The temperature of the first flow is boosted from 40 °C to 53 °C as it flows through the condenser of the heat pump. The second DH flow runs through the evaporator and is the heat source for the heat pump (and is cooled down to around 25 °C). The heated DH water is stored in a stratified accumulator tank and instantaneously heats tap water in a micro plate heat exchanger [10], when the tapping starts. Here the district heating storage tank is used in order to lower DH flow, heat pump capacity and investment cost.

Variant **B** resembles **A** - the only difference is that return water from hot water heat exchanger (and possibly space heating) is used as hot source in the heat pump. This variant has a reduced DH flow when compared to **A**.

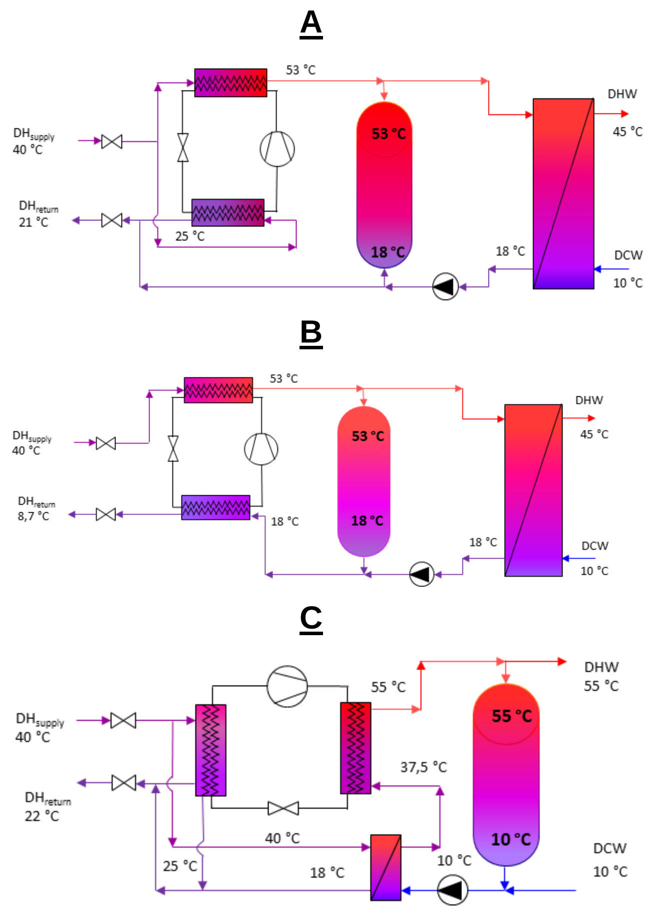


Figure 1 Analysed microbooster heat pump DHW concepts

In Variant **C** cold tap water is heated to 55 °C in the heat pump. DHW is stored at higher temperature than DH water in order to avoid formation of 'legionella' bacterium. In order to reduce required heat pump capacity, the cold water is preheated in a heat exchanger by using district heating water. The heat source of the heat pump is, as in variant **A**, district heating supply water.

For each micro booster heat pump variant, a numerical model has been implemented in Engineering Equation Solver (EES) using the assumptions presented in Table 2. More details on the numerical models and some results has been published previously [6]. In this paper some assumptions have been changed for the heat pump, to better represent the actual working conditions in the considered system. The heat pump is switched on from the start of the tapping sequence until the re-filling of the stratified tank is completed. Steady state operation can be assumed for the heat pump, as fluctuations from the hot water tapping profile are managed in the stratified tank. The storage volume of all the considered solutions has been calculated individually to allow similar operation patterns and operation time for all the heat pumps.

Table 2 Assumptions used in modelling DHW systems with micro booster heat pump

| Variable | Assumption |
|---|---|
| Refrigerant | R600a |
| Isentropic efficiency of compressor, / | 0.5 |
| HEX pinch temperature difference in both Condenser and Evaporator, K | 2.5 |
| Pinch temperature in Tap-water HEX ($Q_{MAX}$=32 kW), K | 8 |
| Temperature of DH return from the evaporator (variants A & C) , °C | 25 |

The main results of the calculations are summarised in Table 3. The flow of DH water, electricity consumption and exergetic efficiency are averaged values, which is possible due to steady state operation in the heat pump units.

Table 3 The results of three micro booster heat pump-based DHW system calculations

| | Microbooster Heat Pump variants | | |
|---|---|---|---|
| | A | B | C |
| DH flow, l/h | 85 | 50 | 75 |
| Power, W | 142 | 214 | 155 |
| Coefficient of performance (COP) | 5,3 | 3,5 | 5,0 |
| Exergetic efficiency | 0,43 | 0,41 | 0,42 |
| Storage size required, l | 128 | 128 | 100 |

From the table it can be seen that variant A has the lowest required power capacity and the highest district heat flow. When DH flow is reduced and the return water is used in the evaporator in variant B, more power is needed to boost the DH water temperature. The reason is low temperature of the return water (around 18 °C), entering the evaporator. As a consequence the heat pump in variant B has low COP. In variant C more energy has to be used to heat the DHW. Here domestic hot water is heated to 55 °C, i.e. 2 °C higher than in the case of primary DH water. Furthermore, even though the cold tap water is pre-heated to 37,5 °C before entering the heat pump it is still lower than the temperature of the DH water entering the heat pump in variants A and B.

The differences in district heating water flow in the three analysed hot water systems will not have any effect on the size of service pipes, since they are already oversized due to low energy consumption of the house and the fact that the smallest DH pipe size available on the market has been assumed.

The relation between the required heat (DH flow) from the district heating network and the additional electricity needed is of primary interest, as both are needed to produce hot water with the micro booster heat pump unit. Heat and electricity are in many cases produced as main products in the Combined Heat and Power (CHP) plant, and in this way the interaction becomes important. As exergetic efficiency is a measure of both the inputs and products (the product is in this case the constant amount of domestic hot water) the objective is to minimize the amount of heat and power required as the energy source for the heat pump. As the DH supply water has lower exergy content than electricity [5], the heat pump configuration with the lower power consumption and the higher heat consumption has the highest exergetic efficiency. With the highest exergetic efficiency the lowest amount of exergy (or available work) is used to complete the process, and thereby the highest fuel efficiency is reached. It is observed that due to the differences in heat pump configuration the significant differences in COP are not reflected equally significant in the exergetic efficiency. Thus, it is of importance to take both measures into account to do a consistent evaluation.

In variants A and B district heating and not domestic hot water is stored in the tank (Figure 1), which eliminates the risk of legionella formation in the DHW. The content of hot water after the heat exchanger on its secondary side, in DHW pipes, is possible to be kept under 3 litres. This is the maximum permissible hot water amount in the DHW system in order to avoid legionella if no additional treatment is applied, according to the German guidelines (DVGW, W551) for hot water systems [7]. In variant C the possibility of bacteria formation increases, as DHW is stored in the tank. In order to reduce the risk additional energy is needed to occasionally increase the temperature in the tank to 60 °C.

When comparing the required storage tank size (Table 3) variant C has an advantage of smaller hot water storage requirement. Usually smaller storage tanks are desired due to practical reasons, such as available space for the consumer DH station at the households. A smaller tank could also lead to lower heat losses. On the other hand DHW is stored at higher temperature (variant C) than the heated DH water in variants A and B, which would lead to higher heat losses. Heat losses are neglected in the calculations, as they are assumed of similar magnitude when considering the total installation.

When comparing A and B concepts, it seems that heat pump in variant A will have more stable operation conditions, as district heating supply water flows through both, condenser and evaporator. Whereas in case of variant B, temperature of the return water, flowing through evaporator, can vary, depending on e.g. cold tap water temperature.

Based on the lowest electricity consumption as well as other advantages and disadvantages variant A has been chosen for further development.

## CONSUMER DHW UNIT WITH ELECTRIC HEATER AND COMPARISON WITH MICRO BOOSTER HEAT PUMP

Even though the micro booster heat pump is expected to use significantly less additional electricity than electric water heaters, the latter solution can be expected to have lower investment costs and more simple design (Figure 2). In order to compare the costs and benefits of micro-booster heat pump and electric water heater DHW concepts for low temperature district heating, three electric heating alternatives have been calculated. The chosen micro-booster variant A is then compared with the 3 electric heater alternatives.

In the first electric heating alternative (D) the heat pump is replaced by an instantaneous electric heater, which boosts DH temperature from 40 °C to 53 °C. The design is more simple when compared to the variant A and only one DH flow is used for hot water preparation. In the alternative E district heating water flows through a coil, which is mounted in a hot water tank. Cold tap water in the tank is pre-heated to 35 °C by the coil and further heated up to the required 55 °C by an electrical heater, also installed in the tank. Finally, in the alternative F only electricity is used to heat domestic hot water in the tank with the installed electric heater.

The microbooster heat pump and the electric heating alternatives are compared, based on energy (e.g. increased electricity) consumption, exergetic efficiency, $CO_2$ emissions, as well as annualised investment and operation costs. Thermodynamic analysis has been performed using the same tool and assumptions as described in the previous section. The yearly costs have been calculated for assumed hot water consumption of 3200 kWh.

Cost calculations are performed for private consumers, assuming low temperature district heating supply to the single family houses. Additionally, socioeconomic costs of hot water preparation are compared based on the projected future energy costs in order to include the expected development of the Danish energy system into the analysis [9]. Investment costs of different alternatives include only costs, related to hot water installations of a consumer substation in a low energy single family house with low temperature district heating supply. The heating part of the substation is assumed to be the same for the analysed house, regardless of the hot water installation. All hot water units are assumed to have 15 years economic lifetime. A 6 % discount rate has been used for the private consumer and 3 % in the socioeconomic calculations.

District heating and electricity prices for private consumers are based on the latest data by the Danish Energy Regulatory Authority [8] (see Table 4). District heating prices for households include only variable heat costs, since the house is connected to a DH network and the fixed yearly fees have to be paid anyway. District heating prices in Denmark vary depending on the DH company and span between 3 and 21 ¢/kWh. For the calculations average and minimum DH price has been used. Electricity prices are based on the price level for consumers with yearly consumption of 4000 kWh and include energy and $CO_2$ taxes. Private investment costs and energy prices also include VAT, which in Denmark reaches 25 %. Socioeconomic district heating and electricity costs (Table 4) as well as $CO_2$ emission rates (kg/GJ) of district heat and electricity are based on the estimations by the Danish Energy Agency [9].

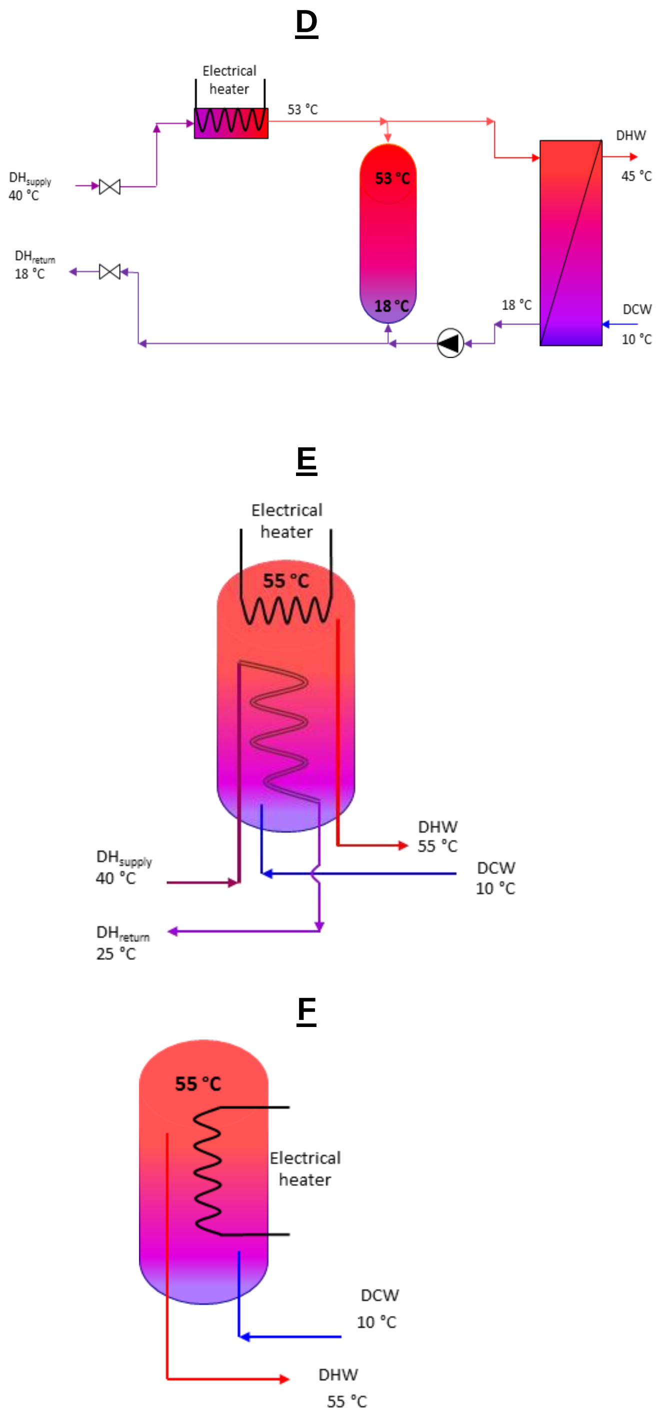


Figure 2 Analysed electric heater DHW concepts

$CO_2$ emissions are based on district heating and electricity production in 2011, while socioeconomic energy prices reflect DH and electricity costs in 2030.

Table 4 District heating and electricity prices

| ¢/kWh | Average | Min |
|---|---|---|
| DH price, private | 8,4 | 3,0 |
| DH price, socioeconomic, 2030 | 3,5 | |
| EL price, private | 30,3 | |
| EL price, socioeconomic, 2030 | 11,2 | |

The main calculation results regarding DH and electricity capacities needed and system efficiencies are summarised in Table 5.

Table 5 The results of micro booster heat pump- and electric heater- based DHW system calculations

| | Microbooster heat pump and electric heater variants | | | |
|---|---|---|---|---|
| | A | D | E | F |
| DH flow, l/h | 85 | 50 | 65 | 0 |
| Power, W | 142 | 749 | 896 | 2017 |
| Coefficient of performance (COP) | 5,3 | 1,0 | 1,0 | 1,0 |
| Exergetic efficiency | 0,43 | 0,14 | 0,12 | 0,06 |
| Storage size required, l | 128 | 128 | 100 | 100 |

The highest exergetic efficiency of the system is achieved in variant A, where the heat pump is used for boosting the DH water temperature. At the same time the highest share of the total energy for hot water heating comes from district heating in this alternative (93 %), see Figure 3. Other variants (D, E and F) have considerably higher electricity consumption, which is not desired. When electricity consumption increases, exergetic efficiency decreases. Thus, the advantage of micro booster heat pump – only moderate increase in electricity consumption – is clearly illustrated here. If a large share of electricity is produced in wind power plants and other non-dispatchable renewable energy technologies, higher electricity consumption can be acceptable, also due to the possibility for providing balancing services for the electricity grid (since the boosted DH or domestic hot water is stored in the tank making electricity consumption flexible). However, increased power consumption might require reinforcements of electricity distribution networks if considerable share of consumers would choose e.g. variant F.

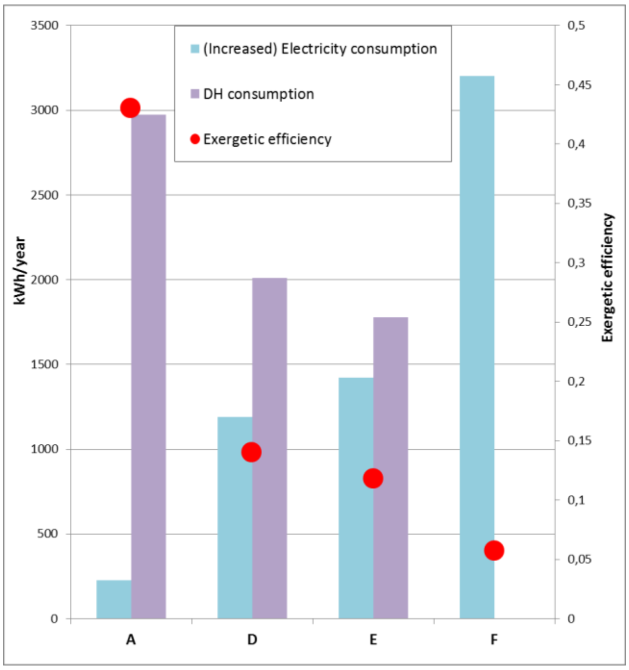


Figure 3 Energy consumption in DHW system and exergetic efficiency

From Figure 4 it can be seen that, based on the fuel mix in production of district heat and electricity today, the microbooster heat pump alternative causes the lowest yearly $CO_2$ emissions. Clearly, the emissions from DH production can be significantly lower if low temperature and renewable energy sources, such as solar, geothermal energy or biomass, are used. For electricity it also depends on whether fossil fuel-based production will be repalced by renewable energy ressources (e.g. wind or biomass).

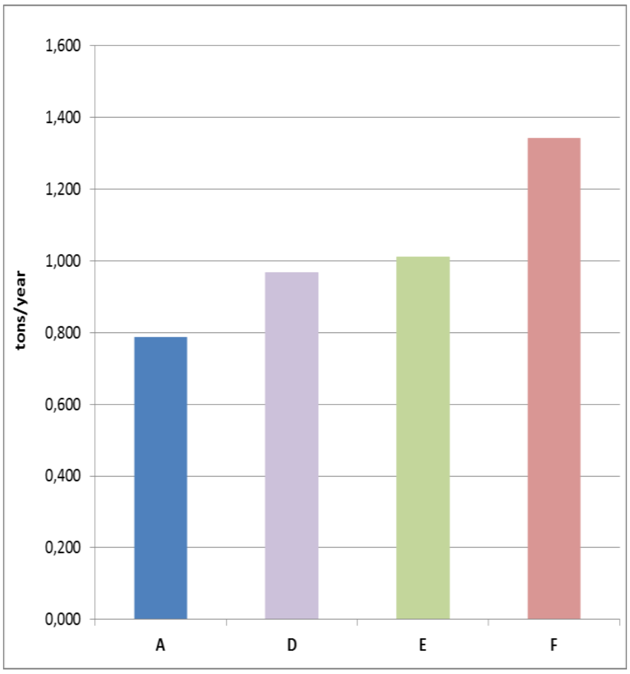


Figure 4 $CO_2$ emissions, caused by different hot water heating alternatives

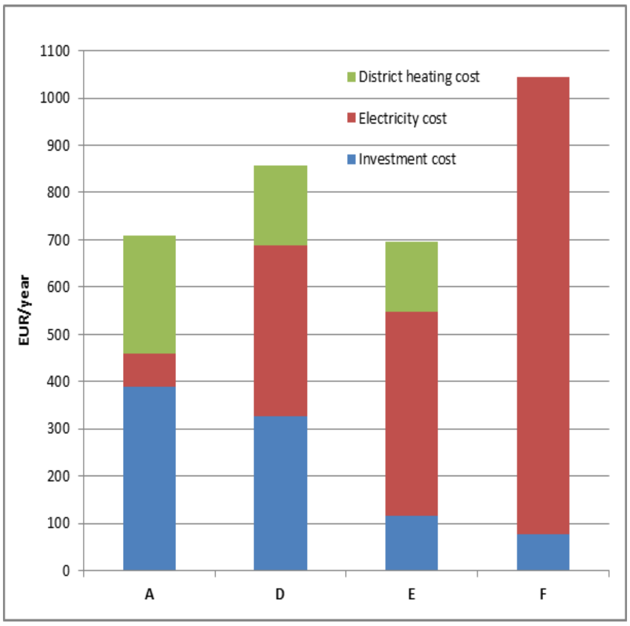


Figure 5 Yearly costs for private consumers, average DH price and 6 % interest rate

Figure 5 and Figure 6 include yearly costs of different hot water heating alternatives for private consumers with average and lowest variable district heating prices respectively.

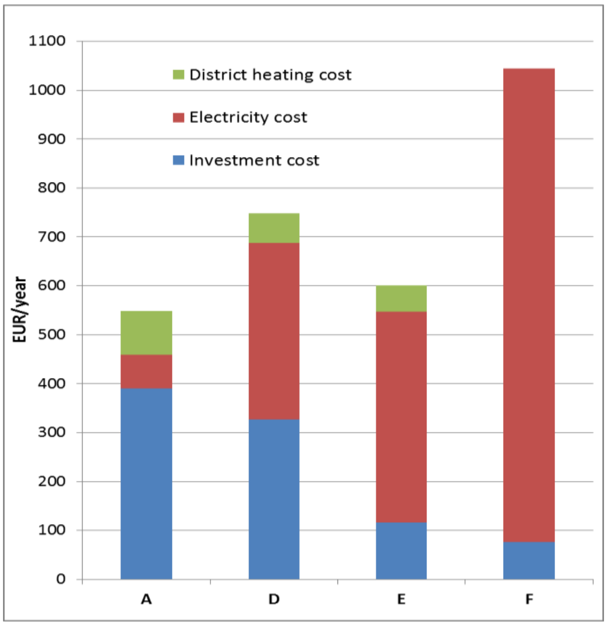


Figure 6 Yearly costs for private consumers, minimum DH price and 6 % interest rate

Investment costs account for the largest share (55 %) of the yearly expenditures when the micro booster heat pump alternative is chosen. At the same time yearly operation costs are high when electric water heaters are installed – between 62 % and 93 % of the total yearly costs. From the figures it can be seen that the least cost alternatives are A and E. With average DH price (Figure 5) variant E has the lowest yearly cost, which is only marginally lower than for variant A. Low DH price (Figure 6) leads to reduced operation costs for all hot water installations (except for variant F) – but most significantly when the micro booster heat pump is used. Hence, variant A is the least cost alternative in this case.

If hot water consumption is lower (e.g. 1240 kWh/year) than the one, used in the calculations (3200 kWh/year), operation costs decrease and the electric heating alternatives become more cost efficient than heat pump-based system. While the investment in a micro booster heat pump is more beneficial with high DHW consumption.

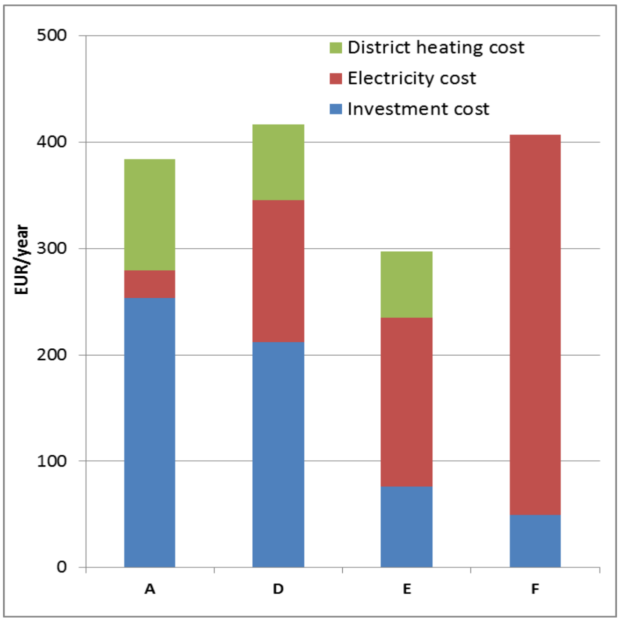


Figure 7 Yearly socioeconomic costs (2030 prices), 3 % interest rate

In general, the conclusion can be made that it is critical to reduce investment costs of the micro booster heat pump. Clearly, use of heat pump in the low temperature DH consumer substation can already today be cost-efficient for private consumers with hot water consumption of around 3200 kWh/year. When looking at the results of the socioeconomic calculations with 2030 energy prices (Figure 7) it is obvious that the cost of the micro booster unit has to be reduced by approximately one third for this concept to be more cost efficient than variant E from the socioeconomic point of view. The micro booster heat pump hot water unit is at the prototype stage today, thus a certain cost reduction might be expected.

Figure 8 compares the total energy consumption in the low energy single family house with different hot water installations. Here hot water demand is calculated according to the guidelines in the recent Danish Building Regulations (Table 1) and is lower than the demand, used for cost calculations.

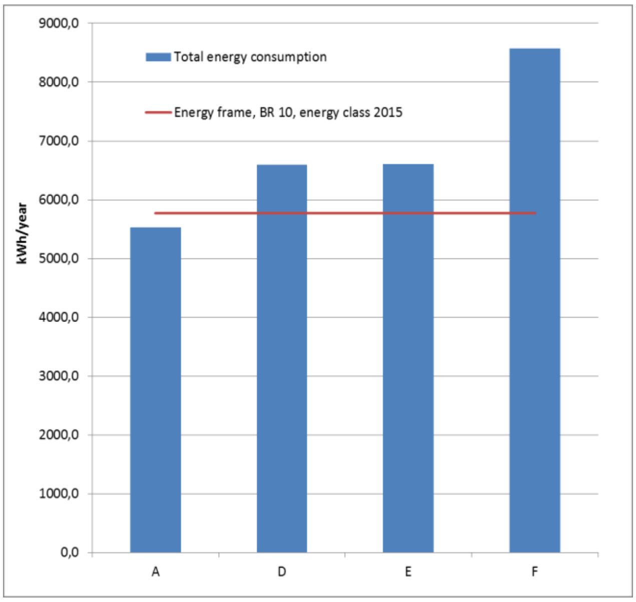


Figure 8 Comparison of total energy consumption in a building with energy frame, according to BR 10

Only variant A complies with the energy frame for buildings of low energy class 2015. The reason is high electricity consumption of electric heating alternatives, which is in this calculation weighted by a factor 3 when compared to the district heating consumption. Thus, energy policy of today encourages district heating consumption and promotes electricity savings in building installations. Consequently, a micro booster heat pump-based hot water installation is the most suitable concept, with low temperature (~40 °C) district heating supply according to the Danish Building Regulations.

## CONCLUSION

Different concepts for domestic hot water preparation when district heating supply temperature is reduced to 40 °C have been presented and compared in the article. The reduction of DH temperature implies the use of an additional energy source (electricity) for DHW preparation. Two main concepts of utilising the additional energy have been compared – based on heat pump and electric heater technologies.

Based on the performed calculations several main conclusions can be drawn. From the cost perspective it is not obvious that heat pump use in DHW system (variant A) is the most beneficial concept under current technology and energy prices for the private consumers or based on future socioeconomic costs. Combined electric and DH water heater in the DHW tank (variant E) is the competing technology. On the other hand, heat pump alternative reduces electricity consumption by more than 6 times, which is an important advantage in the light of the expected more rapid increase in electricity prices, when compared to the prices of the district heat. The benefits of reduced electricity consumption are reflected in the calculated exergetic efficiencies of the two alternatives (0,43 and 0,12 for variant A and E respectively), which reflect consumption of primary energy. According to the recent Danish Building Regulations the DHW system with the micro heat pump is the best alternative, due to the lowest electricity consumption.

## FUTURE WORK

As a part of the Danish Energy Technology Development and Demonstration project (EUDP 11-I, J. nr. 64011-0076) the first prototype of the DHW system with micro booster heat pump has been built according to the design of the variant A. The laboratory tests have shown that it is possible to achieve high heat pump COP and prepare the domestic hot water at the required temperature. Five consumer DH stations with the micro booster heat pump will be installed in single family houses, supplied with 40 °C district heating, for demonstration of the technology during the heating season 2012/2013.

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