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# Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective

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## Abstract

District heating (DH) systems are important components in an energy efficient heat supply. With increasing amounts of renewable energy, the foundation for DH is changing and the approach to its planning will have to change. Reduced temperatures of DH are proposed as a solution to adapt it to future renewable energy systems. This study compares three alternative concepts for DH temperature level: Low temperature (55/25 °C), Ultra-low temperature with electric boosting (45/25 °C), and Ultra-low temperature with heat pump boosting (35/20 °C) taking into account the grid losses, production efficiencies and building requirements. The scenarios are modelled and analysed in the analysis tool EnergyPLAN and compared on primary energy supply and socioeconomic costs. The results show that the low temperature solution (55/25 °C) has the lowest costs, reducing the total costs by about 100 M€/year in 2050.

## Keywords

Energy system analysis
Socioeconomic costs
Fuel consumption
Energy efficiency
EnergyPLAN simulations

## Abbreviations

| | |
|---|---|
| COP | Coefficient of performance |
| DEA | Danish Energy Agency |
| DH | District heating |
| DHW | Domestic hot water |
| HP(s) | Heat pump(s) |
| IDA | The Danish Society of Engineers |
| LTDH | Low-temperature district heating |
| PES | Primary Energy Supply |
| RE | Renewable energy |
| SH | Space heating |

## 1. Introduction

Existing district heating (DH) systems and organisations are challenged by the transition towards 100% renewable energy (RE) supply [1]. The RE sources are variable in time which is different from the conventional heat supply based on fossil fuels that can be combusted according to the demand. This is not only the case for DH, but for all energy sectors (electricity, transport, industry etc.), and a holistic approach including all sectors is needed to develop an efficient energy supply in the context of 100% RE [2].

At the same time heat savings are implemented in the building stock and new buildings are of much better energy standards that the old ones, which will reduce the heat demand density and thereby further challenge the existing DH supply. Also the economic framework for DH production will change, as RE to a larger extent is based on investment costs rather than fuel consumption [3].

The 4th generation of DH (4DH) is a framework in which solutions for these challenges can be developed. 4DH emphasises the need to integrate DH more with other energy sectors, by introducing new heat sources and conversion technologies that utilise synergies between the sectors. It is also a key element that the temperature levels of DH supply generally should be reduced to improve production efficiencies and reduce grid losses [1].

### 1.1. Low-temperature District Heating

A number of studies have investigated the concept of low-temperature district heating (LTDH) and aspects of this including benefits, challenges, costs and possible future technological solutions.

In [4] Dalla Rosa et al. model a DH system in Canada in detail comparing different temperature sets, concluding that supply temperatures reduced towards 70 °C from above 100 °C is a feasible solution, whereas lower temperature sets (below 60 °C) depend on the achievable system benefits because of increased costs. Similar tendencies are found by Ommen et al. [5] for the heat and electricity systems of Greater Copenhagen. Here, supply temperatures below a level where electric boosting of domestic hot water (DHW) become necessary, are found not to be feasible in terms of consumer costs.

Baldvinsson and Nakata compare in [6] medium temperature DH with LTDH, LTDH with low heat demand and a combination of medium temperature DH and LTDH in a cascading system, for a specific mixed urban area in Japan. It is found that in a system with normal heat demand LTDH is not feasible, compared to LTDH combined with low heat demand which is feasible. For the latter, the optimal plant supply temperature level is found to be around 52 °C in general with temperature boosting up to 65 °C in the winter. In another study on LTDH for some very different case areas in Austria, the energy, economy and ecology are assessed for scenarios with different temperature configurations, some with electric DHW temperature boosting and some without [7]. The results show to be different for the different cases, but generally conclude that the availability of low temperature heat sources to the DH system is important.

Among the challenges of implementing LTDH is the need for reduced return temperature to maintain a good temperature difference between supply and return. Gadd and Werner present in [8] a method for fault detection in DH substations to avoid high return temperature using the temperature difference as indicator. If the return temperature cannot be sufficiently reduced, the pipe dimensions or pumping costs will increase to cover the same heating demand. Tol and Svendsen describe in [9] a method to dimension the pipe system in LTDH systems in an optimal way introducing temperature boosting in peak demand times, and thereby keeping pipe dimensions and heat losses to a minimum.

Another challenge is the sufficiency of the supply temperature to meet heat demands in the buildings. Østergaard and Svendsen indicate in [10], based on simulation of typical building types, that it is feasible to provide space heating (SH) to even old buildings, that have been energy refurbished, using DH supply temperatures below 50 °C. The DHW is more complicated because of the risk of legionella infection. Yang et al. present in [11] a number of solutions for prevention of legionella infection in the DHW supply. These include temperature boosting using electricity, limitation of DHW volume using instantaneous heat exchangers and different sterilization methods. Furthermore, Yang et al. [12] assess different DHW preparation methods for supply temperatures below 45 °C using direct electric heating or HP boosting to a sufficient temperature level. Østergaard and Andersen [13] even consider a supply temperature as low as around 35 °C, using a booster HP, which is also indicated on the basis of the demonstration project in [14]. Electricity consumption for heating is generally not an efficient solution in a system perspective [15] which is also found in [16], but might provide a new picture when combined with temperature reductions in DH.

No studies have so far analysed the temperature level on a large scale energy system level from a societal point of view, which is necessary to provide more general recommendations.

### 1.2. Long-term Energy System Analysis

In this study five scenarios describing five concepts of DH with a focus on different temperature levels are chosen and the costs and benefits of each of these are assessed. The study will have its point of departure in a Danish context analysing the scenarios implemented into holistic energy models of Denmark for 2035 and 2050 developed in the IDA Energy Vision project where scenarios from the Danish Energy Agency (DEA) are used as reference. Here, the “Wind” scenario is most similar to the IDA scenario [17]. This study indicates, by socioeconomy and fuel consumption, which DH concept generally fits best into a future RE system in Denmark, and thereby contributes to how DH can be seen in the overall strategy and planning for the Danish energy sector.

For this study, a number of concepts within LTDH is identified on characteristics of the temperature set and means for DHW preparation with a conventional temperature set as reference. These are presented in Table 1. These concepts are further defined and put into an energy system context in Chapter 2.

*Table 1: Main characteristics of considered concepts for district heating in future energy systems*

| | **Conventional** | **Low Return Temp.** | **Low Temp.** | **Ultra-Low Temp. (Elec.)** | **Ultra-Low Temp. (HP)** |
|---|---|---|---|---|---|
| Nominal supply temperature [˚C] | 80 | 80 | 55 | 45 | 35 |
| Nominal return temperature [˚C] | 40 | 25 | 25 | 25 | 20 |
| Additional DHW preparation method | - | - | - | Direct electric | Booster heat pump |

In this paper the analysis and results are presented in the three following chapters. In Chapter 1 an introduction, literature review and background for the area is presented. In Chapter 2 the materials and methods are presented, first describing the purposes of the different scenarios followed by details on the assumed differences between the scenarios. The results of the analyses are presented in Chapter 3 and in Chapter 4 results and the implications of these are discussed comparing them with previous findings.

## 2. Materials and Methods

The scenarios, characterising different DH concepts, use existing models of the energy system in Denmark for 2035 and 2050, implementing changes in these consequent to the change of temperature assumption. The changes include grid losses, energy production and conversion efficiencies, potential utilisation of heat sources and investment costs in buildings and the supply system.

### 2.1. Analysed Scenarios

The analysed scenarios are based on the scenarios designed in the project IDA Energy Vision [17] for 2035 and 2050. These scenarios assume some degree of reduced temperature in the DH systems, but no specific temperatures are mentioned. Here, it is assumed that the IDA scenarios are equivalent to the Low temperature scenario (55/25) of the present study, and the dependent parameters are calculated for the other scenarios based on this. The analysed scenarios can be seen as a stepwise progression in reduction of temperatures and interventions in the buildings. They are briefly described below:

- **Heat savings** (Save) serves as a reference for the other scenarios and represents a situation where savings in space heating have been implemented (as for all the five scenarios) but the DH temperatures are kept at a conventional level. This is done because savings in heat demand is a prerequisite for reducing the temperatures in a feasible way.
- **Low return temperature** (Return) represents a situation where implementation of building improvements to reduce the return temperature is performed while keeping the conventional supply temperature. The purpose of the scenario is to show the relevance of reducing the return temperature.
- **Low temperature** (Low) represents a situation where both supply and return temperatures are reduced to the lowest possible level where no electric boosting of DHW in the buildings is necessary.
- **Ultra-low temperature using direct electric boosting** (Ultra) represents a situation where the supply temperature is further reduced, making temperature boosting of the DHW necessary, here done using direct electric heaters.
- **Ultra-low temperature using heat pump boosting** (HP) represents a situation where the supply and return temperatures are further reduced, here using micro HPs to boost the DHW temperature as needed. This scenario is based on more assumptions and simulated data compared to the others for which better data is available.

#### 2.1.1. Domestic Hot Water Preparation

In the three first scenarios it is assumed that the preparation of DHW is solely done with an instantaneous heat exchanger, whereas in the scenarios Ultra and HP, electric boosting is needed to provide a comfortable DHW supply limiting the risk for legionella. All scenarios are designed to be able to meet the same comfort and hygienic requirements [12].

In the Ultra scenario electricity is consumed in an electric heater in the DHW system of the building. Here, the water is heated according to the official comfort requirements of 45 °C, after preheat by DH. The hygienic requirements, to avoid legionella are not compromised in this way because the water is heated instantaneously. In cases with long internal pipe systems it may be needed to use electric tracing [18]. The electricity consumption is assumed to be 14% of the DHW demand [12], and since this electricity is heating the DHW it is assumed to replace an equivalent amount of the heat supply from DH.

In the HP scenario the electricity consumption is for the compressor in the HP. The heat pump is placed in a separate circuit with a storage tank and a heat exchanger connected to cold usage water. The water is stored at 50 °C to be able to meet comfort requirements after the heat exchanger. This is done to reduce the needed capacity of the booster heat pump and the frequency of on/off switches. Here, as well, the hygienic requirements are not compromised because the DHW is produced instantaneously on demand. The temperature has to be raised more than in the Ultra scenario because of the lower supply temperature and storage requirement, but because of the COP of the HP the electricity consumption is at the same level. It is here assumed to be 16% of the DHW demand, based on data from [13] provided by the authors, in which the used booster HPs are presented and discussed. The COP of these varies from 5.5 to 7.5 during the year.

The electricity demands in the Ultra and HP scenarios are distributed according to the variations in DHW demand. In the HP scenario, where individual thermal storages are integrated, it may be possible to use the HPs intelligently, but compared to the household HPs for heating, these booster HPs are small in capacity and the effect will be small [19].

### 2.1.2. Additional costs

When comparing the scenarios, a number of cost assumption related to the differences in the scenarios are made. The three categories and the specific cost assumptions made can be seen in Table 2.

To reduce the return temperature from the majority of buildings, some replacements of valves and radiators will be required, which is estimated in [20] to be approximately 10,000 DKK (1,300 €) per building. For the calculation of the total additional costs it is assumed that the replacement of valves and radiators will be done on average 10% before the end of their technical lifetime or have equally higher investment costs than standard devices.

The electric heater is today available in retail, but as an independent unit supplementary to the DH substation. The model used in [12] can be purchased for approximately 900€ [21]. If the Ultra scenario is implemented in a larger scale, it can be assumed that the unit will be sold in larger numbers and be an integrated part of the DH substation, reducing the costs. It is here assumed that the unit cost can be reduced to 220€ (one third of the cost for the micro HP).

The micro booster HP is not available today in retail, but the units have been developed for a demonstration project in single family houses, where the additional cost for the HP unit is 15,000 DKK (2,000 €) [14]. The HP is here an integrated part of a DH substation, but it is assumed that the cost can be reduced to 670 € (one third of the demonstration unit cost) accounting for the potential benefit in multifamily buildings and the economy of scale in the production of larger quantities. The sensitivity of the results to these assumptions are discussed in Section 4.3.

The different scenarios have different average temperature differences between supply and return, which means that a different flow rate is required to deliver the same amount of heat. On the short term, this will mean different flow and cost for pumping, but on the long term it is assumed that these changes will be evened out by using more appropriate pipe dimensions. This is also indicated in [7] and [4]. It is in general assumed that the DH grid is replaced gradually and the differences in costs will therefore only be related to the dimensions of the pipe networks, because the replacement will be done at some point anyway. Therefore, based on the relative changes in temperature difference, the total pipe costs are assumed to change according to the rates seen in Table 2. The total DH grid costs are estimated based on the method presented in [22]. It is assumed that the insulation standard in 2035 is an average of Series 2 and 3 whereas in 2050 it assumed to be an average of Series 3 and 4 due to gradual improvement of pipe insulation standard towards 2050.

The values of total annualised costs in Table 2 are calculated based on the total investment cost, the technical lifetime of investments and a discount rate (See Section 2.3). Valves, radiators, electric heater and micro HPs are assumed to have technical lifetimes of 20 years, whereas the DH grid is assumed to have a technical life time of 40 years [23].

*Table 2: Assumptions on additional costs for the different scenarios.*

| Category | Parameter | **Save** | **Return** | **Low** | **Ultra** | **HP** |
|---|---|---|---|---|---|---|
| 1. Valves and radiators | Replacement [€/building] | 0 | 130 | 130 | 130 | 130 |
| | Total annualised cost [M€/year] | 0 | 19 | 19 | 19 | 19 |
| 2. DHW heater / micro booster HP | Investment [€/building] | - | - | - | 220 | 670 |
| | Total annualised cost [M€/year] | - | - | - | 37 | 112 |
| 3. DH grid costs | Total DH grid costs [B€] | 20.1 | 20.0 | 20.3 | 20.5 | 20.7 |
| | Change in grid costs [%] | -1.0 | -1.5 | - | 1.0 | 2.0 |
| | Total annualised cost [M€/year] | 869 | 865 | 878 | 887 | 896 |

### 2.2. The EnergyPLAN Analysis Tool

EnergyPLAN is an advanced energy system analysis tool developed for analysis of large scale energy system dynamics which allows for modelling of 100% RE. It is a simulation tool that calculates one full year on an hourly time resolution. Special focus is on the integration of the different energy sectors: electricity, heating, transport, and industry and the dynamics between these on an hourly basis. EnergyPLAN has also been applied in [3], [17], [22] and [24] for modelling of 100% RE systems. A complete documentation of this can be found in [25].

For this analysis, a modified version of EnergyPLAN has been developed where version 12.4 has been used as a starting point. The modification changes the input type of the COP for HPs in DH from a fixed value to an hourly time-dependent input. This is done to reflect the changes in COP when the supply and return temperatures and the temperature of the heat source are changed.

### 2.3. Socioeconomic Cost Calculation

The socioeconomic costs are calculated as total annual costs for the given energy system including annualised investments costs, fuel costs, variable and fixed operation and maintenance costs and $CO_2$-emission costs. The investments are annualised using a discount rate of 3%. Public economic measurements as taxes, levies, subsidies etc. are not included in the socioeconomic costs.

### 2.4. Application of Temperature Profiles

The temperature levels of DH systems are not constant from hour to hour or month to month, e.g. due to compensation for demand fluctuation. These changes may have an influence on the system benefits of low temperature DH. Therefore, parameters sensitive to DH temperature changes have been calculated with an hourly time resolution based on temperature profiles.

Temperature measurements from the Danish Rindum DH plant from 2015, provided by the plant manager, have been used to calculate temperature profiles for Heat Savings, Low Return, Low temperature and Ultra-low temperature scenarios. For the HP scenario, simulated data from [13] have been used to calculate the hourly profiles.

Table 3 shows the assumed average temperature levels in the DH systems for the high heating season (November-April), and low heating season (May-October). The temperatures are not calculated dynamically, but the measured profiles are scaled to meet the level seen in the table. This means that the return temperatures are not depending on the supply temperatures.

The resulting temperature profiles are shown in Figure 1 and Figure 2. Figure 2 shows the profile of the 20 °C return temperature has a different tendency than the two others. This is caused by the ability of the booster HP in this scenario to decrease the return temperature in the non-heating season further than the output of the SH system.

The temperature profiles have been used to calculate hourly heat losses, COP of HPs and efficiency of solar thermal production. The details of how the temperatures have been applied to calculate these inputs are described further in Sections 2.5 and 2.6.

*Table 3: Average temperature levels in the scenarios for the high and low heating seasons*

| [°C] | **Save.** | **Return** | **Low** | **Ultra** | **HP** |
|---|---|---|---|---|---|
| Supply temperature – heating season | 80 | 80 | 58 | 45 | 35 |
| Return temperature – heating season | 40 | 25 | 25 | 25 | 20 |
| Supply temperature – low heating season | 73 | 73 | 54 | 41 | 30 |
| Return temperature – low heating season | 42 | 26 | 26 | 26 | 18 |

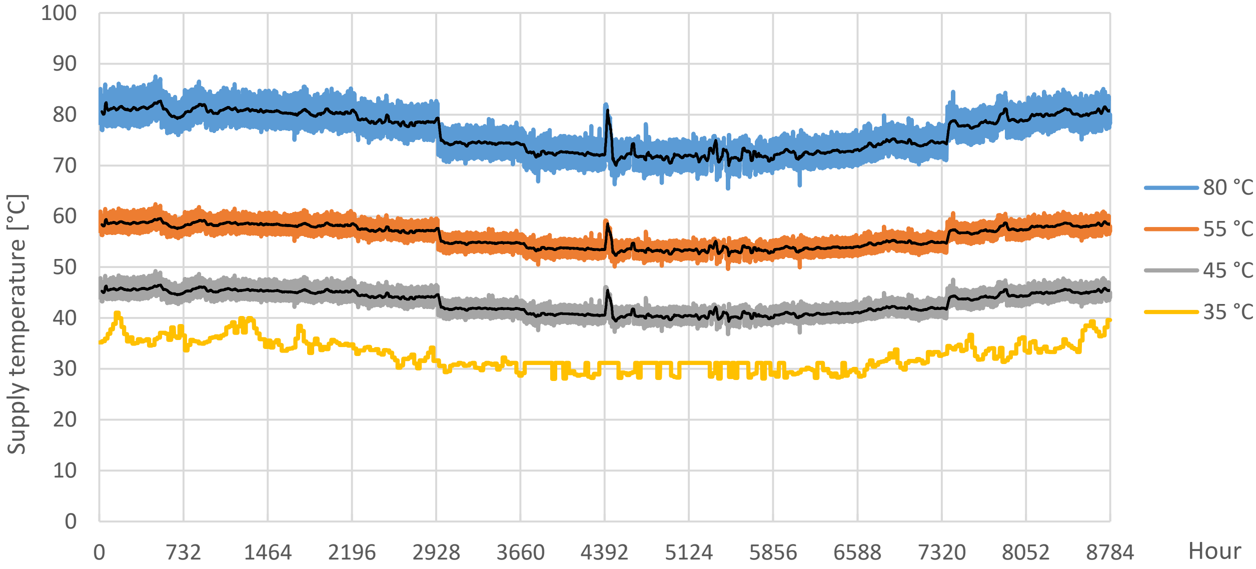

*Figure 1: Hourly supply temperature profiles applied in the analyses. For 80, 55 and 45 °C a 24-hour moving average is added (black lines) to show the general trends.*

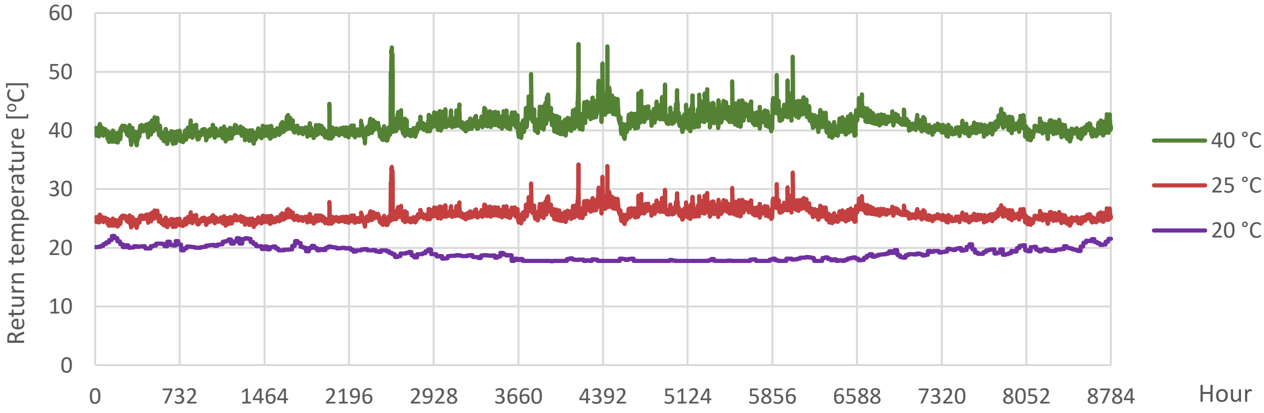

*Figure 2: Hourly return temperature profiles applied in the analyses.*

### 2.5. District Heating Demands and Losses

The heat demand in DH describes the total demand for heat input to the buildings supplied with DH. This includes SH, DHW and internal heat losses from the HPs in the HP Scenario. The heat demands for the scenarios are calculated based on the figures presented in the *Future Green Buildings* project [26] for the building stock and potential heat savings. It is assumed that 66% of the total heat demand will be covered by DH in 2035 and 2050. Here the total savings in SH in existing buildings are 45% towards 2050. The demand in new buildings are 41.3 kWh/m$^2$ for SH and 13.7 kWh/m$^2$ for DHW.

In Table 4 the components of the heat demands are presented. SH and DHW are fixed through all five scenarios, but different between 2035 and 2050 because of continued implementation of heat savings and a general change in the building stock and use. Based on [12] it is assumed that 14% of the DHW demand in the Ultra scenario is covered by electricity. For the HP scenario it is assumed that it has a thermal storage [13,14] with a heat loss of 10% of the DHW. 50% of the electricity consumption in the pump (16% of the DHW based on data from [13]) is considered a loss that can be utilised for SH, corresponding to 50% utilisation of the electricity for the thermodynamic cycle. This is not counted in the total demand because it is from electricity and therefore in brackets in the table. For the heat losses from thermal storage and electricity consumption in the HPs, it is assumed that 30% can be utilised in the building as SH and the rest is lost as increased heat loss from the building, due to location of the HP and operation during low heating season.

The grid losses are calculated based on results from modelling and analysing the flows in a DH network using the DHM-model applying different pipe insulation series and DH temperature levels [27], [22]. The grid loss (See Table 4) is distributed to an hourly profile using the supply and return temperatures at plant level.

*Table 4: District heating demand and production composition for the scenarios in 2035 and 2050*

| | **2035** | | | | | **2050** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| [TWh] | **Save** | **Ret** | **Low** | **Ultra** | **HP** | **Save** | **Ret** | **Low** | **Ultra** | **HP** |
| Space heating | 21.4 | 21.4 | 21.4 | 21.4 | 21.4 | 18.4 | 18.4 | 18.4 | 18.4 | 18.4 |
| Domestic hot water | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 4.3 | 4.3 | 4.3 | 4.3 | 4.3 |
| Heat from electricity | - | - | - | -0.5 | - | - | - | - | -0.6 | - |
| Thermal storage loss | - | - | - | - | 0.4 | - | - | - | - | 0.4 |
| HP heat loss | - | - | - | - | (0.3) | - | - | - | - | (0.3) |
| Internally utilised loss | - | - | - | - | -0.2 | - | - | - | - | -0.2 |
| Total demand | 25.2 | 25.2 | 25.2 | 24.7 | 25.4 | 22.7 | 22.7 | 22.7 | 22.1 | 22.8 |
| Total grid loss | 5.0 | 4.7 | 4.2 | 3.8 | 3.6 | 3.9 | 3.7 | 3.2 | 2.9 | 2.7 |
| Grid loss / production [%] | 16.5 | 15.8 | 14.1 | 13.2 | 12.3 | 14.7 | 14.1 | 12.4 | 11.4 | 10.5 |
| Total production | 30.2 | 29.9 | 29.4 | 28.4 | 28.9 | 26.5 | 26.3 | 25.8 | 24.9 | 25.5 |

### 2.6. Efficiency of Energy Conversion Units

Most energy conversion units in DH systems depend on the supply and/or return temperatures in the network. In the following, the included production units whose efficiency are affected by the DH temperatures are presented and it is explained how their relation to the DH temperatures is included in the analysis.

#### 2.6.1. Condensing boilers

Fuel boilers in DH can improve their efficiency by condensing the flue gas from the combustion. The lower the return temperature received from the grid, the more heat can be extracted from the flue gas. How much the efficiency can be improved depends on the fuel type and moisture content. Based on [28] it is assumed that reduced return temperature from 40 °C to 25 °C and 20 °C will improve the average efficiency of fuel boilers from 0.95 to 1.00 and 1.02 respectively.

#### 2.6.2. CHP Plants

CHP plants mainly benefit from a reduction in the supply temperature. As the supply temperature from a CHP plant is lower, the electric efficiency will improve because of a higher total temperature difference. A Carnot efficiency equation has been used. See Equation 1.

$$\eta = 1 - \frac{T_{Low}}{T_{High}} \qquad \text{(Equation 1)}$$

Here, η is the Carnot efficiency, $T_{Low}$ [K] is the supply temperature and $T_{High}$ [K] is the high temperature in the combustion [29]. $T_{High}$ is here assumed to be 500 °C. The found efficiencies are used to scale the CHP electric efficiencies from the IDA models. The thermal efficiencies of the CHP are reduced corresponding to the increase of the electric efficiency to keep the same overall efficiency.

### 2.6.3. Heat Pumps

The coefficient of performance (COP) of a HP improves with both supply and return temperature reductions. The calculation of the HP COP is based on a Lorenz cycle. See Equation 2.

$$COP = \eta * \frac{T_{High}}{T_{High} - T_{Low}} \qquad \text{(Equation 2)}$$

Here, η is the system efficiency of the HP, assumed to be 0.4 (including losses in heat exchangers between HP refrigerant and DH and heat source fluid), $T_{High}$ is the logarithmic mean high temperature in the HP condenser and $T_{Low}$ is the logarithmic mean low temperature of the HP evaporator [13,30]. $T_{High}$ and $T_{Low}$ are defined in Equation 3.

$$T_{High}\ or\ T_{Low} = \frac{T_{in} - T_{out}}{Ln(T_{in}) - Ln(T_{out})} \qquad \text{(Equation 3)}$$

Here, $T_{in}$ and $T_{out}$ are the inlet and outlet temperatures of the condenser and the evaporator in the HP. It is assumed that the heat source for the HPs can be cooled 5K.

The COP is calculated for every hour, based on the DH temperature profiles described in Section 2.2 and a heat source profile. The heat source temperature (See Equation 4), should resemble an average of all the utilised heat sources. The seasonal variations are defined by measurements of sea water temperatures from [31]. Other heat sources, such as low-temperature industrial waste heat or sewage water, often have higher temperatures than sea water. Therefore, a constant temperature addition ($K_{Addition}$) is added to the sea water temperature ($T_{Sea\ water}$) to calculate an estimate heat source temperature ($T_{Heat\ source}$).

$$T_{Heat\ source} = T_{Sea\ water} + K_{Addition} \qquad \text{(Equation 4)}$$

The constant temperature addition ($K_{Addition}$) is different for central DH in the bigger cities compared to the decentral DH in the smaller towns. In the bigger cities, the amount of good heat sources relative to the heat demand is lower than in the smaller towns [32]. The better heat sources with higher temperatures are assumed to be utilised before those with lower temperatures. At some point, a DH company will run out of good heat sources, and they will have to use less efficient heat sources to further expand the heat pump capacity. This point will occur earlier in the bigger cities (central DH) than in the small towns (decentral DH) because of the lower amount of heat sources per demand. This is taken into account by defining $K_{Addition}$ to 10K for the decentral DH, but only 5K in the central DH.

### 2.6.4. Solar Thermal

The output of solar thermal plants depends on the supply and return temperatures but also the ambient temperature of the solar thermal panels. The bigger the temperature difference between the temperature of the working fluid in the solar panel and the surrounding air, the larger the heat loss and thereby lower efficiency [33]. The relation is shown in Figure 3.

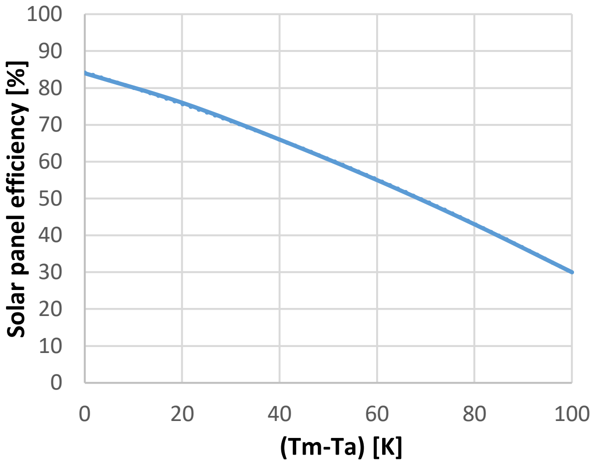

*Figure 3: Efficiency of a solar panel as a function of the temperature difference between the medium panel temperature (Tm) and the ambient air temperature (Ta). Derived from* [34].

### 2.6.5. Geothermal

In the Danish context, geothermal resources are only utilised for DH in three locations, and all using absorption HPs. The benefits of lower DH temperatures to the production from geothermal plants are mentioned in several studies, including [1,35]. No quantitative assessment of the potential has been found, though. Here, it has been assumed that a reduced return temperature improves the annual production, as the temperature difference thereby increases by 5% and 7% when reduced to 25 °C and 20 °C respectively. Reduced supply temperature is assumed to reduce the need for HPs and thereby the costs for geothermal plants. The HP accounts for 29% of a geothermal plant costs [36], and it is assumed that 50%, 75% and 100% of this can be saved at 55 °C, 45 °C and 35 °C respectively. This is assuming that the geothermal heat source is above 35 °C, which is the case for all plants in Denmark [37].

### 2.6.6. Industrial Excess Heat

Excess heat from industrial processes can be used for DH supply either using HPs or via direct heat exchange. Direct heat exchange requires the DH supply temperature to be lower than the one for the excess heat. In [38] it has been assessed that 4 PJ of low temperature excess heat can be recovered using HP at today's temperature sets. Following this, it is in this study assumed that 25%, 50% and 75% of this can be recovered for DH supply in direct heat exchange, as the supply temperature is reduced to 55 °C, 45 °C and 35 °C respectively.

## 2.7. Required Production Capacity

An indirect effect of improved efficiencies and reduced demand in the DH system is the change in the required production capacity, due to changes in peak demand and utilisation time of the conversion units. This is done to include the potential change in investment costs related to production facilities and thereby making the scenarios economically comparable. The changes are performed iteratively to make all parameters match the requirements in the results of the final simulation. The following list presents all capacities that have been updated and how these have been updated.

- **Fuel boilers** in DH systems have been adjusted in capacity relative to the change in peak heat demand.
- **Condensing power plants** have been adjusted relative to peak electricity demand. This is only relevant in the Ultra and HP scenarios, where there is an increase in electricity demand.
- **CHP plants** have been adjusted in capacity relative to the number of full load hours of the plants.
- **HPs** have been adjusted in capacity relative to the number of full load hours of the plants.
- **Offshore wind power** capacity has been adjusted to generate the same amount of excess electricity as in the Low scenario.

## 3. Results

An overview of the analysed scenarios and the main results are presented in Table 5. The results will be further elaborated in the following.

*Table 5: Overview of central scenario parameters and results.*

| | 2035 | | | | | 2050 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Save** | **Ret** | **Low** | **Ultra** | **HP** | **Save** | **Ret** | **Low** | **Ultra** | **HP** |
| Temperature set [°C] | 80/40 | 80/25 | 55/25 | 45/25 | 35/20 | 80/40 | 80/25 | 55/25 | 45/25 | 35/20 |
| Additional DHW preparation method | - | - | - | Direct elec. | Booster HP | - | - | - | Direct elec. | Booster HP |
| Electricity consumption in DHW preparation [TWh] | 0 | 0 | 0 | 0.5 | 0.6 | 0 | 0 | 0 | 0.6 | 0.7 |
| Grid loss share [%] | 16.5 | 15.8 | 14.1 | 13.2 | 12.3 | 14.7 | 14.1 | 12.4 | 11.4 | 10.5 |
| Total DH Supply [TWh] | 30.2 | 29.9 | 29.4 | 28.4 | 28.9 | 26.5 | 26.3 | 25.8 | 24.9 | 25.5 |
| Total energy system costs [B€] | 13.28 | 13.27 | 13.23 | 13.24 | 13.33 | 13.88 | 13.84 | 13.86 | 13.97 | 13.84 |
| - Reduction in energy system costs [M€] | - | 11 | 48 | 35 | -50 | - | 79 | 123 | 98 | -6 |
| Total PES [TWh] | 138.9 | 138.4 | 138.3 | 138.7 | 138.7 | 133.5 | 133.1 | 132.8 | 133.2 | 133.4 |
| - Reduction in PES [TWh] | - | 0.46 | 0.59 | 0.21 | 0.20 | - | 0.35 | 0.67 | 0.34 | 0.10 |

In Figure 4 it is shown how the DH production mix is changing between the scenarios. It can be seen that excess heat production is increasing, due to improved efficiencies, and at the same time CHP and HP production is decreasing as a consequence of this. It can also be seen that the surplus production (the production above the DH supply markers) is increasing with reduced temperatures, which is caused by the increase of inflexible heat production in the low heating season from waste, excess heat, geothermal and solar thermal heat production.

The surplus heat will materialise in a reduced supply of excess heat from industries or cooling via sea water, cooling tower or similar. The increasing surplus heat may indicate a potential for optimisation of the heat source mix. In the scenarios with low temperatures, the boiler, HP and CHP operates very few hours during the summer, but there is still an overproduction of heat.

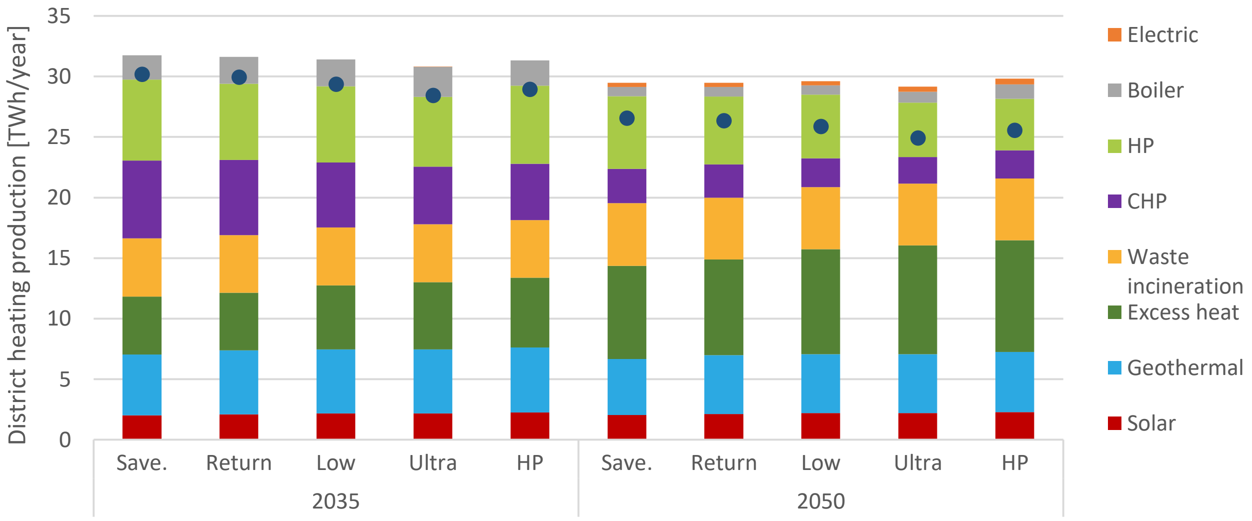

*Figure 4: Distribution of district heating production between production units for the five analysed scenarios, in 2035 and 2050.*

The primary energy supply (PES) seen in Figure 5, shows the total changes as a result of all changes in the scenarios. It can be seen that reduction of supply and return temperatures does not influence the PES or fuel consumption significantly. The reduction in PES is in all scenarios less than 0.7 TWh, with the lowest total fuel consumption and PES in the Low scenario compared to the Heat Savings scenario. When the PES of these five scenarios are compared to the DEA Wind scenario, it can be seen that a significant saving is obtained. This is due to the applied measures in the IDA scenarios that make use of synergies in the integration of energy sectors.

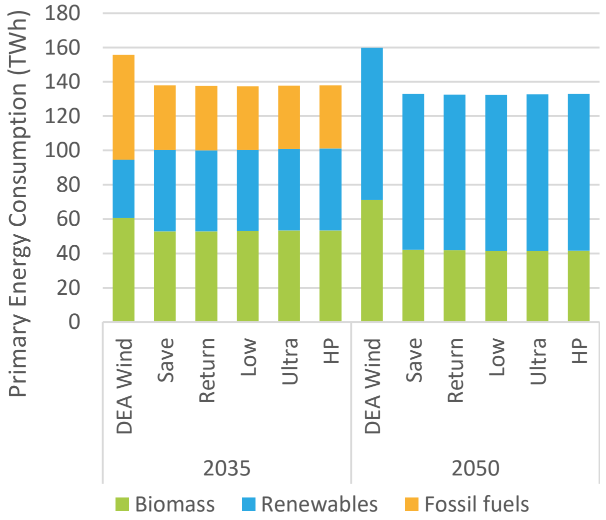

*Figure 5: Primary energy supply in the five analysed scenarios and the DEA Wind Scenario, for 2035 and 2050, divided on biomass, fluctuating renewables and fossil fuels.*

Figure 6 shows the overall economic results of the scenarios where a breakdown of the costs into Variable costs (fuel and variable operation costs), Operation costs (fixed operation costs) and Investment costs. The results show that the scenarios Return, Low and Ultra all are economically feasible compared to the Heat Savings scenario, and that the Low scenario has the lowest costs in both 2035 and 2050. The HP scenario has higher costs than the Heat Savings scenario under the given assumptions. This is mainly due to the investment costs in the individual HPs. As a sensitivity analysis, different fuel cost levels are included in the analysis, as seen in the figure.

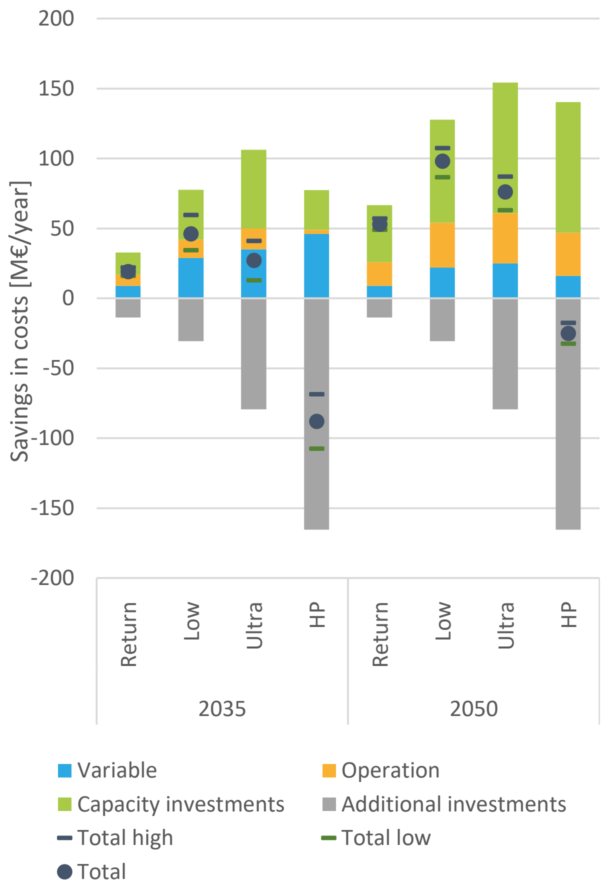

*Figure 6: Savings in total costs, divided on Variable costs, Operation and maintenance costs and Investment costs, for the four alternative scenarios relative to the Heat Savings scenario for 2035 and 2050. The sensitivity of the results to high (+50%) and low (-50%) fuel costs is shown compared to the total costs.*

## 4. Discussion and Conclusion

The feasibility found in this analysis is based on socioeconomy, but this does not mean that these solutions are also business economically feasible to a DH company. The results should be seen as guidelines to policymakers designing the concrete economic framework for DH development. The results apply on a general level for Denmark, but there will most likely be DH areas that make exceptions from the general conclusions, given specific conditions making them different from a typical case.

### 4.1. Reduction of Temperature Set

The results show that reducing temperatures in DH is a feasible strategy on the medium and even more on the longer term, in a transition towards more RE in Denmark. The results indicate that a reduction of return temperatures alone, considering the required investments, is a feasible strategy already today and increasingly with more RE penetration. In the 2050 model the savings are seven times larger than the additional investments. This is at the same time a prerequisite for a substantial reduction of the supply temperature. As the supply temperature is reduced towards the level where electric boosting of the DHW temperature is required, the costs keeps decreasing. From here, through the Ultra and HP scenarios, the costs increase because the additional investments surpass the savings.

### 4.2. Significance of Investment Costs

It can be noticed in the results that a reduction in fuel consumption, which might intuitively be the reason to introduce LTDH, is not actually the main benefit on the system level. In all scenarios, except the Return scenario for 2035, the reductions in capacity investments are larger than the variable and operational costs together. As seen in Figure 6, the reductions in capacity investments are increasing until they peak in the Ultra scenario and are lower in the HP scenario, whereas the additional investments have an exponentially increasing tendency through the scenarios. This indicates that a theoretical optimum exists in how low the temperature should be. This is also what can be seen in the trend of the reduction in total cost which peaks in the Low scenario under the given assumptions.

### 4.3. Electricity for Domestic Hot Water Boosting

The two scenarios that use electricity for boosting of the temperature of the DHW show lower reduction in socioeconomic costs, and the Low scenario without electricity use for DHW therefore seems like the most feasible strategy. As mentioned, the investment costs are of great importance to the results. The total socioeconomic savings are 100 and 75 M€/year for the DH supply systems in Denmark for the Low and Ultra scenarios respectively. The calculated additional investment costs for the electric heaters are 37 M€/year, and if the costs of these can be reduced by two thirds, the scenarios would be economically on the same level. On the other hand, if the increase in pipe costs is larger than assumed here, the results will tip more in favour of the Low scenario. Because of the high additional costs in the HP scenario and the relatively low increase of the system benefits this is not seen as an option that can be feasible in general. The HP solution might be feasible in concrete cases under the right circumstances, though.

If the costs of the Low and Ultra scenarios would be on the same level, there is still a risk in the Ultra scenario, because the larger investments in the buildings lock the demand to that solution. If these investments are made it is still possible to operate at higher temperatures, but then the investments have been wasted. If an additional unit is added to the DH substation, an electric heater or especially a booster HP, it will also increase the need for maintenance and the risk for errors. The Low scenario is more simple in the sense that it only requires investments that would be feasible anyway and thereby nothing is wasted if the temperatures are not reduced as much or as fast as planned.

### 4.4. Synergy between LTDH and Savings in Space Heating

One important assumption in this study is the implementation of savings in SH of approximately 45% in existing buildings [17] and new buildings following the building codes with low SH demands as well. In this study, only modest changes in the cost for the DH grid are included because the assumed heat savings enable a reduction in temperature difference between DH supply and return. If no savings in SH are implemented, the temperature difference between supply and return cannot be reduced as much as suggested in this study, and thereby the benefits cannot be achieved either. Alternatively, significantly higher costs in DH grid investments will have to be considered to account for the higher flow needed to cover the demand.

### 4.5. Sensitivity of the Results

The sensitivity of the results to a number of important parameters have been analysed. The costs for the household investments and electricity consumption in DHW boosting are relatively uncertain, because no large-scale implementation have been done, but the values assumed are rather optimistic. Therefore, the costs and electricity consumption will more likely be higher in the Ultra and HP scenarios, making these less feasible compared to the others. In Figure 6, the sensitivity to fuel price changes is presented. These changes in fuel costs can change the relation between the savings in the scenarios, but not the overall results. The same tendency can be seen when altering the applied interest rate and, in the 2035 case, the $CO_2$-price.

In this study the IDA models of Denmark in 2035 and 2050 are assumed as starting points for the scenario analyses. The pace of the transition towards 100% RE do not influence the conclusions, since the relations between the scenarios are similar in 2035 and 2050. If the development goes in a completely different direction than proposed in the IDA Energy Vision [17], the results may not be representative.

### 4.6. Conclusion

It can be concluded that it is a feasible strategy to reduce DH temperatures on medium and long term in the development towards a RE system. To reduce the return temperature to about 25 °C requires replacement and adjustment of the building heating systems, but this is feasible to do so, even if the supply temperature is not reduced, with an annual reduction of socioeconomic costs of 50 M€/year in 2050 for the DH supply system in Denmark. The supply temperature should be reduced as much as possible until electric boosting of DHW becomes necessary, which happens at about 55 °C and gives an annual reduction in socioeconomic costs of about 100 M€/year. The feasibility on a general level of a further temperature reduction to e.g. 45 °C, taking local temperature boosting of DHW into account, is very questionable and will rely on a very low investment cost in the units to heat the DHW. A solution with micro HPs for temperature boosting seems beyond realistic from an economic perspective, but under the right circumstances in small concrete areas it might be feasible. Before considering electric boosting of temperatures, organisational issues related to trade-offs between benefits for the DH company of reduced temperature and the increased costs for electricity for the consumers have to be solved.

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