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Economic comparison of low-temperature and ultra-low-temperature district heating for new building developments with low heat demand densities in Germany

Isabelle Best*, Janybek Orozaliev and Klaus Vajen

University of Kassel, Institute of Thermal Engineering, Department Solar and Systems Engineering, Kurt-Wolters-Str. 3, 34125 Kassel, Germany

ABSTRACT

District heating risks to lose competitiveness the lower the linear heat density of a district is. The distribution network needs to be highly efficient in order to ensure economic feasibility. The heat distribution temperatures are crucial to keep distribution heat losses as low as possible. For a new development in Germany consisting mainly of single family houses, two district heating networks at different supply temperature levels are examined in terms of economic and efficiency aspects. Depending on the required temperature level and temperature difference between supply and return the economics of the heat supply system change. The required pipe diameters are affected, supplementary system components are needed due to lower supply temperatures etc. This study analysed the impact of design temperature and operating strategy on the economic feasibility of the distribution infrastructure, the district heating network and shows the impact on system costs. The total heat generation costs are separated in costs originating from the central heat supply unit, the distribution infrastructure, and the decentralized heat supply units and system engineering. The analysis discusses how the system design temperature effects the fix costs and variable costs of new heat supply systems based on (ultra-)low-temperature district heating. Added to this, an exemplary seasonal strategy was investigated, which provides a switch-off of the network during low load summer period, avoiding heat distribution losses. This study demonstrates that ultra-low-temperature district heating ensures important improvement of heat distribution efficiency, favorable conditions for renewable heat integration while showing no economic disadvantage compared to low-temperature district heating.

Keywords:

Fourth generation district heating;
Low heat demand density;
Ultra-low-temperature district heating;
Heat network design ;

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1. Introduction

Future smart thermal energy systems are based on a combination of renewable technologies using wind, geothermal, and solar thermal power along with residual resources to meet the heat demand [1]. District heating infrastructures and large thermal storages play an important role in future energy systems as demonstrated by various projects in Denmark in recent years [2]. The heat supply system should distribute heat with low heat losses. However, district heating risks to lose competitiveness the lower the linear heat demand density of a district is. The planned new housing area "Zum Feldlager" (Kassel, Germany) comprises of 131 buildings

* Corresponding author: e-mail: solar@uni-kassel.de

Abbreviations

DH	District Heating
DHW	Domestic Hot Water
DN	Nominal Diameter
HP	Heat Pump
LTDH	Low-Temperature District Heating
PE -X	cross-linked polyethylene
PN	Nominal Pressure
SDR	Standard Dimension Ratio
SH	Space Heating
SPF	Seasonal Performance Factor

on a land area of 115,000 m^2. The housing area will consist mainly of single family houses, resulting in a low building density with a plot ratio of 0.25 according to [3]. It represents a heat demand sparse area with a very low linear heat demand density of around 650 kWh/(m·a). In this case the distribution network needs to be highly efficient in order to ensure economic feasibility. The heat distribution temperatures are crucial to keep distribution heat losses as low as possible. Likewise, the heat supply system should include renewable energies, as much as possible.

Therefore, two district heating networks for the new housing development "Zum Feldlager" at different supply temperature levels are examined in terms of economic and efficiency aspects.

In Germany, a conventional district heating network for a new housing development of the third generation would be designed for flow temperature of 70 °C and return temperatures of 40 °C – 50 °C. This flow temperature ensures domestic hot water preparation and space heating supply. However, in case of low heat demand densities of below 600 kWh/(m*a) these operating temperatures can cause distribution losses of over 15%. Furthermore, in order to use the potential of waste heat and of renewable energies flow temperatures of district heating systems should be reduced. The vision of the fourth generation district heating aims at low flow temperatures below 70 °C in order to favour integration of temperature sensitive technologies. An ultra-low-temperature district heating system even shows flow temperatures below 50 °C, thus it always needs supplementary technologies in order to meet the domestic hot water demand temperature of 45 °C in single family houses and 60 °C in multi-family houses. Distributed solar thermal systems or (booster) heat pumps can be used for DHW preparation or temperature boost. This results in various possible heat supply systems aiming at a high share of renewable heat, which leads to different system engineering in buildings and different substations. Moreover, a lower temperature level and temperature difference between supply and return lead to higher volume flow rates. Consequently, the required transportation pipe diameters are affected. Energy utilities and plant operators fear increased auxiliary energy demand and high investments for the heat distribution infrastructure. Thus, an economic assessment has been conducted in order to evaluate the impact of the chosen temperature level and temperature difference on the economic competitiveness of a district heating network. The assessment comprises the impact on pipe design, auxiliary energy demand, and energy consumption including distribution heat losses. It represents an economic evaluation with strong focus on the distribution infrastructure especially of small thermal networks for low heat demand density areas in Germany.

Various investigations have been conducted in the field of low-temperature district heating (LTDH) questioning design and operating temperatures of district heating-based heat supply systems. The studies investigated technological solutions, cost reduction potentials, and challenges specifically for low heat demand density areas. To name few: in [4] the IEA DHC CHP Annex VIII discussed and evaluated techniques for the reduction of piping costs and heat losses from heat distribution among others. Also in [5] the IEA DHC CHP Annex V addressed various research questions ranging from system engineering regarding substation design through energy-efficient DH networks to concepts and technologies for the new generation of DH systems. In [6] Tol and Svendsen demonstrated a new method to design district heating networks achieving smaller pipe diameters taking simultaneity of the heat consumers involved into account. Furthermore, in [7] Lund and Mohammadi pointed out that a higher insulation standard is the most feasible solution for 4^{th} generation DH systems. When it comes to ultra-low-temperature district heating (ULTDH), several research questions arise regarding the domestic hot water (DHW) preparation due to very low DH supply temperatures of 35 °C – 45 °C. In [8,9] Yang et al. evaluated different DHW preparation methods via ULTDH and discussed the advantages and challenges of in-line heaters for temperature boost, as well as substation designs to achieve low return temperatures of DHW preparation. In [10] Ommen et al. investigated the optimal integration of booster heat pumps in ULTDH. In [11] Lund et al. compared three different alternative concepts for DH temperature level on a long-term energy system perspective. The study stated that a low-temperature DH of 55/25°C shows the lowest costs for DH systems in Denmark. No study directly compared low-temperature DH of 70°C/40°C with very low DH design temperature of 40°C/25°C focusing on the distribution heat costs specifically for new building developments, which is necessary to provide more general recommendations regarding the realization of ULTDH.

2. Boundary Conditions

2.1. Case Study – The New Housing Development "Zum Feldlager"

The planned new housing development "Zum Feldlager" (Kassel, Germany) comprises of 131 buildings with 253 accommodation units. One accommodation unit has in average 115 m^2 dwelling area. The housing development will consist mainly of single-family houses, terraced houses and semi-detached houses, all showing 1–1.7 accommodation units. The buildings were calculated to meet the requirements of the German KfW-70 low-energy building standard according to the Energy Saving Ordinance 2016 [12].

The buildings were calculated with the reference building characteristics shown in Table 1. A total dwelling reference area of 34,770 m^2 was calculated. In a first step, the space heating demand of each building was computed according to the German standard DIN V 4108-6 [13]. Additionally, the peak heating load for every building was computed according to DIN EN 12831 [14]. The resulting total yearly space heating demand is 1,426 MWh/yr, which is a specific space heat demand of 41 kWh/(m^2·a). Furthermore, the domestic hot water demand was determined according to the German standard DIN 18599, which assumes 11 kWh/(m^2·a) for single family and terraced houses and 15 kWh/(m^2·a) for multi-family houses. A domestic hot water demand of 382 MWh/a results. Thus, in total the new development is assumed to have a heating demand of 1,808 MWh/a.

Table 1: Building characteristics

Transmission Coefficient in $W/(m^2 \cdot K)$	
Outer walls	0.28
Windows	1.3
Roof	0.2
Bottom building section	0.35

2.2. Generation of Heat Load Profile

Within the framework of the joint research project "Geo-solar district heating for the development "Zum Feldlager" (in German: Geosolare Nahwärmeversorgung für die Siedlung 'Zum Feldlager'") the new building development and the corresponding heat supply system was modelled with the software TRNSYS. Dynamic simulations were conducted in cooperation with the Fraunhofer Institute of Building Physics from Kassel. The model consists of all heat supply units, a simplified distribution infrastructure, and clustered consumers. The 131 buildings were clustered in 22 representative buildings and then displayed as single thermal zone models. According to design characteristics of each building type, there were various possibilities for the number of consumers of domestic hot water. These possibilities were sub-grouped into three main cases: typical single-family houses, double single-family houses and multi-family houses. All other possibilities were realized by considering multiplication factors for each case. Regarding the domestic hot water demand, demand profiles were generated by using a stochastic modelling tool "DHWcalc" that was developed within IEA SHC-Task 26. It takes into consideration the Gaussian-Distribution and different time scales to generate various load profiles [15]. A rather medium to high domestic hot water consumption was chosen of 40 ltr/(pers.d) at a tap temperature of 45 °C. Precise and realistic domestic hot water systems consisting of all system engineering components were designed with accordance to VDI 6002 [16] and VDI 2067 Blatt 12 [17]. The resulting annual heat load profile is shown in Figure 1. The space heating (SH) demand is depicted in blue, while the domestic hot water (DHW) demand is displayed in red. Keeping room temperatures constant, a total space heating demand via dynamic simulations of 1,392 MWh/a results, which is a deviation of 2.5% compared to the static calculations according to DIN V 4108-6. This deviation is acceptable and proves that the model shows realistic results. The following heat load profile is taken as a base for the further evaluation.

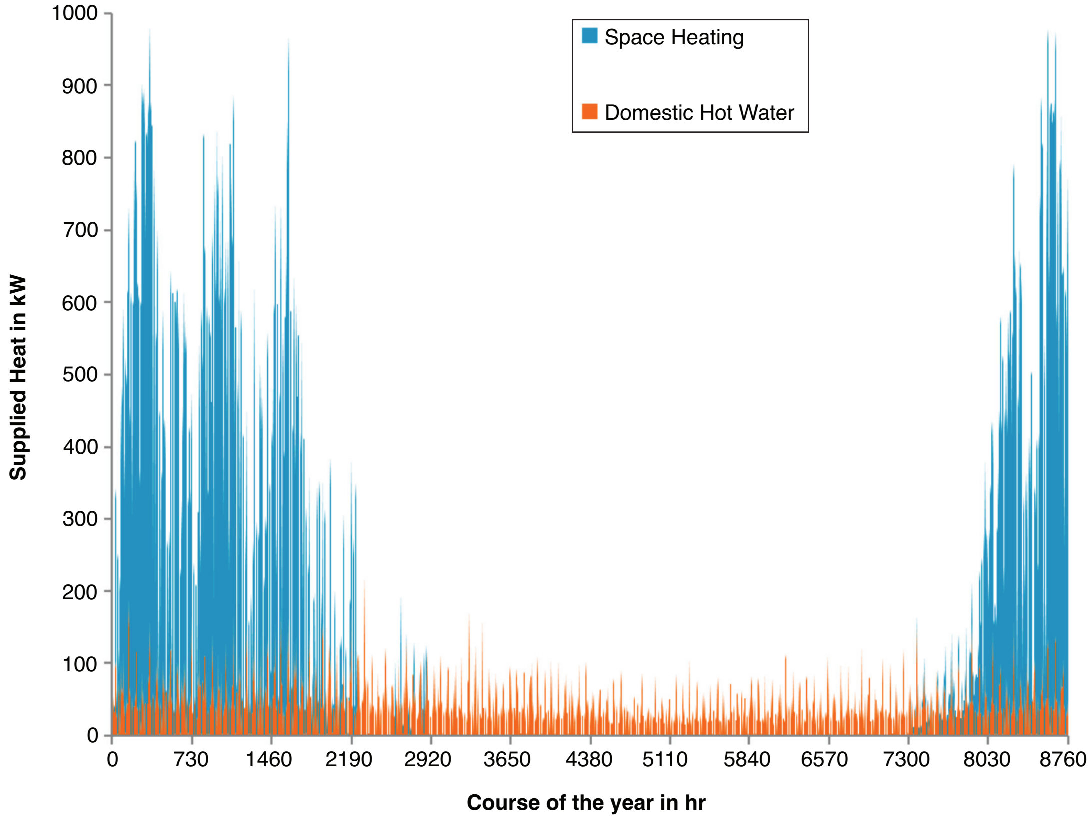

Figure 1: Calculated hourly heat load profile of the housing development "Zum Feldlager", in blue the space heating demand, in red the domestic hot water demand

2.3 Boundary Conditions for Economic Evaluation of New District Heating Networks for New Developments

If the DH system is subdivided in three parts, it would be: the central heat generation, the distribution infrastructure and heat supply to the consumer or heat generation components on the secondary side (consumer side) in case of semi-decentralized systems. The economics and planning of district heating are generally based on a cost advantage, which the central heat generation has in comparison to local heat generation solutions. Depending on the temperature level of heat generation the components´ design of the distribution network differs. Basically, the pipe diameters and pumps are directly affected by the chosen heat generation temperature level. Likewise, the heat losses of the system are affected. Regardless of the heat generation technology, DH must meet the costs for the distribution network, which has generally a significant impact on the fix costs. This study discusses the impact of chosen supply temperature on the distribution costs and likewise on the economics of DH system. It does not show a heat supply optimization, because of the variety of possible heat generation concepts. To compare the distribution networks of different supply temperatures the conventional distribution costs were analyzed including following categories according to [18]:

- The distribution capital costs, which includes annual repayments of investment capital for the construction of the distribution network and its components
- The heat distribution loss costs
- The distribution pressure loss costs, which is equal to auxiliary costs due to the electricity consumption of pumps
- The distribution maintenance costs

The distribution costs are dominated by the distribution capital costs, strongly depending on the pipe diameter and linear heat density, which will be discussed and evaluated in detail. The distribution heat loss costs are linked to the heat generation costs, that originates in conventional systems from central units like CHP units, waste incineration plants or general speaking the power plant park. The focus of this study are small DH networks for new developments with the objective integrating a high share of renewables.

The central heat generation costs are comprised of:

- Heat generation costs based on the capital costs for the installed capacity of heat supply units
- Variable costs per heat unit and the operating time (operating costs)

The investment appraisal of the DH system was conducted pre-defining the investment period to the economic lifetime or operating time of the components and distribution infrastructure, which was set to 30 years for the distribution infrastructure and 15 years for heat generation technologies and components on the secondary side. An annuity method was applied setting the internal rate of return (IRR) to 5.6%, representing a known hurdle rate (minimum rate of return the company will accept) from energy utilities. The capital costs are thus shown as present value (discounted value). The maintenance and service costs were evaluated according to the VDI 2067, which recommends fixed rates of investment to calculate the maintenance and service costs depending on the technology used [19]:

The net specific electricity costs were assumed to be 0.17 €/kWh for large consumers and 0.24 €/kWh for small consumers like households in Germany [20]. The variable costs were computed at the base of the results from dynamic simulations. The annual distribution costs were calculated and discussed considering central heat generation and decentralized heat generation costs for two different DH networks: for an ultra-low-temperature district heating system and a low-temperature district heating system.

Table 2: Annual maintenance and service cost rates according to VDI 2067

	Share of investment
Distribution infrastructure	0.5%
Substations	3.0%
Energy Centre	2.0%
Central Heat Pump	3.0%
Central Peak Load Heater	3.0%
Seasonal Storage	0.5%
Secondary devices	3.0%

2.4 Network Operating Characteristics

Mostly, a thermal network is operated with the objective of meeting the total heat demand that is the SH demand and the DHW demand. Add to this, the second objective is to ensure a set supply temperature. For new building developments, a supply temperature of 40 °C is sufficient to supply modern SH systems like floor heating systems. When it comes to DHW preparation, the network supply temperature needs to be higher. In Germany, especially regarding multi-family houses, the network supply temperature needs to be approx. 70 °C to minimize the risk of legionella contamination. A central heat supply technology would ensure the heat supply year-round, which is applied for the low-temperature district heating (LTDH) system in this study. However, a seasonal operating strategy that provides a switch-off of the network during low load period can avoid high relative distribution losses. In this case, the DHW demand during the summer must be met by a supplementary unit in the building. The outcome of this is a semi-decentralized heat supply system. The supplied heat via the network is reduced by the DHW demand occurring during the summer. The remaining heat demand consists mainly of space heating demand. Thus, a lower network supply temperature of approx. 40 °C is sufficient, which here represents the idea of ultra-low-temperature district heating (ULTDH) [11]. The linear heat demand density is reduced in case of ULTDH. The resulting linear heat demand densities on different operating conditions for the assumed new development are shown in the following table. The

Table 3: Linear heat demand densities on different network operating conditions

	LTDH Winter: 70 °C/40 °C Summer: 70 °C/40 °C	ULTDH Winter: 40 °C/25 °C Summer: 40 °C/25 °C	ULTDH Winter: 40 °C/25 °C Summer: no operation
Heat Supply	100% DHW + 100% SH	54% DHW + 100% SH	24% DHW + 100% SH
Linear heat demand density	653 kWh/(m·a)	581 kWh/(m·a)	532 kWh/(m·a)

DHW supply rates were calculated assuming a DHW preheating via the DH network.

The DH network geometry was kept constant for all DH layouts. For each building a connection capacity was determined. The total connected capacity amounts to 927 kW. The single-family houses show a connected capacity of in average 5 kW, while the multi-family houses need in average a connected capacity of 18 kW. The typical German substation includes a hot water storage tank of 200 l (single family house) to 1,500 l (multi-family house). Instantaneous DHW preparation via DH could be an efficient alternative, but is rarely applied in Germany.

The following economic study distinguishes between the explained systems ULTDH and LTDH, and added to this, discusses the impact of an exemplary switch-off of the network during low load period.

3. Thermal Network Design

To evaluate this effect of the chosen system design temperature, it has been differentiated between two design temperature levels: for 70 °C supply and 40 °C return (temperature difference ΔT = 30 K) as well as for 40 °C supply and 25 °C return (ΔT = 15 K). Both piping networks were designed for the maximum heat load. According to [21,22] different design approaches exist, which are shown in Figure 2. Depending on the inner diameter, a flow velocity is recommended, which limits the specific pressure drop over the pipe length. A threshold of maximum specific pressure drop of 100 - 150 Pa/m is common in order to avoid increased pump energy demand and corrosion [18].

Dissenting recommendations are given by the Austrian board of trustees for Agricultural and Rural Development (ÖKL) that demonstrate flow velocities causing pressure drops of approx. 300 Pa/m for inner diameters of 40 to 80 mm (purple line) [23]. Additionally, the piping manufacturer's recommendations (ISOPLUS) were examined (marked in green and orange). The ISOPLUS maximum flow velocity curve shows flow velocities from 1.2 to 1.5 m/s for small inner diameters resulting in specific pressure drops below 200 Pa/m. In case of composite aluminium and cross-linked polyethylene (PE-X) pipes even higher flow velocities are allowed because of lower surface roughness (k = 0.007) of the pipe and lower risk of corrosion issues. Regarding PE-X pipes manufactures list flow velocities up to 3.0 m/s for pipes of Standard Dimension Ratio (SDR) 11. As consequence, it is a matter of economic DH network operating, which maximum flow velocity is chosen.

In this study, the maximum flow velocity values of ISOPLUS were used as design basis. The maximum heat load occurs less than 200 hours per year (pump operating hours to meet 80% – 100% of the heat load). Thus, high pressure drops > 200 Pa/m of short duration were allowed. According to the connected capacity, a volume flow and the corresponding pipe diameter were

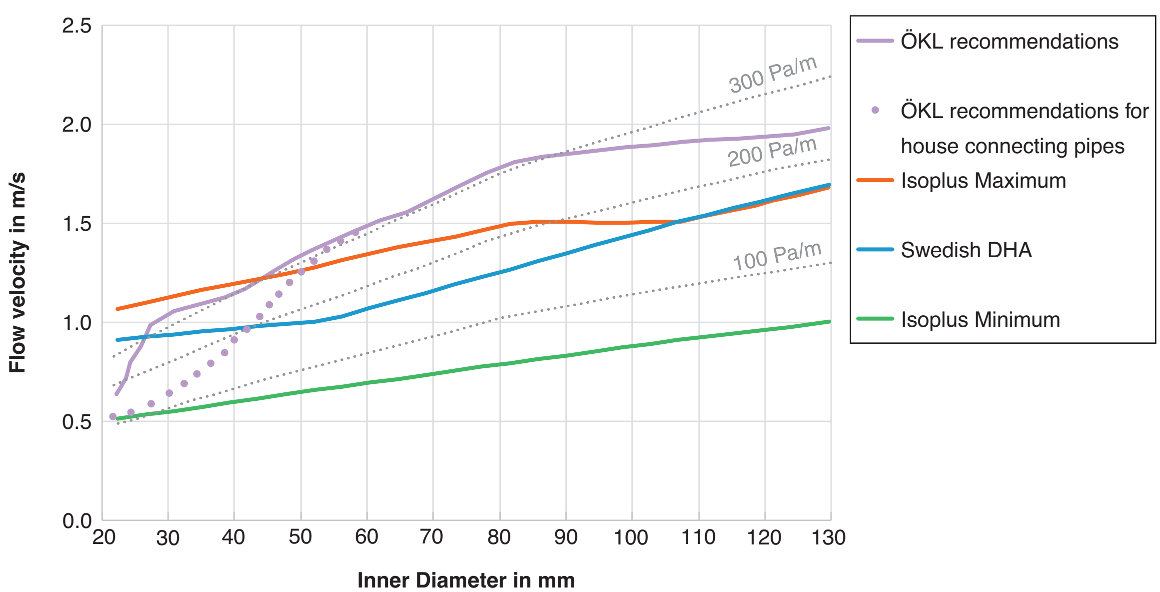

Figure 2: Different pipe design recommendations to ensure economic operation of the network

computed for each branch. The resulting pipe route length sums up to 2.89 km. The connecting pipes were defined to have 1.31 km, while the transportation pipes were calculated to have 1.58 km route length. Thus, nearly 45% of the total pipe length results from house connecting pipes (10 m route length per house substation). The assumed DH network is a simple small network of three separate main branches (tree geometry). Each branch has a network pump, so the pressure drop is calculated separately for each branch. The following bar chart depicts the total sum of supply and return pipe length of the three branches by differentiating between the needed nominal pipe diameters (DN). A standard plastic jacket compound pipe was assumed with a pressure nominal of 6 bar. The bar chart clearly demonstrates that even in case of ULTDH, pipe diameters of DN 20 suffice for the connecting of houses. Furthermore, in case of ULTDH a slight shift to higher DN can be observed. Nevertheless, it results only in few meters of DN 80 as largest DN.

4. Distribution Costs

4.1. Distribution Capital Costs

In order to evaluate the economic effect, the total network costs were determined with a medium cost approach for new building developments for unmade terrain and rigid pipes according to [24] (see Figure 4, blue dashed line). Specific construction costs were assumed of 190 €/m for DN 20 to 300 €/m for DN 80. This medium cost approach was also approved by [25] and can still be considered valid in 2017 according to the German District Heating Association AGFW. Nevertheless, there is an optimization potential according to [26], who showed that specifically in rural areas the specific construction costs can be reduced

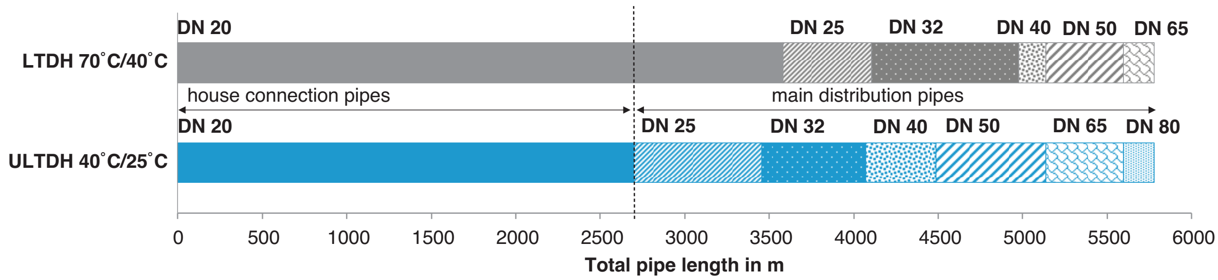

Figure 3: Nominal pipe diameter distribution showing the sum of supply and return pipes

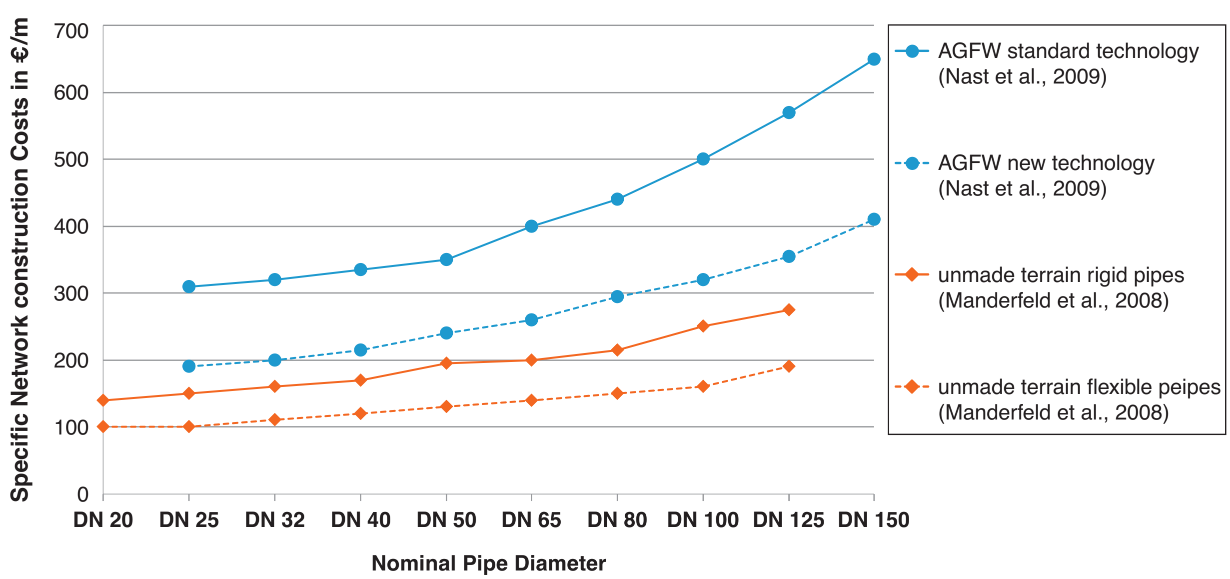

Figure 4: Specific network construction costs including construction costs and pipe material costs

using for example flexible pipes (see orange dashed line). This data applies only for Germany, it may differ in other countries.

For the ULTDH, average specific construction costs for the transportation pipes of 233 €/m have been computed. The LTDH shows a slightly lower value of average 226 €/m pipe length, which is a cost decrease of 3%. The connecting pipes are considered via the house-lead in costs, which were assumed with a fixed value of 3,600 €/household. Additionally, average costs for substations of 4,000 €/unit were taken into account. The distribution capital costs for the piping network were calculated for each DH system. The results are depicted in Figure 5. The distribution capital costs (discounted value) for the ULTDH network are shown by the blue stacked bar, while the distribution capital costs (discounted value) for LTDH network are shown in grey. Furthermore, it has been distinguished between costs resulting from main distribution pipes and house connection pipes, house lead-in costs, substations, and network pumps. The main costs were caused by the latter mentioned house lead-in costs and the substations. The main distribution pipes amount only to 25% in case LTDH and 26% of ULTDH of the total capital costs for the distribution infrastructure (without planning costs). The capital costs of LTDH network amounts to 111 k€/yr, while the ULTDH network causes net annual costs of 113 k€/yr. Despite the low temperature difference of 15 K in case of ULTDH, no economic disadvantage occurs. The networks show almost equal annual capital costs.

4.2. Pressure loss costs

The auxiliary energy demand was investigated based on the DH network designs and heat load characteristic of the assumed new building development. The auxiliary energy demand, namely the pump energy costs are caused by the pressure drop, needed volume flow and is directly linked to the heat load characteristic. As shown in Figure 6 the needed maximum volume flow rate differs significantly between ULTDH and LTDH due to the different temperature differences between supply and return. In case of LTDH, a total volume flow rate of 30 m^3/hr is needed to meet the maximum heat load. Due to the small temperature difference between supply and

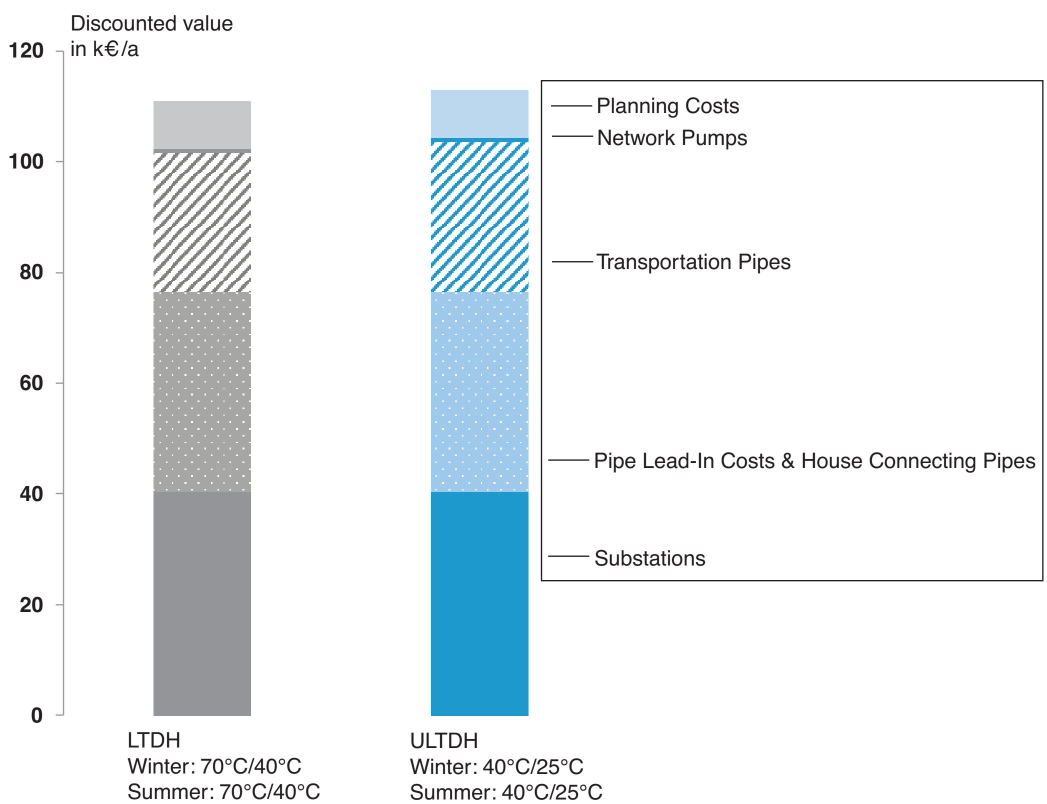

Figure 5: Net annual costs for the thermal network the thermal network LTDH (grey) and of ULTDH (blue)

return of the ULTDH, a twice as high total volume flow as LTDH volume flow rate is needed to meet the maximum heat demand. Nevertheless, the resulting maximum pressure drop through the ULTDH network does not differ significantly compared to LTDH network.

At this point, it has to be highlighted that the maximum heat load (80% – 100% of heat load) occurs only less than 200 hours per year. The pressure drop course follows the volume flow, thus the actual pressure

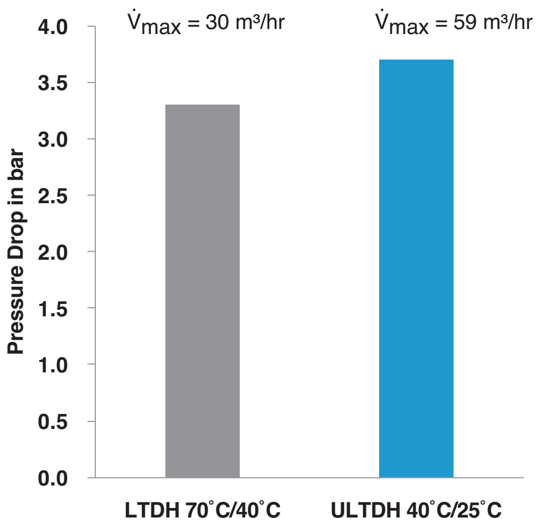

Figure 6: Pressure drop and needed volume flow at maximum heat load

drop is much lower in the main time of the year than the shown maximum pressure drop here. Supplementary, the operating strategy has a significant impact on the auxiliary energy demand. If DHW and SH are supplied via DH, the network needs to be operated the whole year. If a semi-decentralized system is planned, the DHW demand can be supplied partly or fully via individual technologies like heat pumps or solar thermal systems (roof installations). In order to evaluate the impact, a ULTDH network of year round operation (marked in blue) is calculated as well as ULTDH network, which is offline during low load period (see Figure 7, marked in orange). Therefore, for each DH branch a high efficiency network pump was designed according to the calculated pressure drop and needed volume flow. The heat load characteristic of the new building development was taken as basis. Furthermore, it was assumed that the pumps are controlled according to the differential pressure.

In case of a conventional LTDH, a total nominal electrical pump power of 1.7 kW was calculated. A year-round operation leads to an electricity consumption of 4.3 MWh/a caused by the network pumps. In case of the ULTDH, a total nominal electrical pump power of 3.2 kW was calculated, the resulting electricity consumption amounts to 8.7 MWh/a at year-round operation. Even if the auxiliary energy demand for the year-round operation of a ULTDH is nearly twice the value of the LTDH, it represents only 0.6% of the

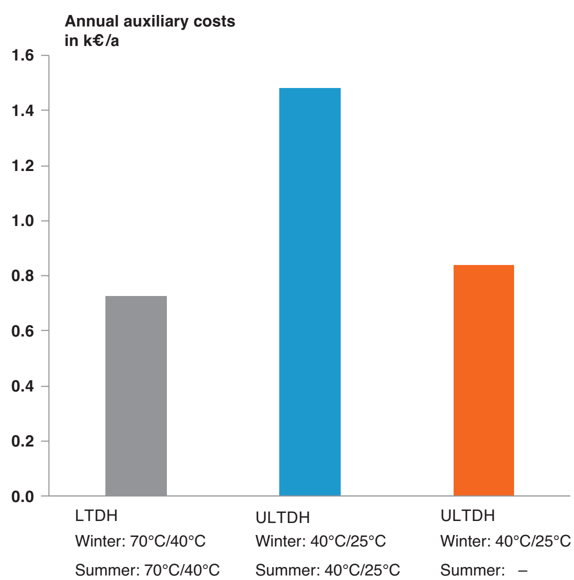

Figure 7: Resulting annual auxiliary costs distinguishing between conventional operation of LTDH network (grey), full year operation (blue) and a seasonal offline (orange) of ULTDH network

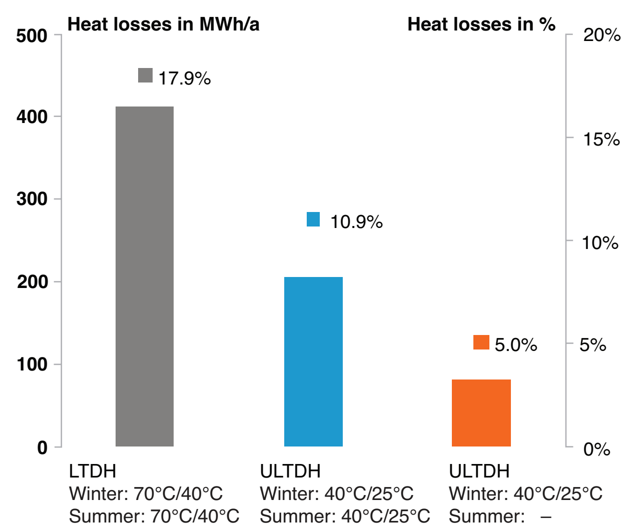

Figure 7: Heat distribution losses of the ULTDH and the LTDH network (with standard insulation)

total supplied heat. This electricity consumption can be reduced about 44% by applying a seasonal strategy, which comprises that the network would only be operated during space heating period (corresponding to 3400 operating hours per year). For the LTDH network the auxiliary energy demand caused by the network pumps represents 0.3% of the total supplied heat. Thus, the electricity consumption plays a sub-ordinate role despite the low flow temperatures and the low temperature difference of the ULTDH and has no significant impact on the system efficiency.

4.3. Heat Distribution Loss Costs

In operation, a DH network shows a characteristic heat loss rate mainly depending on the pipe type and diameter as well as insulation thickness and the temperature gradient between the pipe and the surrounding ground. The heat losses have been calculated and modeled for the two different heat supply temperature levels taking single rigid plastic bonded pipes as a basis [27]. The insulation class standard was assumed. Added to this, a seasonal operating strategy was calculated, assuming that the ULTDH network is only operated during space heating period as previously explained.

A conventional LTDH network at year-round operation for the new building development shows distribution losses of 17.9%. In contrast, the ULTDH network shows only distribution heat losses of 10.9%. Providing a seasonal operating strategy, the distribution losses can further be reduced to 5.0%.

Thus, a reduction of design and operating temperature from 70 °C (40 °C return) to 40°C (25 °C return) reduces the heat loss capacity by 50%, from 47 kW to 23.5 kW. The heat distribution losses decrease from 411 MWh/a to 206 MWh/a. The switch-off of the network during low load period further halves the heat distribution losses.

4.4. Total heat distribution costs

The resulting overall distribution costs are presented in the following bar chart (see Figure 8). The distribution costs are mainly driven by capital costs. The maintenance costs show 0.5% of the investment per

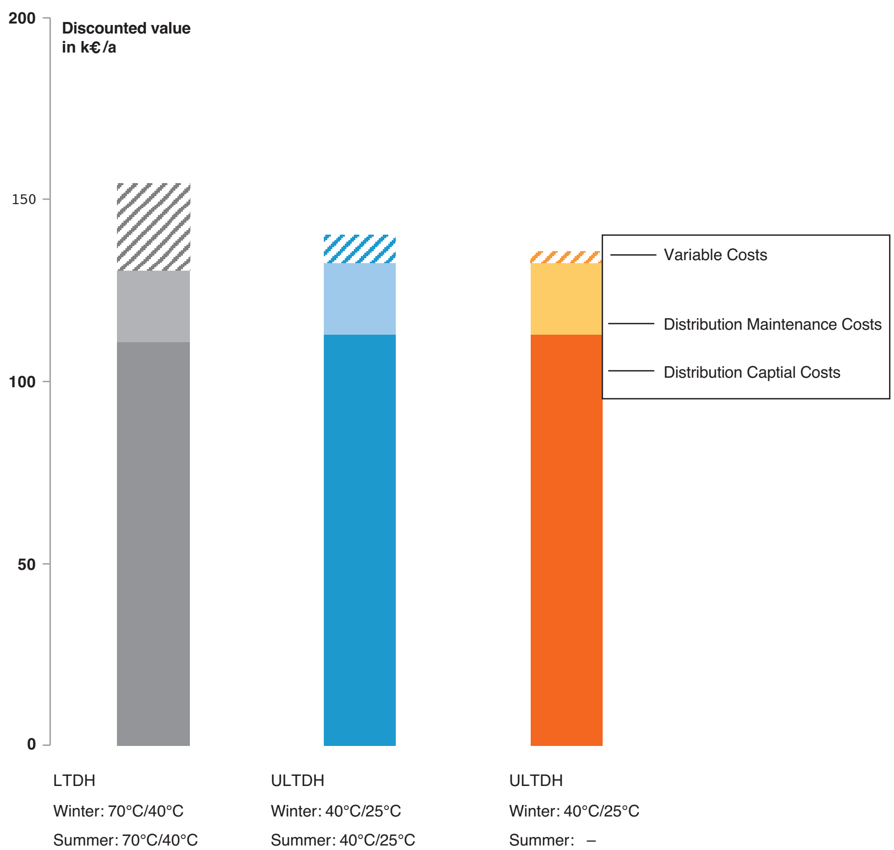

Figure 8: Heat distribution costs

year. The heat distribution losses are variable costs depending on the heat demand and operating time. They must be compensated supplementary to the heat demand by the central heating generation. Thus, the ULTDH has a cost advantage only due to reduced distribution losses.

By choosing the highest insulation standard, the distribution losses can be reduced by 18 – 20% compared to the standard insulation. A further improvement can be achieved using twin pipes. Static calculations indicate a decrease of 38% of distribution losses using twin pipes instead of single pipes for this specific DH network. However, single pipes were chosen because cost functions only for this standard case were available in literature.

At the same time, the linear heat density decreases with the lower supply temperature. The DHW must be met by supplementary units on the consumer side. In order to evaluate this effect, the following section determines central heat generation costs and decentralized heat generation costs defining an exemplary total heat generation system.

5. Central and decentralized Heat Generation Costs

Usually, the heat generation is a mix of different technologies distinguishing between peak load supply and base load supply. A variety of different heat supply technologies is possible that must be chosen according to the individual boundary conditions.

This study shows the economic characteristics of the heat supply system designed for the new housing development “Zum Feldlager” consisting of:

- a ground source heat pump for base load and an electric heater for peak load
- a borehole thermal energy storage
- a tank thermal energy storage (buffer storage)
- uncovered solar thermal collectors for ground regeneration

The central heat generation costs are calculated to demonstrate the impact of operating temperatures on the economics of the heat supply system. The capital costs show the base of the heat generation costs, but shall play here a secondary role. This is because the design and operating temperatures have a major impact on the variable costs. Therefore, a heat pump (HP) was determined raising the return temperature from the return flow of the network to the set supply temperature: in case of ULTDH to supply temperatures of 33°C - 40°C, in case of the LTDH to supply temperatures of 65°C - 70°C. A seasonal performance factor (SPF) of 4.4 for the ULTDH system and a SPF of 2.8 for LTDH network was assumed. These values are typical values corresponding to the temperature lift and source temperature level. The resulting electricity consumption of the heat pump and the peak load heater to meet the heat demand was calculated depending on the DH network and operating strategy. The peak load heater ensures 4.5% of the total heat demand. The electricity consumption is labeled as variable costs and they are depicted in the following bar chart (see Figure 9, striped bar parts). The fully colored bar parts represent the fix costs of the central heat generation. The central heat generation capital costs are equal in all three described DH systems amounting to 125 k€/a. The striped parts indicate the variable costs of the network versions. The main difference in variable costs between LTDH and ULTDH originates from the higher SPF of the ULTDH system. This emphasize the importance and impact of the heat generation performance, here the seasonal performance factor benefitting from lower supply temperatures of the ULTDH system.

The LTDH system shows the highest variable costs that amount to 133 k€/a representing 48% of the total heat generation costs. The ULTDH system at year-round operation shows a significant reduction of the variable costs of the LTDH system amounting to 82 k€/a. The ULTDH with seasonal operating strategy presents a further slight decrease of variable costs, which can be explained by the lower heat supply.

However, ULTDH needs decentralized heat supply units. The decentralized units were determined as follows:

- for the ULTDH system:
  - DHW air to water heat pumps with a 300l hot water storage tank for single family houses (interior installation, SPF = 3, tank storage thermal power loss of 68 W)
  - DHW storage tanks with electric back-up systems for multi-family houses (European ecolabel C, thermal power loss of 140 – 168 W)
- For LTDH system:
  - DHW storage tanks of 200 l for single family houses with electric back-up systems (European ecolabel B, thermal power loss of 59 W)

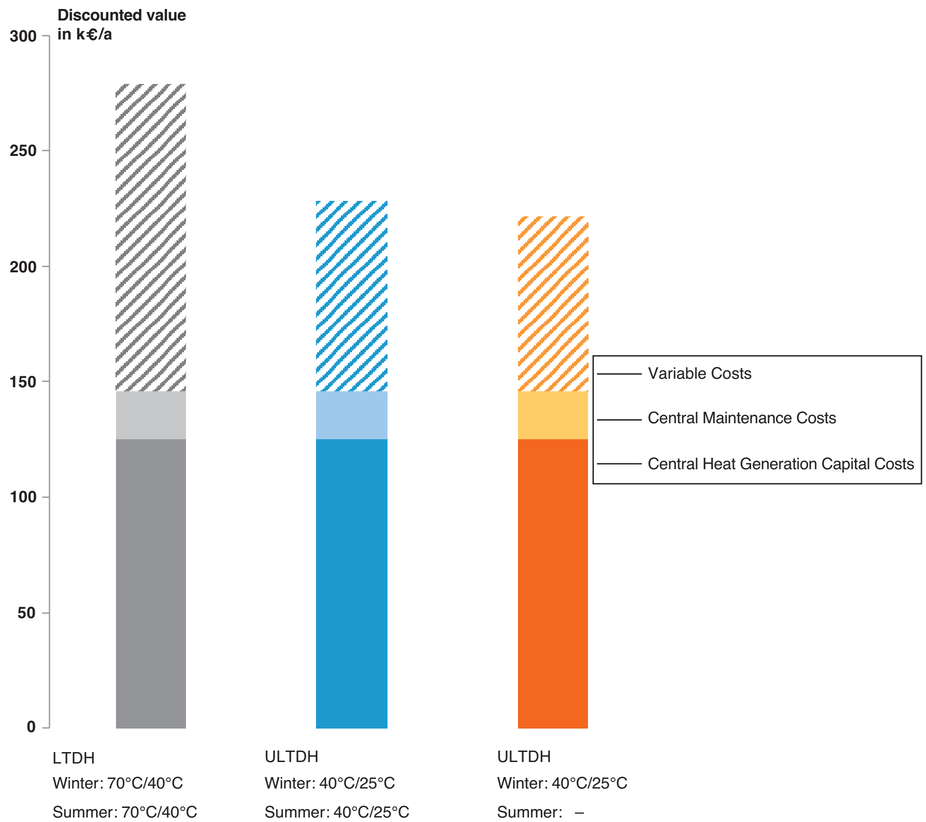

Figure 9: Central Heat Generation Costs

- o DHW storage tanks of 800 - 1000 l for multi- family houses with electric back-up systems (European ecolabel C, thermal power loss of 140 – 168 W)

Once more the capital costs should play a secondary role. The resulting variable costs are of major interest. They reflect the decentralized heat generation as well as the emerging heat storage losses (see Figure 10, striped bars). In case of LTDH, the resulting variable costs show the storage heat loss costs of 4.5 k€/a, which are made up by the central heat generation and equals 20% of the DHW demand. In case of ULTDH at year-round operation, the DHW demand is met by 46% by the decentralized heating units, which is the DHW heat pump and the electric back-up systems. Thus, variable decentralized heat generation costs of 27.5 k€/a occur. Regarding ULTDH with summer switch-off, the DHW demand is met by 76% by the decentralized units. In consequence, variable decentralized heat generation costs of 36.3 k€/a arise. Due to the slightly larger storage tanks, 23% DHW heat storage losses occur in case of ULTDH.

6. Influence of DH Design and Operating Temperature on Variable Costs

This section sums up the previous results and provides the overall system comparison.

The first sections stated that a lower distribution temperature of ULTDH does not increase the capital costs of a DH network if designed appropriately allowing relatively high pressure drops of 200-300 Pa/m of short duration. The heat distribution losses of ULTDH are reduced significantly, which increase the economics of the overall heat supply system. In order to answer the question, if a reduction of supply temperature in the distribution infrastructure only shift the heat loss problem to the consumer side, the variable cost structure of the three analyzed DH networks is discussed (see Figure 11).

The variable costs can be subdivided in central operating costs (grey), distribution heat loss costs (blue), DHW storage tank heat loss costs (orange) and decentralized operating costs (yellow). In case of ULTDH

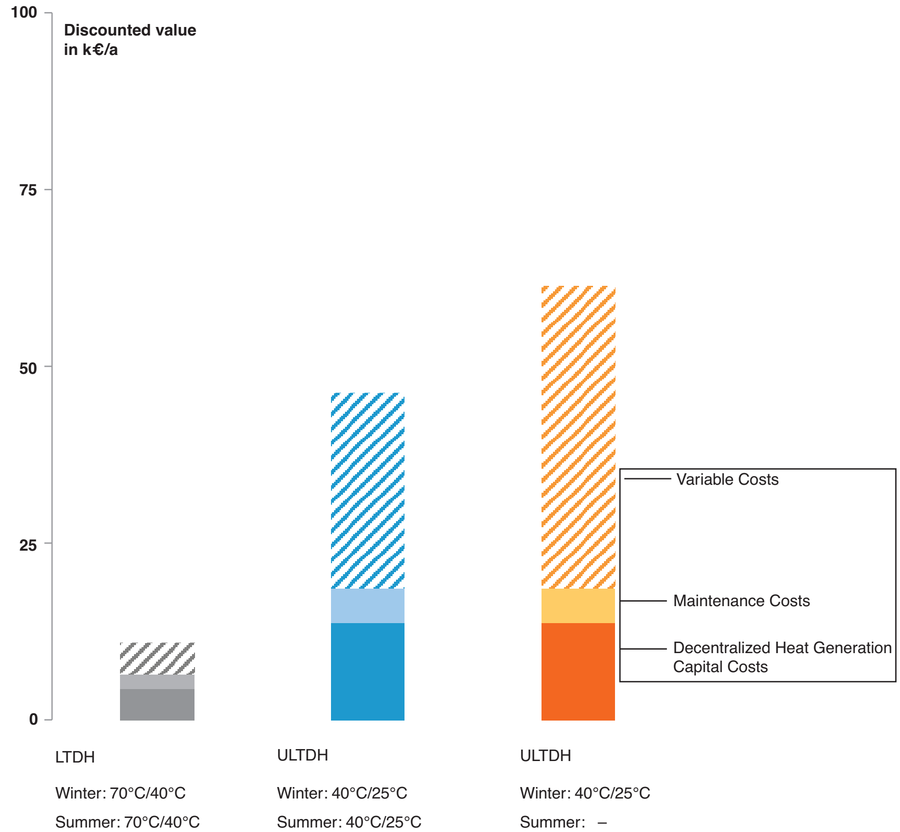

Figure 10: Decentralized Heat Generation Costs

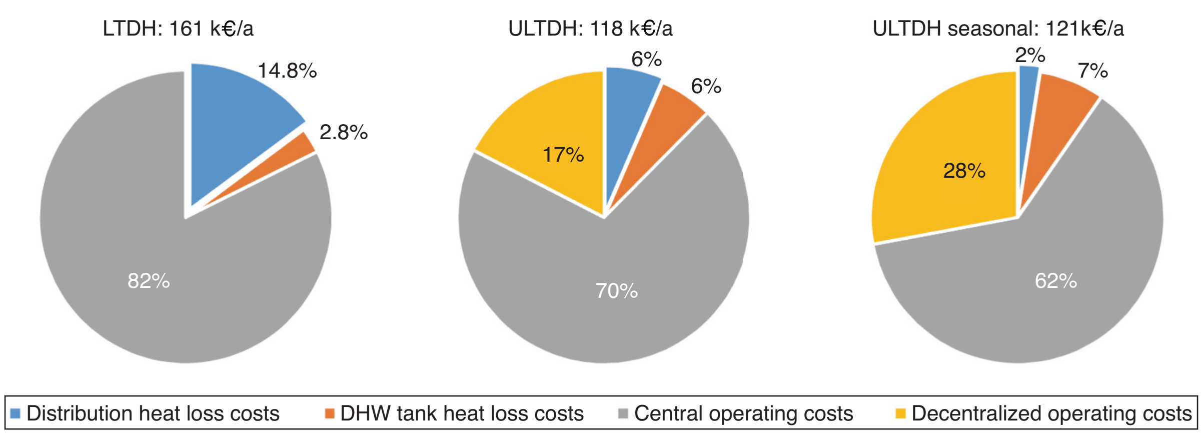

Figure 11: Variable cost structure

system the decentralized operating costs arise, originating from the needed temperature boost for the DHW.

Nevertheless, the overall variable costs are reduced from the LTDH system to the ULTDH system by about 27%. This is mainly due to the better SPF of the central heat pump in case of the ULTDH, but also due to the reduced heat distribution losses. Even if the share of decentralized DHW preparation (decentralized operating costs) amount 17% of the overall variable costs and supplementary storage heat loss costs occur, the ULTDH system is more beneficial than the LTDH system. An ULTDH system with switch-off during low load period, is similar in terms of economic efficiency compared to the year-round operated ULTDH system.

In conclusion, the DH design and operating temperatures determine the efficiency of the used heat supply technology (in case of a heat pump) and the DH network efficiency. On the given boundary conditions, the lowest specific heat distribution costs are achieved by the ULTDH network that is calculated to be operated year-round. The resulting total specific distribution costs are listed in the following table:

The exemplary LTDH total system costs consist of 35% distribution costs. These distribution costs can be reduced by 9% reducing the DH temperatures from 70 °C/ 40 °C to 40 °C/ 25 °C. The results demonstrate that a seasonal strategy for the ULTDH network can further avoid distribution heat losses. Specific distribution costs of 82 €/MWh arise for the LTDH network. The specific distribution costs increase slightly about 2% in case of ULTDH because of the reduced linear heat density. This effect is intensified the lower the linear heat density is. Nevertheless, also in terms of specific distribution costs, the ULTDH is more cost efficient than the conventional LTDH for new building developments. Of course, this is only valid for the given boundary conditions.

7. Discussion

This study aimed at analyzing the impact of design operating temperatures on the feasibility of a thermal network for new building developments in Germany. The economic assessment was conducted taking the planned new building development “Zum Feldlager”, which comprises 131 buildings as a basis. The new buildings show a low heat demand, which leads to a low linear heat demand density. Two different thermal networks have been compared: a LTDH network of 70 °C supply and 40 °C return in contrast to an ULTDH network of 40 °C supply and 25°C return.

It was shown, that in case of ULTDH the maximum volume flow rate to meet the maximum heat load is doubled compared to the LTDH network due to the low temperature difference of 15 K. This leads to slightly larger transportation pipe diameters and an auxiliary energy demand twice as high as the one calculated for the LTDH system. However, the auxiliary energy demand for the network pumps plays a negligible role. The capital costs of the LTDH and the ULTDH distribution infrastructure were shown to be nearly equal. The results stated that a lower distribution temperature does not increase the capital costs of a DH network if designed appropriately allowing relatively high pressure drops of around 200 – 300 Pa/m of short duration. The distribution losses are reduced significantly, which increases the economics of the overall heat supply system. Regarding the specific distribution costs, the ULTDH system with year-round operation shows the best results. The results demonstrate that the performance of the central heat generation, in this study the SPF of the central heat pump, is a sensitive factor. Another heat source temperature or different set supply temperatures can have a large impact on the overall system economic efficiency.

An additional switch-off of the network during low load period (summer) results in a decrease of distribution losses of 70% compared to the LTDH network, but shows no significant economic advantage compared to the year-round operation of ULTDH network. The calculation of the annual heat distribution costs and the specific distribution costs proved that an ULTDH network can be competitive and more cost-efficient compared to a LTDH network. In conclusion, it has been shown that low DH design and operating temperatures of around 40 °C supply and 25 °C return improve the performance of heat pump based heat supply systems significantly, ensure important improvement of heat distribution efficiency and show no disadvantage compared to LTDH networks.

In this study an electricity-based heat supply system was analyzed, but integrating renewable energies like solar thermal energy can further reduce the variable costs significantly. The cost analyses were based on cost characteristics, which are only valid for Germany.

Table 4: Influence of DH operating temperature and strategy on the specific heat distribution costs

	LTDH **Winter: 70°C/40°C** **Summer: 70°C/40°C**	**ULTDH** **Winter: 40°C/25°C** **Summer: 40°C/25°C**	**ULTDH** **Winter: 40°C/25°C** **Summer: -**
Central heat supply	100% DHW + 100% SH	54% DHW +100% SH	24% DHW + 100% SH
Central supplied thermal energy	1,808 MWh/a	1,679 MWh/a	1,539 MWh/a
Total distribution costs	154 k€/a	140 k€/a	136 k€/a
Specific distribution costs	82 €/MWh	84 €/MWh	88 €/MWh
Total system costs	444 k€/a	415 k€/a	419 k€/a

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