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Ecological and economic analysis of low-temperature district heating in typical residential areas

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Abstract

Potential waste heat integration in low-temperature district heating (LTDH) systems is a main task for future sustainable heat supply. For evaluation of efficient LTDH integration in residential areas, investigations of the typical building stock are useful.

In this study, we present an economic and ecologic investigation of two LTDH supply temperatures in multiple typical residential areas. We show which design have the strongest impact on efficient heat supply in terms of electricity usage and low specific heating costs. Therefore, we design nine representative residential areas derived from dwelling types of the German building stock. Within these areas, we investigate LTDH supply performance in combination with decentralized boosting heat pumps. In addition, we compare the results to an individual heat supply by air-water-heat pumps.

The results show that the fraction of domestic hot water on total heat demand and the design of decentralized heat pump systems capacities impact LTDH operation efficiency. LTDH network installation with operation temperatures around 60 °C are most advantageous in residential areas with a high share of space heating demand.

Key Innovations

- We investigate LTDH supply in combination with decentralized heat pumps in representative German residential areas and show the most effective operation environments for two LTDH supply temperatures.
- We compare the investment and operational costs of LTDH supply with decentralized heat pumps to an individual supply with air-water-heat pumps.

Practical Implications

It is important to design the heat pump and electric heater rated capacities for decentralized heat pump systems in combination with LTDH systems accurate to operational conditions.

Introduction

With the European Green Deal, the EU presents a strategy for greenhouse gas emission reduction to achieve the target of zero net emissions in 2050. The building sector in Germany is responsible for a third of CO_2 emissions. Thus, improving efficiency in this sector allows significant reduction of overall CO_2 emissions (Schmidt et al. (2016)). District heating is a key technology for the heat supply of buildings. For a future sustainable heating sector, it is necessary to integrate waste heat and renewable heat sources to unlock potential advantages. Operating temperatures in LTDH networks are decreased in comparison to existing district heating temperatures to utilize low-temperature heat sources, like waste heat from various processes, and to reduce heat losses (Lund et al. (2014)).

In some cases, LTDH temperatures are too low to fulfill high temperature requirements of heat demands. Especially old heating systems and domestic hot water (DHW) preparation have higher temperature requirements. In such cases, heat pumps (HP) can increase supply temperatures to the required temperature level. A central HP, which is located near the heat source, can increase supply temperatures (Yang and Svendsen (2018)). Another possibility is the increase of supply temperature by multiple decentralized HPs, which are located at the supplied buildings (Arabkoohsar (2019)). Schmidt et al. (2017) showed that LTDH can already supply the space heating demands of modern buildings with low supply temperatures. Brand and Svendsen (2013) found out that heat demands of buildings in different refurbishment stages can be supplied by LTDH most of the year without supporting HPs. Successful preparation of DHW by LTDH in combination with decentralized HPs has already been shown by Elmegaard et al. (2016) and Thorsen and Ommen (2018). As a result of various heating demands and temperature requirements, the successful operation of LTDH in different building areas depends on supplied building types (Köfinger et al. (2016)). The German residential building stock consists of various dwelling types

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with different sizes and years of construction. In residential areas, different fractions of these dwelling types are presented resulting in various heat requirements. If different residential areas in the surrounding of an utilizable low-temperature heat source exist, it is difficult to estimate the most efficient LTDH integration. To show LTDH performance in different building environments, we present an ecological and economic investigation of LTDH integration in various representative residential areas.

First, we demonstrate the identification and creation of representative residential areas. Second, we describe different heat supply scenarios and simulation models for the investigation of LTDH performance and the comparison to an individual air-water-HP supply. Third, we present the simulation results and compare operation performances and costs of all scenarios. Finally, a conclusion and an outlook for further work finish this study.

Methodology

In this study, we create representative residential areas with simplified assumptions for buildings' appearance and their technical heat equipment to show the most efficient heat supply in different building environments for various LTDH temperatures. Results of this comparison could be used for decision-making processes in which residential area a low-temperature heat source should be utilized by LTDH, or should rather be supplied by individual air-water-HPs, concerning less additional energy usage and from an economic point of view. For that comparison, we first describe the creation of the investigated residential areas followed by a further description of the supply scenarios and concerning simulation models.

Dwelling types and residential areas

The EU project *EPISCOPE*, also known as *TABULA*, defines building typologies of various countries in Europe (Stein et al. (2016)). From these statistics, we choose nine residential dwelling types of the German building stock which differ in the year of construction and building size. We select three building kinds of the German building stock, single-family house (*SFH*), terraced house (*TH*) and multi-family house (*MFH*). Furthermore, we select three different year of construction classes of the German building typology defined by *TABULA*. The oldest buildings were built around 1950 (*old*). New buildings have a technical building standard based around 2015 (*new*). A further class is located between *old* and *new*, and corresponding buildings were built around 1985 (*mid*).

Based on the nine chosen dwelling types and their fraction in the German building stock (Loga et al. (2015)), we construct nine average, representative residential areas. We investigate all nine residential areas with the same total amount of buildings and a constant area size or rather a constant network length. However, the heat demand densities of the residential areas differ because of various heat demands of presented dwelling types in these areas. Figure 1 shows the nine resulting residential areas and their heat demand densities.

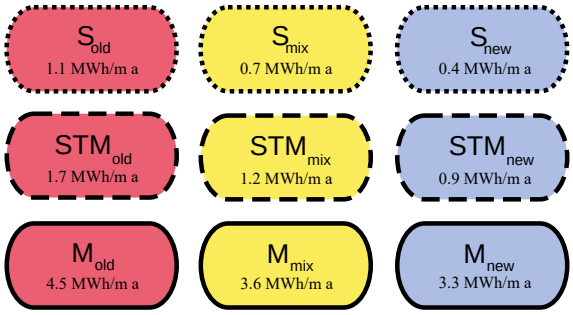

Figure 1: Representative residential areas and heat demand densities, located year of construction classes differ from left to right with colors and located building kinds differ from top to bottom with surrounded marking.

In Figure 1 year of construction classes of buildings placed in the residential areas differ from left to right. The red marked residential areas on the left solely consist of old buildings (*old*). In the right residential areas with the blue color theme, solely new buildings are presented (*new*). Buildings from all three year of construction classes are located in the three yellow marked residential areas in the middle (*mix*). From top to bottom the kind of the presented buildings differs. In the residential areas on the top marked by dotted lines, solely SFHs are located (*S*). Residential areas containing only MFHs are presented by areas on the bottom surrounded by continued lines (*M*). The remaining three dashed surrounded residential areas in the middle demonstrate mixed residential areas with SFHs, THs and MFHs (*STM*).

These nine created residential areas are investigated with different heat supply options, two various LTDH operating temperatures and an individual air-water-HP supply. With nine residential areas and three supply options, we investigate 27 heat supply scenarios in total. In the following, the model creation and assumptions for this approach are described.

Heat supply scenarios

For this study, we assume that the year of construction classes of buildings are directly linked to temperature requirements for space heating (SH) demand. Based on investigations by Pfnür et al. (2016) and characterizations of typical heating systems in buildings (Albers (2018) and Bohne (2019)), we determine design supply temperatures and heating curves in the dwelling types depending on their year of construction class. Table 1 summarizes the assumed supply

temperatures for the heating systems. With an average design temperature difference of 15 K (Bohne (2019)), return temperatures are also given in Table 1.

Table 1: Assumed design temperatures of heating systems depending on the year of construction class in [°C]

	supply temperature	return temperature
old	75	60
mid	55	40
new	45	30

For each dwelling type, we simulate SH-demand with the python tool *TEASER* (Remmen et al. (2018)). With the referenced floor area from the used dwelling types of *TABULA*, we compare simulated SH-demand profiles to specific demand values from the literature (Pfnür et al. (2016)). From this comparison, we deduce that the simulated demand profiles are a good representation of the heat loads' differences in the German building stock.

For DHW-demand, we adapt typical DHW preparation profiles from the German DIN EN 15450 (Deutsches Institut für Normung (2007)) to the used dwelling types by taking the amount of apartments and building size into consideration. For that reason, DHW demand of MFH differs between the year of construction classes, because the defined MFH types of *TABULA* contain different numbers of apartments. Furthermore, we determine a minimal DHW-temperature restriction of 60 °C to suppress potential legionella growth. Table 2 presents the resulting DHW-demands and the nominal DHW-heat loads of each dwelling type.

Table 2: Nominal DHW-heat load and total DHW-demand per day for all dwelling types

	Nominal DHW-heat load [kW]	Total DHW-demand [kWh/d]
SFH, TH	2.7	8.1
MFH_{old}	18.0	54.0
MFH_{mid}	20.0	60.0
MFH_{new}	34.0	102.0

Because occupancy and individual variation of heat requests are not modeled within this approach, we consider the heat load diversity of LTDH by changing the referenced time of SH- and DHW-demand profiles. Therefore, we shift the SH- and DHW-demand profiles of the supplied buildings by various time steps to reach typical district heating heat load diversities (Winter et al. (2001)).

For the LTDH networks, we model two-pipe networks with constant supply temperatures and a design temperature difference of 20 K between supply and return. To investigate impacts of supply temperatures, we consider two operating temperatures, 60/40 °C and 40/20 °C. The potential waste heat source in this case could be the cooling system of a data center. Cooling systems of data centers provide supply temperatures with only small fluctuations and have fixed return temperature requirements for cooling purposes. Depending on the installed cooling system technique (air- or water-cooled), data centers provide different temperature levels up to 60 °C (Huang et al. (2020)).

In the LTDH scenarios, each building is connected to the network by a substation. Figure 2 points out the operational behavior of this substation. Heat demand can be directly supplied by the network, if the actual return temperature of the heating system is 5 K (temperature gradient of the heat exchanger) below network design return temperature on the primary side. In case the required heating temperature is higher than the actual network temperature, the water-water-HP system increases the heating temperature.

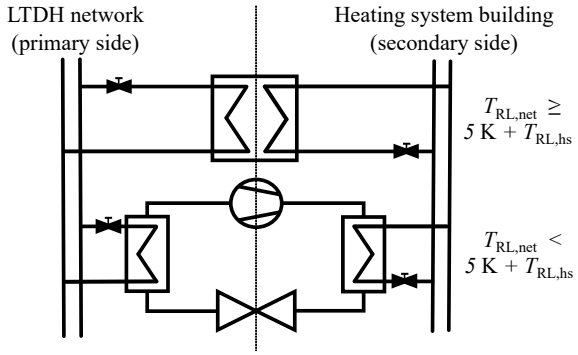

Figure 2: Substation of building with heat exchanger and HP, where heat is transferred from the LTDH network on the left to the building's heating system on the right. $T_{RL,net}$ is network return line temperature and $T_{RL,hs}$ is heating system return line temperature.

A HP system consists of a water-water-HP and an additional electric heater (EH) for peak loads. We design thermal rated capacities of HP and EH with the German VDI 4650 (Verein Deutscher Ingenieure (2019)) and DIN V 4701-10 (Deutsches Institut für Normung (2003)) individually for each dwelling type based on their nominal heat demand. Different shares of supplied heat by HP and EH are discussed later in the results.

We simulate all LTDH scenarios in Modelica and use submodels, e.g. HP, EH or pipes, from the Modelica library *AixLib* (Müller et al. (2016)). For a robust and fast generation of all models, we use the python package *uesgraphs* (Fuchs et al. (2016)). *Uesgraphs* is a framework to visualize different types of energy networks and to generate simulation models based on given network information. First, we design one net-

work topology containing one heat source and 100 consumers. We use the network topology, shown in Figure 3, with constant pipe lengths for all scenarios. Depending on the residential area and network supply temperature, we adapt presented dwelling types to the dots and calculate necessary pipe diameters. Second, we create individual Modelica models for each scenario with adapted data from *uesgraphs*.

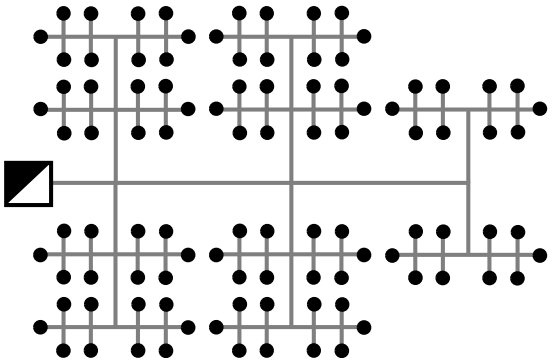

Figure 3: Network topology for LTDH scenarios, one heat source (square) connects buildings (dots) with a two-pipe system (lines).

In addition, we build simulation models for individual heat supply with air-water-HPs. In these individual supply scenarios, air-water-HPs in the buildings supply necessary heat by using ambient air as the heat source. All in all, we create nine residential areas and combine them with three different heat supply systems, LTDH with 60 °C supply temperature, LTDH with 40 °C supply temperature and an individual supply by air-water-HPs.

Results

This section presents simulation results of all 27 heat supply scenarios. In addition to energetic results, we estimate investment and operational costs of all scenarios to consider also economic differences.

To compare the heat supply performance of investigated residential areas, we define a factor that is similar to the mean coefficients of performance of all HPs in the buildings. The annual network performance (ANP) factor describes the heat demand ($Q_{\mathrm{demand},i}$) of all buildings ($\mathrm{N_{buildings}}$) relative to additional used electricity ($W_{\mathrm{el},i}$) for the electric heating systems (1).

$$\mathrm{ANP} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{N_{buildings}}} Q_{\mathrm{demand},i}}{\sum_{\mathrm{i=1}}^{\mathrm{N_{buildings}}} W_{\mathrm{el},i}} \quad (1)$$

ANP describes LTDH supply performance in a specific period, in this case one year. A high ANP refers to an efficient LTDH supply because the additional electricity demand is low. In contrast to that, a low ANP indicates high electricity usage relative to supplied heat demands.

We use two identified influences on ANP to present the results, direct heat share and electric heater share. On the one hand, direct heat share represents the fraction of heat demand, which is supplied directly by the network via the heat exchangers. On the other hand, electric heater share (EHS) describes the share of EH generated heat on total supplied heat by the electric heating system. As a reminder, an electric heating system consists of a HP and an EH for peak loads. EHS is an indicator for electricity usage efficiency because with an EH more electricity is used for the same supplied heat than with a HP.

40 °C LTDH scenarios

The ANP results of residential areas supplied by 40 °C LTDH in relation to direct heat share are presented in Figure 4. The shape and color of the data points are related to the nine residential areas (*Figure 1*).

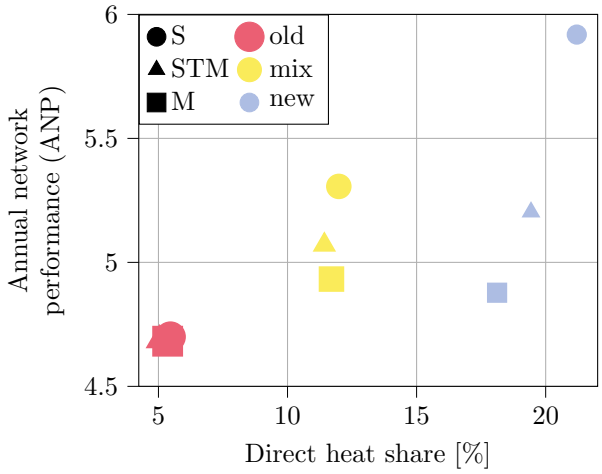

Figure 4: ANPs of 40 °C LTDH scenarios depending on direct heat share

Residential areas with only old buildings achieve the lowest ANPs around 4.6. A high share of SFH in residential areas (M < STM < S) yields to highest ANPs, whether containing all year of construction classes ($\mathrm{S_{mix}}$) with 5.3 or including only new buildings ($\mathrm{S_{new}}$) with 5.9. With rising MFH share in residential areas (S < STM < M), lower ANPs are achieved by mix and new scenarios.

Figure 5 shows ANPs of 40 °C LTDH scenarios in relation to summarized EHSs of all supplied buildings. With Figure 5 the ANP distinctions between residential areas with constant year of construction classes are explained. In mix and new residential areas, EHS increases with rising MFH share (S < STM < M) resulting in decreasing ANPs.

60 °C LTDH scenarios

ANP results of 60 °C LTDH scenarios are shown in Figure 6. With higher LTDH temperatures, also higher ANPs are achieved by supplied residential areas. The main reason for that is the bigger amount of

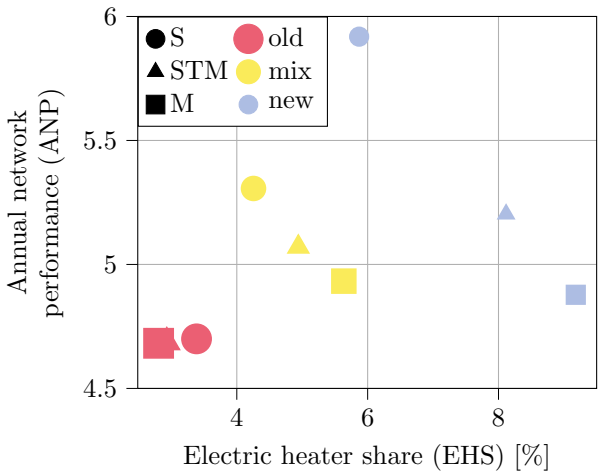

Figure 5: ANPs of 40 °C LTDH scenarios depending on EHS

direct supplied heat without the necessity of temperature increasing by the electric heating systems. Residential areas containing only old buildings achieve high ANPs around 12.2 and results are nearly independent of appearing building kinds. Only supply of S_{mix} and S_{new} yield to higher ANPs with 13.9 respectively 12.7. With higher MFH share (S < STM < M) within the mix and new residential areas, ANPs decrease.

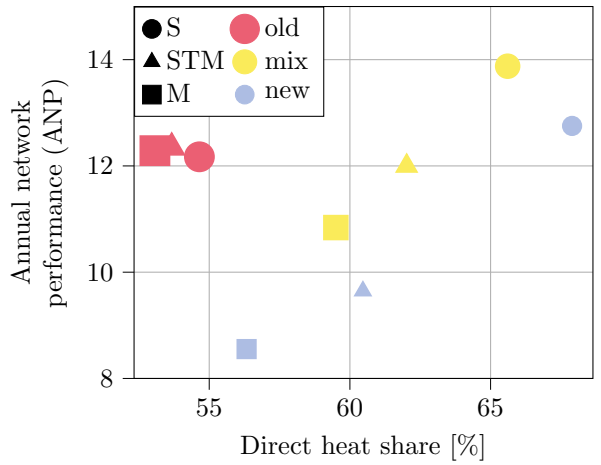

Figure 6: ANPs of 60 °C LTDH scenarios depending on direct heat share

Figure 7 shows ANPs in relation to summarized EHSs of all supplied buildings. Residential areas containing only old buildings have the lowest EHSs resulting in relatively high ANPs. In the remaining investigated areas, lower EHSs of areas with mainly SFHs result in higher ANPs than in residential areas with mainly MFHs.

Individual supply scenarios

In addition to the investigated LTDH scenarios, we simulate individual supply scenarios for all residential areas. In this case, all buildings are not supplied by LTDH but with individual installed air-water-HPs, which supply SH- and DHW-demands. We simulate

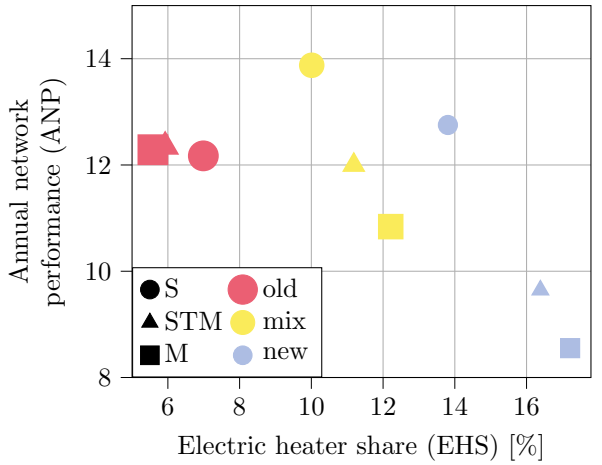

Figure 7: ANPs of 60 °C LTDH scenarios depending on EHS

annual air-water-HP performance for each dwelling type independently and calculate the resulting ANPs for residential areas to compare them to the LTDH scenarios. Figure 8 shows ANPs for all nine individual supply scenarios.

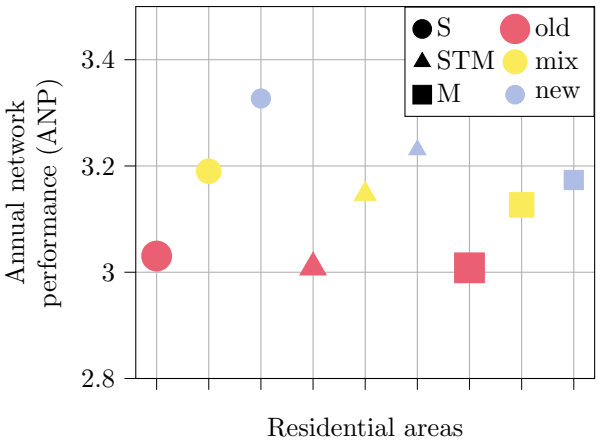

Figure 8: ANPs of individual supply scenarios with air-water-HPs

Residential areas containing only old buildings achieve the lowest ANPs as a result of high SH temperature requirements. Supply of S_{new} yields to highest ANP resulting from low SH temperature requirements. However, all individual supply scenarios achieve much lower ANPs than the LTDH scenarios. Due to higher and more constant temperatures in the network supply line, water-water-HPs can work much more efficiently than air-water-HP with ambient air as the heat source and the related fluctuating temperatures.

Investment and operational costs

For the economic investigation, it is assumed that in all 27 scenarios it is necessary to install HPs. In addition, we estimate the installation costs of pipes for all LTDH scenarios. We calculate total annualized

costs C_{tot} of all scenarios by (2).

$$C_{\text{tot}} = I_{\text{HP}} \cdot a + I_{\text{network}} \cdot a + c_{\text{electricity}} \cdot (W_{\text{el,pump}} + \sum_{\text{i=1}}^{N_{\text{building}}} W_{\text{el,building},i}) \quad (2)$$

With I_{HP} standing for HP system installation costs, depending on necessary thermal rated capacities, and I_{network} representing pipe installation costs depending on pipe diameter and length. $W_{\text{el,building}}$ and $W_{\text{el,pump}}$ represent electricity demand for electric heating system and for central circulation pump of LTDH network. For the operational cost, we use electricity price $c_{\text{electricity}}$ for HPs and circulation pump. Furthermore, a is used as the capital recovery factor with a twenty year time span and an interest rate of 4 %. We calculate resulting specific heating costs c_{heat} in relation to supplied heat by (3).

$$c_{\text{heat}} = \frac{C_{\text{tot}}}{\sum_{\text{i=1}}^{\text{N}_{\text{building}}} Q_{\text{demand},i}} \quad (3)$$

In comparison to a conventional heat supply, we also show the heating costs of gas heat supply. To show the resulting heating costs when conventional heating systems are replaced, no investment costs for gas boilers are assumed. Figure 9 presents the heating costs of all scenarios.

The lowest heating costs occur in residential areas with high heat demand densities, or rather in areas with a high share of old buildings or MFHs. Individual supply scenarios with air-water-HPs have the highest costs in almost every residential area. Heating costs of conventional gas supply are equal for all nine residential areas because we only consider fuel costs and no investments, which leads to relatively low costs. Nevertheless, heat supply by 60 °C LTDH yields lower heating costs in some residential areas than conventional gas supply, especially in areas with high heat demand densities.

Discussion

In this section, we discuss the different influences on ANP and the design approach of the electric heating systems. Finally, we summarize the main results of this study.

New buildings have modern heating systems, so that low supply temperatures are sufficient to cover SH-demands. Thus, these buildings can be supplied most of the time directly by the network and do not need additional support by HPs. For 40 °C LTDH supply temperature, this leads to rising ANPs of the residential areas $\text{S}_{\text{mix/new}}$ and $\text{STM}_{\text{mix/new}}$ (*Figure 4*).

Different ANPs of residential areas with a constant share of year of construction classes (old, mix, new) are explained by different SH- and DHW-demand shares in the various dwelling types. In this study, DHW-demand is independent of year of construction class and only depends on the number of apartments in each dwelling type. However, SH-demand depends on the year of construction class due to different insulation standards. Therefore, SH-demand share decreases and DHW-demand share increases from old to new year of construction class (*Table 3*). In addition, DHW-demand share of MFH dwelling types is mostly in general higher than in the two other dwelling types.

Table 3: DHW-demand share of total heat demand for all dwelling types in [%]

	old	**mid**	**new**
SFH	8.4	12.1	21.5
TH	9.3	22.1	23.7
MFH	13.3	19.0	34.8

DHW-demand is supplied by HP or EH because the required DHW temperature of 60 °C cannot be reached solely by LTDH in any scenario. The network can supply SH-demand directly depending on ambient temperature and the related heating system supply temperature. In conclusion, SH-demand share is an indicator for the potential of direct heat supply ability without additional electricity usage. Therefore, differences in SH-demand, or rather in DHW-demand share (*Table 3*), between building kinds and year of construction classes have an impact on ANP results (*Figure 4* and *Figure 6*).

Within mix and new residential areas, EHS values rise with a higher share of MFHs (S < STM < M) leading to lower ANP results. Overall scenarios the EHS rises with a higher share of new buildings in the residential areas (*Figure 5* and *Figure 7*). This results from the different thermal rated capacities of HP and EH in the various dwelling types. Based on VDI 4650 and DIN V 4701-10, the design process of HP's and EH's thermal rated capacities are determined by fixed fractions of the total nominal heat load (SH- and DHW-demand). Because SH-demand is higher in old buildings, also corresponding heating systems are designed with a bigger rated heat capacity than the systems in new buildings with a lower nominal SH-demand. However, DHW-demand is a big heat power request to the heating systems that occurs frequently and is independent of the year of construction class. Because of that, peak loads, concerning the heating system's capacity, are more often reached in new buildings. So in new buildings, EH hast to support heat requests more often than in old buildings, where HPs have higher rated heat capacities. A similar correlation for higher DHW-demand share in MFH than in SFH can be seen as well (*Table 3*). That has the same effect on the electric heating systems, resulting in higher EHS for residential areas with mainly MFHs in contrast to areas with

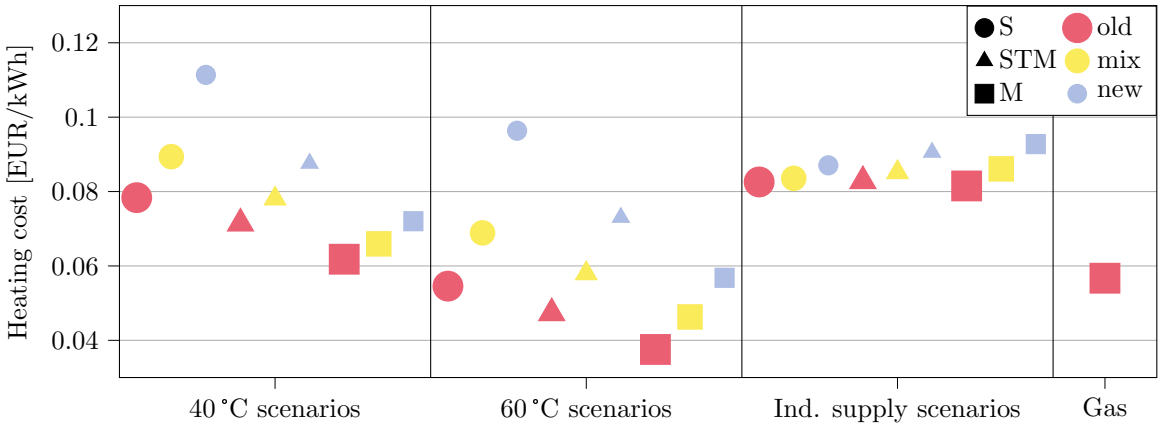

Figure 9: Heating costs of all investigated scenarios

mainly SFHs.

We suspect, that by an individual design of HP's and EH's rated capacities to the real operational environment the resulting EHS in operation could be much smaller. Because of smaller EHS, the LTDH supply would be more efficient.

Within the 40 °C scenarios, the direct heat share seems to have a stronger impact on ANP results because S_{mix} and S_{new} reach high ANPs despite the relative high EHSs (*Figure 5*). Within the 60 °C scenarios, the influence of EHS increases which leads to high ANPs also for residential areas with old buildings (*Figure 7*).

To summarize the main findings, we can conclude that if a 60 °C heat source is available for heat supply, especially residential areas with a high share of old buildings should be utilized by LTDH because of low heating costs and high ANPs or rather a small relative additional electricity usage. If a 40 °C heat source could be utilized by LTDH, the supply of various residential areas is a trade-off between high supply efficiency and low heating costs.

In all investigated residential areas, individual heat supply by air-water-HPs shows lower energy efficiency and in most cases heating costs are higher than with LTDH supply. In conclusion, if heating systems of multiple buildings are renovated or installed simultaneously, and a low-temperature heat source can be utilized, LTDH installation with decentralized water-water-HPs should be preferred over an individual heat supply by air-water-HPs. Nevertheless, with optimally designed HP capacities, a mixed scenario with LTDH implementation and partly individual air-water-HPs, depending on existing dwelling types, could increase overall heat supply efficiency. This option should be investigated in future work.

Conclusion

We present an investigation of LTDH heat supply for average, representative residential areas in Germany. Based on nine residential areas, we investigate supply efficiency and heating costs of heat supply scenarios with 40 °C and 60 °C LTDH networks (with decentralized water-water-HPs) and compare them to a supply scenario with individual air-water-HPs.

Based on the calculations, it can be concluded that the temperature of utilized low-temperature heat source affects the efficiency of supply to different residential areas decisively. LTDH networks with 40 °C supply temperature show high efficiency in areas with a high share of new SFHs. However, with 60 °C supply temperature also areas with old buildings are efficiently supplied because of more direct supplied heat without using the electric heating systems. From an economic point of view, residential areas with high heat demand densities should be favored for LTDH development. Installations of individual air-water-HPs for SH- and DHW-demand show much lower supply efficiency and higher heating costs in nearly every investigated residential area.

In future work, a more detailed survey should concentrate on the individual design of the electric heating systems, more precisely on the design of HP's and EH's thermal rated capacities, to achieve more efficient supply by LTDH in combination with decentralized HP systems.

Nomenclature

Acronyms

ANP	annual network performance
DHW	domestic hot water
EH	electric heater
EHS	electric heater share
HP	heat pump
LTDH	low-temperature district heating
M	residential area with only multi-family houses
MFH	multi-family house
S	residential area with only single-family houses
SFH	single-family house
SH	space heating
STM	residential area with all three building kinds

TH	terraced house

Abbreviations

mid	middle year of construction class
mix	residential area containing buildings of all three year of construction classes
new	newest year of construction class
old	oldest year of construction class

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