Central versus Semi-decentralized Solar District Heating for Low Heat Demand Density Housing Developments in Germany

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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 housing area in Germany consisting mainly of single family houses, solar district heating concepts at two different supply temperature levels of 70°C supply and 40°C supply are examined in terms of economic and efficiency aspects. Depending on the required temperature level of the heat supply concept the component's design differs. A system with 70°C supply temperature is based on a central heat supply with a heat pump and ground-mounted solar collectors, whereas the system with 40°C supply temperature is a semi-decentralized concept with central heat pump for space heating and decentralized solar thermal systems and electric back-up heaters for domestic hot water preparation.

Keywords: solar district heating, low heat demand density, ultra-low-temperature district heating

Abbreviations

BTES	Borehole Thermal Energy Storage
DH	District Heating
DHW	Domestic Hot Water
GSHP	Ground Source Heat Pump
HP	Heat Pump
PTES	Pit Thermal Energy Storage
SH	Space Heating
TTES	Tank Thermal Energy Storage
B / W	Brine /Water

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 (Lund et al., 2014). 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 (SDH solar district heating, 2017). 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 on a land area of 115,000 m². 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 (Persson and Werner; Persson and Werner, 2011). It represents a heat demand sparse area with a very low linear heat demand density of around $580\ \mathrm{kWh/(m_{trench} \cdot yr.)}$. 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 solar district heating concepts for the new housing area "Zum Feldlager" at different supply temperature levels are examined in terms of economic and efficiency aspects in this study. In Denmark, the implementation of solar heat is characterized by large central ground-mounted solar thermal collector fields connected to thermal networks and seasonal storages. The opposite case occurs in Germany. A broad implementation of ground-mounted large-scale solar thermal collector fields in district heating systems is limited because of high land prices. Individual solar thermal systems are currently dominating the German market. Key issue is, under which boundary conditions a central solar district heating system is more beneficial than a semi-decentralized district heating system for very low linear heat density areas in Germany, like the housing development "Zum Feldlager". Accordingly, the heat generation costs have been calculated considering components' investment, system operating costs as well as maintenance and service costs for two exemplary heat supply systems.

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2 Boundary Conditions

2.1 Description of the New Housing Development

The planned new housing development “Zum Feldlager” (Kassel, Germany) comprises of 131 buildings on a land area of 115,000 m². The housing development will consist mainly of single family houses, resulting in a low building density with a plot ratio of 0.25 according to (Persson and Werner, 2011). The buildings were calculated to meet the requirements of the German KfW-70 low-energy building standard according to the Energy Saving Ordinance 2016 (Gesellschaft für Rationelle Energieverwendung e. V., 2016). This means that the buildings were designed to have a specific heating demand below $50\ \mathrm{kWh}/(\mathrm{m}^2 \cdot \mathrm{yr})$. The space heating demand of each building was calculated according to the German standard DIN V 4108-6 (Deutsches Institut für Normung e. V., 2003). Additionally, the peak heating load for every building was computed according to DIN EN 12831 (Deutsches Institut für Normung e. V., 2012). Regarding the domestic hot water demand, demand profiles were generated by using a stochastic modelling tool developed by Jordan et al. for IEA SHC-Task 26, which takes into consideration the Gaussian-Distribution and different time scales to generate various load profiles (Jordan and Vajen, 2001). The total heat demand was calculated to amount $\approx 1{,}656\ \mathrm{MWh}/yr$, that comprises of one quarter DHW ($\approx 380\ \mathrm{MWh/yr}$) and of three quarter for space heating (SH) ($\approx 1{,}285\ \mathrm{MWh/yr}$). It represents a heat demand sparse area with a low linear heat demand density of around $580\ \mathrm{kWh}/(\mathrm{m}_{\mathrm{trench}} \cdot \mathrm{yr})$ assuming a total district heating (DH) pipe length of 2.89 km.

2.2 Generation of Heat Load Profile

Within the framework of the joint research project “Geosolare Nahwärmeversorgung für die Siedlung Zum Feldlager” the new building development and the corresponding semi-decentralized solar DH 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 distribution infrastructure was simplified calculating the average pipe diameter of the district heating network branches and the corresponding pipe length. The characteristics of standard plastic jacket compound pipes with standard insulation were assumed. The 131 buildings were clustered in 22 building typologies 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 taking into account multiplication factors for each case. Precise and realistic domestic hot water systems consisting of all system engineering components were designed in accordance to VDI 6002 (Verein Deutscher Ingenieure e. V., 2014) and VDI 2067 Blatt 12 (Verein Deutscher Ingenieure e. V., 2000). The resulting annual heat load profile is shown in Fig. 1. The space heating (SH) demand is depicted in blue, while the domestic hot water (DHW) demand is displayed in red. The heat load profile is taken as a base for system design and calculation of the central solar DH system (see section 2.3).

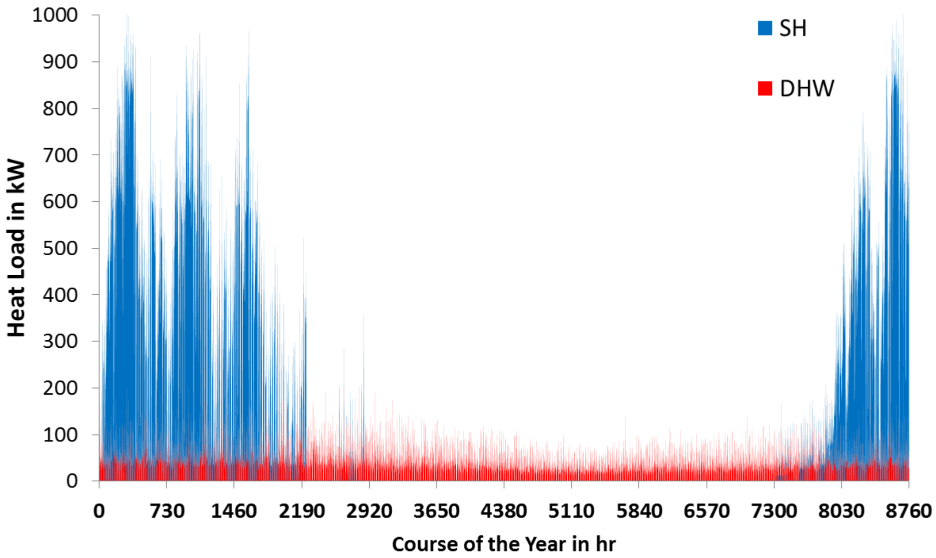

Fig. 1: Calculated hourly heat load profile of the housing development “Zum Feldlager”, in blue the space heating demand, in red the domestic hot water demand

2.3 Design Requirements and Basis of Comparison

Both solar DH systems presented were designed to achieve a renewable heat supply of ≈ 80 % of the total heat demand of the new building development. Considering that the renewable energy already covered roughly 29% of gross electricity generation (total volume of electricity generated in Germany) in 2016, the electricity consumption of each solar DH system had to be below 427 MWh/yr. The number of buildings and inhabitants, as well as the DH geometry and pipe length were kept constant. Depending on the required temperature level of the heat supply concept the components´ design differs. Also, the heat distribution network design (pipe diameters, pumps) was adapted according to the distribution temperatures. The central solar DH system is compared to the semi-decentralized DH system for low heat density housing developments in Germany taking following criteria into account:

- Investment for heat supply components
  (decentralized versus central solar thermal system, heat pump, electric peak load heater,
  borehole thermal energy storage, pit thermal energy storage, tank thermal energy storage)
- Investment for the distribution infrastructure (material and burring costs for pipes)
- Prices for land area
- Maintenance and service costs
- Operating costs.

The discounted present value of capital costs, service and maintenance costs, and operating costs was calculated on a base period of 30 years including proportional reinvestments after 15 operating years (central heat pump, decentralized hot water storages, electric back-up heater, components of the uncovered collector field) with an interest rate of 5.6 %. All heat supply components, the DH infrastructure, pumps, the energy centre (centre building with utilities), site development costs, connection, and commissioning costs were considered. Furthermore, the characteristic operating costs were computed at the base of the results from dynamic simulations and static calculations. The maintenance and service costs were evaluated according to VDI 2067 Blatt 1, which recommends fixed rates of investment to calculate the maintenance and service costs depending on the technology used (Verein Deutscher Ingenieure e. V., 2012).

3 System Design

3.1 Central Solar District Heating System

The first concept introduced in this paper is similar to Danish systems like the DH system in Braedstrup and the German DH system in Crailsheim (Nußbicker-Lux, 2010; SDH solar district heating, 2017). The supply temperature of 70°C ensures DHW preparation and SH supply via a low-temperature district heating network. The heat supply system consists of (see Fig. 2):

- A central large-scale, ground-mounted collector field,
- A central heat pump supplemented by an electric peak load heater,
- A Pit Thermal Energy Storage (PTES),
- And a low-temperature district heating network of 70 °C supply and 40 °C return temperature.

The shown functional diagram of the heat supply concept shows only the main components and does not include heat exchangers, pumps, valves etc. for reason of simplicity (see Fig. 2). The district heating network is simplified and represented by a supply line and a return line. The DH network is operated throughout the year with a fixed supply temperature. A linear heat demand density of $576\ \mathrm{kWh/(m_{trench}\cdot yr)}$ was determined.

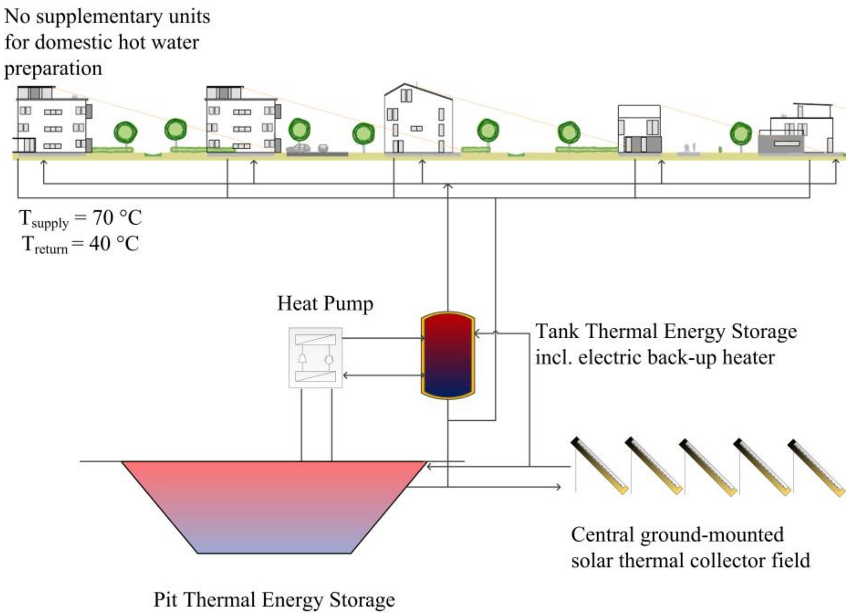

Fig. 2: Central solar district heating based on low-temperature district heating network

The solar thermal system was designed with the free software ScenoCalc Fernwärme 2.0 (Solites, 2017). The heat demand profile shown above served as a basis for the system design. The seasonal PTES is dimensioned in order to achieve a high solar fraction and at the same time low solar heat surplus. A specific storage volume of 3.3 m³/ m² collector area was found to be reasonable (via parameter variations) resulting in the lowest solar heat surplus. The collector field is connected through a heat exchanger to the PTES (heat exchanger temperature difference 5 K). An additional heat exchanger is assumed between the PTES and the DH network (heat exchanger temperature difference 5 K). In order to meet the requirements of renewable heat share of 80 %, the system was designed as follows:

Tab. 1: System design of the central solar district heating system

Component	Size
Flat plate collectors (ground mounted)	2,400 m²
PTES	8,000 m³
Heat Pump	593 kW_{th} (at W0/W35) / SPF 3.8
Tank Thermal Energy Storage (TTES)	100 m³
Electric peak load heater	740 kW nominal power
DH operating Temperatures	Summer: 70 °C / 40 °C Winter: 70 °C / 30 °C
Software for design and calculation	TRNSYS and ScenoCalc Fernwärme 2.0

3.2 Semi-decentralized solar district heating system

The second concept is a semi-decentralized concept based on an ultra-low-temperature district heating network. The supply temperature of 40°C ensures space heating. However, supplementary components for Domestic Hot Water (DHW) preparation are needed. A linear heat demand density of $432\ \mathrm{kWh}/(\mathrm{m_{trench}} \cdot \mathrm{yr})$ has been determined, as only space heating is provided by the district heating.

The heat supply consists of (see Fig. 3):

- Distributed solar thermal systems (mounted on the building roofs) for DHW preparation,
- Uncovered solar thermal collector fields for thermal ground regeneration,
- A central Ground Source Heat Pump (GSHP) supplemented by an electric peak load heater,
- A Borehole Thermal Energy Storage (BTES),
- And an ultra-low-temperature district heating network with 40 °C supply and 25 °C return temperature.

Furthermore, a seasonal operating strategy is applied in order to keep distribution losses low. The heat network is operated during the space heating period from October to April only and distributed solar thermal systems on the building roofs combined with electrical back-up heaters ensure DHW preparation throughout the year. The GSHP and the DH is offline in the period of May to September. Only the thermal ground generation is operated through one DH branch. The uncovered solar collector field supplies the BTES with low temperature heat. Thus, the ground temperature is kept constant over the calculated 30 operating years. Also here, the shown functional diagram of the heat supply concept shows only the main components and does not include heat exchangers, pumps, valves etc. for reason of simplicity (see Fig. 3). The district heating network is simplified and represented by a supply line and a return line.

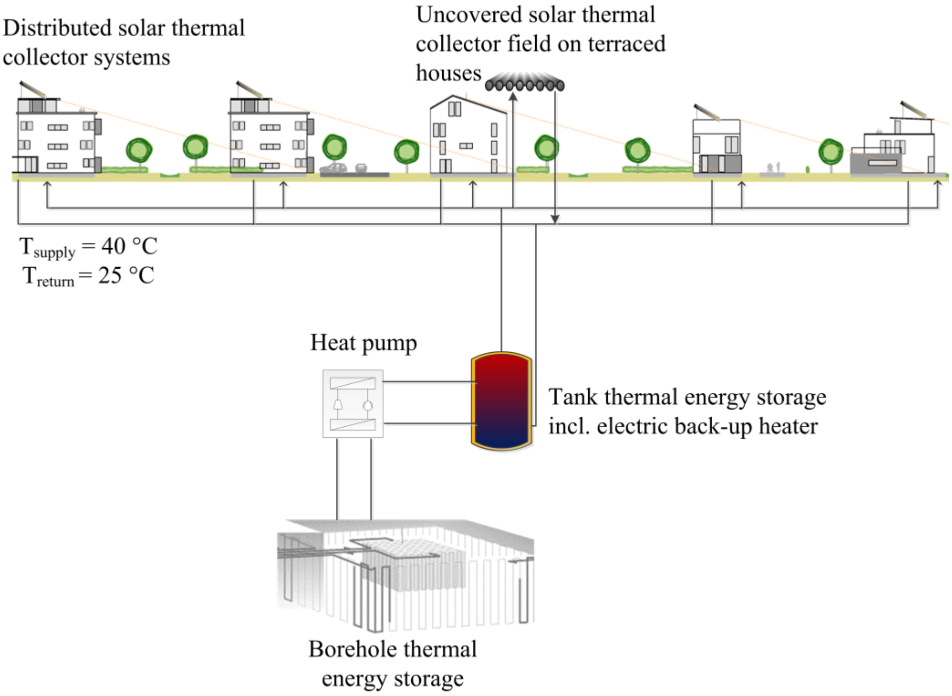

Fig. 3: Semi-decentralized solar district heating based on an ultra-low-temperature district heating network

The semi-decentralized solar DH system was modeled with the software TRNSYS (see section 2.2). The GSHP was designed to meet 60 % of the maximum heat load. The distributed solar collector systems are determined to ensure a solar fraction $f_{sol\ in}$ of ≈ 70 % (average solar fraction of the energy input into the hot water storage).

Tab. 2: System design of the semi-decentralized solar district heating system

Component	Size
Distributed solar DHW systems	820 m² (on the buildings roofs)
Distributed hot water storage tanks in buildings with electrical back-up heaters	300 l (for single family houses) to 1,700 l (for large multifamily houses)
BTES	92 boreholes, 120 m depth
Heat pump	593 kW_{th} (at W0/W35) / SPF 4.6
Tank Thermal Energy Storage (TTES)	20 m³
Electrical peak load heater	740 kW nominal power
Uncovered solar collectors for thermal ground regeneration	1,800 m² on several large building roofs
DH operating temperatures	Summer: - C / - °C Winter: 40° C / 25 °C
Software for design and calculation	TRNSYS

3.3 Network Design

The housing development has been sub-divided in three parts that are supplied by three DH branches. The DH network geometry was kept constant. For each building a connection capacity was determined. The piping network was designed for the maximum heat load. Depending on the heat supply system, 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). Additionally, the piping manufacturer’s recommendation (ISOPLUS) for maximum flow velocities were applied (Nussbaumer and Thalmann; Nussbaumer and Thalmann, 2014). According to the connected capacity a volume flow and the corresponding pipe diameter were computed for each branch. The resulting pipes sums up to 2.89 km pipe length. The connecting pipes were defined to have 1.71 km, while the transportation pipes were calculated to have 1.18 km. The following bar chart depicts the sum of supply and return pipe length (including the connecting pipes) broke down into nominal pipe diameter (see Fig. 4).

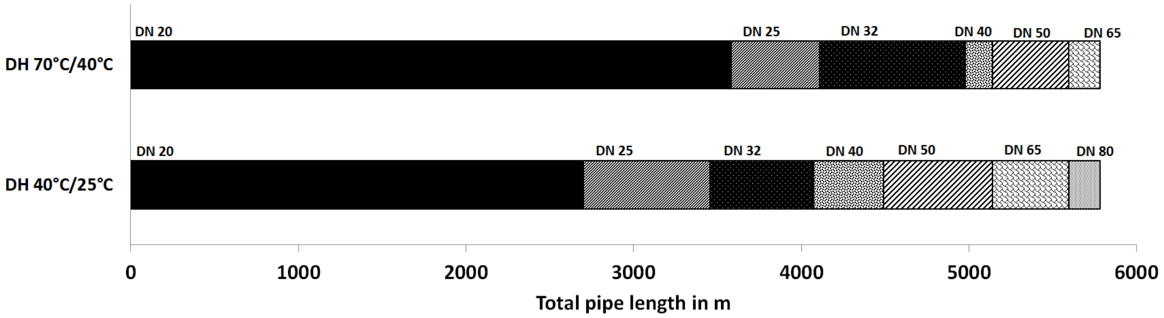

Fig. 4: Nominal pipe diameter distribution showing the sum of supply and return pipes

Based on the nominal pipe diameter (DN) distribution, the network costs were determined with a medium cost approach for new building developments for unmade terrain and rigid pipes after (Nast et al., 2009) (see Fig. 5, red dashed line). The medium cost approach was also approved by (Klöpsch et al., 2009) and can still be considered valid in 2017. Nevertheless, there is an optimization potential according to Manderfeld, who showed that specifically in rural areas the specific network construction costs can be reduced using for example flexible pipes (see grey dashed line) (Manderfeld et al., 2008). This data applies only for Germany, they may differ in other countries.

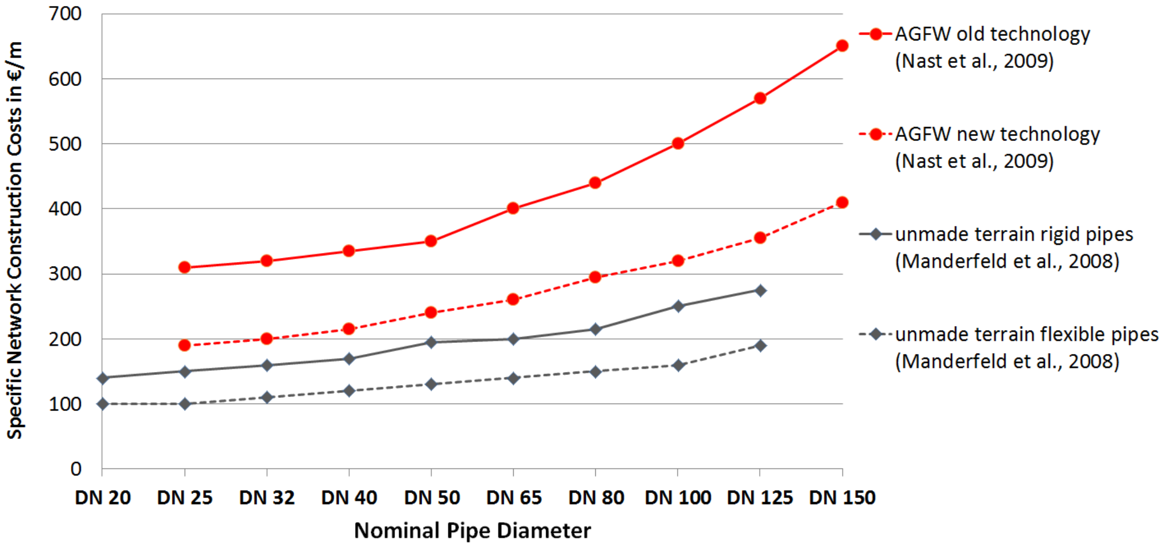

Fig. 5: Specific network construction costs including construction costs and pipe material costs

In operation a DH network shows a characteristic heat loss rate that depends mainly on the pipe type, pipe diameter, insulation, and the temperature gradient between the pipe and the surrounding ground. The relative heat distribution losses increase, the lower the linear heat demand density is. Consequently, the operating costs are affected. For this reason, the heat losses have been calculated and modeled for the two different heat supply systems taking single rigid pipes as a basis (Arbeitsgemeinschaft QM Fernwärme: Nussbaumer, Thomas et al., 2017).

4 System Efficiency

The central solar DH network was designed to meet the requirement of ≈ 80 % renewable heat supply of the total heat demand of the new building development. Thus the electricity consumption has to be below 427 MWh/yr. On the basis of the designed DH network ≈ 18 % distribution heat losses occur within one operating year (see section 3.3). The HP was assumed discharging the PTES from 40°C to 10°C, which results in a seasonal performance factor *SPF* of 3.8. The corresponding maximum electricity consumption of the HP was calculated to be ≈ 310 MWh/yr. taking distribution heat losses and auxiliary energy demand of the system into account. According to these assumptions, the solar collector field needs to ensure ≈ 40 % solar fraction of the total heat demand (fraction of solar energy that meets the heat demand including distribution heat losses). Thus, a large collector field of 2,400 m² of flat plat collector gross area was determined. This corresponds to a solar heat supply of ≈ 800 MWh/yr. to the DH network. The remaining ≈ 60 % of the heat demand are met by the HP. The seasonal storage, which consists of 8,000 m³, causes ≈ 14 % heat losses, which are already subtracted from the yearly solar heat supply. The electrical peak load heater was assumed to supply only 4 % of the heat demand which shall be covered by the HP.

In contrast to the central DH system, the distributed solar collector systems were designed only for the DHW preparation. They were calculated to meet fully the DHW demand during the non-SH period, which allows keeping the DH network and the HP offline during this period. The simulation's results demonstrated a solar fraction of DHW demand $f_{sol\ out}$ of ≈ 58 % (average solar fraction of the DHW net energy). Besides this, the DHW is preheated via DH network during space heating period up to ≈ 29 % (fraction of the DHW net energy). The remaining ≈ 13 % are covered by electrical back-up heaters. Regarding the HP design, the approach was to keep supply temperatures of the DH network as low as possible in order to achieve a high seasonal performance of the HP and at the same time to avoid heat losses through the network. The calculations showed that a *SPF* of 4.6 (without peak load heater) is achieved following this approach (supply 40 °C return 25 °C). Add to this, only 5.5 % heat distribution losses occur through the DH network, due to the low operating temperatures and the seasonal operating strategy. The uncovered solar collectors (roof top installation) fully ensure thermal regeneration of the BTES during the non SH period. This means, the BTES is charged or rather regenerated with the amount of energy which was subtracted during space heating period. The total electricity consumption amounts to 413 MWh/yr., thus it meets the requirement of 80 % renewable heat supply. The resulting total electricity consumption of the different solar DH system is listed in the following table:

Tab. 3: Comparison of Electricity Consumption

Component	**Central Solar DH system Electricity Consumption in MWh/yr.**	**Semi-decentralized Solar DH system Electricity Consumption in MWh/yr.**
Heat Pump, DH heat losses	55	16
Heat Pump operating	251	294
DHW electrical back-up heaters	**-**	50
Central electrical peak load heater	47	16
Sum without auxiliary energy demand	***353***	***376***
Auxiliary Energy demand (pumps)	54	37
Total Sum	**407**	**413**

5 Economic Evaluation

Hereafter, the results of the economic evaluation are presented. This section examines the net annual costs without and with subsidies of the two different solar DH systems. Thereby, specific costs of the components are discussed. Also, the maintenance and service costs as well as the operating costs are considered. Additionally, the impact of land area prices and the type of seasonal storage are highlighted.

5.1 Net Annual Costs of the Central Solar DH System

The specific investment for each component was evaluated. First, the DH network costs for transportation pipes were calculated on the basis of the computed DN distribution of the network. The network was characterized by a majority of small diameters of DN 20 and DN 32. This results in an average 226 €/m pipe length (Nast et al., 2009) (see section 3.3) Together with costs for substations, house-lead-in costs, and network pumps, they build total investment for the central distribution infrastructure. Secondly, the central flat plate collector field was calculated based on a gross collector area of 2,400 m². Taking the economy of scale into account, specific collector costs of 380 €/m² were assumed. Furthermore, the pit storage (PTES) was examined. It was designed according to the Danish principle. The Danish pit storages are typically without surface sealing and only covered by insulation material and a canvas cover. Thus, costs of only 45 €/m³ water equivalent incur. However, as a result the seasonal storage cover is not usable as leisure space for example. Consequently, costs for land area use for the PTES installation and the collector field incurred (blue parts in the pie chart, see Fig. 6). Land area prices for green areas and for solar system installations were assumed according to standards in Kassel. The specific investment for each component is listed in the following table:

Tab. 4: Specific investment of the central solar DH system's components

Network construction costs	226 €/m_{tr}	(Nast et al., 2009)
Costs for substations	4,000 €/unit	(Stuible et al., 2016)
House-lead-in costs	3,600 €/unit	(Stuible et al., 2016)
Network Pumps	3,350 €/unit	(wilo, 2017)
Solar System Collector Costs	380 €/m²	(Verein Deutscher Ingenieure e. V., 2017)
PTES	45 €/m³ water equivalent	(Solites, 2016; Freistaat Thüringen Ministerium für Umwelt, Energie und Naturschutz, 2016)
Land area	8 €/m² for green areas, 15 €/m² for land areas for solar system installations	(BORIS Hessen, 2016)
HP	195 €/kW_{th}	(Lambauer et al., 2008; Wolf et al., 2014)
Peak load heater	100 €/kW	Assumption, expert knowledge

According to the specific investment the total annual investment was determined based on the system components design. The following figure shows the results of the detailed economic evaluation of the central solar DH system (see Fig. 6). The net annual heat costs comprise of operating costs, maintenance and service costs, as well as the investment. The bar chart shows the net annual costs without taken subsidies into account. In absolute values the total annual system costs are ≈ 415 k€/yr. Thereof 61 % are investment (252 k€/yr.), 22 % result from maintenance and service and only 18 % are caused by system operating. Thus, the fixed cost rate is 83 %.

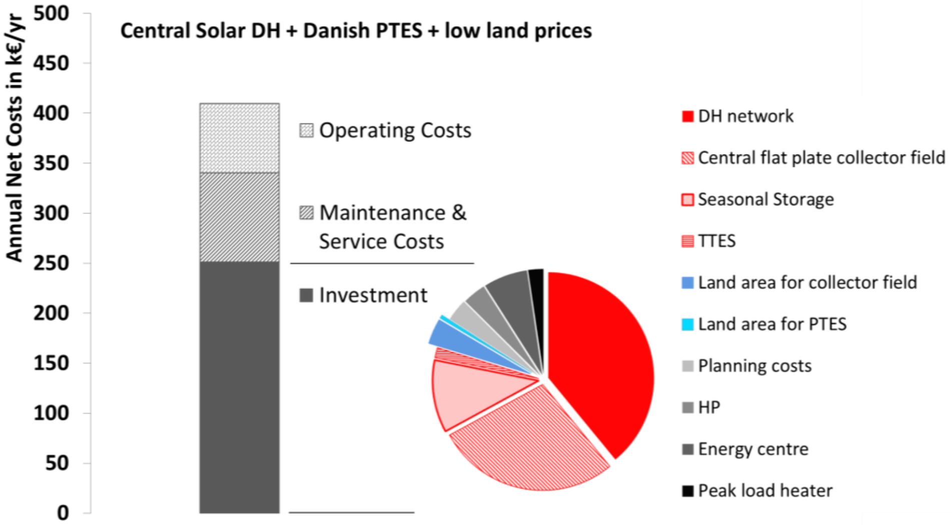

Fig. 6: Net annual costs for a central solar district heating system (left) and the breakdown of the investment (right) at a base period of 30 years

The break-down of investment demonstrates the three most cost-intensive system components: the DH network (39 %), the central collector field (28 %), and the pit storage PTES (11 %). The pie chart shows also several other points of expenses marked in grey. They are considered to be nearly constant through the different heat supply systems. They comprise of planning costs, the heat pump, the peak load heater, and the energy centre. Together they amount to 16 % of the investment. The land area costs represent an ideal situation and can be seen as a low cost approach. Nevertheless, they amount to 4 % of the total investment (marked in blue).

On top of the investment, maintenance & service costs and operating costs are added. The maintenance and service costs were evaluated according to fixed rates recommended by VDI 2067, whereas the operating costs represent the system operating characteristic. Here, the operating costs result only from the yearly electricity consumption, which mainly reflects the HP performance and secondly the auxiliary energy demand of pumps (see section 4). The HP achieves a SPF of 3.8 and supplies 60 % of the total heat demand. To sum up, the net annual costs amount to 415 k€/yr. This results in specific net heat generation costs of 249 €/MWh for a total heat demand of 1,665 MWh/yr. without subsidies.

5.2 Net Annual Costs of the Semi-decentralized Solar DH system

Similar to the economic evaluation of the central solar DH system, the calculations were conducted for the semi-decentralized solar DH. First the specific costs for system components were investigated. The DH network costs resulted to be almost the same as the costs of the central solar DH network, despite the lower temperature level and the smaller temperature difference of 15 K between supply and return. The DH network transportation pipes amount of average 233 €/m_{tr} (Nast et al., 2009), which is an increase of 3 % compared to the central solar DH system. The costs for substations as well as house-lead-in costs were assumed to be the same as previously shown. In contrast to the central solar DH system, distributed flat plate collector systems were planned of 820 m² in order to supply the DHW demand during non-space heating period. Thus, higher specific solar thermal system costs incur of 742 €/m² (Stuible et al., 2016). The BTES was designed in cooperation with the Institute of Geotechnics of the University Kassel, which computed the BTES to have 92 boreholes of 120 m depth. Specific costs of 63 €/m borehole depth were determined. The land area above the BTES was assumed to be still usable as green space, because the boreholes are installed 1 m under the surface. Consequently, no additional costs for land area occur.

The specific investment for each component is listed in the following table:

Tab. 5: Specific investment of the semi-decentralized solar DH system's components

Network construction costs	233 €/m_{tr}	(Nast et al., 2009)
Costs for substations	4,000 €/unit	(Stuible et al., 2016)
House-lead-in costs	3,600 €/unit	(Stuible et al., 2016)
Network Pumps	3,490 €/unit	(wilo, 2017)
Solar System Collector Costs	742 €/m²	(Stuible et al., 2016)
BTES	63 €/m borehole depth	(Institute of Geotechnics of the University Kassel)
Land area	-	
HP	195 €/kW_{th}	(Lambauer et al., 2008; Wolf et al., 2014, & requests for proposals of manufacturers)
Peak load heater	100 €/kW	assumption

The central solar DH system shall be compared with a semi-decentralized solar DH system, which was designed especially for the new building development “Zum Feldlager”. Therefore, the net annual costs were examined similarly to the central solar DH system. The results are shown in the following diagram. Fig. 7 displays the net annual costs of the semi-decentralized solar DH system. The net annual costs consist of 64 % investment (284 k€/yr.). Furthermore, maintenance and service costs amount to 22 % of the total heat generation costs, which can be summed up to a fixed cost rate of 86 %. The investment is dominated also by three main system components: the DH network (37 %), followed by the BTES (31 %), and the distributed solar collector systems (17 %). In case of the semi-decentralized solar DH system the operating costs were determined via dynamic simulations (see section 2.2). Similar to the central solar DH system analyses, the specific electricity costs were assumed to be 0.17 €/kWh, which applies to large consumers. Regarding DHW preparation, the electricity consumption of the electrical back-up heaters was rated with 0.21 €/kWh, which applies to small consumers in Germany. The HP performance, thus the *SPF* has the largest impact on the operating costs. The electricity consumption of the HP is 310 MWh/yr. (*SPF* = 4.6) that generates costs of 68 % of total operating costs. This implies the distribution heat losses through the network already. To sum up, the net annual costs amount to 443 k€/yr.. This results in specific net heat generation costs of 266 €/MWh for a total heat demand of 1,665 MWh/yr. without subsidies.

In conclusion the semi-decentralized DH system shows 7 % higher net heat generation costs than the central solar DH system. However, this applies only for the given boundary conditions. Specifically, this applies for sites with very low land area costs and for the assumed seasonal storage type. In order to investigate the impact of these parameters on the total net heat generation costs, a sensitivity analysis was conducted.

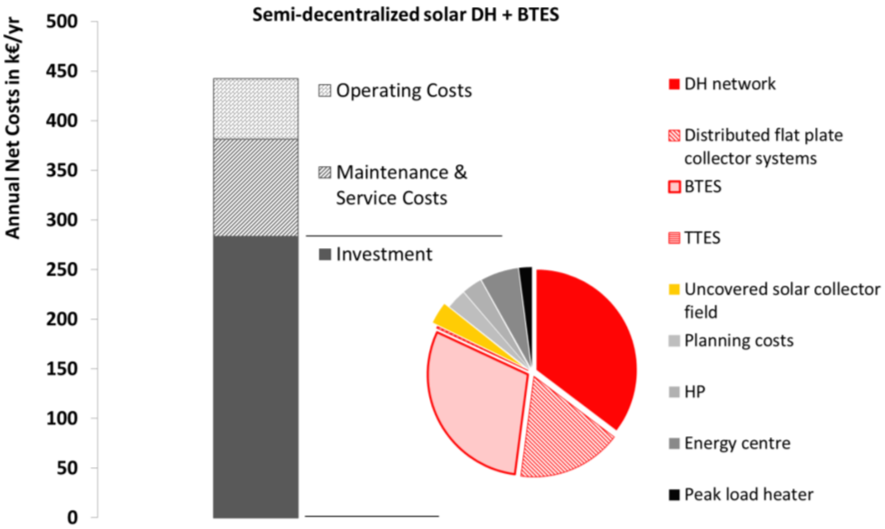

Fig. 7: Net annual costs of the semi-decentralized solar DH system for the new housing development „Zum Feldlager“ at a base period of 30 years

5.3 Sensitivity analysis of land area prices and PTES type

In Germany the availability of open space is restricted, which results in high land prices. In order to demonstrate the upper limit of heat generation costs, the land use for solar system installations (3.5 times the collector area) was calculated with land prices of 175 €/m² land area. This represents the land value of the district, where the new housing development “Zum Fedlager” will be build. Additionally, seasonal storages with surface sealing were realized in Germany in the recent years in order to be able to still use the area as leisure space. In case of PTES with a surface sealing, the specific costs increase significantly as demonstrated from various German projects (Solites, 2016). The specific costs can increase up to 200 €/m³ water equivalent (Freistaat Thüringen Ministerium für Umwelt, Energie und Naturschutz, 2016). For sensitivity evaluation reasons, the central solar DH system was calculated with a PTES with surface sealing applying 142 €/m³ water equivalent, which represents the average of several projects realized in Germany. The results of the sensitivity analysis are presented in the following bar chart (see Fig. 8). The light grey bars show the total net annual costs without subsidies (left axis) and the net heat generation costs (right axis). Besides this, the net heat generation costs considering subsidies are displayed by the striped bars. Compared to the initial event of the central solar DH (bar pair on the left side) the net heat generation costs increase about 38 % in case of high land area prices (second bar pair from the left). The semi-decentralized solar DH system was optimised to use as little land as possible. The distributed solar collector systems as well as the uncovered solar collector field for ground regeneration were planned as roof installations. No supplementary land is needed, which makes this heat supply concept competitive. In case of PTES with surface sealing, land costs are saved, because it is assumed that the storage cover can be used as leisure space (third bar pair). Despite this, the net heat generation costs do not increase significantly (5 % increase) compared to the second version of the central solar DH due to the high investment of the PTES with surface sealing. Considering subsidies, a new funding program (Wärmenetze 4.0, in English district heating 4.0) aiming at the implementation of sustainable and renewable DH systems entered into force end of September 2017. On this basis, subsidies of 30 % - 40% of the total investment can be received. This leads to the lowest specific heat generation costs of 198 €/MWh in case of the initial central solar DH system, and 207 €/MWh in case of the semi-decentralized solar DH system. Compared to the previous funding programme for renewable energies in Germany (KfW, 2016), this means a cost reduction of 10 % in case of the central solar DH system and 19 % in case of the semi-decentralized solar DH system.

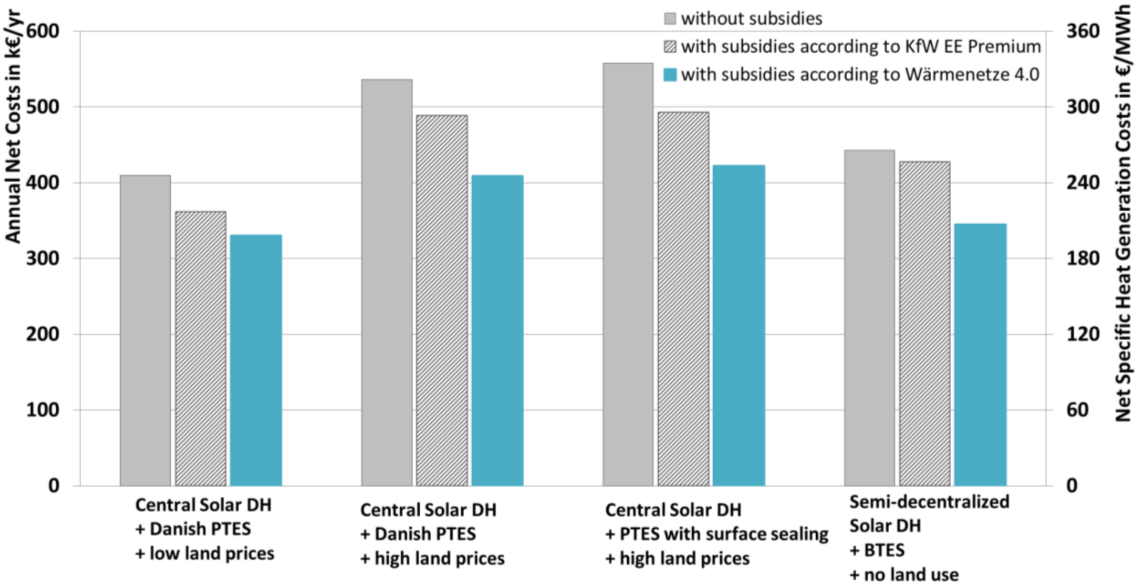

Fig. 8: Net annual costs and net heat generation costs of the central solar DH system under different PTES types and land prices compared to the semi-decentralized solar DH system with and without subsidies

In conclusion, in case of low land prices and a cost-efficient PTES without surface sealing a central solar DH system is 4 % less expensive than the semi-decentralized solar DH system taking subsidies according Wärmenetze 4.0 into consideration. Thus, the semi-decentralized is an economically competitive heat supply system under the given boundary conditions and assumptions. Without subsidies the central solar DH system is 6 % less expensive than the semi-decentralized solar DH system. Thus, in case of low land prices below 15 €/m², a central solar DH following the Danish example is slightly more beneficial than the semi-decentralized solar DH system from an economic point of view. In case of high land prices the heat generation costs of the central solar DH system increase about 30 % without subsidies and 24 % with the subsidies of the funding programme Wärmenetze 4.0. Thus, land prices have a high impact on the system feasibility and have to be considered within economic analyses.

6 Discussion

Two different solar district systems have been designed for the new building development “Zum Feldlager”, which represents a low heat density area. Both developed heat supply systems were designed under the precondition to achieve a renewable heat supply of ≈ 80 %. Key issue was to identify the preferable system from the economic point of view. Detailed economic analyses were conducted in order to determine the net heat generation costs of each system comprising of investment, maintenance and service as well as operating costs. At this point, it has to be said, that a medium cost approach was chosen. The specific costs for solar thermal collectors were considered conservatively. The maintenance costs are determined applying fixed percentages of investment according the German VDI 2067, which might be overestimating the costs in case of large systems. In conclusion, the economic analyses showed that the central solar district heating system is only favorable under specific boundary conditions: low land prices and low costs for the seasonal pit thermal energy storage. If the land prices are greater than 15 €/m², the semi-decentralized solar district heating system is to be preferred. In conclusion the semi-decentralized DH system shows 6 % higher net heat generation costs than the initial central solar DH system at low land prices (without subsidies). However, this applies only for the given boundary conditions. Specifically, this applies for sites with very low land prices and for the assumed specific solar thermal system costs. Due to the fact, that the central solar collector field makes 28 % of the investment of the central solar DH system (based on a PTES following the Danish examples), the specific solar thermal system costs represent a sensitive parameter. Furthermore, both heat supply systems were designed to achieve 80 % renewable heat supply. If this is not the requirement, the solar fraction can be reduced by lowering the collector area and likewise increasing the HP operating hours. This would lead to lower net heat generation costs. On the other hand, in case of lack of open space, the semi-decentralized solar DH system represents an energy efficient, sustainable and economic alternative to the central solar DH system.

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7 References

Arbeitsgemeinschaft QM Fernwärme: Nussbaumer, Thomas, Thalmann, S., Jenni, A., Ködel, J., 2017. Planungshandbuch Fernwärme ISBN 3-90870505-30-4. www.verenum.ch/Dokumente/PLH-FW_V1.0.pdf. Accessed 26 June 2017.

BORIS Hessen, 2016. Hessische Verwaltung für Bodenmanagement und Geoinformation. https://hvbg.hessen.de/immobilienwerte/boris-hessen. Accessed 9 October 2017.

Deutsches Institut für Normung e. V., 2003. Thermal protection and energy economy in buildings Part 6: Calculation of annual heat and annual energy use. https://www.beuth.de/de/vornorm/din-v-4108-6/63939447. Accessed 18 December 2017.

Deutsches Institut für Normung e. V., 2012. Heatings system in buildings - Method for calculation of the design heat load - Supplement 2: Simplified method for calculation of the design heat load and the heat generator capacity. https://www.beuth.de/de/norm/din-en-12831-beiblatt-2/150360566. Accessed 18 December 2017.

Freistaat Thüringen Ministerium für Umwelt, Energie und Naturschutz, 2016. Zukunft Sonne! Solarthermie und Fernwärme: Ein WEgweiser für die Praxis. Solites - Steinbeis Forschungsinstitut für solare und zukünftige thermische Energiesysteme, Stuttgart.

Gesellschaft für Rationelle Energieverwendung e. V., 2016. Energieeinsparverordnung EnEV 2016, Kassel.

Jordan, U., Vajen, K., 2001. Realistic Domestic Hot Water Profiles in Different Time Scales. Universität Marburg.

KfW, 2016. Merkblatt Erneuerbare Energien. KfW-Programm Erneuerbare Energien "Premium", Frankfurt.

Klöpsch, M., Besier, R., Wagner, A., 2009. Reicht für Kunststoffmantelrohre die Standarddämmung? Wirtschaftliche Dämmung von KMR. Euro Heat & Power (12), 46–54.

Lambauer, J., Fahl, U., Ohl, M., Blesl, M., Voß, A., 2008. Industrielle Großwärmepumpen - Potenziale, Hemmnisse und Best-Practice Beispiele. Institut für Energiewirtschaft und Rationelle Energieanwendung (IER).

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J.E., Hvelplund, F., Mathiesen, B.V., 2014. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 68, 1–11.

Manderfeld, M., Jentsch, A., Pohlig, A., Dötsch, C., Richter, S., Bohn, K., 2008. Abschlussbericht Forschungsvorhaben Fernwärme in der Fläche RDH (Rural District Heating) . Ermittlung des Fernwärmepotentials unter Berücksichtigung der neuester Verlegeverfahren und unterschiedlicher Energiedargebote in der Fläche der Bundesrepublik Deutschland.

Nast, M., Ragwitz, M., Schulz, W., Bürger, V., Leprich, U., Klinski, S., 2009. Ergänzende Untersuchungen und vertiefende Analysen zu möglichen Ausgestaltungsvarianten eines Wärmegesetzes. Ausarbeitung im Auftrag des Bundesministeriums für Umwelt, Naturschutz und Reaktorsicherheit. DLR, Fachhochschule für Wirtschaft Berlin (FHW), Öko-Institut, IZES, ISI, BEI. www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/publications/Endbericht_Waermegesetz-11.pdf. Accessed 18 December 2017.

Nussbaumer, T., Thalmann, S. Influence of system design on heat distribution costs in district heating. http://www.sciencedirect.com/science/article/pii/S036054421630113X?via%3Dihub. Accessed 18 December 2017.

Nussbaumer, T., Thalmann, S., 2014. Sensitivity of System Design on Heat Distribution Cost in District Heating. ISBN 3-908705-27-4. verenum and Swiss Federal Office of Energy, Zürich. www.ieabcc.nl/publications/IEA_Task32_DHS_Cost_Analysis.pdf. Accessed 18.12.17.

Nußbicker-Lux, J., 2010. Simulation und Dimensionierung solar unterstützter Nahwärmesysteme mit Erdsonden-Wärmespeicher. Dissertation.

Persson, U., Werner, S., 2011. Heat distribution and the future competitiveness of district heating. Applied Energy 88 (3), 568–576.

SDH solar district heating, 2017. Ranking List of European Large Scale Solar Heating Plants. http://solar-district-heating.eu. Accessed March 2017.

Solites, 2016. saisonalspeicher.de. Das Wissensportal für die saisonale Wärmespeicherung. Solites Steinbeis Forschungsinstitut für solare und zukunftsfähige thermische Energiesysteme. http://www.saisonalspeicher.de/. Accessed 9 October 2017.

Solites, 2017. ScenoCalc Fernwärme 2.0. SDH tools. Solites - Steinbeis Forschungsinstitut für solare und zukünftige thermische Energiesysteme. http://solar-district-heating.eu/ServicesTools/SDHcalculationtools.aspx. Accessed 9 October 2017.

Stuible, A., Zech, D., Wülbeck, H.-F., Sperber, E., Nast, M., Hartmann, H., Reisinger, K., Budig, C., Orozaliev, J., Pag, F., Vajen, K., Erler, R., Janczik, S., Kaltschmitt, M., Niederberger, M., 2016. Evaluierung von Einzelmaßnahmen zur Nutzung erneuerbarer Energien im Wärmemarkt (Marktanreizprogramm) für den Zeitraum 2012 bis 2014. Evaluierung des Förderjahres 2014.

Verein Deutscher Ingenieure e. V., 2000. Economic efficiency of building installations - Effective energy requirements for heating service water Blatt 12. https://www.beuth.de/de/technische-regel/vdi-2067-blatt-12/32138558. Accessed 19 December 2017.

Verein Deutscher Ingenieure e. V., 2012. Economic Efficiency of building - Fundamentals and economic calculation VDI 2067 Blatt 1. https://www.beuth.de/de/technische-regel/vdi-2067-blatt-1/151420393. Accessed 19 December 2017.

Verein Deutscher Ingenieure e. V., 2014. Solar heating for potable water - Basic principles - System technology and application in residential buildings Part 1/2.

Verein Deutscher Ingenieure e. V., 2017. Gründruck VDI 3988 Solarthermische Prozesswärme.

wilo, 2017. wilo-select. wilo-select.com. Accessed 2017.

Wolf, S., Fahl, U., Blesl, M., Voß, A., Jakobs, R., 2014. Analyse des Potenzials von Industriewärmepumpen in Deutschland. Institut für Energiewirtschaft und Rationelle Energieanwendung (IER).