

Comparison of Solar District Heating Concepts at Various Land Prices

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Abstract

Two solar district heating concepts for an exemplary new housing development at different supply temperature levels were examined in terms of economic and energy efficiency aspects. Both district heating-based heat supply systems were designed to meet a renewable heat share of 80 %. Afterwards, the systems were compared within a detailed economic analysis. Key issue is, under which boundary conditions a central solar district heating system is more beneficial than a district heating system with distributed solar thermal systems for very low demand density areas in Germany. Thereby, the impact of land prices due to land use for ground-mounted solar collectors and seasonal storages on the system feasibility was evaluated.

Keywords: solar district heating, fourth generation district heating, low linear heat density, heat generation costs

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
rm	Route meter
we	Water equivalent

1 Introduction

Future smart thermal energy systems must show a high rate of renewable energies along with residual resources to meet the heat demand (Lund et al., 2014). District heating infrastructures and large thermal storages already play an important role in integrated energy systems as demonstrated by various projects in Denmark in recent years (SDH solar district heating, 2017). However, central heat supply systems risk to lose competitiveness the lower the heat demand density of a district is. This applies especially for new building developments with a high share of single family houses in sub-urban and rural areas. High distribution heat losses of 20 % and even higher can occur in case of conventional low-temperature district heating of 70°C/40°C (supply/return). The district heating operating temperatures affect significantly the distribution losses as well as the integration of renewable technologies. Regarding solar heat integration high land prices and competition of land use can hinder the realization of large ground-mounted solar collector fields according to the Danish example. Thus, a broad implementation of large scale solar collector fields is missing currently in Germany. Individual solar thermal systems are dominating the German market. Key issue is, under which boundary conditions a central solar district heating system is more beneficial than a district heating system with distributed solar thermal systems for very low demand density areas in Germany.

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)(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 (GRE Gesellschaft für Rationelle Energieverwendung e. V., 2016). This means that the buildings were designed to have a specific heating demand below 50 kWh/(m² · a). 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 $\approx 1,656$ MWh/yr, that comprises of one quarter DHW (≈ 380 MWh/a) and of three quarter for space heating (SH) ($\approx 1,285$ MWh/a). It represents a heat demand sparse area with a low linear heat demand density of around 580 kWh/(*rm* · a) 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 Nahwärmerversorgung 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 3.1).

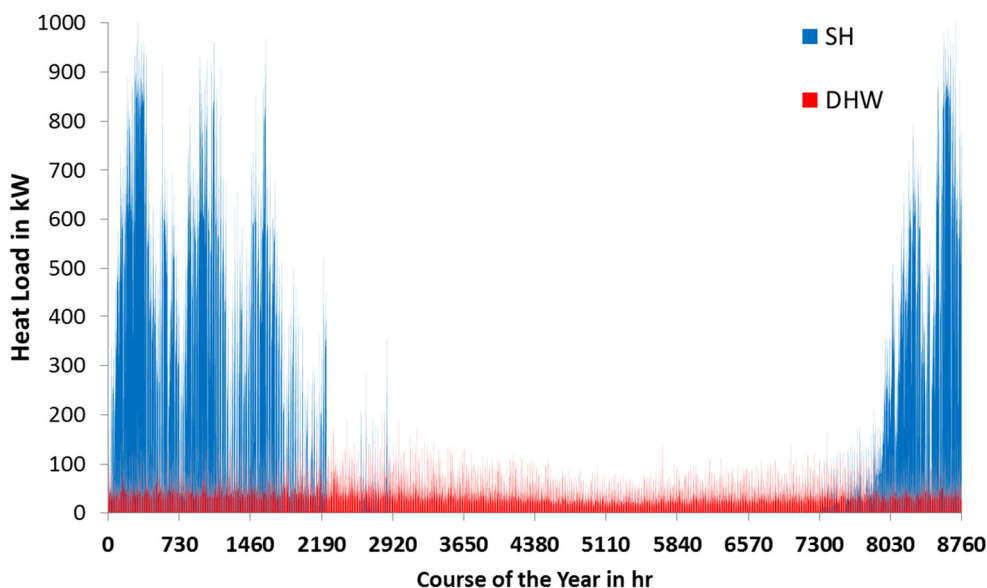


Fig. 1: Calculated hourly heat load profile of the housing development “Zum Feldlager”, in blue the space heating demand, in red the domestic hot water demand

2.3 Design Requirements and Basis of Comparison

Both solar DH systems presented were designed to achieve a renewable heat supply of $\approx 80\%$ 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/a. 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 (variable 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 $576 \text{ kWh}/(\text{rm} \cdot \text{a})$ was determined. 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 $3.3 \text{ m}^3/\text{m}^2$ 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).

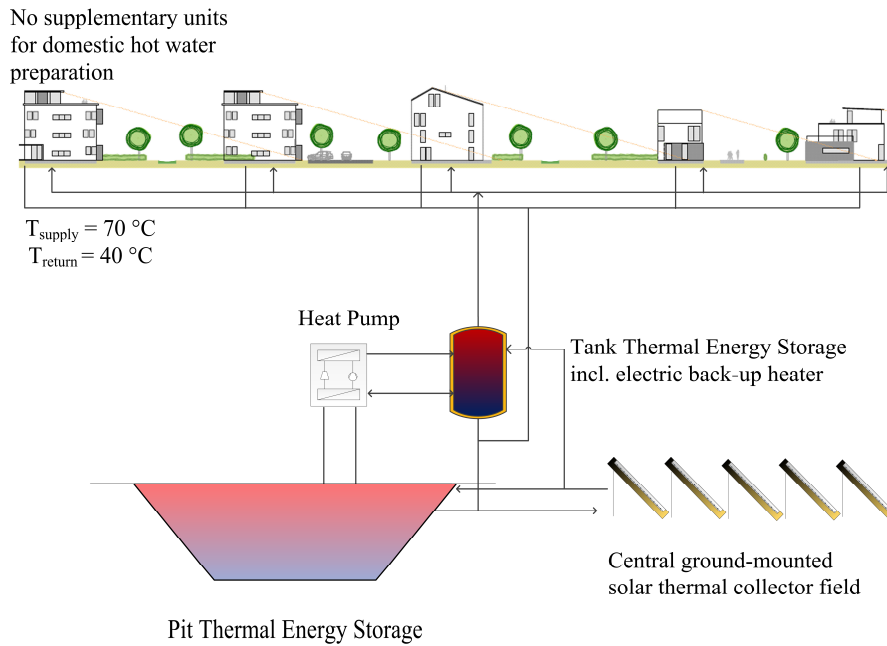


Fig. 2: Central solar district heating based on low-temperature district heating network

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 m ² _{gross}
PTES	8,000 m ³
Heat Pump	593 kW _{th} (at W0/W35) / SPF 3.8
Tank Thermal Energy Storage (TTES)	100 m ³
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 kWh/(rm · a) 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.

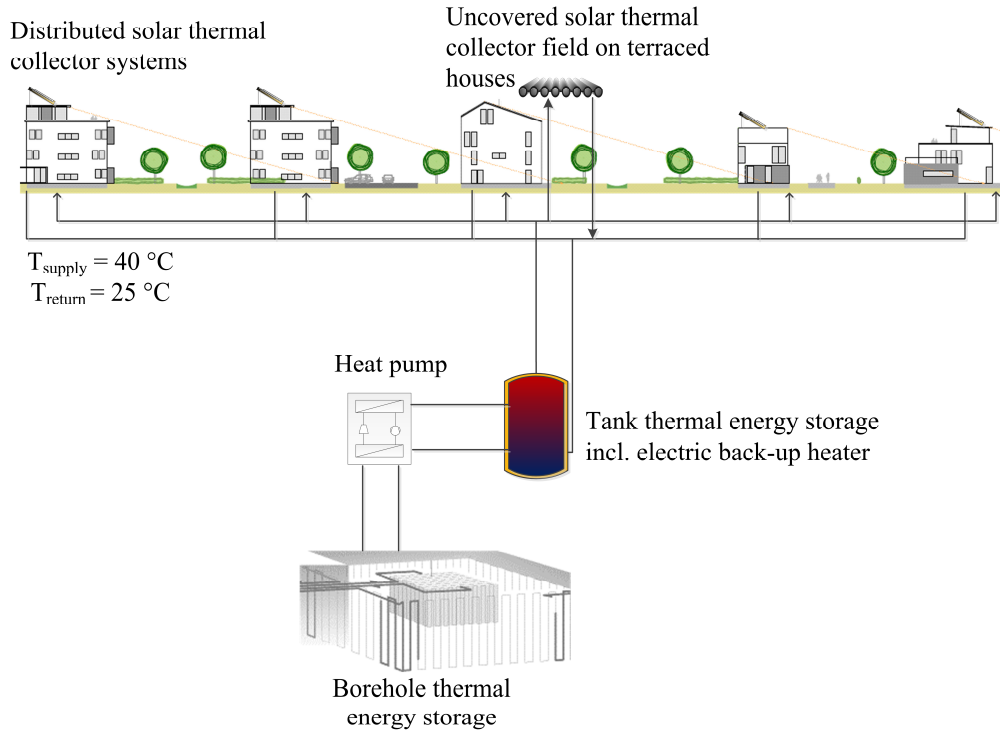


Fig. 3: Semi-decentralized solar district heating based on an ultra-low-temperature district heating network

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 $\approx 70\%$ (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 m ² (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 m ³
Electrical peak load heater	740 kW nominal power
Uncovered solar collectors for thermal ground regeneration	1,800 m ² 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 $\Delta T = 30\text{ K}$) as well as for 40 °C supply and 25 °C return ($\Delta T = 15\text{ K}$). Additionally, the piping manufacturer's recommendation (ISOPLUS) for maximum flow velocities were applied (Nussbaumer and Thalmann, 2014; Nussbaumer and Thalmann, 2016). 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).

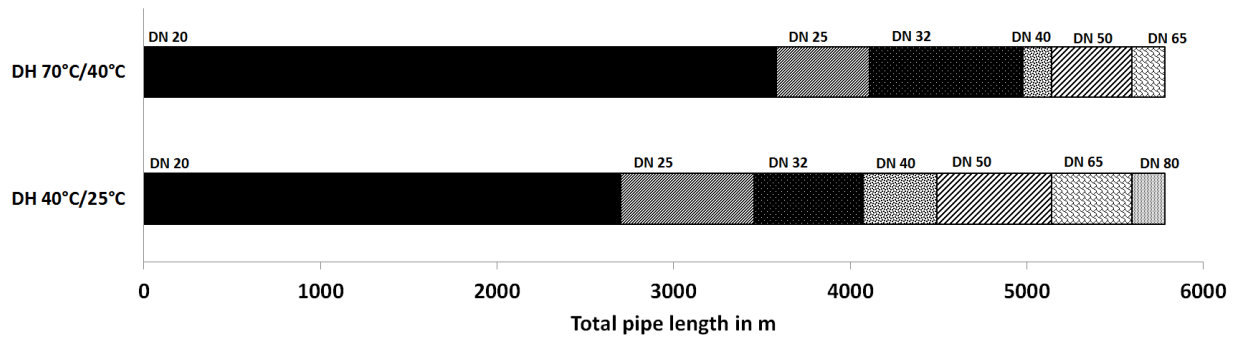


Fig. 4: Nominal pipe diameter distribution showing the sum of supply and return pipes

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). The network construction costs range from 190 €/m (DN 25) to 410 €/m (DN 150). This medium cost approach was also approved by (Klöpsch et al., 2009) and can still be considered valid in 2018. 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 (Manderfeld et al., 2008). This data applies only for Germany, they may differ in other countries. 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 $\approx 80\%$ renewable heat supply of the total heat demand of the new building development. Thus, the electricity consumption has to be below 427 MWh/a. On the basis of the designed DH network $\approx 18\%$ 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/a. taking distribution heat losses and auxiliary energy demand of the system into account. According to these assumptions, the solar collector field needs to ensure $\approx 40\%$ 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 $2,400\text{ m}^2$ of flat plat collector gross area was determined. This corresponds to a solar heat supply of ≈ 800 MWh/a. to the DH network. The remaining $\approx 60\%$ of the heat demand are met by the HP. The seasonal storage, which consists of $8,000\text{ m}^3$, causes $\approx 14\%$ 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 $\approx 58\%$ (average solar fraction of the DHW net energy). Besides this, the DHW is preheated via DH network during space heating period up to $\approx 29\%$ (fraction of the DHW net energy). The remaining $\approx 13\%$ 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/a., 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/a.	Semi-decentralized Solar DH system Electricity Consumption in MWh/a.
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 presents the full-cost accounting without subsidies and examines the resulting net annual costs 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 (variable costs) are considered. Additionally, the impact of land prices and the land requirements for ground-mounted solar collector systems 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 (we) incur. However, as a result the seasonal storage cover is not usable as leisure space for example. Consequently, costs for land use for the PTES installation and the collector field incurred (blue parts in the pie chart, see Fig. 5). Land prices for green areas and for solar system installations were assumed according to standards in Kassel. The specific net investment for each component is listed in the following table:

Tab. 4: Specific net 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 €/m ² _{gross}	(Verein Deutscher Ingenieure e. V., 2017)
Ratio of construction area to gross collector area	3.5	-
PTES	45 €/m ³ water equivalent	(Solites, 2016; Freistaat Thüringen Ministerium für Umwelt, Energie und Naturschutz, 2016)
Land area	15 €/m ² 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
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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. 5). 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€/a. Thereof 61 % are investment (252 k€/a.), 22 % result from maintenance and service and only 18 % are caused by system operating. Thus, the fixed cost rate is 83 %.

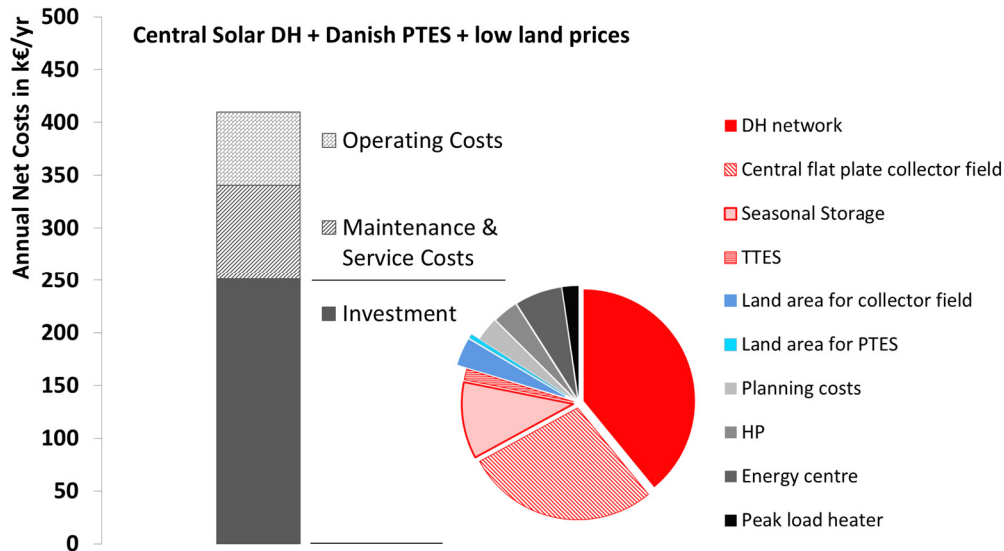


Fig. 5: Net annual costs for a central solar district heating system (left) and the breakdown of the investment (right) at a base period of 30 years

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 use 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€/a. This results in specific net heat generation costs of 249 €/MWh for a total heat demand of 1,665 MWh/a. 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 only slightly higher 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 €/rm (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 of 820 m² were planned 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 98 €/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 €/m ²	(Stuible et al., 2016)
BTES	98 €/m borehole depth	(Solites, 2016; Freistaat Thüringen Ministerium für Umwelt, Energie und Naturschutz, 2016)
Land area	-	
HP	195 €/kW _{th}	(Lambauer et al., 2008; Wolf et al., 2014)
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. 6 displays the net annual costs of the semi-decentralized solar DH system. The net annual costs consist of 64 % investment (284 k€/a). 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/a. (*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€/a.. This results in specific net heat generation costs of 265 €/MWh for a total heat demand of 1,665 MWh/a. 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 prices and for the assumed seasonal storage type. In order to investigate the impact of land prices and land requirements on the total net heat generation costs, a parameter study was conducted.

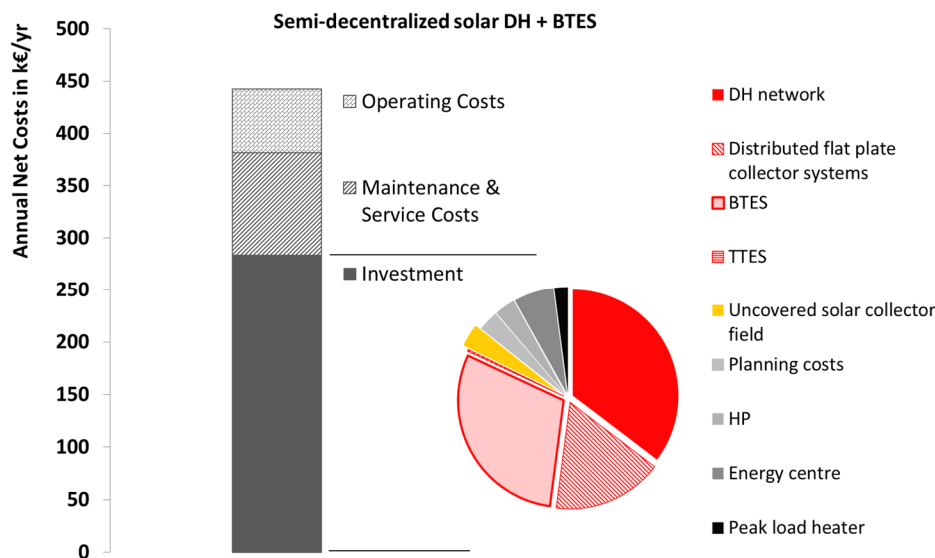


Fig. 6: Net annual costs of the semi-decentralized solar DH system for the new housing development „Zum Feldlager“ at a base period of 30 years

5.3 Variation of land prices for central solar DH

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 maximum land price was set to 180 €/m². This represents the land value of the district, where the new housing development “Zum Feldlager” will be build. However, the land prices as well as the land requirements can differ depending on the boundary conditions. In consequence, the resulting heat generation costs were calculated for land prices in the range of 10 €/m² to 180 €/m². Additionally, the ratio of land requirements for ground-mounted solar collector installation (construction area) to the gross collector area. The following diagram shows the heat generation costs as a function of land price and ratio of construction area to gross collector area (see Fig. 7). Thereby the solar yield was kept constant over the varying ratio of construction area to gross collector area.

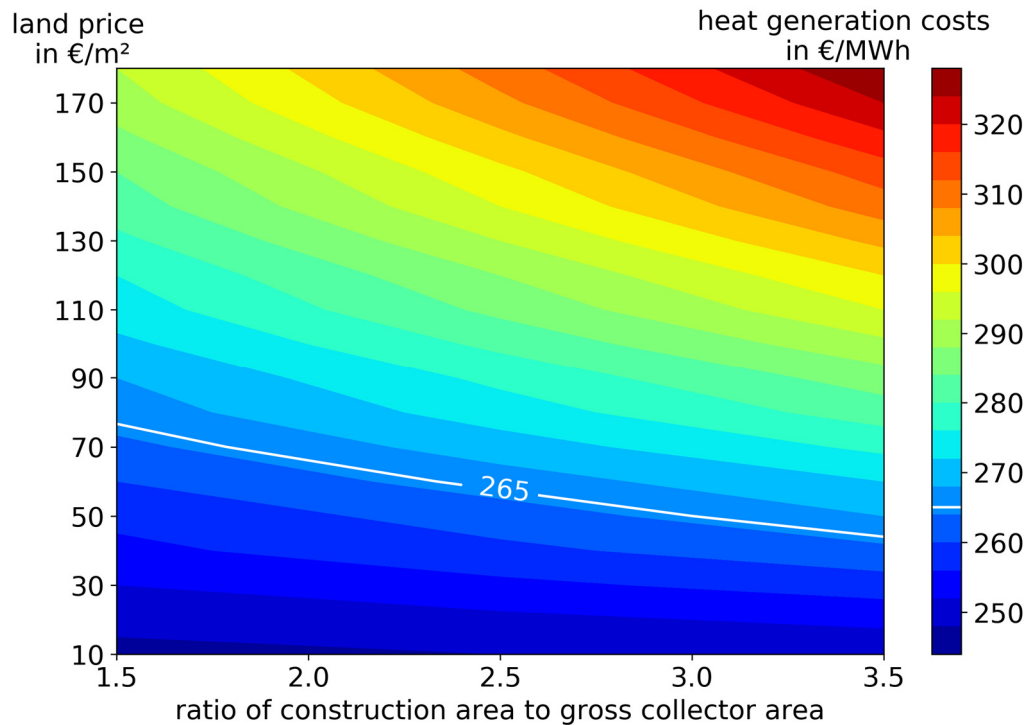


Fig. 7: Heat generation costs for central solar DH as a function of land price and ratio of construction area to collector area

The contour plot shows, that at a ratio of construction area to collector area of 3.5 the total heat generation costs of central solar DH increase about 32 % from very low land price of 10 €/m² to the maximum land price of 180 €/m². At a ratio of construction area to collector area of 1.5 this effect is reduced; the heat generation costs increase about 18 % within the given land price range. Cost parity between semi-decentralized solar DH and central solar DH is achieved at heat generation costs of 265 €/MWh (marked by the white line, see Fig. 7). Below the white line the central solar DH system is more economic than the semi-decentralized solar DH. Above the white line the semi-decentralized solar DH is more economic. This means at land prices greater equal than 75 €/m², the semi-decentralized solar DH is more economic than central solar DH regardless of the ratio of construction area to collector area at chosen assumptions. 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 $\approx 80\%$. Key issue was to identify the preferable system from the economic point of view. Detailed economic analyses were conducted via a full-cost accounting in order to determine the net heat generation costs of each system comprising of investment, maintenance and service as well as operating costs (variable costs). 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 favorable under specific boundary conditions: at land prices lower than 75 €/m² and low costs for the seasonal pit thermal energy storage of around 45 €/m³_{we}. 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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