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SIMULATION STUDY FOR THE SOLAR RETROFITTING OF A DISTRICT HEATING SYSTEM

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Abstract

To boost the dissemination of renewable heat production in Germany's urban housing estates, new concepts for the integration of solar-thermal plants into existing district heating networks have to be developed. The underlying research project of this paper is aiming at a decentralised integration of the collector arrays. It comprises a review of existing large solar-thermal systems, a simulation study and the retrofitting of a district heating network.

In this paper, a simulation based comparison of the energetic and economic performance of several standard system designs including state-of-the-art solar district heating and decentralised plants is conducted. The results serve as a benchmark for the assessment of the novel concept. The model of the district heating network was built in MATLAB/Simulink by use of the CARNOT block set.

None of the simulated concepts leads to a reduction of the already low fossil heat generation costs. Nevertheless, by a decentralised integration of solar-thermal plants of the aimed size, solar fractions of up to 5.7 % can be reached. The investigated systems for a centralised integration reach 3.8 % solar fraction.

Keywords: Solar District Heating, Simulation, Renovation

1. Background

1.1. Current Situation

The reduction of greenhouse gas emissions and fossil energy consumption has been one of the mostly discussed topics in society and science for the past years. The dissemination of solar district heating systems provides the opportunity of a more climate-friendly heat supply in urban areas. According to Nitsch et al. (2012), the future installations of solar thermal district heating systems have to rise rapidly to reach the German government's aims for the reduction of carbon dioxide emissions (Fig. 1).

In Germany, the implementation of large solar thermal systems began in the 1990s, mainly in the context of (federal) research programmes (e.g. "Solarthermie-2000", and "Solarthermie2000plus"). In these projects, several pilot plants were realised and scientifically analysed (Schmidt and Mangold 2003). Furthermore, market conditions and restraints for solar district heating systems were analysed in Europe, for example in the research project "SDHtake-off - Solar District Heating in Europe" from 2009 until 2012 and the currently running follow-up project "SDHplus". Here, in addition, guidelines for planning and operation are created as well as a database of existing installations.

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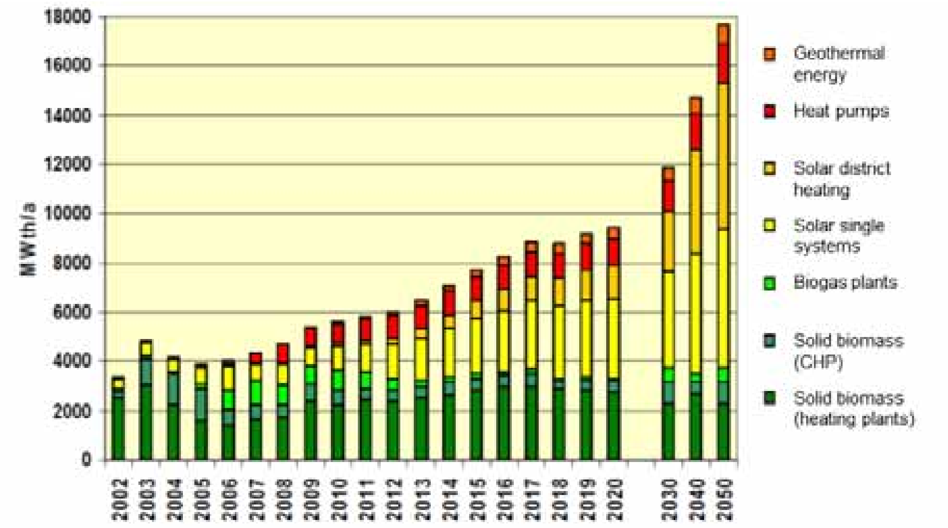

Fig. 1: Necessary future installations and compensations of renewable heat production in Germany (Nitsch et al. 2012)

Current research projects in Germany focus on centralised collector arrays and large seasonal storages to achieve a solar fraction above 50 % (SDH 2014). However, for energetic renovations of densely built-up areas, the feasible dimensions of collector arrays and heat storages as well as their distribution are often limited. Moreover, high storage capacities come along with high investment and heat production costs. According to Zech et al. (2009) the costs of solar district heating systems in Germany are currently not competitive to fossil- or biomass-fired plants (Fig. 2). It can be seen that detached solar-thermal plants (highlighted red) and solar supported district heating (yellow) have the lowest economic performance. The heat generation costs range from 15 Ct·kWh^{-1} up to 39 Ct·kWh^{-1}. These figures could be confirmed by own investigations on existing large solar-thermal plants in domestic applications where costs from 11 Ct·kWh^{-1} to 38 Ct·kWh^{-1} were determined (Beckenbauer et al. 2014). A second point is the wide spread of the costs compared to fossil (blue) or biomass (green) plants. Obviously, there is a higher uncertainty of yields and investment costs of solar-thermal plants compared to conventional technologies.

For a wide-spread utilisation of solar heat in urban domestic areas, new concepts for retrofitting need to be developed which provide cost effectiveness and applicability in existing housing estates.

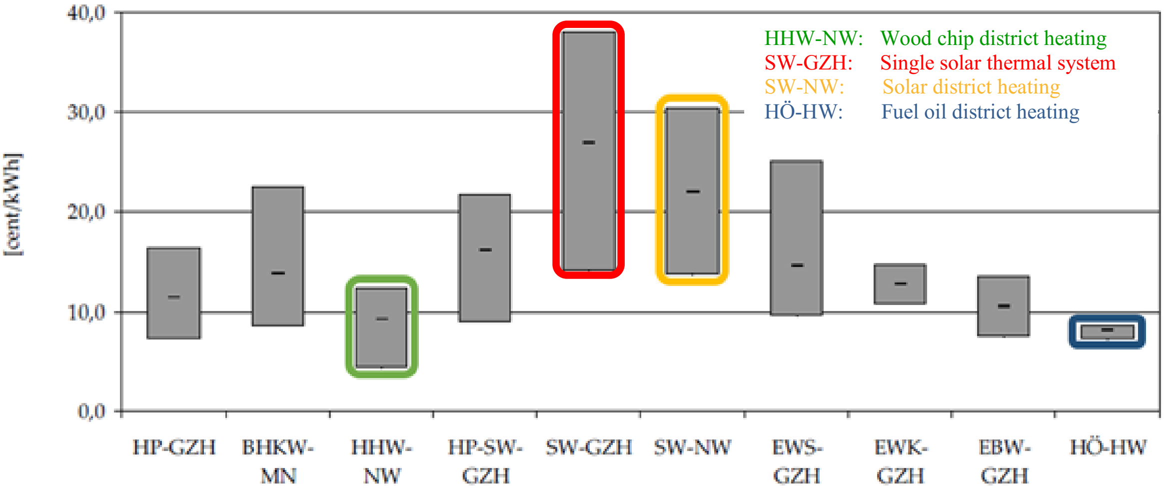

Fig. 2: Heat generation costs of different heating systems (Zech et al. 2009)

1.2. Existing District Heating Network

Against this background, the research project *smartSOLgrid – Solar Smart Grid for the Heating Sector,* intends to retrofit a district heating system in the south of Germany, built in the 1970s (Fig. 3). The object is typical for many urban residential areas and composed of several multi-storey buildings. Only a few of the roofs have favourable orientations and inclinations for the installation of large, contiguous solar collector arrays. The available space inside and outside the buildings is limited. Therefore, the utilisation of large-scale seasonal storages is challenging. Due to the age of the buildings and the high number of residents, these limitations face a high consumption of space heat and domestic hot water.

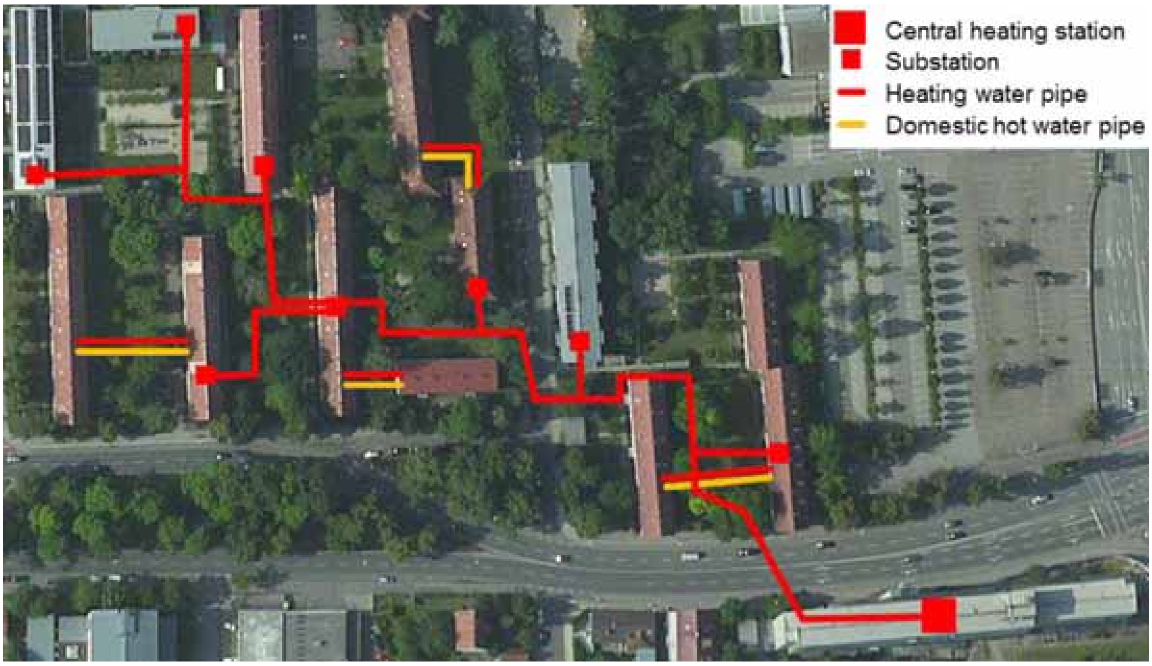

Fig. 3: Existing district heating system

1.3. Approach

In contrast to many current solar district heating systems, the proposed layout is not equipped with an additional solar network parallel to the district heating pipes for a centralised feed of the solar energy. The collector arrays are distributed on several buildings and combined with small-scale diurnal storages. Heat is provided primarily for the domestic hot water production in these buildings. The utilisation of this low-temperature heat sink leads to lower collector temperatures as compared to a centralised system with inlet temperatures depending on the return temperature of the heating network. Higher efficiencies can be reached. In times of high solar irradiation and low energy consumption, the substations feed solar excess heat into the district heating system. This provides an indirect connection to other consumers in the network. The reduced efficiency and stagnation problems which usually come along with large dimensioned collector arrays could be reduced or even prevented by this technology. Therefore, more collectors can be installed on roofs with suitable inclination and orientation.

The realisation of a solar district heating systems with low heat costs in combination with a decent solar fraction can improve the competitiveness of solar-thermal plants compared to conventional heating systems, even in case of limited space. Based on the results of the simulation and renovation phase, general design guidelines will be developed which can help to facilitate solar district heating concept in existing urban areas.

2. Methodology

2.1 Basic Principles of the Study

To assess the benefit of the proposed concept, a simulation study of conventional types of solar district heating systems is conducted prior to the development of the novel layout. This is necessary to get a benchmark of possible solar yields and system efficiencies. The same is conducted with decentralised solar-thermal systems. This means small solar-thermal plants for the supply of single buildings within the network. A few plants of this type are already installed in the investigated object. The support is limited to a contribution to the domestic hot water production up to now. Data for investment costs of these systems, provided by the operator, and of other realised plants in Germany, e.g. from the Solarthermie-2000 programme, are used to project the costs of the approaches.

The first part of the conducted work was a detailed record of the layout of the district heating system as input for the simulation models. A metrological investigation of the buildings provides load profiles for the domestic hot water consumption during one week with a suitable temporal resolution of 40 s. For this purpose, volume flows and temperatures at the domestic hot water pipes near the storage tanks as well as at the connection to the district heating network were measured during operation (Fig. 4). A superposition of these data with the yearly standard load profile for multi-family buildings according to VDI 6002 (2014) is used as input for the hot water consumption.

Fig. 4: Logging of the hot water consumption at a substation

As there are no load profiles available for space heating, the consumption was simulated with the single node house model of the CARNOT-toolbox. The building geometry was modelled and the properties of the walls and windows scaled to fit the known annual consumption.

The simulations were conducted in the MATLAB/Simulink environment under use of the CARNOT block set (Hafner et al. 1999). The model consists of a central heating plant and 9 consumers as there are 9 substations connected to the network and the consumption data refer to these substations. The heat losses of the network and heat storages are taken into account. All used components are standard models of the CARNOT library.

Following key figures are used to compare the investigated plant layouts.

$$SF = \frac{E_{Sol}}{E_{Fos} + E_{Col}} \qquad \text{(eq. 1)}$$

$$\mathrm{HGC}_{Sol} = \frac{Annuity}{E_{Sol}} \qquad \text{(eq. 2)}$$

$$\eta_{Sys} = \frac{E_{Sol}}{E_{Irr}} \qquad \text{(eq. 3)}$$

SY	Solar yield	[MWh·a^{-1}]
SF	Solar fraction	[%]
$\mathrm{HGC}_{\mathrm{Sol}}$	Solar heat generation costs	[Ct·kWh^{-1}]
η_{Col}	Efficiency of the collector circuit	[%]
η_{Sys}	Efficiency of the solar-thermal system	[%]
E_{Fos}	Fossil energy provided by the gas furnace	[MWh·a^{-1}]
E_{Col}	Energy provided by the solar-thermal collectors per year	[MWh·a^{-1}]
E_{Sol}	Energy provided by the solar-thermal system per year	[MWh·a^{-1}]
E_{Irr}	Irradiated energy on the collector surface per year	[MWh·a^{-1}]

2.2 Model of the Existing Network

The investigated plant connects the substations via a piping network of 500 m length. Some of the substations transfer heat to other buildings via separated pipes for space heating and hot water supply. The central heating plant consists of 3 gas furnaces with a total power of 1,945 kW and provides a constant flow temperature of 80 °C throughout the year. This leads to higher return temperatures during summer period, when the space heating circuit is shut down. The possible efficiency of solar-thermal systems depending on to the return temperature is therefore reduced.

The current hydraulic of the system provides an almost constant mass flow through each connected substation. The power transferred to the domestic hot water tank of each substation and the space heating circuit are regulated by the mass flow in these sub-circuits. Space heat is transferred via radiators in the flats. A scheme of the basic plant layout is shown in Fig. 5. The total heat consumption of the buildings during a year is 4,399 MWh where 3,282 MWh are used for space heating, 447 MWh for tap hot water production and 387 MWh for circulation. 283 MWh per year are lost in the district heating piping system.

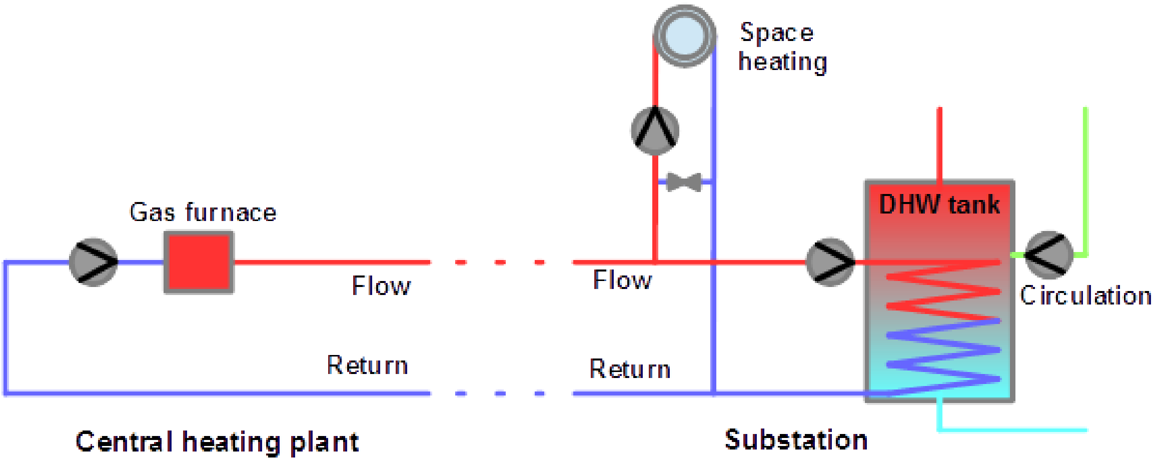

Fig. 5: Scheme of the basic system layout

As the existing district heating network was not originally designed to provide favourable conditions for the integration of solar-thermal heat, some modifications were performed on the basis-layout (i.e. the system without any solar-thermal components). Reduced flow temperatures during summer period were tested in the simulation model to increase the solar yield. It was found that the flow temperate cannot be adequately reduced without affecting the function of the legionella prevention. Therefore, a load depending mass flow was alternatively used to reduce the return temperatures.

2.3 Model of the Investigated Solar-Thermal Plants

Based on the completely fossil-fired networks with and without optimised return temperature (referred as B and B_RT), the integration of a central solar-thermal plant with 500 m² flat plate collectors and a 50 m³ buffer tank is simulated (named C_500_50 respectively C_500_50_RT).

The substations for these variants are kept as in the basic models. Only the central heating plant is modified according to Fig. 6. The return mass flow from the district heating network can be conducted through the whole buffer storage, in case the storage is completely heated up to a sufficient temperature level. Otherwise it is passed by and flows into the storage at about 85 % of the height. On the solar side, the connections to the buffer allow a similar operation. It is possible to heat up the lower (colder) part of the buffer at times with low radiation or the upper (hotter) part, when the temperature delivered by the solar-thermal system is sufficient for pre-heating the network return. The pumps allow a variable mass flow to better fit the desired collector outlet temperature. The flow temperature of the network is kept at 80 °C by the serially connected gas furnaces.

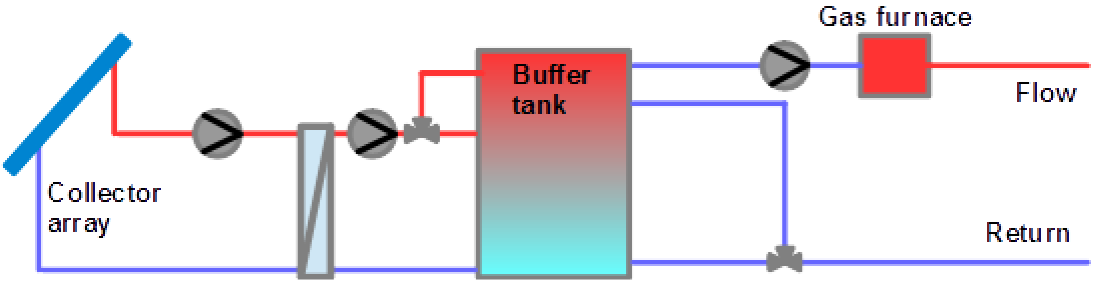

Fig. 6: Scheme of the central solar plant

The volume of the circulating water inside the district heating network is 12 m³. A variant without any additional storage (C_500_0_RT) is part of the comparison to test, if this capacity would be sufficient to store solar excess heat. For this variant, the heat exchanger of the collector array is directly connected to the return pipe of the district heating network. The volume flow of the collector circuit is passed by, as long as the temperate is below the network return temperature. Otherwise it is used to preheat the return before entering the gas boilers.

Simulations with decentralised solar-thermal plants were conducted to get a comparison to the centralised approach. In the first variant (D_HW_500_50), every building is equipped with a solar-thermal system for domestic hot water production (Fig. 7). Therefore, an additional solar storage tank is connected in series between the cold water supply pipe and the fossil-supplied hot water tank. The aperture areas and storage volumes are distributed according to the fraction of the hot water consumption of the building compared to the whole network. This means, a building that consumes 10 % of the whole energy is equipped with 10 % of the installed collector area and storage volume.

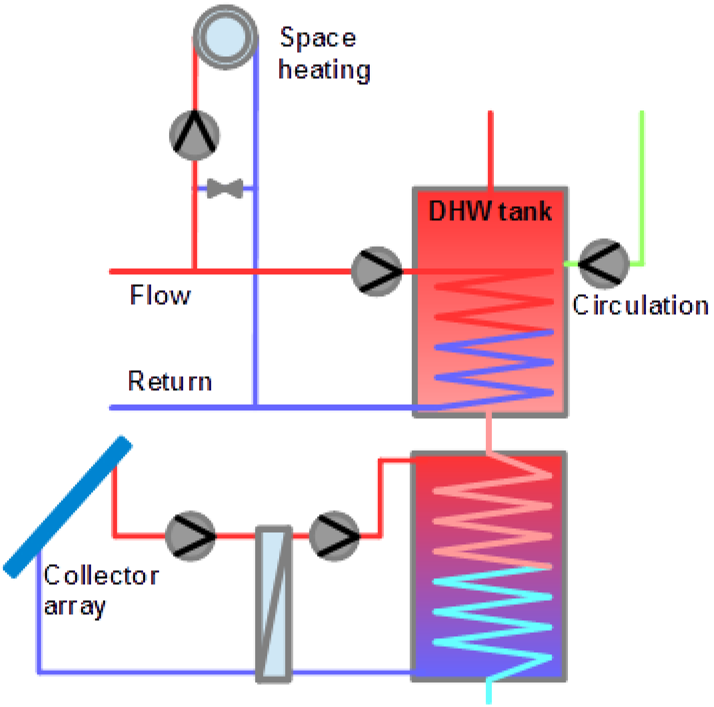

Fig. 7: Scheme of the decentralised solar plants for domestic hot water generation

The second approach is the installation of a buffer tank with connection to the domestic hot water and space heating production as shown in Fig. 8 (D_SH_500_50). The distribution of the collector areas and storage volumes is kept the same as for the variant D_HW_500_50, as the ratio of energy consumption for hot water and space heating is almost the same for all buildings.

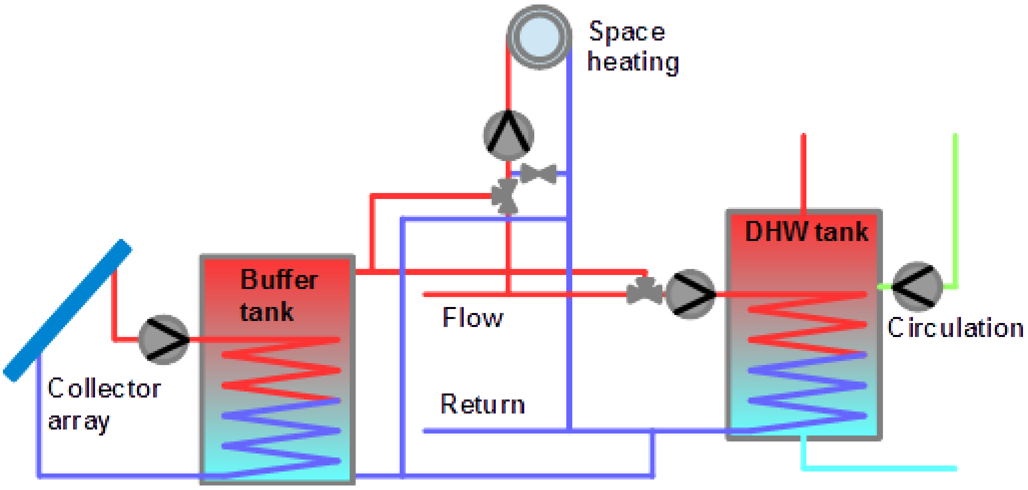

Fig. 8: Scheme of the decentralised solar plants for space heating support

As a third opportunity, the feed of the solar energy directly to the return pipe of the district heating network, is investigated to represent a simple scheme of decentralised feed in (D_RP_500_0_RT). This model is not equipped with any additional storages and the collector circuits transfer the energy directly to the return pipe of the substation via heat exchangers. Again the distribution of the collector arrays is the same as in the other decentralised variants. As the investigated district heating network and the connected buildings are operated by the same housing association, this approach is a realistic opportunity. Many other projects in the past had to focus on a feed from the return into the flow pipes, as the operators of the networks usually have different interests than the owners of the solar-thermal plants. The operators are in general sceptical to changes of the system temperatures. Reasons to that are the increased heat losses by higher flow or return temperatures and the possible reduction of the efficiency of the often used central combined heat and power plants (Schäfer, et al. 2014). A connection to the return pipe reduces the necessary feed temperatures of the solar-thermal system. The additional pump energy consumption is lower, as decentralised pumps are not necessary to overcome the pressure drop from flow to return at the substation.

Tab. 1 gives an overview of the simulations that have been performed.

Tab. 1: Overview of simulated variants

Variant	Description
(B)	Basic system layout without solar support
(B_RT)	Basic system layout without solar support, variable mass flow through substation for reduced return temperatures
(C_500_50)	Basic system equipped with 500 m² collector area and a 50 m³ buffer tank at the central heating plant
(C_500_50_RT)	Basic system with reduced return temperature, equipped with 500 m² collector area and a 50 m³ buffer tank at the central heating plant
(C_500_0_RT)	Basic system with reduced return temperature, equipped with 500 m² collector area but no additional buffer tank at the central heating plant
(D_HW_500_50)	Basic system equipped with 500 m² collector area and 50 m³ buffer tanks distributed over the buildings for domestic hot water support
(D_SH_500_50)	Basic system equipped with 500 m² collector area and 50 m³ buffer tanks distributed over the buildings for domestic hot water and space heating support
(D_RP_500_0_RT)	Basic system with reduced return temperature, equipped with 500 m² collector area distributed over the buildings, no additional storage, solar energy is fed into the return pipe at the substations

3. Results

3.1 Energetic Performance

First, the behaviour of the systems is analysed from the energetic point of view. The relevant results of these simulations are shown in Tab. 2.

Tab. 2: Energetic results of the simulated systems

Variant	SF [%]	SY [MWh]	η_{Sys} [%]
Basis (B)	-	-	-
Basis, reduced return temperature (B_RT)	-	-	-
Central, 500 m², 50 m³, (C_500_50)	3.3	149	22.9
Central, 500 m², 50 m³, reduced return temperature (C_500_50_RT)	3.8	166	25.4
Central, 500 m², no storage, reduced return temperature (C_500_0_RT)	2.3	103	15.8
Decentralised, hot water production, 500 m², 50 m³ (D_HW_500_50)	5.7	254	41.5
Decentralised, hot water and space heating support, 500 m², 50 m³ (D_SH_500_50)	2.6	116	18.9
Decentralised, return pipe feed in, reduced return temperature, 500 m², 50 m³ (D_RP_500_0_RT)	2.6	115	18.8

In Variant B_RT, the return temperature could be reduced from an average of 69.2 °C to 66.8 °C. A further reduction is not possible without negative effects on the continuity of the hot water temperature level.

The integration of the solar-thermal System (C_500_50) leads to a solar yield of 149 MWh per year. This means a solar fraction of 3.3 %. By utilising the return temperature reduction (C_500_50_RT), the solar yield is increased to 166 $MWh \cdot a^{-1}$, meaning 3.8 % solar fraction. The solar-thermal system efficiency rises from 22.9 % to 25.4 %.

The centralised variant without an additional storage performs less efficient than the variant with storage. The possible heat transfer to the return pipe is below the collector power during 80 days from spring until autumn leading to stagnation and a lower solar yield.

According to the buildings structure, the orientation and inclination of the collector arrays for the decentralised plants is less favourable as for the centralised variant. The amount of irradiated energy drops from 653 $MWh \cdot a^{-1}$ to a level of 613 $MWh \cdot a^{-1}$. The system for domestic hot water production achieves a solar fraction of 5.7 % (254 $MWh \cdot a^{-1}$ solar yield). The fraction of the solar energy during summer, when only the hot water production is active is approximately 60 %.

The decentralised system for domestic hot water production and space heating support achieves a solar fraction of 2.6 % (116 $MWh \cdot a^{-1}$ solar yield). Based on this low yield, there seems to be no reason to connect a solar-thermal system of the investigated size to the space heating circuit of the buildings.

The system for direct feed into the return pipe contributes 115 $MWh \cdot a^{-1}$ of solar energy to the heat production. This means a solar fraction of 2.6 %. Due to the continuous high temperatures, the efficiency of the collector array is only at 18.8 %. Compared to the basic model B_RT, the average return temperature at the central heating plant rises from 66.8 °C to 67.2 °C.

3.1 Economic Performance

Based on previously installed systems at the housing association, there are references for the installation costs of solar-thermal plants. From these data and the reports of the Solarthermie-2000 programme, the average costs of the different plant sizes were derived (Peuser et al. 2009). The calculation of the costs was performed by the method applied in this programme. It is a simplified annuity method taking into account only the investment without subsidies. The high annuity factor of 8.72 % compensates for the missing calculation of operation and maintenance costs Tab. 3 shows the investment and heat generation costs according to (eq. 2) for the systems.

Tab. 3: Economic results of the simulated systems

Variant	**Invest [t€]**	**HGC_{Solar} [$Ct\cdot kWh^{-1}$]**
Basis (B)	0	-
Basis, reduced return temperature (B_RT)	0	-
Central, 500 m², 50 m³, (C_500_50)	287	16.8
Central, 500 m², 50 m³, reduced return temperature (C_500_50_RT)	287	15.1
Central, 500 m², no storage, reduced return temperature (C_500_0_RT)	240	20.3
Decentralised, hot water production, 500 m², 50 m³ (D_HW_500_50)	388	13.3
Decentralised, hot water and space heating support, 500 m², 50 m³ (D_SH_500_50)	388	29.1
Decentralised, return pipe feed in, reduced return temperature, 500 m², 50 m³ (D_RP_500_0_RT)	321	24.3

The current fossil heat generation costs are at 7 $Ct\cdot kWh^{-1}$. Therefore, it is challenging to reduce the costs by operating a solar-thermal plant. Although it is one of the most expensive systems to install, the lowest solar heat generation costs can be achieved with variant D_HW_500_50. This is due to the high yield of the system. The highest heat generation costs are reached with variant D_SH_500_50. The investment is approximately the same as for D_HW_500_50, but the solar yield is 54 % lower. If the aperture area was reduced to avoid stagnation, the central system without storage might even have economic benefits over the variant with storage as the investment is lower.

Based on this calculation, the decision for a solar retrofitting of the district heating network with standard system designs would have no economic benefit. On the other hand, up to 5.7 % solar fraction can be reached at to decrease the greenhouse gas emissions of the plant. Possible changes of the price of natural gas are not considered in these calculations.

4. Conclusions and Outlook

Like expected, the system for the direct support of the domestic hot water generation is the best in terms of solar yield as well as heat generation costs. The other decentralised systems for an additional support of the space heating and a direct feed into the return pipe of the district heating network show a lower performance.

Central systems could be an alternative, if a reduction of the return temperature was realised. In case of a smaller collector array than considered in this paper, even a plant without additional storage could be an opportunity.

Further studies will be conducted to get a more detailed view on some effects. The influence of solar integration on the efficiency of the fossil furnace is one of these topics. Higher or lower return temperatures may have effects on the combustion process and therefore on the fuel consumption and the exhaust gas composition. An increased amount of partial load condition may also reduce the efficiency. A detailed parameter study for the system could lead to a further optimisation of the results. Different control parameters (like temperate limits, hysteresis), different hydraulic configurations or different heat exchangers (internal, external, in- and outlet heights) should be investigated for this purpose. The integration of other types of solar collectors like vacuum tube collectors will be discussed in future.

A concentration of the collector arrays only on the few buildings with beneficial roof structure could increase the irradiation compared to the decentralised variants discussed. Furthermore, the installation costs would be reduced. The feed of exhaust heat, generated in these plants, into the district heating network could be a measure for the prevention of stagnation. This would only be necessary, if the aperture area was enlarged or smaller storages were used. Other variants like return-flow-feed will be tested.

Based on concrete figures for the costs of the components and the installation effort, a more detailed analysis of the economic performance will be conducted, before a decision is made on the final concept.

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