SIMULATION STUDY ON SOLAR ASSISTED DISTRICT HEATING SYSTEMS WITH SOLAR FRACTIONS OF 35 %

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Abstract – A simulation study on solar assisted district heating systems with solar fractions of 35 % was carried out taking into consideration different types (supply pipe / return pipe temperatures 68/41 °C and 60/30 °C) and various sizes of heat loads from 500 up to 10 000 MWh/a. The meteorological conditions were varied considering three different German locations with relatively low (Hannover), average (Frankfurt/Main) and high irradiation (Würzburg) to make the results applicable for most regions of Germany. Results have shown that specific solar heat costs are between those of systems with a solar fraction (f_{sol}) of 10 and 50 % and amount to 13.6 - 26.0 €Ct./kWh for Frankfurt climatic conditions depending on plant size. Compared to systems with f_{sol} of 50 %, especially small-scale district heating systems (up to 1 000 MWh/a) with f_{sol} of 35 % feature moderate investment costs, recommending them for this field of application. Specific solar heat costs are between 4 - 7 % higher for heat load types 68/41 °C compared to 60/30 °C. Based on the specific solar heat costs for Frankfurt conditions, Würzburg costs are between 7 - 13 % lower and Hannover costs up to 8 % higher, depending on plant size.

1. INTRODUCTION

The demand of thermal heat amounts to 31 % of the total end energy consumption in Germany [Geiger, Wittke, 2002]. Private households contribute 21 % to this end energy consumption and thus have the potential to save a lot of energy. Within the scope of the German research programme “Solarthermie-2000” solar thermal plants with solar fractions (based on total heat demand) of 5 to 10 % (only heating of domestic hot water) and of approximately 50 % (solar assisted district heating systems with seasonal heat storage) were developed and built. Solar assisted district heating systems with solar fractions of 35 % bridge the gap between these systems and feature moderate investment costs compared to systems with higher solar fractions. Therefore they are recommended to be built in large numbers to save fossil fuels and to reduce CO_2-emissions.

2. ASSUMPTIONS

2.1 Hydraulic scheme

Based on the state of the art of solar assisted district heating systems a reference system was defined. Several systems in Germany, such as the ones in Friedrichshafen or Hamburg, are built as shown in figure 1. The solar circuit is separated by a heat exchanger from the storage circuit since a water-glycol-mixture (60/40 weight-%) is used to protect the collector field (flat plate collectors) against frost damage at temperatures below 0 °C. The heat store is a cylindrical water tank made of concrete. It is ground buried and insulated by granular glass material laterally and on the top. There are three levels of charging respectively discharging in the store. A load heat exchanger which separates the storage circuit from the district heating net is installed to preheat the return flow of the buildings. If necessary a boiler is operating to reach the demanded supply pipe temperature. To avoid running the district heating net with higher than the demanded supply pipe temperatures cold return pipe fluid can be admixed.

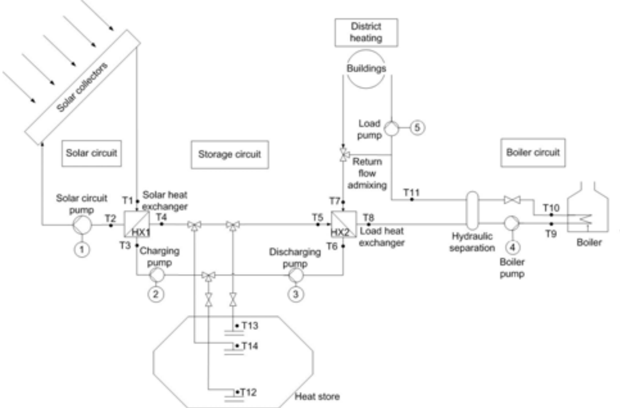

Figure 1: Scheme of the reference system

This reference system was integrated into the transient simulation programme TRNSYS [TRNSYS] to compute the thermal behaviour. In table 1 additional information concerning different input data is given.

Table 1: Input data for the TRNSYS simulations

Collector:	Orientation to south with tilt angle of 45 ° η_0 = 0.8, u_1 = 3.6 W/(m² K), u_2 = 0.02 W/(m² K²), capacity = 7 kJ/K, specific flow rate 14 kg/(m² h), TRNSYS type 101 (MFC)
Heat store:	Cylindrical water tank made of concrete, ground buried, insulated by granular glass material (λ = 0.075 W/(m K)) on top (70 cm) and wall (50 cm), TRNSYS type 142 (XST)

2.2 Heat loads

Heat loads and especially return pipe temperatures are a crucial point for the efficiency of a solar thermal plant. For new buildings it is essential to achieve low return pipe temperatures of the district heating net of at maximum 40 °C (yearly mean temperature weighted by volume flow). For this study two types of heat loads (supply pipe / return pipe 68/41 °C and 60/30 °C) as shown in table 2 were taken into consideration. The heat loads were obtained by evaluating the thermal behaviour of existing district heating nets and carrying out TRNSYS-simulations of complete district heating nets.

Table 2: Considered heat loads

Heat load:	Obtained by TRNSYS-simulation of district heating net (space heating and domestic hot water (dhw) preparation) **Case 1:** yearly mean temperatures (weighted by volume flow) supply pipe/return pipe 68/41 °C, dhw supply by charging of decentral dhw storages, multifamily residences, load varied from 500 to 10 000 MWh/a **Case 2:** supply pipe/return pipe 60/30 °C, dhw supply by compact domestic delivery stations, terraced houses, load varied from 500 to 2 500 MWh/a

2.3 Meteorological conditions

To make this study valid for most parts of Germany three different locations with different meteorological conditions were chosen for the simulations. The test reference year [Blümel et. al., 1986] of Hannover represents the northern part of Germany with relatively low irradiation (irradiation on horizontal surface: 928 kWh/(m² a), irradiation on collector plane 1 057 kWh/(m² a)). Frankfurt/Main is taken to represent average German climatic conditions (1 038 resp. 1 148 kWh/(m² a)) and Würzburg to characterise locations with relatively high irradiation (1 119 resp. 1 247 kWh/(m² a)). Figure 2 shows the monthly irradiation on collector plane of the different locations.

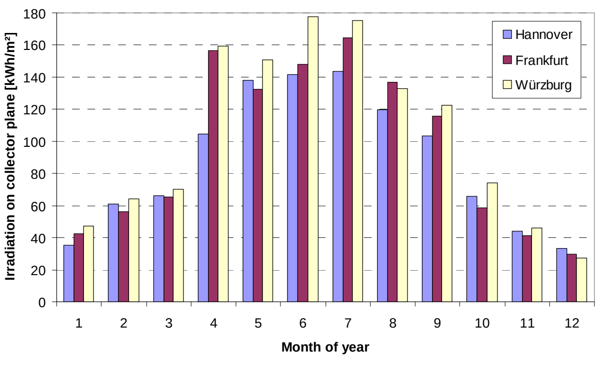

Figure 2: Monthly irradiation on collector plane (tilt angle 45 °) for different meteorological conditions

2.4 Calculation of profitability

Calculation of profitability is carried out for every simulated system according to standard VDI 2067. Specific solar heat costs [€Ct./kWh], as a result of calculations of profitability, are taken as a characteristic factor for the efficiency of the considered systems.

To determine the total investment costs (including design and value added tax (VAT), without subsidies) of heat store and collector fields as well as the amount of additional charges data for realised plants were taken. In this conservative costing, future cost savings e. g. due to progress in manufacturing of parts are not taken into consideration. Table 3 gives some further details about the calculation of profitability.

Table 3: Details of calculation of profitability

Capital-related costs:	Interest rate of 6 %/a Calculated service life of collectors 25 years and of heat store 50 years
Maintenance costs:	Collectors, heat store, buildings: 1 %/a (of investment costs)
Operation-related costs:	Collectors, heat store, buildings: 0.25 %/a (of investment costs)

3. SYSTEM SIMULATIONS

3.1 General

System simulations were carried out for heat load types 60/30 °C (sizes: 500, 750, 1 000, 2 500 MWh/a) and 60/41 °C (sizes: 500, 750, 1 000, 2 500, 5 000, 10 000 MWh/a). The ratio of heat store volume to collector area V_{store}/A_{coll} was varied from 0.25 to 2.0 m³/m² for different collector areas depending on the specific heat load (1.2 to 1.9 m²/(MWh/a)). As a result different systems meeting a solar fraction of 35 % were obtained. The one providing the lowest amount of total investment costs and lowest specific solar heat costs was chosen as the most profitable system for a definite heat load type and size.

3.2 Results

Figure 3 and 4 show the specific solar heat costs and the total investment costs for various sizes of district heating nets and different heat load types 68/41 °C resp. 60/30 °C. For Frankfurt conditions and heat load type 68/41 °C specific solar heat costs vary from 13.6 to 26.0 €Ct./kWh and total investment costs from 0.53 to 5.48 millions € depending on plant size, resp. from 16.9 to 24.4 €Ct./kWh and 0.49 to 1.72 millions € for heat load type 60/30 °C. Compared to the specific solar heat costs for Frankfurt conditions, Würzburg costs are from 7 to 13 % lower and Hannover costs up to 8 % higher, also depending on plant size. It is evident that costs are lowest for plants built in Würzburg featuring high irradiation. For the locations Frankfurt and Hannover costs are around the same for small plants up to 1 000 MWh/a. For larger systems the costs for plants built in Hannover are highest whereas in the case of Frankfurt the costs are median compared to systems in Hannover and Würzburg. Independent of heat load temperatures, for all investigated locations and loads up to 1 000 MWh/a the most cost effective system is obtained by a ratio V_{store}/A_{coll} of 0.25 m³/m². Since this ratio is the lower limit of V_{store}/A_{coll}, further simulations were carried out down to a ratio of 0.05 m³/m² for a small-scale plant of 500 MWh/a. The results indicate an optimum ratio V_{store}/A_{coll} of 0.10 m³/m². The reduction of the solar heat costs of 1.6 % (solar heat costs 25.6 €Ct./kWh) compared to the 500 MWh/a plant (68/41 °C) shown in table 4 is small, whereas the stagnation time of the collector field (1 100 m²) more than doubles up to 234 h. Because the volume of the heat store at a ratio V_{store}/A_{coll} of 0.1 m³/m² is quite small for a ground buried heat store, further detailed studies with a TRNSYS buffer tank (type 140) will be performed as a next step.

For larger heat loads (2 500 to 10 000 MWh/a) the ratio V_{store}/A_{coll} is rising from 0.75 to 1.0 m³/m² (Frankfurt and Würzburg) resp. 0.25 to 0.75 m³/m² (Hannover). Although the irradiation is higher in Frankfurt, the considered plants have the same costs in Hannover and Frankfurt. This is due to the found ratio V_{store}/A_{coll} of 0.25 m³/m² for cost-effective small plants which does not allow to store heat seasonally but monthly and is connected with some stagnation of the collector field ($Stag_{coll}$) in the summer for all three locations. Therefore the higher irradiation in Frankfurt compared to Hannover leads to more hours of stagnation of the collector field and does not increase the solar fraction because in winter there is slightly more irradiation in Hannover than in Frankfurt.

With increasing ratio of V_{store}/A_{coll} more heat can be transferred from the summer into times with high heat demand and the costs become proportional to the yearly irradiation. This effect can be seen from figure 5. With increasing heat loads the associated heat stores become also larger leading to higher efficiency of heat storage due to a decreasing ratio of heat store surface to heat store volume, and hence lower heat losses. With a ratio V_{store}/A_{coll} higher than 0.25 m³/m² the stagnation time of collector fields decreases significantly.

In table 4 the most profitable system parameters for climatic conditions of Frankfurt are summarized.

Table 4: Most profitable system parameters

System parameters for Frankfurt/Main and heat load type 68/41 °C				
A_{coll} [m²]	V_{Store}/A_{coll} [m³/m²]	Heat load [MWh/a]	$Stag_{coll}$ [h]	Solar heat costs [€Ct./kWh]
975	0.25	500	101	26.0
1 400	0.25	750	103	23.6
1 900	0.25	1 000	133	22.6
3 500	0.75	2 500	0	17.9
7 000	0.75	5 000	0	15.7
12 750	1.00	10 000	0	13.6
System parameters for Frankfurt/Main and heat load type 60/30 °C				
A_{coll} [m²]	V_{Store}/A_{coll} [m³/m²]	Heat load [MWh/a]	$Stag_{coll}$ [h]	Solar heat costs [€Ct./kWh]
900	0.25	500	126	24.4
1 350	0.25	750	153	22.6
1 400	0.50	1 050	0	21.1
3 250	0.75	2 500	0	16.9

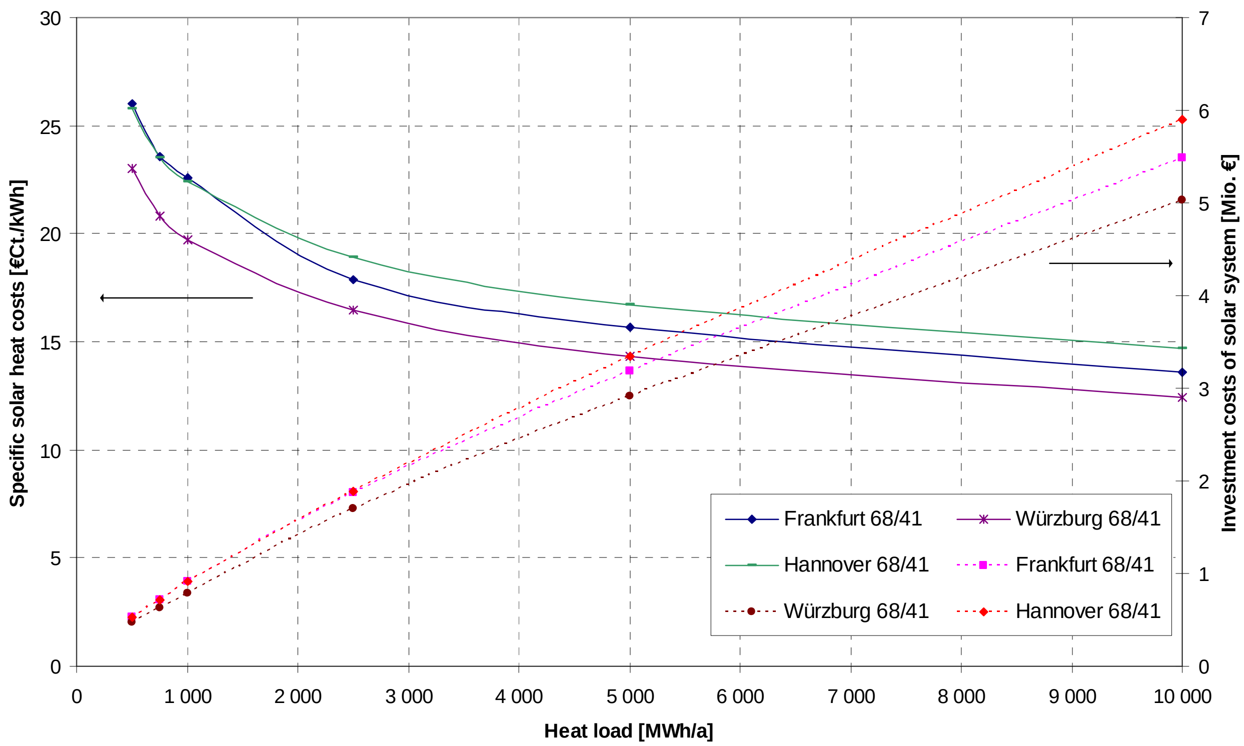

Figure 3: Specific solar heat costs and total investment costs of different system sizes in Frankfurt/Main, Hannover and Würzburg (heat load type 68/41 °C)

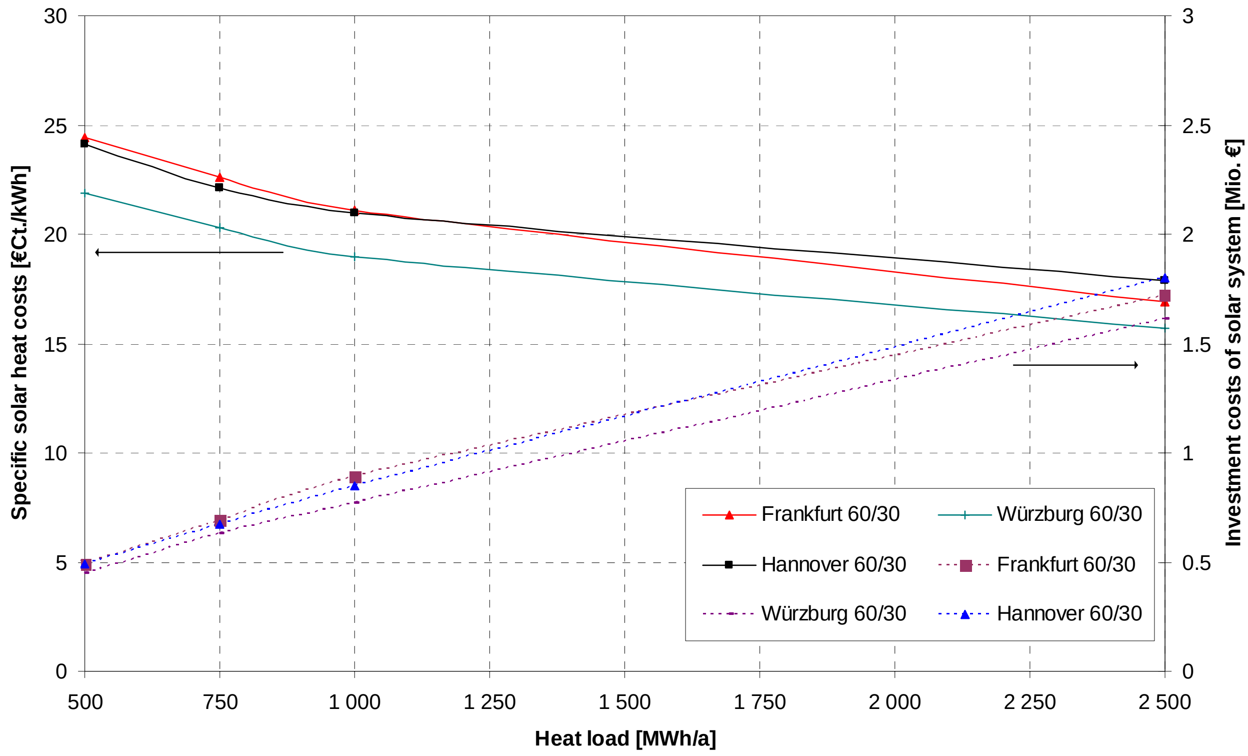

Figure 4: Specific solar heat costs and total investment costs of different system sizes in Frankfurt/Main, Hannover and Würzburg (heat load type 60/30 °C)

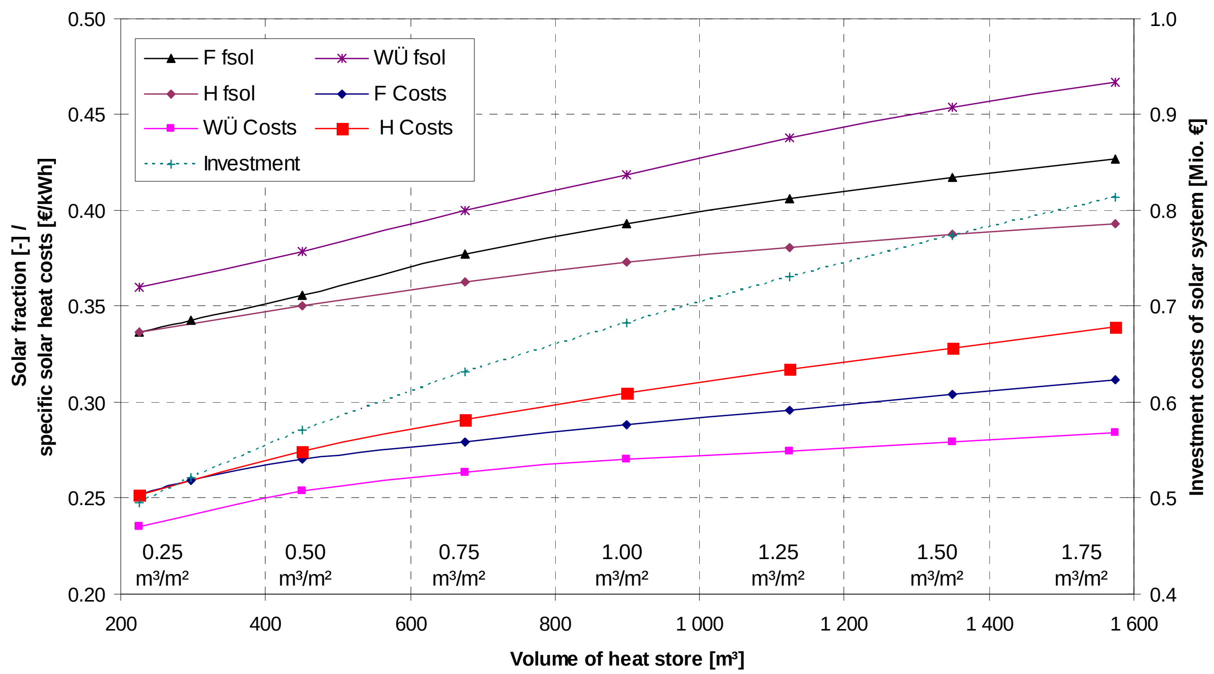

Figure 5: Influence of meteorological conditions (H: Hannover, F: Frankfurt, WÜ: Würzburg) on costs and solar fraction (heat load type 68/41 °C and heat load 500 MWh/a, collector area 900 m²)

Table 5: Costs of systems with solar fractions of 50 % (meteorological conditions: Frankfurt/Main)

System parameters for Frankfurt/Main and heat load type 68/41 °C						
A_{coll} [m²]	V_{Store}/A_{coll} [m³/m²]	Heat load [MWh/a]	Invest. [Mio. €]	Solar heat costs [€Ct./kWh]	Comparison Invest.* [%]	Comparison solar heat costs* [%]
1 250	1.25	500	0.93	30.4	+76	+17
1 800	1.25	750	1.22	27.0	+72	+14
5 200	1.50	2 500	2.89	19.6	+55	+10
20 000	1.50	10 000	8.49	14.5	+55	+7
System parameters for Frankfurt/Main and heat load type 60/30 °C						
A_{coll} [m²]	V_{Store}/A_{coll} [m³/m²]	Heat load [MWh/a]	Invest. [Mio. €]	Solar heat costs [€Ct./kWh]	Comparison Invest.* [%]	Comparison solar heat costs* [%]
1 100	1.25	500	0.85	27.9	+74	+14
2 000	1.50	1 000	1.39	22.8	+64	+7
4 750	1.50	2 500	2.70	18.0	+57	+7
*: Comparison of investment costs resp. solar heat costs from f_{sol} 35 % to f_{sol} 50 % systems						

3.3 Comparison with systems of different solar fraction

The specific solar heat costs for plants with solar fractions of around 7 % are between 12 and 16 €Ct./kWh for small collector fields of around 100 m² to collector fields bigger than 1 000 m² [Peuser, 2002]. In table 5 solar costs of some plants with solar fractions of 50 % and climatic conditions according to Frankfurt/Main, also simulated in this study, are given. Going from a solar fraction of 35 % to 50 % the solar fraction is increased by 43 %. The comparison between the costs given in table 5 and in figure 3 resp. figure 4 indicates higher investment costs from 55 to 76 % for heat loads of 10 000 to 500 MWh/a and a solar fraction of around 50 %. The specific solar heat costs rise from 7 % to 17 % for heat loads of 10 000 MWh to 500 MWh/a moving from a system with solar fraction of 35 % to 50 %. Therefore, especially for small-scale district heating systems up to 1 000 MWh/a the application of solar assisted district heating systems with solar fractions of 35 % is recommended.

5. CONCLUSIONS

A simulation study was carried out to determine optimum system parameters for solar assisted district heating systems with solar fractions of 35 % at lowest investment costs and specific solar heat costs. As a result, the specific solar heat costs are between those of systems with solar fractions of 5 - 10 % and 50 %. Compared to systems with solar fractions of 35 % systems with solar fractions of 50 % have investment costs which are between 46 to 83 % higher for heat loads from 10 000 down to 500 MWh. Therefore small-scale district heating is the preferred field of application for these systems.

Specific solar heat costs are 4 - 7 % higher for the heat load type 68/41 °C compared to 60/30 °C. Based on the specific solar heat costs for Frankfurt conditions, Würzburg costs are 7 - 13 % lower and Hannover costs up to 8 % higher, depending on plant size.

For small district heating systems (500 and 750 MWh/a) the most profitable solar systems (lowest investment costs and lowest solar heat costs) are obtained with a ratio V_{store}/A_{coll} of 0.25 m³/m², leading to moderate stagnation times of the collector field. For heat loads of more than 1 000 MWh/a, the most profitable ratio V_{store}/A_{coll} increases up to 1.0 m³/m².

Other solutions concerning the ratio V_{store}/A_{coll} are also possible if financial penalties up to 10 % are accepted. Future work will investigate the monetary and energetic sensitivity of the considered systems with f_{sol} 35 % with respect to the variation of the ratio V_{store}/A_{coll}. The influence of different boundary conditions (buffer tank especially for a low ratio V_{store}/A_{coll} of 0.1 m³/m², heat demand, collector efficiency etc.) on the thermal performance of the systems will also be examined. Furthermore more effort has to be carried out on the field of small solar assisted district heating systems to shorten the stagnation time of collector field.

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