Extension of Germany’s Largest Solar District Heating System with Seasonal Thermal Energy Storage

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Abstract

This publication introduces several measures to extend and optimize Germany’s largest solar district heating system with seasonal thermal energy storage, located in southern Germany in the city Crailsheim. The aim of the extension is to achieve a solar fraction above 50 % in order to reduce CO_2 emissions and to demonstrate the functional and economic attractiveness of solar district heating systems with seasonal thermal energy storage. The investigated measures comprise different concepts for the extension of the solar thermal collector area with high-efficiency flat-plate collectors and the extension of the borehole thermal energy store, which serves as seasonal thermal energy store in the system. As an alternative, the installation of an overground hot water thermal energy store is considered to increase the heat storage capacity. Other measures are the installation of a second heat pump as well as the reduction of the return flow temperature of the district heating grid. Further, combinations of the above mentioned measures are investigated. The effects of the specific measures are quantified by means of annual system simulations with the transient simulation software TRNSYS 17.

Keywords: solar district heating, seasonal thermal energy storage, high solar fractions, system simulation, TRNSYS

1. Introduction

The currently largest central solar district heating plant with seasonal thermal energy storage (CSHPSS) in Germany is located in Crailsheim, which is a small city with a population of about 33 000 in the south of Germany. The CSHPSS was built between 2004 and 2011 in two main construction phases. With an initially planned solar fraction of 50 %, the system is a flagship project for solar thermal district heating grids.

The CSHPSS in Crailsheim supplies heat to the district heating grid Hirtenwiesen II. Fig. 1 shows the development of the annual heat demand of the district heating grid as well as the solar fraction. Through the years, the heat demand of the district heating grid increased continually due to the construction and connection of new buildings. With over 7 000 MWh at the beginning of the year 2017, the heat demand is more than 1.7 times higher than the 4 100 MWh which were assumed in the original plans for the current stage of the heat generation system. The solar fraction reached a maximum of about 42 % in the year 2014, but due to the increasing heat demand, the solar fraction of the entire system is decreasing and was at a level of about 27.5 % in 2016. In order to enlarge the share of solar energy in the system, an extension and optimization of the solar district heating system is planned. Various measures to reach this aim were investigated with the help of transient system simulations, carried out with the simulation software TRNSYS 17. The aim of these measures is to achieve a solar fraction of more than 50 %. Finally, the most promising concept will be further investigated for implementation, considering ecological, technical, energetic as well as economical aspects. However, the focus of this publication lies only on the technical and energetic aspects.

More detailed descriptions of the CSHPSS in Crailsheim as well as the results of the system monitoring over the last years can be found in various publications, e.g. Bauer et al. (2009, 2013 and 2015), Bodmann et al. (2005) or Kurz and Schopf (2012).

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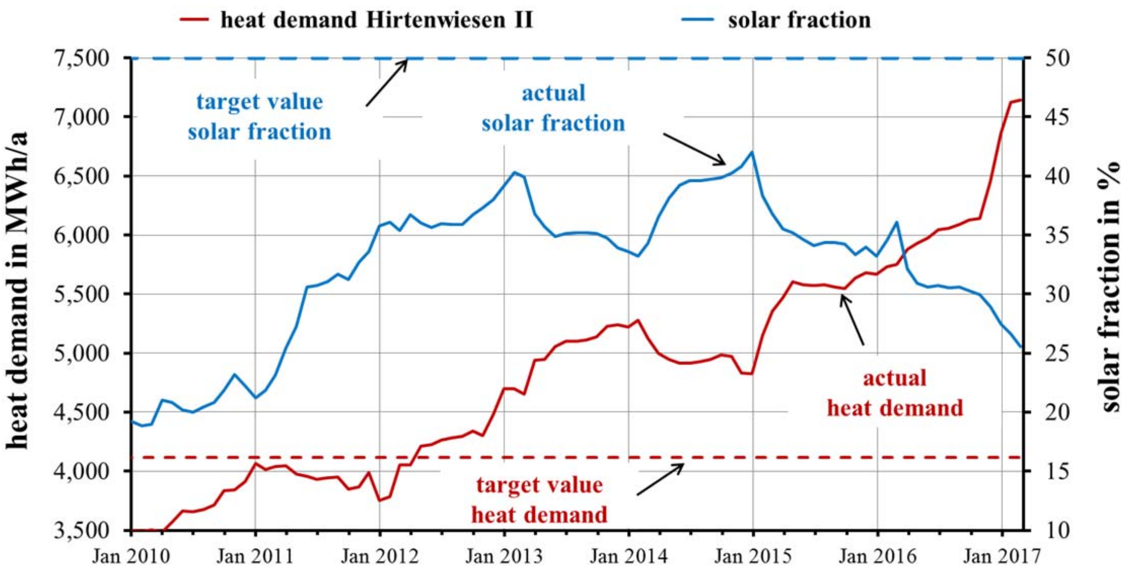

Fig. 1: Development of the heat demand and solar fraction of the district heating grid Hirtenwiesen II.

2. Reference system and methods

The simulation software TRNSYS 17 was used to develop and assess different measures and concepts for the extension and optimization of the CSHPSS in Crailsheim.

The performance of the existing system, see Fig. 2, which serves both as reference for the investigated concepts and as source of validation for the simulation model with monitoring data, is described in the sections 2.2 and 2.3. The definitions of the performance figures are defined in section 2.1. Finally, section 2.4 introduces the different investigated concepts.

2.1 Performance figures

Four performance figures are used in this publication in order to assess the performance of the system and specific components namely

- the solar fraction f_{sol},
- the efficiency of the borehole thermal energy store η_{BTES},
- the efficiency of the hot water thermal energy store η_{HWTES} and
- the seasonal performance factor of the heat pump SPF_{HP}.

The fraction of heat in the district heating grid Hirtenwiesen II covered with solar thermal energy is expressed using the solar fraction f_{sol}, which is defined as

$$f_{sol} = \frac{Q_{SHE} - Q_{HWI} - W_{HP,el}}{Q_{HWII}}, \qquad \text{(eq. 1)}$$

with

Q_{HWI}	heat transferred to the district heating grid Hirtenwiesen I in order to prevent stagnation [MWh],
Q_{HWII}	total annual heat consumption of the district heating grid Hirtenwiesen II [MWh],
Q_{SHE}	solar heat transferred at the preheating solar heat exchanger [MWh] and
$W_{HP,el}$	electrical energy consumption of the heat pump [MWh].

The efficiency of the borehole thermal energy store η_{BTES} is described as

$$\eta_{BTES} = \frac{Q_{BTES,dischar}}{Q_{BTES,char}} \qquad \text{(eq. 2)}$$

with

$Q_{BTES,char}$	heat charged to the BTES over the period of one year [MWh] and
$Q_{BTES,dischar}$	heat discharged from the BTES over the period of one year [MWh].

The efficiency of the hot water thermal energy store η_{HWTES} is defined in an analogous manner.

In order to quantify the efficiency of the heat pump, the seasonal performance factor of the heat pump SPF_{HP} is used

$$SPF_{HP} = \frac{Q_{HP,cond}}{W_{HP,el}} \qquad \text{(eq. 3)}$$

with

$Q_{HP,cond}$	annual useful heat provided by the heat pump [MWh] and
$W_{HP,el}$	annual electrical energy consumption of the heat pump [MWh].

2.2 Description of the existing system

The CSHPSS in Crailsheim was built for the heat supply of a new part of the city erected on the area of a former military base. The current system setup is shown in a schematic design in Fig. 2 and is described in brief in the following.

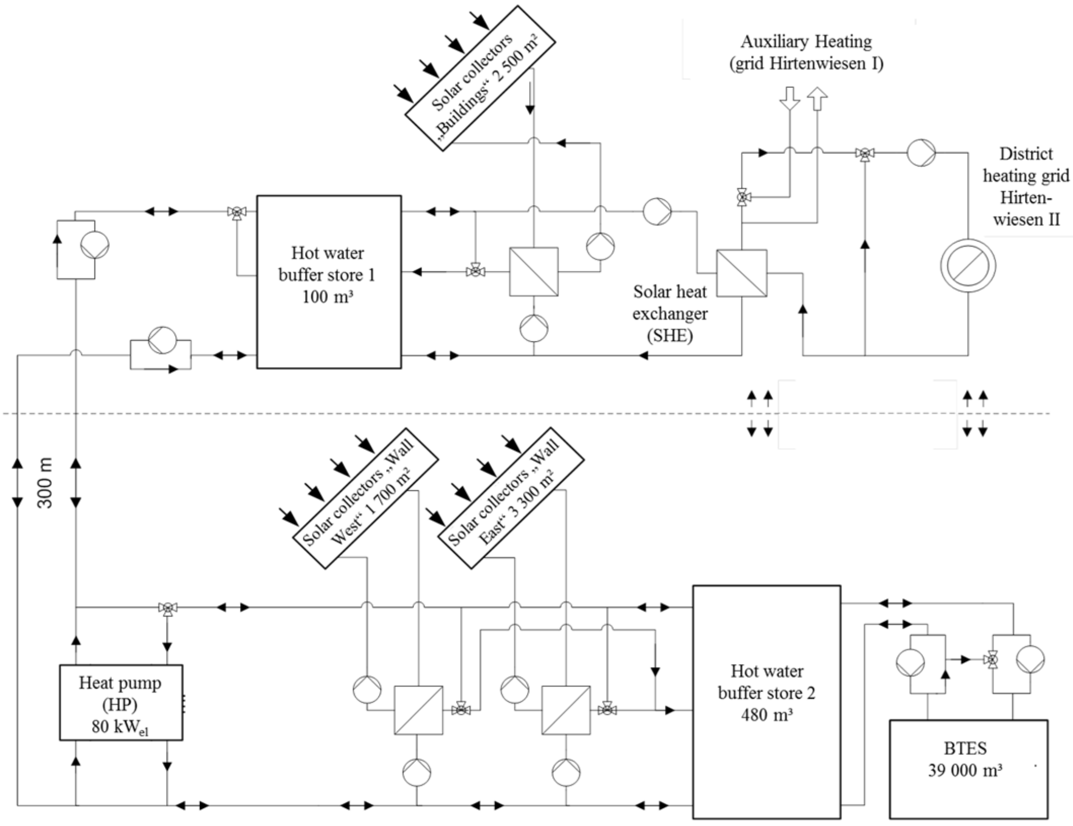

Fig. 2: Schematic design of the existing solar district heating system in Crailsheim.

The solar thermal system consists of three collector fields. Two collector fields are installed on noise barrier walls (“Wall West” and “Wall East”) with a collector aperture area of 1 700 m² and 3 300 m², respectively. Additionally, there are flat-plate collectors mounted on the roofs of the former and retrofitted barracks buildings as well as on the local school building and gymnasium with a total collector aperture area of 2 500 m². The total thermal power output of the solar thermal systems is at present about 5.2 MW. A borehole thermal energy store with a volume of 39 000 m³ serves as seasonal thermal energy store. The BTES can be charged by the collector fields “Wall West” and “Wall East” via a hot water buffer store with a volume of 480 m³. In order to discharge the BTES to lower temperatures, a compression heat pump with an electrical power of 80 kW is installed. The second part of the system consists of a hot water buffer store with a volume of 100 m³, which is charged by the collector field installed on the buildings. If necessary, thermal energy can be transferred between the two buffer stores. The annual heat consumption of the solar district heating grid was 6 862 MWh in 2016.

2.3 Validation of the simulation model

Transient system simulations were carried out with the simulation software TRNSYS 17 based on a simulation model that was validated beforehand with extensive monitoring data from the years 2013 to 2016. Because the conditions in 2016 were nearest to the mean values of the considered years, the measured weather data of the year 2016 were used as input data for the simulation of the reference system. Tab. 1 shows the comparison between the measured and simulation data for the reference year 2016.

Tab. 1: Absolute and relative deviations between measurement and simulation data of the CSHPPS in the reference year 2016.

Quantity	Unit	Measurement	Simulation	Δx_{abs}	Δx_{rel} [%]
f_{sol}	[%]	27.5	28.3	- 0.8	- 2.9
η_{BTES}	[%]	57.3	63.6	- 6.3	- 11.0
SPF_{HP}	[-]	4.8	4.7	0.1	2.1
Q_{HWII}	[MWh]	6 862	6 861	1	0.0
Q_{SHE}	[MWh]	2 283	2 336	- 53	- 2.3
Q_{HWI}	[MWh]	175	158	17	9.7
$Q_{HP,cond}$	[MWh]	1 061	1 114	- 53	- 5.0
$W_{HP,el}$	[MWh]	221	235	- 14	- 6.3
$Q_{BTES,char}$	[MWh]	731	647	84	11.5
$Q_{BTES,dischar}$	[MWh]	419	411	7	1.7

Generally, there is a good consistence between measured and simulation data. The explanation for the relatively high deviations in the values concerning the BTES is the different conditions in the simulation and in reality. In the simulation, the time period is three years, where every year has the same boundary conditions. Only the third year of the simulation is used for the evaluation. Consequently, the final and initial temperature profiles of the BTES and the buffer stores at the beginning and the end of the year are exactly the same which is not the case in reality. The deviations in the heat transferred to the district heating grid Hirtenwiesen I can be explained by the fact, that the heat transfer is often controlled manually in reality, for example if the weather forecast predicts a hot and sunny day and the stores are already full. This behavior cannot be reproduced in the simulation.

2.4 Concepts for system extensions and optimization

Several single measures as well as their combinations were considered and assessed in order to increase the solar fraction of the CSHPSS in Crailsheim to a value above 50 %. Tab. 2 shows an overview of the single measures presented in this publication.

Tab. 2: Overview and description of possible measures for the extension and optimization of the solar district heating system.

Measure	Description
HFC	Installation of high-efficiency flat-plate collectors (HFC)
BTES	Enlarging of the borehole thermal energy store (BTES) from 80 to 160 borehole heat exchangers
HWTES	Integration of a seasonal hot water thermal energy store (HWTES) with a volume of 8 000 m³
HP	Installation of a second heat pump with a rated electrical power of 80 kW
RFT45	Reduction of the mean return flow temperature of the district heating grid from 48.1 °C to 45 °C
RFT40	Reduction of the mean return flow temperature of the district heating grid from 48.1 °C to 40 °C

One measure is the extension of the collector field energy output by the installation high-efficiency flat-plate collectors (HFC). Different collectors and combinations of collectors were simulated. Tab. 3 shows the resulting collector field power output of the four collector configurations HFC1 to HFC4.

Tab. 3: Total collector field power output[1] of the CSHPSS for the four different HFC configurations.

Collector configuration	Power output [MW]
HFC1	7.24
HFC2	7.17
HFC3	7.38
HFC4	7.34

As the solar gain is increased, the capacity of the seasonal thermal energy store should be increased as well. For that purpose two different measures were investigated: The first measure (BTES) extends the BTES by doubling the current number of borehole heat exchangers, the second measure integrates an overground seasonal hot water thermal energy store (HWTES) with a volume of 8 000 m³ into the system. In order to increase the thermal energy extracted from the BTES and therefore its efficiency, the integration of a second heat pump (HP) with the same rated electrical power of 80 kW as the existing heat pump was investigated.

The volume weighted mean return flow temperature of the solar district heating grid was 48.1 °C in the year 2016, according to monitoring data. A reduction of the mean return flow temperature would increase the efficiency of the collectors as well as reduce the heat losses of the grid and the thermal energy stores and therefore increase the solar fraction of the system. Simulations with mean return flow temperatures of 45 °C (RFT45) and 40 °C (RFT40) were carried out.

3. Simulation results

The actual configuration of the CSHPSS with the measured weather data of the year 2016 serves as the reference system for all simulations. Due to the assumption that more buildings will be connected to the district heating grid in the following years, an annual heat consumption of the district heating grid Hirtenwiesen II of 7 000 MWh is assumed for the simulations. Due to the slightly higher heat consumption, the solar fraction of the reference system is reduced to 27 %.

Fig. 3 shows the solar fraction, the seasonal performance factor of the heat pump as well as the efficiency of the BTES for simulations with all four HFC configurations and all of their possible combination with one additional measure. Generally, the differences between the HFC configurations are relatively small at about 2-3 %-points

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[1] Basis: Solar Keymark certificates: Power output of the collector module at a temperature difference between collector and ambience of 50 K.

between the configurations HFC2, which shows the lowest solar fractions, and HFC3, which shows the highest solar fractions. Regarding the single measure HFC, the solar fraction can be increased by 11 %-points compared to the reference system to a total value of 38 %. The extension of the BTES has no positive influence on the solar fraction. The reason for this is that the energy output of the heat pump is not increased as well. Consequently, more heat is charged to the BTES, but the amount of heat that is discharged from the BTES does not increase in the same magnitude. This also leads to a decrease in the efficiency of the BTES but also to the best seasonal performance factor of the heat pump in both measures BTES and HWTES. The reason for the higher performance of the heat pump are the higher temperatures in the BTES and therefore a smaller temperature lift for the heat pump. The installation of a second heat pump has the opposite effect than the extension of the storage capacity. The seasonal performance factor decreases significantly due to lower BTES temperatures while the efficiency of the BTES increases significantly due to the higher heat pump power output.

The most promising measure in terms of increasing the solar fraction is the reduction of the mean return flow temperature of the district heating grid to a value of 40 °C. This leads to an increase of the solar fraction by at least 5 %-points compared to the measure HFC, depending on the collector configuration. However, none of the concepts shown in Fig. 3 turned out to be sufficient to obtain a solar fraction of 50 %. Accordingly, other concepts combining several measures have been investigated.

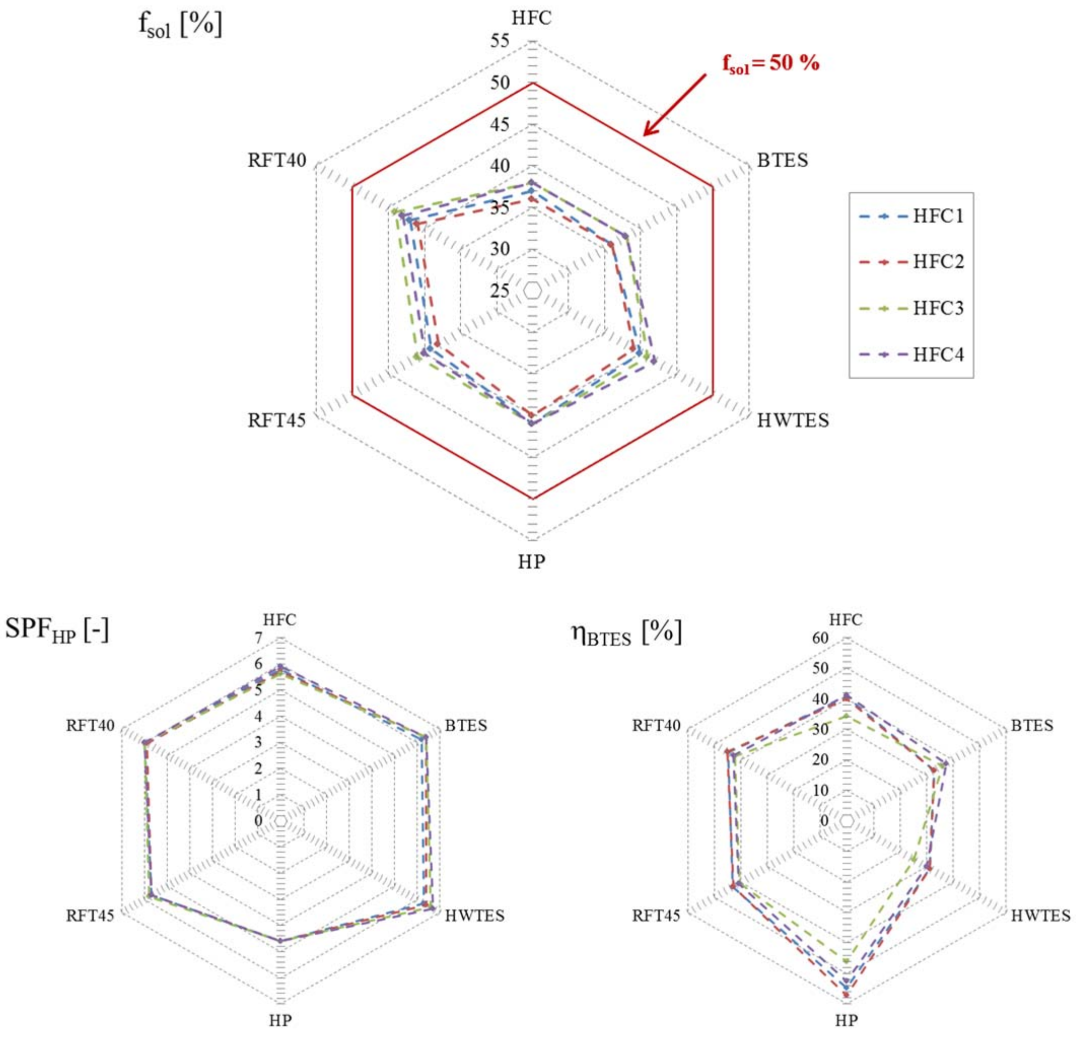

Fig. 3: Simulation results for selected investigated system concepts.

The installation of a HWTES was preferred compared to the extension of the BTES, consequently only concepts including a HWTES are shown in Fig. 4. Additional to the performance figures shown in the previous figure, the efficiency of the HWTES is presented in Fig. 4.

Like before, the concepts including a second heat pump have a positive effect on the efficiency of the BTES. Since the BTES and the HWTES are installed in parallel and the heat pump can discharge both, the efficiency of the HWTES is increased as well. The seasonal performance factor of the heat pump on the other hand is reduced due to lower temperatures in the stores.

With the concept using a HTES, a second heat pump as well as the reduction of the mean return flow temperature of the district heating grid to 45 °C a solar fraction of 50 % can only be reached using the collector configuration HFC3. A further reduction of the mean return flow temperature to 40 °C leads to a further increase of the solar fraction to or above 50 %, except for HFC2 with a solar fraction of 49 %. High solar fractions of almost 50 % can also be reached with the collector configurations HFC3 and HFC4 by a combination with the measure RFT40, without the installation of a second heat pump. However, the installation of a second heat pump is recommended because it leads to an extension of the effectively usable storage capacity of the CSHPSS.

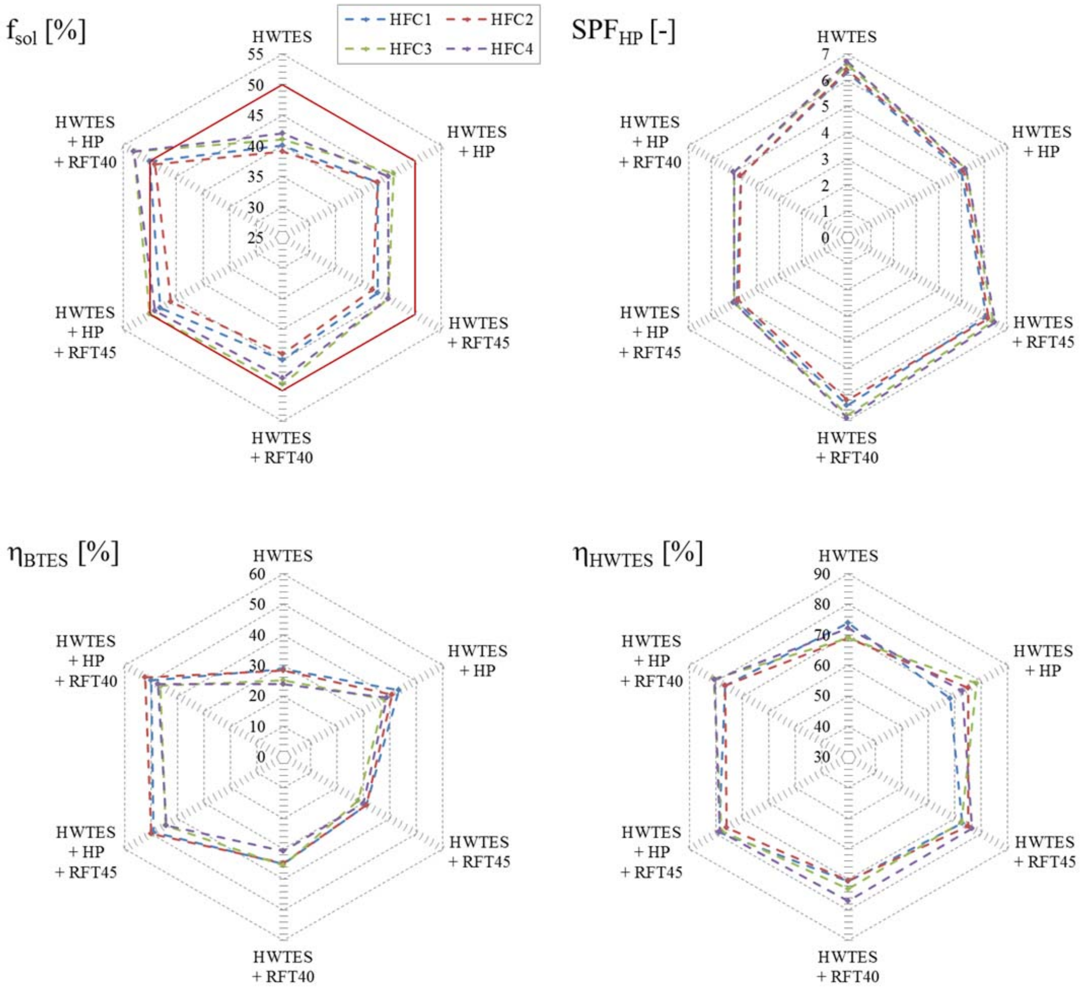

Fig. 4: Simulation results for selected investigated system concepts.

Conclusions

The concepts assessed regarding the extension and optimization of the solar district heating system in Crailsheim were presented and discussed in this publication. The concepts which lead to a solar fraction of around 50 % comprise the option of enlarging the solar thermal system with high efficient flat plate collectors (HFC) with a collector area of about 2 500 m² as well as the integration of a second heat pump (HP) with an electrical power of 80 kW and a hot water thermal energy store (HWTES) with a volume of 8 000 m³. A further increase of the solar fraction above 50 % can be achieved by the additional reduction of the return flow temperature of the district heating grid to 40 °C.

Considering the simulation results, the owner of the CSHPSS intends to extend the system with an enlargement of the collector area, a HWTES and a second heat pump. Additionally it is planned to introduce measures which offer the consumers incentives to reduce the return flow temperature of their heat transfer stations. The detailed planning of the enlargement of the CSHPSS is currently in progress, considering amongst other issues different locations and hydraulic integrations of the HWTES, as well as an adaption and optimization of the control strategy.

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Appendix: Units, Symbols and Abbreviations

Tab. 4: Symbols

Quantity	Symbol	Unit
Collector area	A	m^2
Solar fraction	f_{sol}	%
Heat charged to BTES	$Q_{BTES,char}$	MWh
Heat discharged from BTES	$Q_{BTES,dischar}$	MWh
Heat provided by the heat pump	$Q_{HP,cond}$	MWh
Heat to the district heating grid Hirtenwiesen I	Q_{HWI}	MWh
Heat consumption district heating grid Hirtenwiesen II	Q_{HWII}	MWh
Heat charged to HWTES	$Q_{HWTES,char}$	MWh
Heat discharged from HWTES	$Q_{HWTES,dischar}$	MWh
Heat transferred through solar heat exchanger	Q_{SHE}	MWh
Seasonal performance factor of the heat pump	SPF_{HP}	-
Electric energy consumption of the heat pump	$W_{HP,el}$	MWh
Absolute deviation	Δx_{abs}	MWh, %, -
Relative deviation	Δx_{rel}	%
Efficiency of the BTES	η_{BTES}	%
Efficiency of the HWTES	η_{HWTES}	%

Tab. 2: Abbreviations

Abbreviation	
BTES	Borehole thermal energy store
CSHPSS	Central solar heating plants with seasonal thermal energy storage
HFC	High-efficiency flat-plate collector
HP	Heat pump
HWTES	Hot water thermal energy store
RFT40	Mean return flow temperature 40 °C
RFT45	Mean return flow temperature 45 °C
TRNSYS	Transient systems simulation software