Germany's largest Solar District Heating System with Seasonal Thermal Energy Storage in Crailsheim
- Monitoring Results and Future Potentials -

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Abstract – Germany's largest solar district heating system (SDH system) with seasonal thermal energy storage is located in Crailsheim, a city with approximately 34 000 inhabitants, around 80 km northeast from Stuttgart. The solar yield of the system achieves the planned values but due to an extension of the district heating network the heat demand is meanwhile much higher than originally planned. Consequently, the solar fraction of the system is lower than expected for the current operating conditions. In this paper the latest monitoring results and potentials of optimizing the system will be presented. The optimization must be carried out under energetic and economic considerations so that in best case the solar heat costs can be further decreased due to the optimization measures.

1. Introduction

Germany's largest solar district heating system (SDH system) with seasonal thermal energy storage was built in Crailsheim on a former military compound. More than 300 dwellings, mostly consisting of single family houses, a school and a gymnasium are supplied with thermal energy for space heating and hot water preparation throughout the district heating network "Hirtenwiesen II" (HW II). The solar heating plant, as shown in Figure 1, consists of two parts, of which the first one was taken into operation in 2004. The first part consists of collector fields with a total size of 2 492 m² installed on apartment buildings, on the school and on the gymnasium, a hot-water buffer store with a volume of 100 m³ and a heat transfer station that supplies the missing heat produced by a cogeneration plant from a neighbouring district heating network into the district heating network HW II. The second, mainly seasonal operating part consists of a 4 918 m² large collector area mounted on a noise barrier, a second buffer store with a volume of 480 m³ and a borehole thermal energy store with a volume of about 39 000 m³. Additionally, an electric driven compression heat pump with an electric capacity of 80 kW_{el} is integrated to facilitate the solar thermal energy of the seasonal part of the district heating system more efficient.

The planned heat demand of the district and for the current solar district heating system size was 4 100 MWh/a, out of which 50 % could be covered by solar thermal energy. Due to the connection of more buildings and thus more heat consumers to the district heating network, the heat demand has exceeded the planned value by 38 % in 2015 resulting in a total heat demand of 5 671 MWh/a. Consequently, the solar fraction of 50 % could not be reached so far, although the solar collector yield with a value of 2 809 MWh/a has exceeded the planned value. In 2014 the highest value for the solar fraction of 42 % was achieved for the system due to a relatively warm winter and a year with above average solar irradiation.

In this paper the latest monitoring results of the SDH system in Crailsheim are presented. In detail it will be explained what are the deviations of the system compared to planned values and how this affects the system operation and performance. Moreover, potentials of optimizing the system will be pointed out taking the reduction of solar heat costs in consideration. Thus, a good balance between the improvement of the energetic behaviour of the system and minimal investment costs will be elaborated.

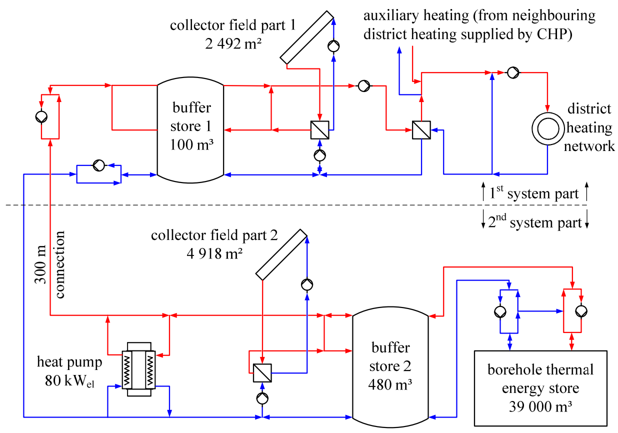

Figure 1: Simplified schematic of the SDH system in Crailsheim

2. Monitoring Results

The development of the SDH system is a good example of how difficult it is to plan and operate a system that is effected by many boundary conditions like weather, heat consumers and changing size of district heating network. The annual heat demand is shown in Figure 2, which is calculated for the past 12 months at each time step, and the corresponding solar fraction[1] from beginning of 2009 until May of 2015. Additionally, the target values for the planned heat demand and the planned solar fraction are indicated. It can be seen that the heat demand has exceeded the planned value of 4 100 MWh/a already in spring 2012. The planned solar fraction of 50 % has not been reached yet. Failing the target is not caused by an inefficient system, although there is space for optimization, but moreover due to a faster enlargement of the solar district heating network by connecting more consumers and thus increasing the total heat demand of the district.

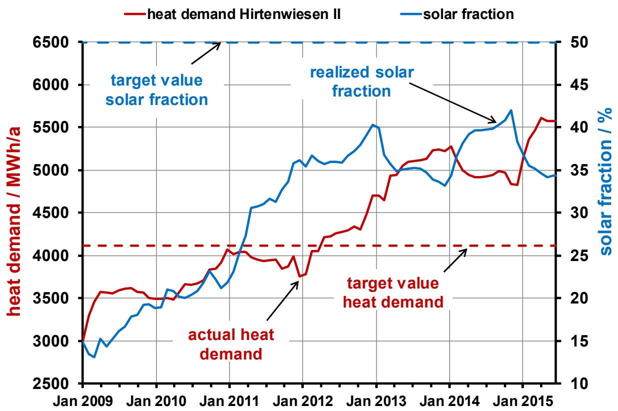

Figure 2: Development of the heat demand and solar fraction of the district heating network Hirtenwiesen II compared to planned values

In Table 1 the planned values and some characteristic figures for the years 2011 to 2014 are listed . It can be seen that in 2012 and 2014 the solar yield of the solar collectors has exceeded the planned value of 2 575 MWh/a. In 2014 the solar heat delivered to the district heating network HW II has nearly reached the planned value of 2 097 MWh/a.

The reason why the solar heat delivered to the district heating network does not reach the planned values, although the solar yield of the collectors does or even exceeds it, has a cascade of reasons. In summer time some solar heat is delivered into a neighboring district heating network, which is not included in the energy balance. Consequently, the solar heat cannot be used in the district heating network HW II. The reason therefore is that stagnation of the solar thermal collectors can be avoided by this measure. As shown in Figure 1 there is a 480 m³ large buffer store (buffer store 2) in the 2nd system part. Its task is to buffer the peaks of solar heat delivered by the solar thermal collectors and charge this thermal energy steadily into the borehole thermal energy store (BTES). During operation of the system it was decided to reduce the maximum charging temperature of the BTES from originally planned 80 °C to 70 °C in order to secure a long-term and stable operation of the borehole heat exchangers (BHE) which are made of cross-linked polyethylene (PE-Xa). Subsequently, less heat than planned can be charged into the BTES (see Table 1) and overheating of the 2nd system part can occur, which causes stagnation of the solar thermal collector fields of this system part. Additionally, the heat pump, installed to utilize the solar thermal energy of the 2nd system part more efficiently, has been realized with a lower capacity than planned. This electric driven compression heat pump using the high temperature refrigerant R227ea has an electric capacity of 80 kW_{el}. Planned were two heat pumps with together a capacity of 258 kW_{el}. Thus, less solar heat can be discharged from the BTES. Besides the above explained reasons defect solar thermal collectors with an area of 246 m² have been taking out of operation in 2012. They represent one field on the noise barrier wall, on which the solar thermal collectors of the 2nd system part are installed. The missing solar yield of this field affects slightly the solar yield of the entire system.

Table 1: Characteristic figures of SDH system in Crailsheim on an annual basis [1]

		value planned [2]	2011	2012	2013	2014
collector area at the end of the year	m²	7 325	7 410	7 410*	7 410*	7 410*
solar yield of collectors	MWh	2 575	2 337	2 740	2 319	2 631
solar heat delivered to heating net HW II	MWh	2 097	1 342	1 841	1 754	2 025
total heat demand of heating net HW II	MWh	4 116	3 750	4 700	5 223	4 822
auxiliary heating (from CHP)	MWh	1 715	2 407	2 580	3 078	2 525
heat charged to BTES	MWh	1 135	781	707	659	747
heat discharged from BTES	MWh	830	-	382	386	312
solar fractions	**%**	**51,0**	**35.8**	**39.2**	**33.6**	**42.0**

* since May 2012 are 7 164 m² in operation (corresponding to 246 m² out of operation)

[1] $solar\ fraction = \frac{solar\ heat\ delivered\ to\ the\ district\ heating\ network\ (HW\ II)}{total\ heat\ demand\ of\ district\ heating\ network\ (HW\ II)}$

3. System Optimization and Extension

Originally, the heat generation and storage part of the SDH system were planned to be extended once the heat demand of the district heating network increases in later development steps due to an extension of the grid and/or the connection of more heat consumers. As previously explained this has happened earlier than expected.

Originally, two enlargements of system components have been regarded for this case. First one is the extension of the solar thermal collector field to a total area of about 10 000 m². The second measure is the enlargement of the BTES. The BTES is designed in such a way, that additionally to the existing 80 BHE, 80 new BHE can be installed in a ring shape around the existing BTES and thus nearly double its volume to about 76 000 m³. Beside structural optimization, improvements in the operation can be achieved by adjusting the control strategy.

Within the project "WinterSuN" [1], that has ended in September 2015, first transient system simulations have been carried out to predict the future system performance and to determine first optimization measures. After having consulted the system operator (Stadtwerke Crailsheim) the heat demand of the district heating network HW II is estimated to be about 6 000 MWh/a within the next years for the final stage of the extension. Some results of the performed simulation study are shown in Figure 3 taking the increased heat demand into account. As reference and to validate the system simulation the data of the year 2012 were used. The simulation results match well to the monitoring results presented in Table 1. In a first step the increased heat demand at final stage of the extension of the district heating network ("increased heat demand") has been regarded without changing anything in the heat generation and storage part of the system. The minor deviation from 1 MWh/a in the heat demand compared to the planned value is caused by simplifications in the simulation and its imperfect accuracy.

The higher final heat demand causes a decrease of solar fraction from 40 to 35 %. The solar heat can be used more directly in summer and intermediate times and thus the yield of the solar thermal collectors increases by about 200 MWh/a corresponding to 7 %. As a consequence of the higher direct use of the solar heat, less heat will be charged into the BTES and also less heat can be regained in winter time as can be seen by the decreased value for the heat discharged from the BTES in Figure 3. The increased heat demand and the corresponding higher amount of solar heat directly used changes the operational behaviour of the BTES. To increase its useable storage capacity, the control strategy of discharging the BTES has been changed in a next step. The aim is to discharge the BTES to lower temperatures as also the maximum temperature has been decreased due to less heat charged into the BTES. By modifying the control strategy, the BTES can be discharged to about 4 K lower minimum temperatures at the centre of the store compared to before. Thus, the storage efficiency can be increased and about 78 MWh/a corresponding to 27 % more heat discharged from the BTES. This does not affect the solar yield significantly but more solar heat charged into the BTES can be regained and used. The solar fraction can be increased by 1 percentage point.

In a last step the effect of 5 K lower network return flow temperatures (mean volumetric temperature) has been investigated. Due to the constant connection of new buildings to the grid currently and in the past years the network return flow temperature was temporarily more than 10 K higher than the planned value of 35 °C. This has been caused by inefficient operating strategies of the heating systems within the buildings during and after construction in order to dehumidify the new buildings. Compared to the values of 2012 the network return flow temperature was simulated 5 K lower having a mean volumetric temperature of 40,3 °C. This change increases the solar yield of the collectors and about 100 MWh/a more solar heat can be delivered to the district heating network HW II. So, the solar fraction can be increased by 2 percentage points compared to the system modifications performed before.

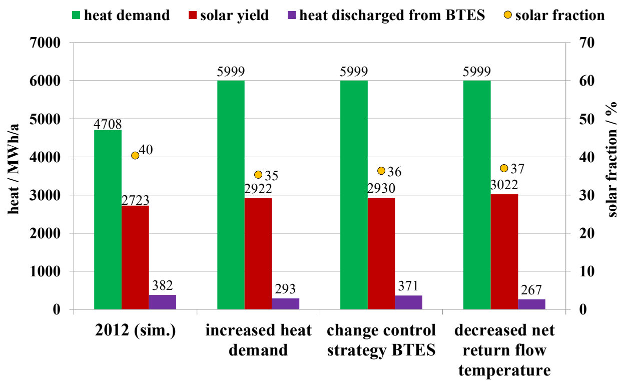

Figure 3: Simulation results for the SDH in Crailsheim implementing different modifications

As the simulation results reveal, changes in the system operation without structural interventions have only small impact. Hence, enlargement of the system is discussed and its impact is estimated. A detailed study of the optimization of the system and its realization will be part of the research project "CROW - Extension and Optimization of the Solar District Heating System Hirtenwiesen II in Crailsheim as well as Research on Solar District Heating and Seasonal Thermal Energy Storage" founded by the German Ministry for Economic Affairs and Energy (BMWi) and expected to start in October 2016. Beyond others, mainly the flowing measures will be investigated in detail:

- Increasing the solar collector area or the solar collector capacity respectively
- Integrating an additional heat pump
- Enlarging the BTES

Currently, 7 410 m² of standard flat plate collectors are installed in the system. This corresponds to a solar collector capacity of about 5.2 MW_{th}. For the final extension status of the system 10 000 m² corresponding to about 7 MW_{th} were planned. Initially, it was planned to extend the solar thermal collector area with standard flat plate collectors. Mainly two reasons lead nowadays to a new option compared to the original planning performed about 15 years ago. Presently, an area of 4 910 m² of flat plate collectors are installed on a noise barrier wall between the living area and an industrial park. In total solar thermal collectors with an area of 2 200 m², from which 246 m² are already out of operation, are suffering of technical failures and need to be replaced in near future. Furthermore, highly efficient flat plate collectors like "MT-Power" of the manufacturer TVP-solar [3] have been developed in recent years. Those collectors have up to the double thermal performance as standard flat plate collectors. Even though the specific prices of those high efficient collectors are higher than the price of standard flat plate collectors it could be a cost effective measure to replace the failing 2 200 m² by such high efficient flat plate collectors. The reason for this is that the entire periphery including the substructure can be reused with minimal adjustments. Thus the required solar collector capacity of about 7 MW_{th} can be achieved by this approach. Furthermore, an innovative way of maintaining SDH and even improving the solar thermal system can be investigated in reality. Within the project CROW in a first step arrays of about 14 m² collector area will be replaced by different high efficient flat plate collectors and tested in-situ in order to identify the most suitable collectors for the local boundary conditions in specific and for SDH applications in general under real operation conditions.

The monitoring results of the operation of the existing system have also shown that the BTES is used differently than planned. Neither the maximum charging temperature nor the minimum discharging temperature have reached the planned values. Thus, the effective usable storage capacity has not yet been reached. This is mainly due to the limited charging temperature and the too low capacity of the heat pump. Changing the charging temperature will most likely not be realized due to durability reasons concerning the material of the BHE. The integration of an additional heat pump could improve the performance of the BTES. Thus, the BTES can be discharged to lower minimal temperatures and hence its usable storage capacity can be increased by decreasing heat losses to the surrounding ground due to lower temperature differences between BTES and underground [4]. Additionally, "power-to-heat" concepts using the heat pumps to charge the BTES or the buffer stores by using excess renewable electricity could be a promising add-on option feature that needs to be assessed in detail.

Enlarging the BTES from 80 to 160 BHE might be unnecessary combining the first two measures. However, if further storage capacity is required, this option needs to be considered especially taking "power-to-heat" concepts into account. Nevertheless, it can be estimated that enlarging the BTES is the most cost intensive measure of the three ones discussed above. Especially, if an additional heat pump is required for this option in order to enable an efficient operation of the extended BTES.

4. Conclusions and Outlook

The SDH system in Crailsheim is a good example of how difficult it is to plan and operate such a system which is affected by multiple influencing and hardly to predict developments and changes in system components and their operation. In the scientific accompaniment of past research projects, the system performance could be monitored in detail and possibilities for optimization could be identified. Within the given boundary conditions, the system is operating well as it can be seen e.g. for the solar yield of the solar thermal collectors, which exceeds the planned values. A solar fraction of 50 % for the system that was defined as one of the key characteristic value could not be reached yet. Mainly, the higher heat demand of the district heating net HW II but also changes in the size of system components and different operating conditions cause the failing of this benchmark.

First simulations taking the predicted final value for the heat demand of the district heating network HW II into account show, that with the current system equipment for heat generation and storage a solar fraction of 35 % will be achieved. Small changes in operation by adjusting the control strategy can improve the system performance towards higher solar fractions. The increase is within a few percentage points and consequently not very significant.

Structural changes are expected to have a higher impact. To investigate these potentials, the upcoming research project "CROW" will explicitly approach this task. It is the aim of the involved stakeholders to upgrade the SDH system in Crailsheim to achieve the originally planned solar fraction of 50 % for the final extension state of the system. Therefore, new technological developments on component level e.g. highly efficient solar thermal flat plate collectors as well as future interaction with other energy supply system e.g. interaction with the electric grid will be taken into account. Hereby, an economic solution is pursued decreasing the solar heat costs. The maintenance, refurbishment and repowering of SDH system in Crailsheim is a not negligible side result of the future project CROW by e.g. replacing existing and partly defect solar thermal standard collectors by new and highly efficient flat plate collectors by reusing existing infrastructure.

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