Experimental plant for analyzing the technical feasibility of decentralized solar heat feed-in

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Abstract

To investigate the decentralized feed-in of solar heat into district heating networks, an experimental plant was built in Düsseldorf. This plant is composed of a collector field with 218 $m^2_{Aperture}$ and a prototype feed-in substation. The setup is installed in a multi-family building, which is supplied by district heat from Stadtwerke Düsseldorf AG. The following publication focuses on three main parts:

1. Technical challenges for solar thermal plants with decentralized feed-in into district heating networks.
2. The hydraulic design of the experimental plant.
3. First monitoring results of the solar heat feed-in.

Keywords: decentralized feed-in, solar heat, district heat, experimental plant

1. Introduction

The research project “Decentralized integration of heat from renewable energies into the CHP district heating system of Stadtwerke Düsseldorf AG” (short title SWD.SOL) started in May 2015. Five project partners are involved: the utility Stadtwerke Düsseldorf AG, the German district heating association AGFW, the housing company Rheinwohnungsbau GmbH Düsseldorf, the environmental agency of the state capital (Umweltamt Landeshauptstadt Düsseldorf) and the Steinbeis Research Institute Solites.

The objective of the project is to analyze the technical feasibility of decentral heat feed-in based on the example of a mid-large solar thermal plant. For this purpose, an experimental plant composed of a prototype feed-in substation and a collector field with 218 $m^2_{Aperture}$ (232 m^2_{Gross}) was installed in a multi-family building supplied by district heat. The experimental plant is located in Düsseldorf.

The operational behavior of the plant is monitored and evaluated. These measurement data deliver the base for a simulation study, whose aim is to optimise the controlling and operational management concept of the feed-in station. The following publication focuses on three main aspects. At first, the technical challenges for solar thermal plants with decentralized feed-in into district heating networks are discussed. At second, the hydraulic design of the experimental feed-in station is presented. As third aspect, first monitoring results of the solar heat feed-in are shown.

2. Bases

The section addresses the technical boundary conditions at the feed-in and extraction location of solar thermal plants with decentralized heat feed-in into a district heating network. See Fig. 2 for an illustration of the terms.

All in all, the technical boundary conditions at the feed-in and extraction location are determined by the hydraulic pressure and the temperature of the fluid inside the DH network. The following part contains a description of the boundary conditions, which are relevant within the context of decentralized heat feed-in. This part is considering the return to supply feed-in variant only (RF/SF feed-in).

- Temperature level
  The temperature level at the feed-in location is determined by the supply temperature of the central heat feed-

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in unit. For that, an adjustment depending on the ambient temperature is very common. This leads to variations in the temperature level at the feed-in location, which can be classified as slow according to time. Based on the DH network and the position in this network, supply flow temperatures between 70 °C to 100 °C are common during summer.

- Temperature difference

Like the temperature level, the temperature difference between the feed-in and extraction location is also subject to changes during the year. Usual values for the summer period vary between 20 K and 30 K. During the transitional periods (spring and autumn), the temperature difference continues to rise. With respect to a variety of DH systems, values of over 40 K are fairly common in the winter period.

- Differential pressure

The differential pressure between the feed-in and the extraction location is substantially determined by the position in the DH network. Values vary between the amount at the hydraulic critical net-point of the DH network (often approx. 1 bar) and the one at the central pump for increasing the network pressure (sometimes larger than 10 bar). Furthermore, the temporal profile of the differential pressure can be subject to very dynamic changes. As the analyses form Lennermo [Lennermo 2015 a] show, network operators are quite often not correctly informed about the real fluctuations of the differential pressure at potential feed-in locations. For example, Fig. 1 shows a section of a measurement series. The specified results relate to the differential pressure between the supply and return pipe at a certain position within the DH system of Malmö at which the heating network operator assumed mostly constant differential pressures.

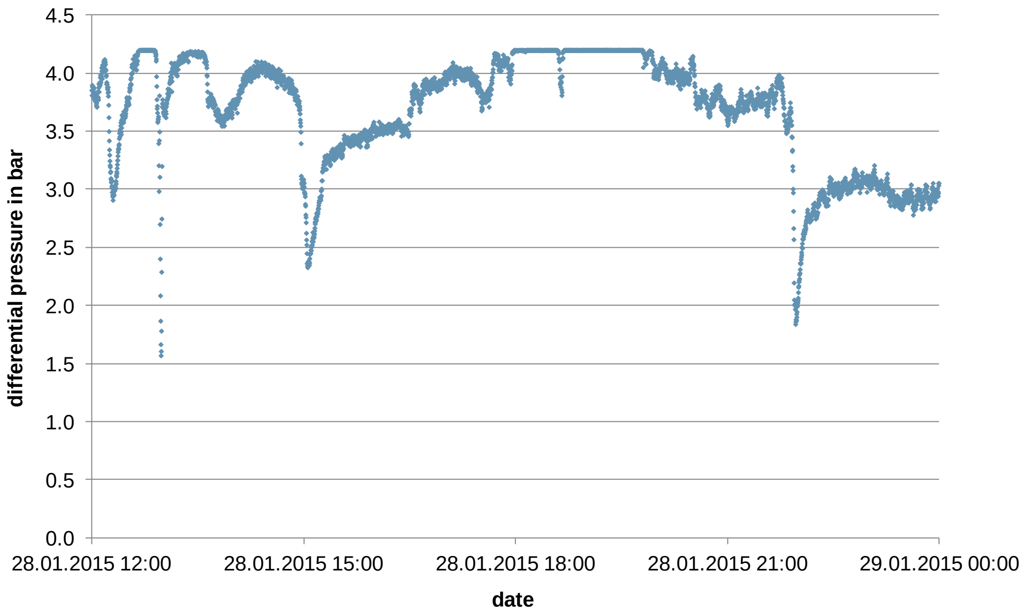

Fig. 1: Instantaneous values of the differential pressure between supply and return pipe; measurement has been done at a potential feed-in location in the DH network system of Malmö, Sweden; time step of measurement 10 s; source [Lennermo 2015 b]

3. Technical challenges

Fig. 2 shows a schematic illustration of a solar thermal plant connected decentrally to the district heating network. The setup can be divided in (i) a collector loop and (ii) a feed-in loop. In the following, the technical challenges for solar thermal plants with decentralized feed-in are summarized. A separation according to the hydraulic loops of the example in Fig. 2 is done.

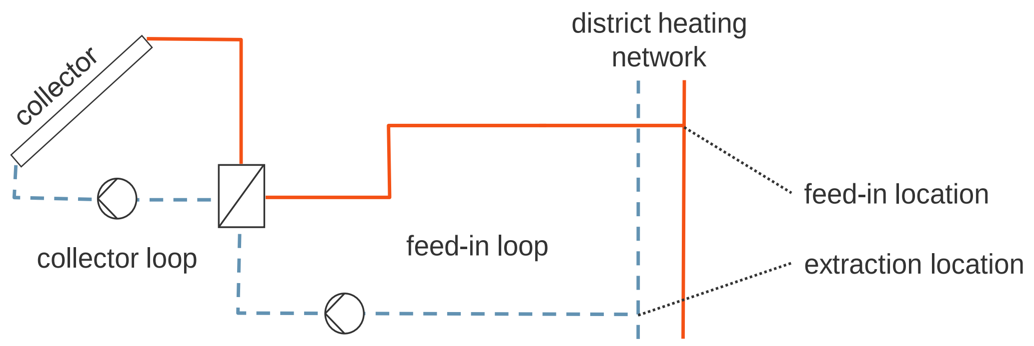

Fig. 2: Schematic representation of a solar thermal plant variant for decentralized feed-in; for way of example the RF/SF feed-in is shown

3.1. Feed-in loop

The plant engineering in the feed-in loop basically has to solve two different tasks. On the one hand, the variable differential pressure between the feed-in and the extraction location must be exceeded to generate a flow rate in the feed-in loop. On the other hand, the flow rate must be adjusted to observe the required target temperature in accordance with the variable solar heat output available at the heat exchanger.

If both influencing parameters (differential pressure and solar heat output to be fed-in) present quick changes over time (which is often the case), it represents a very demanding control task.

However, if just one of the two specified influencing parameters present changes, the required target temperature control can be classified as unproblematic. For example this situation can be compared with solar thermal plants in which the collector loop is connected to a heat storage. In such a plant configuration the differential pressure in the corresponding hydraulic loop (storage charging loop) is almost constant. The almost constant pressure is only influenced by control demands for the pump, due to varying solar irradiation to keep the targeted DH network supply temperature.

Besides, every period without solar heat feed-in leads to a decrease of temperature within the connection pipes between the net heat exchanger and the feed-in location. Consequently, each start-up procedure of decentralized feed-in involves the risk of generating a cold node in the supply pipe of the DH network. To avoid this, technical measures are available (comparable to the solutions existing for conventional substations).

3.2. Collector loop

Compared with the conventional application range of solar thermal plants the temperature conditions in large DH networks are fairly uncommon. Both the temperature level and the temperature difference must be classified as high. In addition the requirement for a low number of start-up procedures of decentralized feed-in (expressed by AGFW) complicates the operation situation. According to this requirement, the temperature differences in the collector loop (classified as high) are to be maintained even during times with medium to low solar irradiation and relatively high temperature levels.

There are limitations for the variation of the flow speed inside the collector loop. The upper limit is defined by the tolerable maximum pressure drop in the hydraulic loop, the lower limit by the behavior of the fluid inside the collectors. According to physics, the degree of flow turbulence decreases in case of reduced flow speed and constant fluid temperature. For thermal and hydraulic reasons, a change of the flow state inside the collectors into the laminar flow range must be avoided during plant operation. Otherwise considerable reduction of the collector efficiency and the hydraulic friction pressure would occur. The latter may result in an unequal flow distribution through the single collector rows within the field since their hydraulic balancing is commonly carried out for turbulent flow conditions.

4. Experimental plant

This chapter gives some general information about the experimental plant and presents the hydraulic design.

4.1. General information about the experimental plant

In May 2017 the experimental plant was taken into operation. Different companies were involved in the implementation of the plant. The collector field was planned and mounted form the company Wagner Solar GmbH, which used a double-glazed flat plate collector for the project. The detailed hydraulic planning as well as the construction of the feed-in substation was done by Kring TWT GmbH. The plant control and the monitoring system were setup by Samson AG as a subcontractor of Kring TWT GmbH. Fig. 3 and Fig. 4 show the collector field and the feed-in substation.

Fig. 3: Solar collector field of the experimental plant

Fig. 4: Feed-in substation of the experimental plant (deformed panoramic view) [AGFW 2018]

4.2. Hydraulic design of the experimental feed-in substation

One objective of the project SWD.SOL is to analyze different hydraulic solution approaches for feeding-in solar heat under comparable boundary conditions. In this regard, four hydraulic solution approaches were realized in the setup of the experimental plant. These approaches are presented below. The hydraulic design of the experimental plant is shown in Fig. 6.

Hydraulic solution approaches for decentralized feed-in of solar heat

To solve the presented technical challenges (see chapter 3) different concepts exist. A review of 33 decentral solar thermal feed-in plants (realized in different European countries) shows four basic solution approaches [Schäfer 2014]. These four approaches are implemented in the feed-in loop of the experimental plant. Fig. 5 illustrate the four solution approaches in a schematically way. An individually description of the approaches is given below.

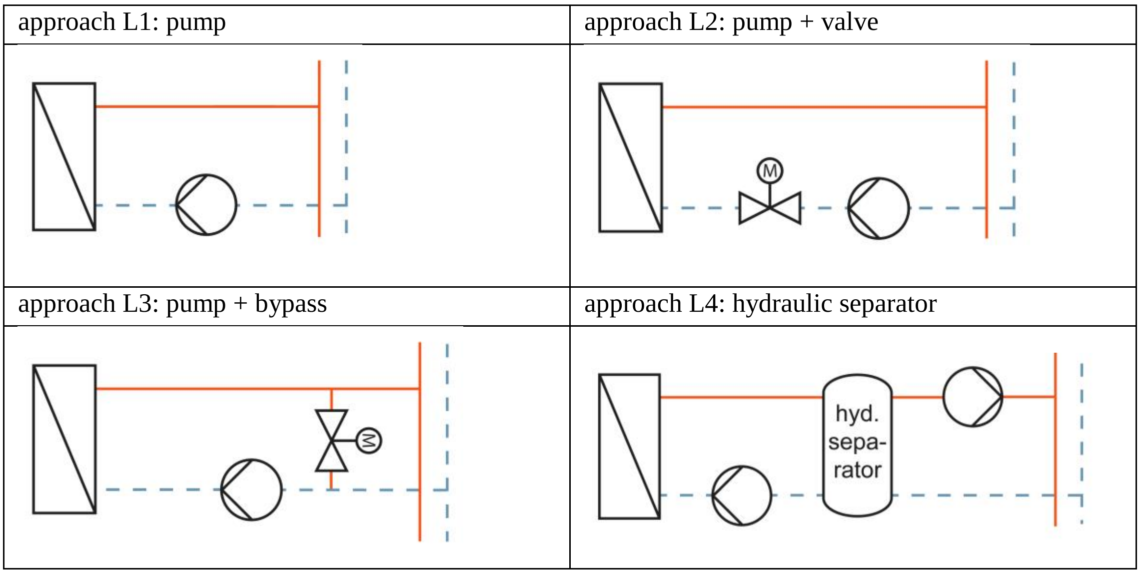

Fig. 5: Schematic representation of the technical solution approaches within the feed-in loop of realized plants (M: motor control)

- Solution approach L1: pump

  Function: Only the pump in the feed-in loop is used as control device. Depending on the operation conditions, the pump must be able to respond to very quick variations of the following parameters:
  a) solar heat to be fed-in
  b) differential pressures to be exceeded between the feed-in and extraction location

  Characteristic: On one hand, the control of the approach requires small effort. On the other hand, the solution approach is only productive in case of connection points without strong gradients of the differential pressures between the feed-in and extraction location. Otherwise, a large number of start-up and shut-down procedures of the pump is necessary to maintain the required target temperature range within the feed-in loop.

- Solution approach L2: pump + valve

  Function: In this context, the control function of the pump is supported by a fast-acting control valve. The pump is primarily used for exceeding the differential pressure. In order to observe the required target temperature during times with fast variations of heat flows inside the collector loop, the fine control of the volume flow is carried out using the control valve.

  Characteristic: Even if the differential pressure between the feed-in and extraction location changes quickly, a very good observance of the required target temperature within the feed-in loop combined with a low number of start-up procedures of the pump can be achieved. On the other hand, the resulting increase in flow resistance caused by the control valve leads to higher demand in electrical energy for the pump.

- Solution approach L3: pump + bypass

  Function: The use of a bypass in the feed-in loop enables the proportionate circulation of the pump's flow rate. The division between the flow rates (fed-in flow rate and circulated flow rate) is carried out in a continuous way. Accordingly, the limitation of the pump's minimum volume flow (reason: self-cooling) does not lead to any restriction with respect to the fed-in flow rates.

  Characteristic: The resulting extension of the variation range of fed-in flow rates can reduce the number of start-up and shut-down procedures of the pump especially during conditions with medium and low irradiation. However, if the differential pressure between the feed-in and extraction location changes quickly the same problems as in solution approach L1 occurs.

- Solution approach L4: hydraulic separator

  Function: The feed-in loop is divided into two hydraulic loops by means of a hydraulic separator. This measure clearly simplifies the control task of solar heat feed-in. The pump in the hydraulic loop located between collector loop and hydraulic separator can be regulated just focusing on the required target temperature. To exceed the varying differential pressure between the feed-in and extraction location, the additional pump is used (hydraulic loop between hydraulic separator and connection point in the DH network).
  Characteristic: The solution approach obtains very good results in observing the target temperature. This also applies to the case of strongly varying differential pressure between the feed-in and extraction location. However, the total costs of the system increase because of the additional components and the number of starts and stops of the feed-in pump can be high. Furthermore, there is a risk of mixing supply and return temperature levels in the hydraulic separator.

Hydraulic design of the experimental plant

A section of the hydraulic structure from the experimental plant is shown in Fig. 6. For reasons of clarity, the diagram does not contain the full collector circuit and the measurement sensors. To indicate the optional combination of single hydraulic elements in the test setup, they are identified using L1), L2), L3) and L4). The alphabetical designation is in line with the solution approaches presented in the section above. Apart from testing the individual solution approaches, the test setup enables to analyze different combinations of them.

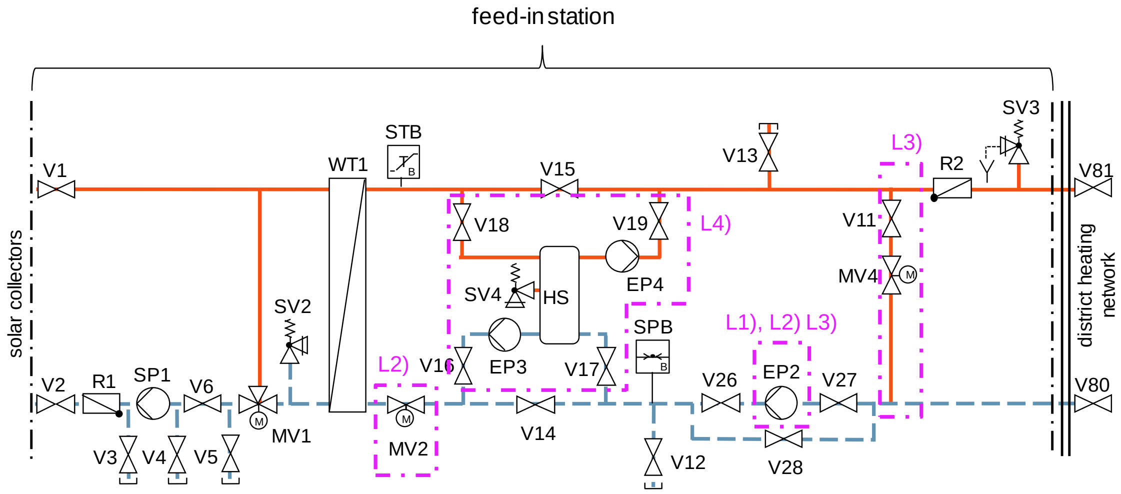

Fig. 6: Schematic representation of the hydraulic structure of the experimental plant (HS: hydraulic separator)

5. First monitoring results

This chapter contains first measurement results, which will be followed by an elaboration of possible improvements. The discussed results are based on the hydraulic operation mode L3 (see Fig. 5).

5.1 Presentation of measurement results

The following Figure 7 shows measurement results of the solar heating plant for an example day in August 2018. During this day the sky was clear, which results in a smooth curve of increasing and decreasing solar radiation throughout the day. Therefore, no dynamics in the system caused by clouds can be seen. For the following discussion, Figure 7 is separated by vertical dash-dotted lines in five sections (corresponding numbers are located above the figure).

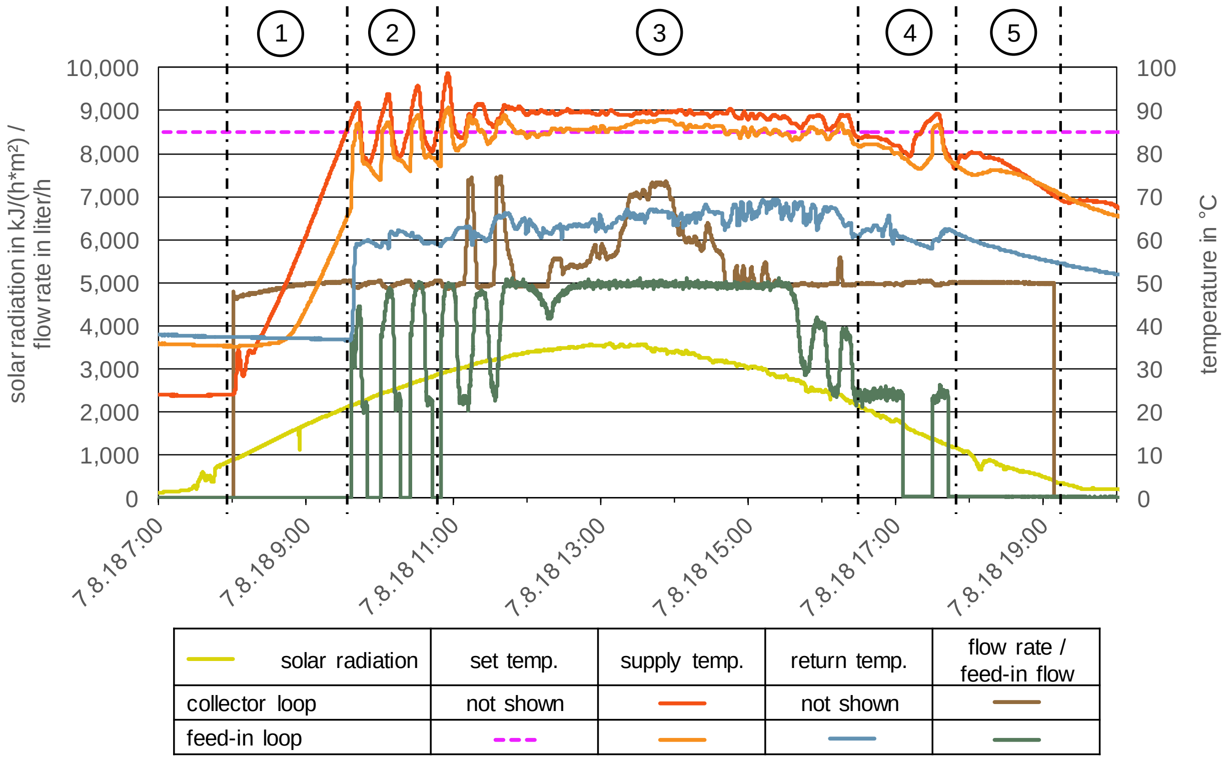

Fig. 7: Measurement results for one selected summer day; plant configuration: solution approach L3 (pump + bypass)

Discussion of the operating results

<u>Phase 1: First heating phase of the collector loop</u>

Generally, the pump in the collector loop starts operation depending on a characteristic curve that uses the irradiation as an input. On the specific example day, the start of the pump is triggered about 8:00 am. In this first phase, the volume flow created by the pump is constant in the collector loop. The feed-in pump is not yet in operation. As the volume flow in the collector loop is constant and heat is not yet transferred to the feed-in loop, the fluid temperature in the collector loop rises continuously.

<u>Phase 2: Operation start of the feed-in loop pump</u>

Once the fluid temperature in the collector loop exceeds the pre-defined threshold of 88 °C, the start of the pump in the feed-in loop is triggered. The speed of the pump within the feed-in loop is in case of the operation mode L3 solely based on the pressure difference between the feed-in and extraction location of the DH network. Accordingly, the volume flow generated by the pump is just based on the conditions in the DH network. In order to achieve the required feed-in temperature, liquid in the feed-in loop is recirculated through the bypass. The volume flow in the bypass is regulated by a motor-driven valve, which uses the temperature difference between the feed-in target temperature and the current feed-in temperature as an input. This mode of control allows varying the feed-in flow between 2,200 and 5,000 liters/h. If the feed-in target temperature is not reached, even though the feed-in flow is on its minimum (maximal flow through the bypass), the pump in the feed-in loop stops operation. An interruption of the pump operation was provoked at 9:50 am, 10:15 am and 10:40 am. These interruptions result in an intermitted feed-in to the DH network and indicate potential for improvement of the control.

Phase 3: Continuous supply to the DH network

The solar radiation during phase 3 is sufficiently high to allow a continuous supply to the DH network with the given possible variation of the feed-in flow. Between 10:50 am and 11:50 am high variations in the feed-in temperature cause an adaptation of the volume flow in the collector loop and feed-in loop. This adaptation in volume flow allows keeping the supply temperature in a range of ±5 K from the set point temperature of 88 °C. From 12:00 am onwards, the mismatch between required and currently supplied feed-in temperature is, to the largest extend, insignificant. The only exception is an increase of the feed-in temperature at about 1:50 pm. At this time, the feed-in loop would need a higher volume flow, which was not intended and is therefore not permitted for the given example day.

Phase 4: Falling stage of the pump operation in the feed-in loop

After 4:30 pm, the solar radiation is too low to allow for a supply of the required feed-in temperature, even though the collector and feed-in loop operates with the lowest possible flow. At about 5 pm, the temperature in the feed-in loop is below the threshold of 80 °C. Therefore, the pump in the feed-in loop stops operation. Because of this stop, the fluid temperature in the collector loop increases again, which triggers another short operation of the feed-in loop pump in the end of phase 4.

Phase 5: Falling stage of the pump operation in the collector loop

With the continuous decrease of solar irradiation on the collector field, the thermal losses of the collector field exceed the energy gains at 6:15 pm, which in turn results in a decrease of the fluid temperature in the collector loop. At 7:10 pm, the pump in the collector loop finally stops operation due to the irradiation, which is below the control characteristic curve for the pump operation.

5.2 Potential for improvement and outlook

Especially phase 2 as well as the beginning and the end of phase 3 offer potential for improvement. Simulations in TRNSYS have shown that depending on the technical possibilities, the intermittent pump operation during phase 2 can be avoided completely. For this avoidance of intermittency, a lower feed-in flow of about 1000 liter/h is required. As the possible lowest feed-in flow of the plant is 2200 liter/h, this cannot be achieved with the current setup. Therefore, suggestions for improvements have been prepared, which shall be implemented and tested in a potential follow-up project of SWD.SOL.

Furthermore, the variation of the feed-in temperature in the beginning of phase 3 implicates improvement potential. Performed simulations point out that on the one hand the minimal and maximal allowed temperature mismatch of the feed-in temperature can be reduced and on the other hand the period to achieve the target feed-in temperature (Fig. 7 between 10:50 am and 11:50 am) can be shortened. To achieve these improvements, a faster variation of the feed-in flow is required. In how far the increased variation speed of the feed-in flow via adjusted values for the PID-control unit is possible will also be elaborated in a potential follow up project of SWD.SOL.

Additionally the relatively early end of phase 3 (4:30 pm) could be delayed. To achieve this delay, the minimum volume flow within the collector loop (currently 5,000 liter/h) has to be reduced. This measure of lowering the pump flow would enable the plant to supply the feed-in target temperature with lower irradiation than in the current control configuration.

6. Conclusion

The decentralized feed-in of solar heat into district heating networks is linked to technical challenges. These challenges were identified and summarized. On this base, an experimental plant with a collector field of 218 m² was developed and realized in Düsseldorf. First monitoring results of the experimental plant show that the plant is able to supply the generated solar heat to the district heating network. During the evaluated feed-in processes, the temperature of the solar heat is equal to the supply temperature of the district heating network or higher (in this case 85 °C). Furthermore, different options to improve the feed-in processes were determined and shall be investigated during the upcoming summer period.

7. References

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