TECHNICAL CHALLENGES FOR SOLAR THERMAL PLANTS WITH DECENTRALIZED FEED-IN INTO DISTRICT HEATING NETWORKS AND DEDUCED PLANT CONCEPT FOR THE EXPERIMENTAL FEED-IN STATION IN THE SWD.SOL PROJECT

Dipl.-Ing. (FH) Kai Schäfer and Dipl.-Ing. Thomas Schmidt
Solites – Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems,
Meitnerstraße 8, 70563 Stuttgart, Germany,
schaefer@solites.de

Abstract – The following publication consists of three technical parts. At first, the technical challenges concerning decentral feed-in of solar heat are discussed. Based on this, the difficulty of controlling the flows to be fed-in is considered. In addition, already realized solutions are comparatively assessed and initial practical experiences are described.
These established bases were used to design a test station, which will decentrally feed-in solar heat into the district heating network of the utility Stadtwerke Düsseldorf (Germany). The hydraulic structure of the test station is presented in the end.

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, a test station composed of a prototype feed-in substation and a collector field with 218 $m^2_{Aperture}$ (232 m^2_{Gross}) will be installed in a multi-family building supplied by district heat.

The operational behavior of the plant will be monitored and evaluated. These measurement data should 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 two aspects, which have already been worked out within the project's framework:

1. Technical challenges for solar thermal plants with decentralized feed-in into district heating networks
2. Hydraulic design of the experimental feed-in station

2. BASES

The section addresses the natural fluctuation of the solar irradiation level and the resulting consequences for the heat output of thermal collectors. Furthermore, the basic variants of decentralized feed-in are presented.

2.1 Solar irradiation and corresponding heat output of thermal collectors

The solar irradiation available at a certain location is subject to a strong natural volatility. During the daily sequence, fluctuations in the solar irradiation of 0 - 100 % (reference: daily maximum value) always occur. Moreover, the changing sun-tracks (e.g. summer vs. winter) and the varying cloudiness result in very different daily irradiation profiles. By way of example, the solar irradiation profiles for two different days at a certain location in Germany are shown in Image 1. Therefor a day without cloudiness (first day sequence) and a day with variable cloudiness (second day sequence) are illustrated. On the indicated day without cloudiness, the irradiation profile assumes a parabolic course with a maximum irradiation of 850 W/m². On the second exemplary day with variable cloudiness, the irradiation profile is subject to much more dynamic changes and the maximum irradiation is only 590 W/m².

Note: Depending on the weather, the irradiation level can vary in a much more dynamic way than illustrated in Image 1.

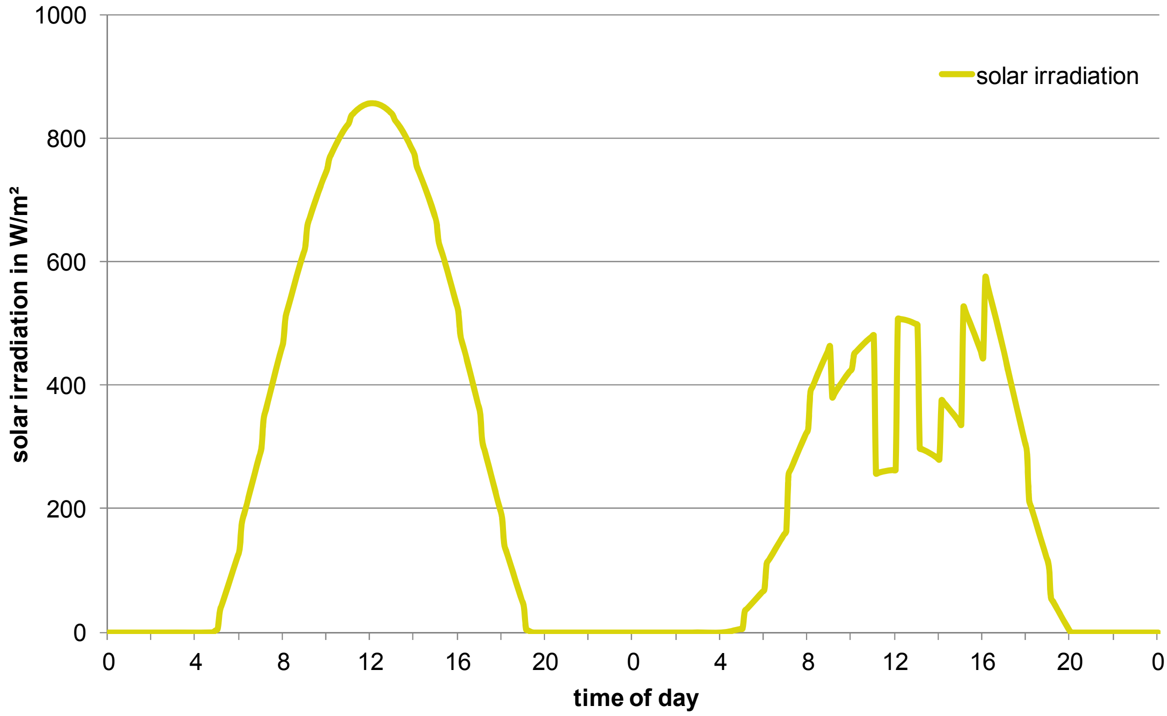

Image 1: Exemplary solar irradiation profile for one day without cloudiness (left) and a day with variable cloudiness (right) related to a horizontal surface

In solar thermal plants, the profile of the solar irradiation has a strong influence on the heat output of the collector. Accordingly, a change in heat output with moderate gradients can be expected on days without cloudiness and, on days with variable cloudiness, the change in heat output will present distinctive gradients. Furthermore, the obtainable daily peak values of heat output are determined substantially by the daily maximum of the solar irradiation. Therefore, the available heat output (profile and amount) of a thermal collector is primarily bound to the uncontrollable profile of solar irradiation. This in turn is determined by the time of the day and the variable weather situation.

2.2 Principle variants of decentralized feed-in

For the decentralized integration of solar heat into DH networks three principle feed-in variants are possible. These variants are represented schematically in Image 2, followed by a short discussion of the respective feed-in variant. Advantages and disadvantages of the respective variants will not be discussed since this was already done in a previous publication of the author during the SDH-Conference in 2014 [Schäfer 2014].

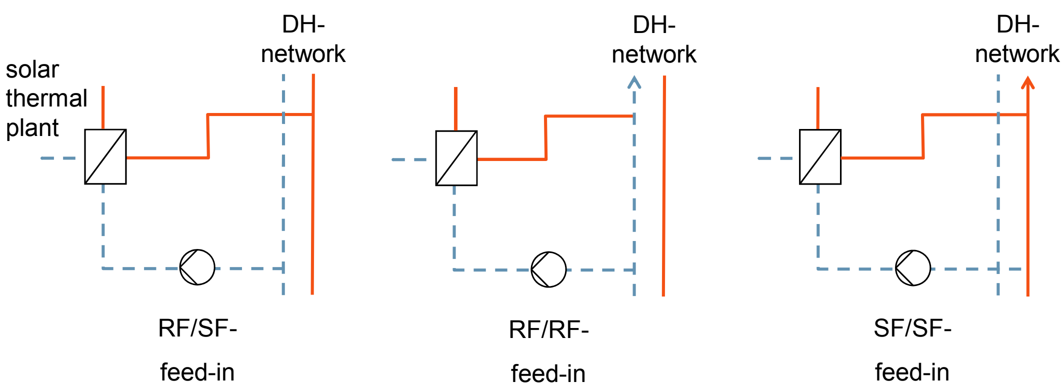

Image 2: Schematic illustration of the three principle decentralized feed-in variants with consistent use of a pump in the feed-in loop (DH-network: district heating network; RF: return flow; SF: supply flow)

Feed-in variants:

a) Extraction from return flow and feed-in into the supply flow - RF/SF

In this feed-in variant fluid from the return flow of the district heating network (DH network) gets extracted, heated up and fed into the supply flow. The temperature difference depends on the operation point of the DH network as well as the specifications of the network operator and changes according to that. The pump flow in the feed-in station must be varied and adjusted according to the solar heat input and the required temperature difference. In this feed-in variant the highest pressure differences within the feed-in loop occur, which can easily amount to several bar depending on the DH network and the position inside the network.

b) Extraction from return flow and feed-in into return flow - RF/RF

The fluid is extracted from the return flow of the DH network and delivered back into the same pipe after being heated. The limits of temperature increase are usually prescribed by the network operator (usually 5 K - 15 K). The wide dynamic range of the solar heat input requires again a variation of the flow according to the prescribed temperature difference. The differential pressures to be handled at the feed-in location are low.

c) Extraction from supply flow and feed-in into supply flow - SF/SF

Instead of the return flow in this feed-in variant the fluid gets extracted from the supply flow, heated up further and fed back into the supply flow. Similar to the RF/RF-feed-in the acceptable temperature increase is given by the network operator and low differential pressures must be handled at the feed-in location.

3. DISCUSSION OF THE TECHNICAL CHALLENGES

The technical challenges of decentralized solar heat feed-in are derived from two points:

- boundary conditions at the feed-in and extraction location in the DH network
- requirements with respect to the operational characteristics

In the following both influencing conditions are discussed and identified technical challenges are presented. In this context, only the RF/SF feed-in, which represents the preferred feed-in variant of the German district heating association, is referred to.

3.1 Technical boundary conditions at the feed-in and extraction location

In this chapter the technical boundary conditions at the feed-in and extraction location of solar thermal plants with decentralized feed-in are presented. See Image 4 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 separate description of both boundary conditions referring to the RF/SF feed-in variant only.

a) Thermal boundary conditions

- Temperature level
  The temperature level at the feed-in location is determined by the supply temperature of the central heat feed-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 50 K are fairly common in the winter period.

b) Hydraulic boundary conditions

- Pressure level
  The pressure level at the feed-in and extraction location does not have a major relevance with respect to decentralized feed-in. Only the required pressure level of the components depends on this value. Much more important to the heat feed-in is the differential pressure between feed-in and extraction location as well as its change over time.

- 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 (approx. 1 bar) and the one at the central pump for increasing the network pressure (partly 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, Image 3 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.

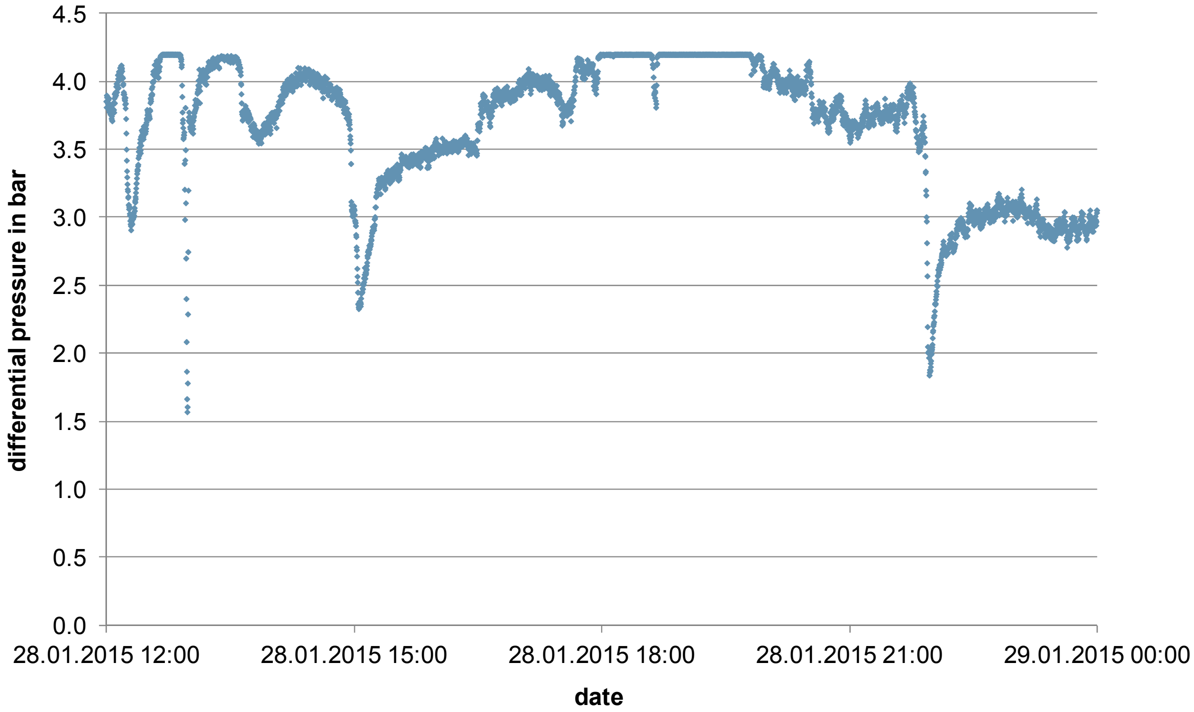

Image 3: Instantaneous values of the differential pressure between supply and return pipe; measurement has been done at a potential feed-in location in the DH network system of Malmö, Sweden; time step of measurement 10 s; source [Lennermo 2015 b]

3.2 Requirements with respect to operational characteristics

Within the research project DEZENTRAL [DEZENTRAL], several requirements of the German district heating association (AGFW) regarding the operational characteristics of solar thermal plants with decentralized feed-in have been identified. The two main ones are:

- low number of pump start-up procedures in the feed-in loop
- low temperature deviation of the solar heat feed-in from the required target temperature level (± 3 K)

However, these two requirements may vary considerably depending on the view of the respective network operator. The results of the research from Schäfer [Schäfer 2014] provide evidence of this.

3.3 Technical challenges

The technical challenges presented here have been deduced from the requirements and technical boundary conditions discussed above. They are divided according to the setup of a solar thermal plant with decentralized feed-in as represented in Image 4.

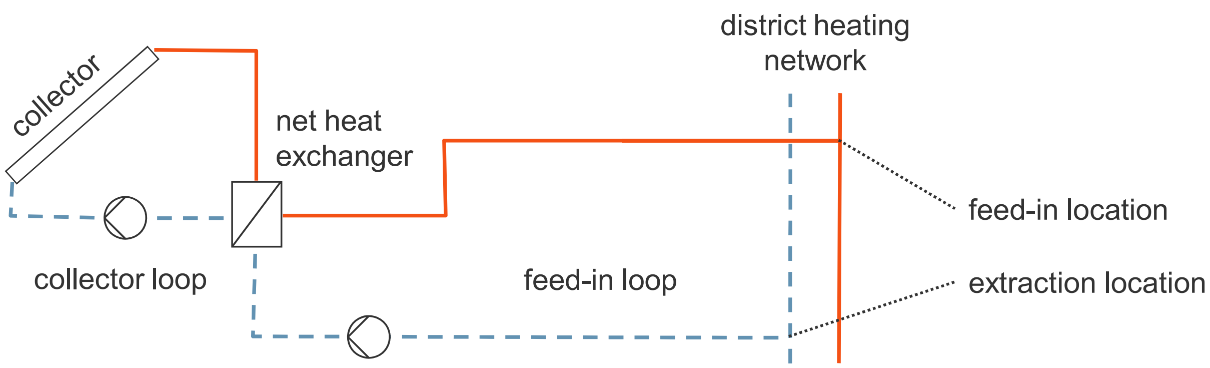

Image 4: Schematic representation of a solar thermal plant variant for decentralized feed-in; for way of example the RF/SF feed-in is shown

a) 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 regulating challenge.

However, if just one of the two specified influencing parameters present changes, the required target temperature regulation can be classified as unproblematic. 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. For that only the observance of the target temperature in case of variable heat output of the collector results in a regulation requirement for the pump.

Besides, every period without solar heat feed-in leads to a decrease of temperature within the connection pipes, which run 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 must be taken (comparable to the solutions existing for conventional substations).

b) 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.

Belong the variation of the flow speed inside the collector loop exists restrictions. The upper limit is defined by the tolerable maximum differential pressure in the hydraulic loop, the lower limit by the behaviour 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. REALIZED SOLUTIONS AND PRACTICAL EXPERIENCES

The technical challenges discussed before, see Section 3, can be solved in different ways. A study of realized plants could identify several solution approaches [Schäfer 2014]. These ones are presented in the following. As far as possible, practical experiences obtained until now and complementary simulation results of the research project DEZENTRAL are described in addition. The paragraph is again divided according to the two hydraulic loops (feed-in and collector loop, see Image 4). Furthermore, only the RF/SF feed-in is considered.

a) Feed-in loop

To solve the regulation requirements in the feed-in loop, the plant examples mentioned show four basic solution approaches. These are illustrated schematically in Image 5 and described individually afterwards. The combination of several solution approaches in one feed-in station is possible, which was already realized for solution approaches b and c.

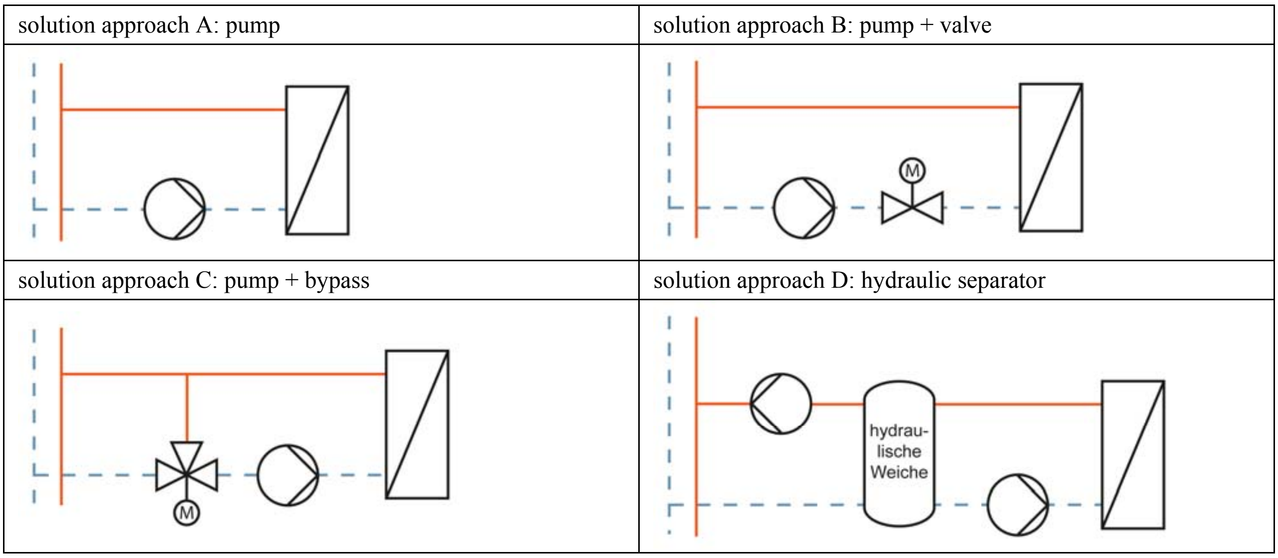

Image 5: Schematic representation of the technical solution approaches within the feed-in loop of realized plants (M: motor control)

- Solution approach A: pump
  <u>Function:</u> Only the pump in the feed-in loop is used as regulating 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
  <u>Practical experience:</u> 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 within the feed-in loop.

- Solution approach B: pump + valve
  <u>Function:</u> In this context, the regulating function of the pump is supported by a fast-regulating 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.
  <u>Practical experience:</u> 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 C: pump + bypass
  <u>Function:</u> 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 (flow rate fed-in 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 flow rates fed-in.
  <u>Practical experience:</u> The resulting extension of the variation range of flow rates fed-in 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 A occur.

- Solution approach D: hydraulic separator
  <u>Function:</u> The feed-in loop is divided into two hydraulic loops by means of a hydraulic separator. This measure clearly simplifies the regulation task of solar heat feed-in. The pump in the hydraulic loop located between collector loop and hydraulic separator can be regulated just focussing 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).
  <u>Practical experience:</u> 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.

b) Collector loop

The study of realized plants and the simulation results of the project DEZENTRAL [DEZENTRAL] make clear that the resulting requirements with respect to the collector loop can be met using collectors available on the market. However, three aspects must be taken into account:

- Selection of the collector
  The collector must be selected depending on the required temperature level at the feed-in location. Selecting an inappropriate product makes it much more difficult to meet the requirements with respect to the operational characteristics defined by the German district heating association AGFW (low number of start-up procedures of the pump within the feed-in loop and observance of target temperature in the narrow hysteresis band).
- Operating method of the collector loop
  The requirements indicated in Section 3.2 result in the necessity of reaching the target temperature inside the collector loop during:
  a) variations of heat flows generated within the collector loop
  b) variations of heat flows extracted from the collector loop
  As operating method of the collector loop a target temperature control with variable flow rates seems to be a constructive approach. In this context however, relatively low flow rates can be required, especially in case of medium to low solar irradiation. The values of the resulting flow rates may clearly undercut the regulating range which is established in the solar thermal industry as low-flow range (flow rate approx. 14 kg/($hm^2_{Aperture}$)).
- Connection of the collector field
  The operating method of the collector loop with low flow rates involves the risk of laminar flow conditions inside the collectors. To ensure that laminar flow conditions are avoided, the hydraulic connection of the collector field must be adjusted accordingly.

The practical experience of realized plants indicates that there is still a clear potential for improvement. This belongs especially to the operating method of the collector loop. The flow rates during medium to low solar irradiation are often too high, resulting in an undesirably high number of annual start-up procedures of the pump in the feed-in loop.

5. TEST STATION IN THE RESEARCH PROJECT SWD.SOL

Based on the results worked out with respect to the technical challenges (see Section 3), a concept for the test station within the project SWD.SOL was developed. This concept combines the four solution approaches presented in Image 5 and enables to test them individually and in combination. A schematic representation of the test station is shown in Image 6. For reasons of clarity, the diagram only contains the valves used to regulate the flow rates. To indicate the optional combination of single hydraulic modules in the test setup, they are identified using A), B), C) and D). The alphabetical designation is in line with the solution approaches presented in Section 4. Apart from testing the individual solution approaches, the test setup enables the comparative evaluation of the respective solution approaches under almost identical boundary conditions at the system limits. This was not possible with the plants implemented so far, since they mostly present only one solution approach in the feed-in loop. In this way, the identification of further recommendations with respect to the suitability of the four solution approaches becomes possible. As further step, the identification of optimisation potentials for the four solution approaches is intended. This is to be carried out based on simulations for which the measurement data of the test station represents an essential input.

Currently, the presented test station is about to be implemented. The call for tender of the plant was divided into two parts in accordance with the hydraulic loops (collector and feed-in loop). The collector loop is implemented by the German company Wagner Solar, which uses a double-glazed flat plate collector for the project. The substructure for the collector mounting system has already been installed. The still outstanding setup of the collector field is synchronised with the installation of the feed-in station. At the moment, the call for tender of the feed-in station is not yet finally completed. The implementation of the entire test station is to be completed by late autumn 2016.

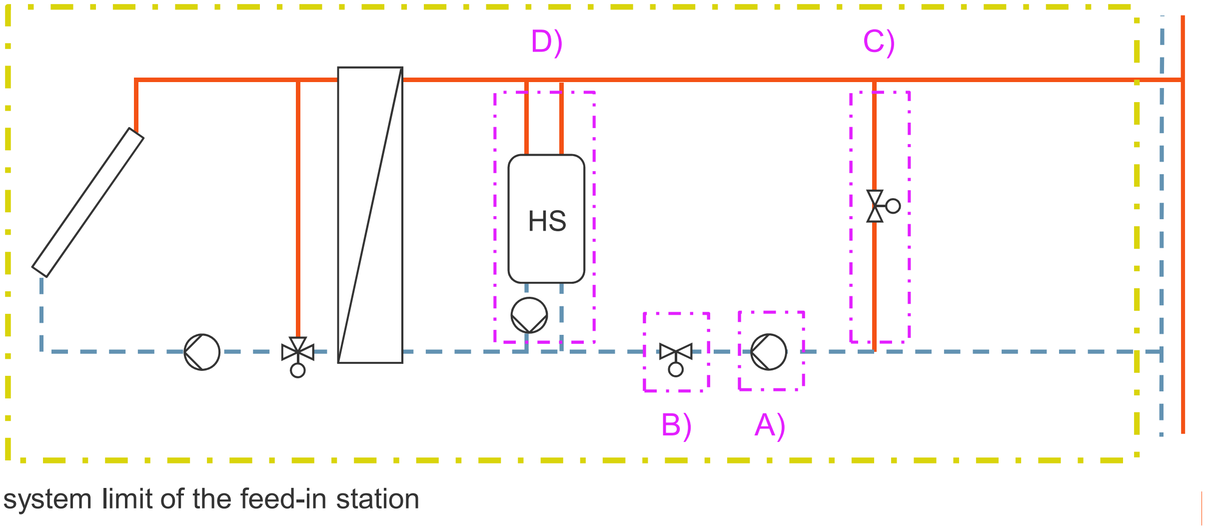

Image 6: Schematic representation of the test station in the research project SWD.SOL (HS: hydraulic separator)

6. SOURCES

[DEZENTRAL]:
Heymann M., Schäfer K., Wagner U., et al.; 2015; Decentralized feed-in in local and district heating networks taking particular attention to the solar heat; national German research project; final report [till yet, not all parts are published]

[Lennermo 2015 a]:
Lennermo G., Lauenburg P.; 2015; Variation in differential pressure at a district heating prosumer substation; Mälardalen University and Lund University; Sweden; Publication, published at the 3rd SDH-Conference in Toulouse

[Lennermo 2015 b]:
Lennermo G. 2015; Variation in differential pressure at a district heating prosumer substation; Mälardalen University; Sweden; Presentation, presented at the 3rd SDH-Conference in Toulouse

[Schäfer 2014]:
Schäfer K., Schlegel F., Pauschinger T.; 2014; Decentralized feed-in of solar heat into district heating networks – a technical analysis of realized plants; Solites – Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems; Stuttgart, Germany; Publication, published at the 2nd SDH-Conference in Hamburg

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