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Planning Tools for Decentralized Heat Supply: Modeling the Effects of Volatile Renewable Energies

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Abstract. An increasing share of decentralized feed-in is necessary for the transition of district heating networks but it comes with various challenges. Software tools for modelling, simulation and optimization allow a theoretical examination of those challenges and possible solutions. Some of these have been used and further developed in the research project ZellFlex. One selected examination is the flexibility of supply temperatures by varying setpoint temperatures for a decentral solar thermal system (500 m²) integrated into an existing district heating network. The analysis of the supply temperature distribution in the network showed: A decrease of the solar thermal feed-in set point temperature by 5 K compared to the supply temperature of the central heat producer seemed acceptable in terms of security of supply, while a 10 K reduction comes with a high risk of undersupply. Furthermore, it was discovered that the points of time with the lowest supply temperatures at the consumers were just before and after they were provided with solar heat due to specific effects concerning temperature loss of the fluid.

Keywords: District Heating, Decentralized Feed-In, Solar Thermal, Heat Storage, Network Simulation, Software Tools, Optimization, Temperature Distribution

1 Software Tools

1.1 Overview and Interaction

District heating networks (DHN) are among the key elements in the penetration of the heat market with renewable energy supply. A significant challenge lies in the restructuring of existing, unidirectional heat supply strategies in such networks. It is important to align planning and implementation strategies with the fact that partially decentralized heat generators within the district heating network or customers transitioning to prosumers take on supply tasks in various load ranges. Therefore, it is crucial to manage the resulting partial bidirectionality. In recent years, tools for various aspects have been developed and tested in direct collaboration between academia and industry:

- Monitoring-based, time-resolved modelling of **heat demand at the customer side (FreePlan)**
- Modelling of large-scale **solar thermal systems** (**FreeSolPy**) as an application of ScenoCalcFW with own extentions
- **Thermo-hydraulic year-round network simulations** of complex existing networks (radial and meshed networks) with central and decentralized heat supply and heat storages (**TRNSYS-TUD**)

- Modelling of the **temperature field in large tank heat storage systems** (up to 50,000 m³) and derivation of a numerical-analytical model for prediction under various charging and discharging strategies (**FreeTTES**)
- **Design and operational optimization** tool, including sector coupling of electricity, heat, and gas supply (**flixOpt**)

Figure 1 displays an exemplary interaction of the software tools presented here. The basic functionality of each tool is described in the following sections. For further details, see the respective publications mentioned.

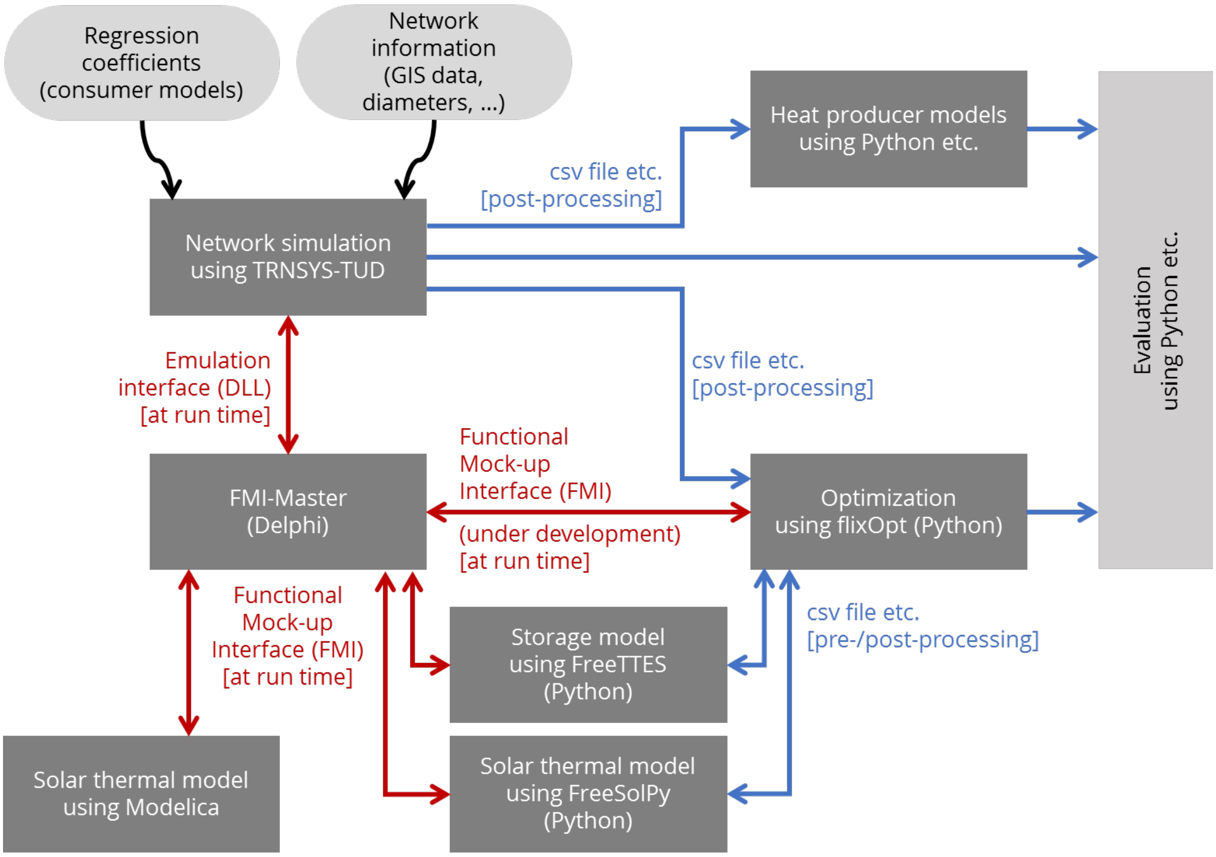

Figure 1: *Exemplary interaction of the various software tools to investigate a green change in DHN*

1.2 Modelling of Consumers' Heat Demand with FreePlan

The basis for conclusive generator optimization and a decisive component for the realistic simulation of district heating networks is the modelling of time-resolved, characteristic heat demand profiles. While aggregated profiles generally prove to be sufficient in the context of optimization, the heat demand in the context of thermo-hydraulic network simulation must be available for each consumer. But time-resolved measurement data are mostly not available up to now. That means: In the context of scenario analyses, synthetic models must generally be used here. While the use of standard load profiles often proves to be too inflexible or generates unrealistically high simultaneity in the partial load case, detailed building models initially require extreme parameterization effort and usually very long computing times in the simulation. Data-based model approaches offer a suitable, high-performance alternative.

FreePlan [1], [2] provides a database of typified regression models based on measurement data of many house substations for the simulation of heat load profiles and is constantly being expanded. The influence of wind speed and solar radiation, for example, proved to be irrelevant for existing buildings, but is checked on an ongoing basis when new monitoring data sets are implemented. The complexity of these currently implemented models is deliberately and consequently kept simple and is mainly limited to the mapping of weekday and daytime-dependent user behavior as well as the influence of outdoor temperature and the differentiation between heating and non-heating periods. This reduces the risk of over-adjustment to measured values. Due to the multiple, linear approach, the respective models are already fully defined by a set of regression coefficients.

The database also includes models for simulating the return flow temperature on the primary side. A regression approach is also used for this purpose, which contains the additional predictors of flow temperature and heat load that are particularly relevant in this context.

The typified models are each characterized by the building type and a few basic parameters. This means that they can be used even when data availability is low. FreePlan is available as an Excel tool and a Python script. The regression approach can be integrated into simulation and optimization tools via common interfaces.

For existing heating networks, there are currently usually only aggregated heat load profiles at the locations where the generators are integrated. To investigate future options for these networks, the volatile reference case must be mapped. In this respect, an automated methodology was developed, too. This assigns a suitable load profile to the often several 1,000 consumers and checks the correspondence with the measured values at the generator location. As an example, Figure 2 shows the application to a network with an annual heat demand of approx. 44 GWh and 258 consumer nodes.

Figure 2: *Example for the comparison of measured and simulated load of a district heating network (difference between simulation and measurement data includes network heat losses)*

1.3 Modelling of Large Solar Thermal Systems with FreeSolPy

An exact forecast of the expected solar yields, both quantitatively and in terms of time, is crucial for determining the optimum size and orientation of new solar thermal systems to be installed. It is also a basis for the optimal dimensioning of storage systems and the operational management optimization of the heat generators.

FreeSolPy [3] is a software program based on the model approaches in [4], [5]. It can be used in pre-processing as well as in the co-simulation for thermal-hydraulic network simulation, taking into account time-accurate system temperatures.

The realistic yield forecast includes a wide range of influences to be mapped. In addition to modeling the collector, this includes complex solar radiation calculations, for example. The values of direct and diffuse irradiation, which are usually measured and forecast by weather services, must be converted to the collector level at the exact location, considering the actual local time. Time-variable shading must be taken into account here. Furthermore, the influence of the return temperatures imposed by the upstream heating network and the required flow temperatures must be implemented. Capacitive effects of the piping system must also be considered in the yield calculation, especially during start-up and shut-down processes.

1.4 Modelling of Temperature Fields in Large Tank Storage Systems

There is currently a lack of efficient storage models (digital twin) – meaning sufficiently accurate predictions of the temperature profile in short calculation times – for large water heat storage tanks, e. g., for thermo-hydraulic network simulations and optimizing the operation of district heating systems. As part of the SPICE project, it was shown – supported by extensive temperature field measurements using DTS measurements (distributed temperature sensing, see Figure 3) - that large tank storages exhibit excellent storage behavior according to the Hedbäck principle and that modeling along a 1D flow path is possible [6].

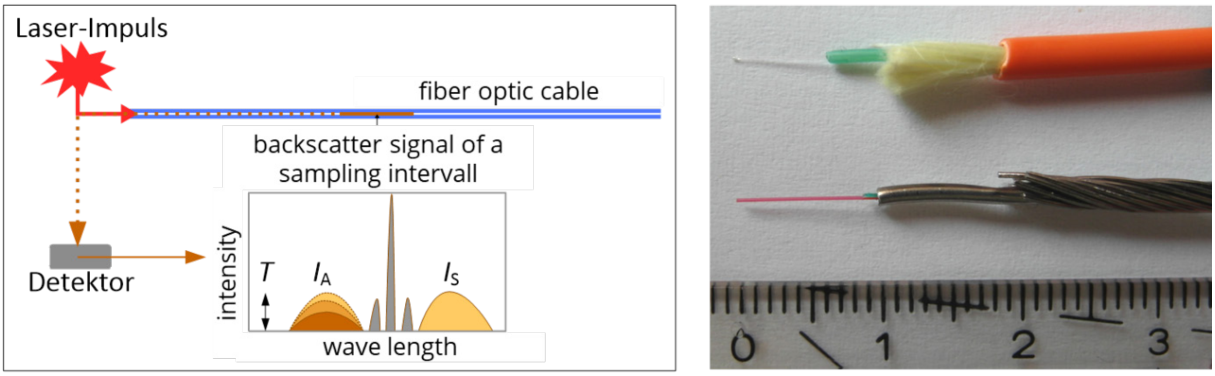

Figure 3: *Basic principle and characteristics of DTS measurement*

Herwig has developed an analytical-numerical storage model which, considering construction details, allows the development of the temperature field to be predicted 300 times faster than in real time, depending on the temperatures and volume flows of the loading and unloading. It should be emphasized that the formation of several temperature transition areas between the hot and cold storage area due to inversions (inflow of a colder mass flow into a warmer layer during loading and vice versa during unloading) during loading and unloading processes is also well modeled. The model was transferred to Python as part of project TWINopt [7], further developed and prepared for coupling with thermo-hydraulic network simulations. The DTS measurement setup is currently being put into operation in the Reuter West heat storage facility of Vattenfall Wärme AG Berlin so that the comparative validation of the simulation tool with live measurement data can take place. In the future, it should also be possible to integrate aquifer heat storage tanks into the simulation [8].

1.5 Thermo-Hydraulic Network Simulations and Simple Models of Heat Generators and Storages using TRNSYS-TUD

In the past, it was sufficient to simulate the thermal-hydraulic situation in district heating networks for stationary cases of maximum load in winter, minimum load in summer and the transition period. With the increasing expansion of decentralized, small-scale heat generation structures on the one hand and the higher volatility of radiation- and wind-based heat supply technologies on the other, at least quasi-dynamic annual simulations are required. This is the only way to map the boundary conditions of the thermal hydraulics and to predict the effects on the dynamic loads of the pipelines, the design of the circulation pumps and the pressure maintenance. Such simulations are possible with the TRNSYS-TUD tool [9]. The partial FMI-based coupling with the presented tools for consumer and generator modeling as well as the digital twin heat storage system makes such predictions possible.

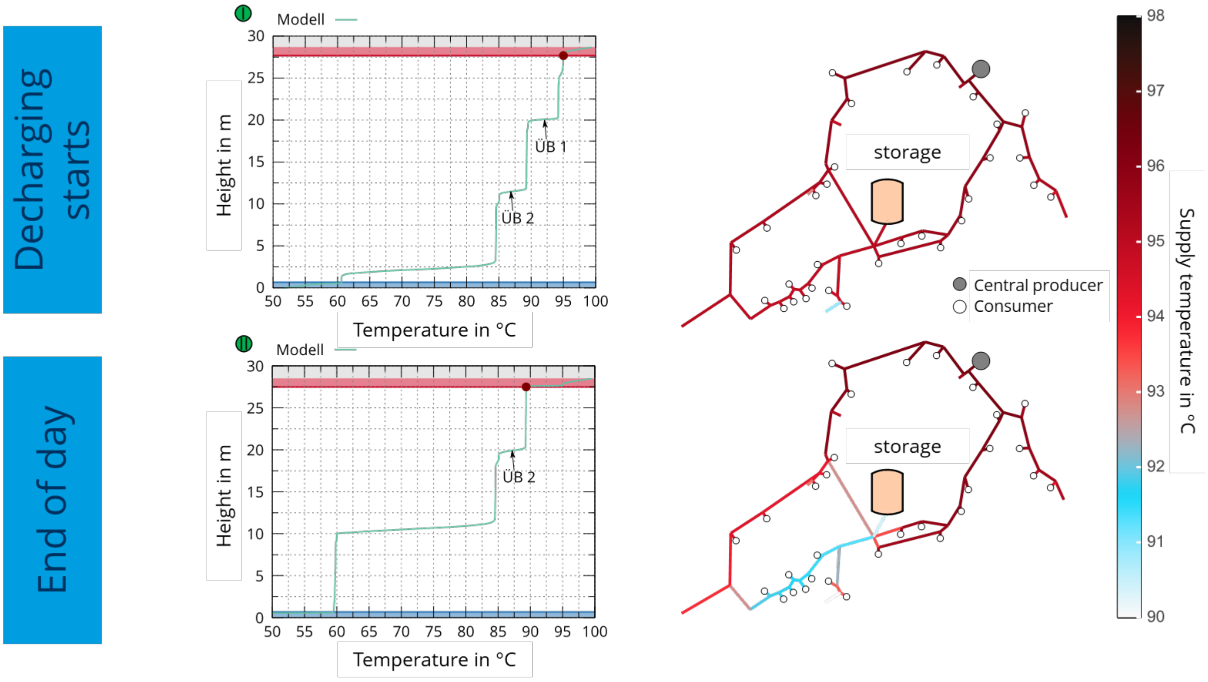

Figure 4: *Example of a TRNSYS-TUD network simulation with a partially decentralized heat storage in a network mesh*

As an example, Figure 4 show simulation results of an existing network. While implementing decentralized renewable energies, it proved necessary to implement an atmospheric heat storage tank with a maximum charging temperature of 95 °C in the existing heating network in a partially centralized network mesh. Due to inversion during storage loading in previous time periods, two transition areas ÜB1 and ÜB2 are formed at the beginning of the day. At the end of the day, a temperature undersupply of the network sections marked in blue becomes clear, which is predicted by the shifting out of the transition area ÜB1 and the then approx. 5 K lower upper storage tank temperature during discharge over the course of the day.

1.6 Design and Operational Optimization (flixOpt)

Even for smaller generation parks, the processes of decision-making for future generation parks and their operational management are becoming increasingly complex. The consideration of the sector coupling of heat - electricity - gas, the integration of renewable energy sources and the associated need for electrical and thermal energy storage, overlaid with volatile economic conditions, are elements of this process. The use of optimization software is almost mandatory to avoid bad investments, to determine efficient operation modes and to identify hidden efficiency potential.

Commercial software products are available on the market, but most of them only serve one target criterion - usually minimal operating costs. The optimization framework flixOpt, developed in Python as part of the SmartBioGrid project [8], offers a decision-making and planning aid for existing energy systems, those to be transformed or those to be completely redesigned. FlixOpt is based on classical model approaches of mixed integer linear optimization. This is used to determine the optimum operational management and optionally the best possible design of individual or all systems in the generation park. Due to the object-oriented, generic implementation, the optimization framework can be used universally. The following components that can be modeled are just a few examples:

- Boilers and CHP systems operated with any fuel
- Heat pumps, waste heat, photovoltaics, solar thermal energy
- Heat storage, batteries, fuel storage
- Demand coverage, purchase and feed-in contracts

The optimization goal is also not limited to the widespread minimization of operating costs. Alternative criteria can be, e. g., the minimization of CO_2 emissions or primary energy requirements. Even a combined consideration of several target variables can also be implemented in the primary objective through optional internalization. An example of how flixOpt can be used is shown in Figure 5. In this example, the heat supply is to be transformed and the oil boiler and one of the pellet boilers are not necessary in the future. In addition to the question of the optimum nominal output of the new systems to be purchased, the best possible use of an area available for solar generation is also included in the optimization.

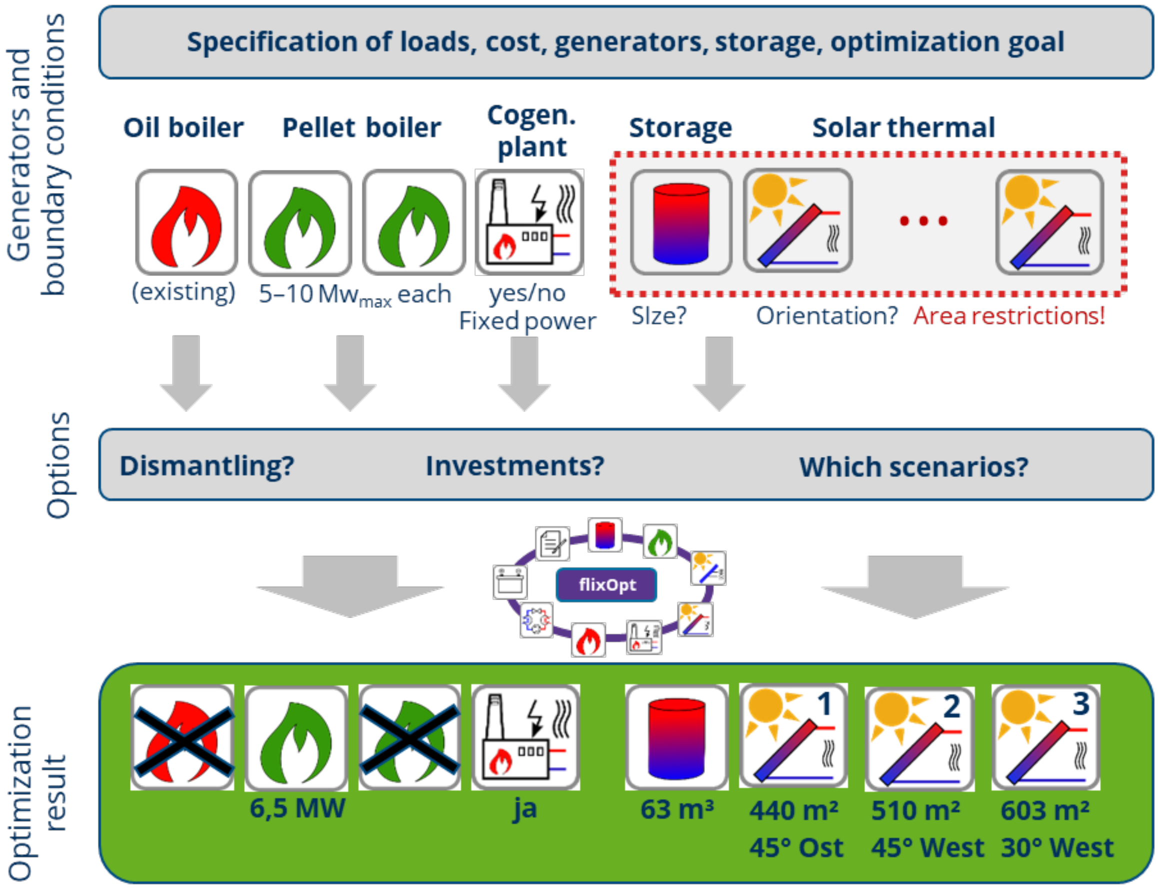

Figure 5: *Schematic representation of a possible investment question and its processing sequence with flixOpt*

The optimization can be carried out for periods of any length and temporal resolution, for which a theoretically optimal result of the operational management is calculated within the framework of the model accuracy using the relevant, time-dependent data (Figure 6). This is combined with the optimal dimensioning of the generation fleet based on the minimization of total costs (annualized investment and annual operating costs).

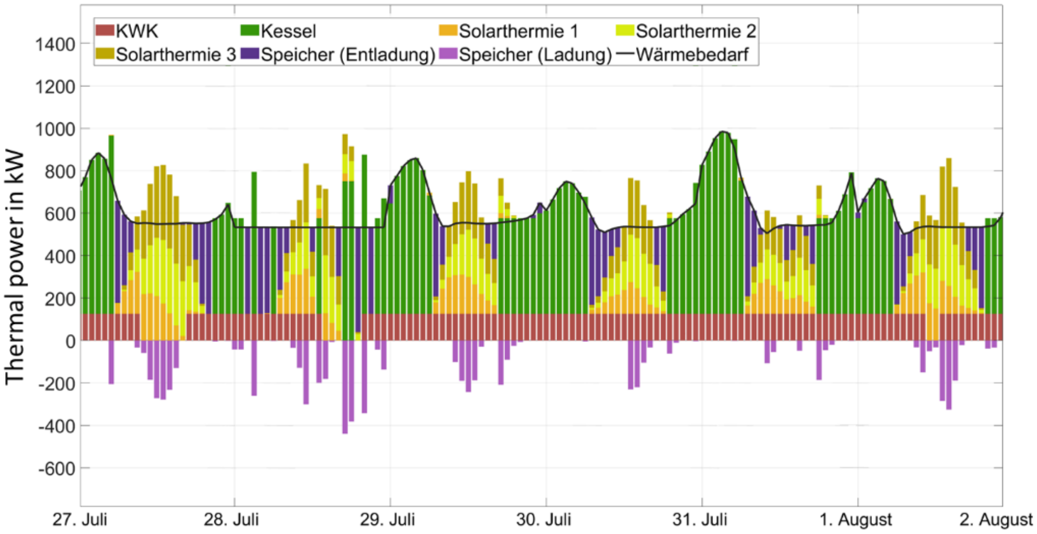

Figure 6: *Example of an optimal generator operation. Loading of heat storage is displayed as negative values*

2 Exemplary Use of Tools: Research Project ZellFlex

2.1 Research Subject and Overview of Use Cases in Project ZellFlex

With increasing shares of renewable heat (including heat pumps and waste heat) in DHN, flexibility of the network operation becomes more and more relevant. For instance, adjusting the supply temperature according to consumer or generator requirements instead of following a fixed supply temperature curve may increase the efficiency and heat feed-in of heat sources such as solar thermal or heat pumps. The ongoing digitalization in the district heating sector creates new opportunities for a more flexible network operation.

In research project ZellFlex, several flexibility measures were examined in models of two existing district heating networks on a theoretical basis [10]. The tools described in section 1 provided the basis for these examinations. The flexibility measures include:

- **Pulsating operation** for temporarily switching off cells using decentralized heat storage and smart control (see Figure 7 - left)
- **Demand-driven supply temperature** for temporal flexibility by aligning actual temperatures with design requirements/guaranteed temperatures or customer requirements (see Figure 7 - right)
- **Local heat retention (type 1)** to reduce heat losses from a long supply line to the cell and the demand of electrical energy for decentralized feed-in pumps.
- **Local heat retention (type 2)** to limit the heat supply from the main network to 20 % (to meet funding requirements of a new construction network according to the German funding program BEW – Bundesförderung Effiziente Wärmenetze)
- **Consumer-oriented, local flexibility of the supply temperature** using heat pumps or mixing stations at partially central network nodes.
- **Generator-oriented, local flexibility of supply temperature** through individual setpoint supply temperatures of decentralized heat generators to increase the share of renewable heat in the network.

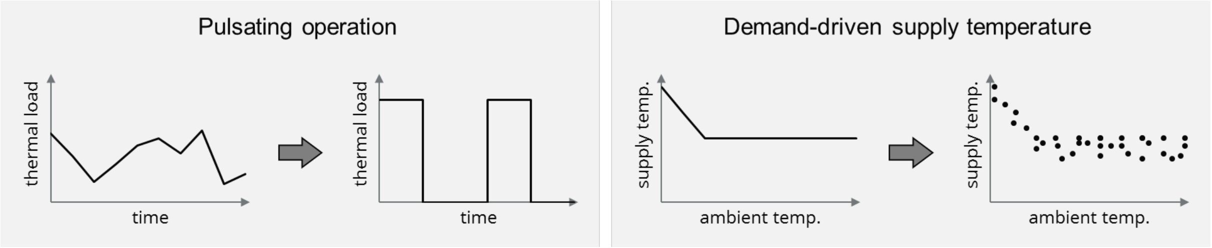

***Figure 7:** Basic principle of two of the flexibility measures examined in research project ZellFlex*

2.2 Exemplary Use Case: Individual Setpoint Supply Temperatures of Decentralized Heat Generators

2.2.1 Research subject

One of the flexibility measures in ZellFlex aims at increasing the share of decentralized, renewable heat in the network by allowing them to feed in with a lower supply temperature than the central heat producer. A model of an existing network with a total of 28,5 MW connected load and one central producer was used for this study (see Figure 8). Subsequently, a decentralized solar thermal plant with 500 m² collector area (350 $kW_{peak,th}$) was added. Behind the feed-in location are four consumers, which have a total connected load of 65.2 kW (without simultaneity) and a total heat consumption of around 110 MWh/a.

In year-round simulations, different scenarios with different setpoints for the solar thermal feed-in temperature were examined (see Figure 9). Supply temperature curve 125/85 means a setpoint temperature of 125 °C in winter and 85 °C in summer, which corresponds to the temperatures of the central heat producer. In scenario 120/80 the solar thermal setpoint temperature is reduced by 5 K compared to the central producer at every timestep and in scenario 115/75 it is 10 K accordingly.

The results are compared to a reference case without solar thermal feed-in.

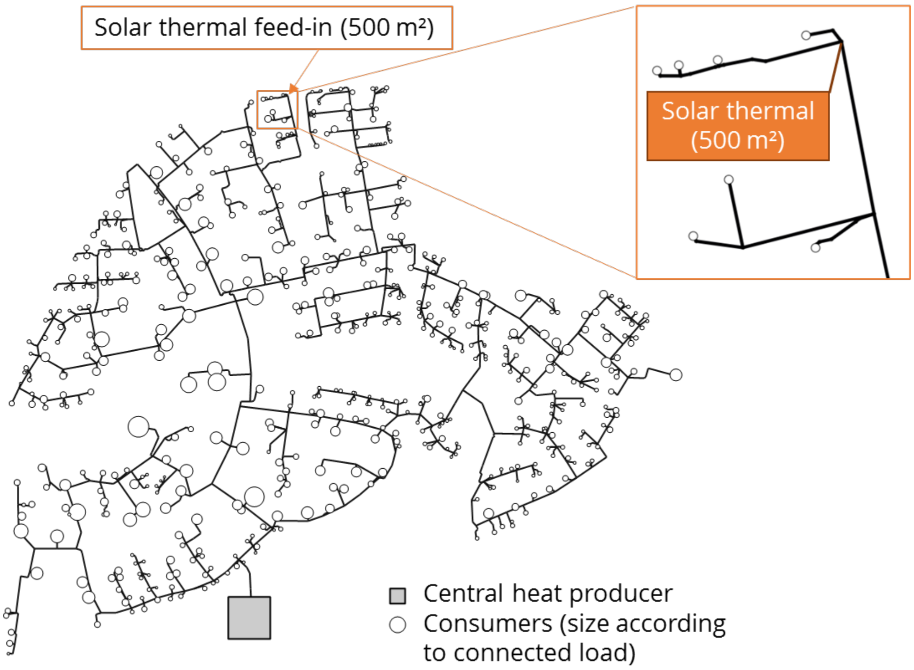

***Figure 8:** Overview of examined district heating network with position of solar thermal feed-in*

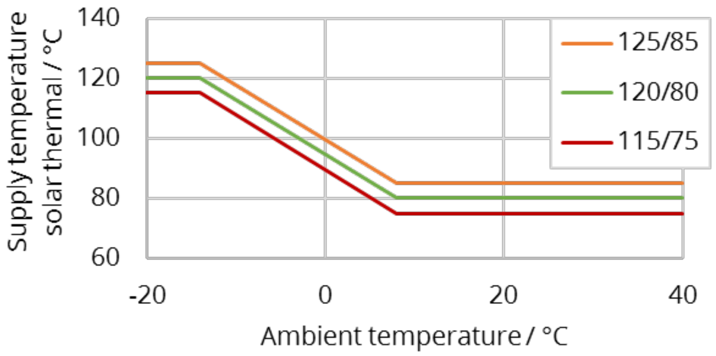

Figure 9: *Setpoint supply temperatures of the solar thermal systems*

2.2.2 Methods and Software Tools Used

The following software tools were used in the specific use case described here:

- The consumers' heat demand was simulated using *FreePlan* database.
- The solar thermal system was simulated using the *Modelica* model.
- A network simulation was carried out using *TRNSYS-TUD*.

Additionally, some post-processing in *Python* was necessary.

Please note: Fixed temperature requirements of the consumers are not considered in the simulation as the corresponding data is not available. Therefore, it is not possible to detect temperature falls below the required target temperature at the consumers. A volume flow limitation is implemented so that individual consumers may be undersupplied in the simulation regarding their heat demand.

2.2.3 Results: Supply temperature distribution in the network

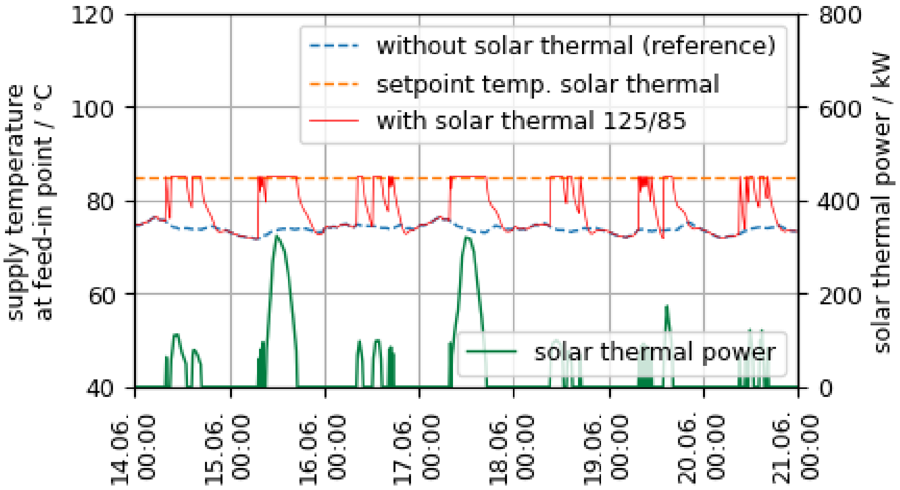

Figure 10: *Temperatures at feed-in location for scenario 125/85*

The temperature at the feed-in location in a summer week (beginning on 14th June at 00:00) is shown in Figure 10 for a solar thermal setpoint temperature of 125/85. Compared to the reference case (no solar thermal; blue line), the supply temperature is expectedly increased as soon as the solar thermal starts feed-in. In Figure 11, the solar thermal setpoint temperature is 115/75. In this case, the temperature at the feed-in position is quite equal to that of the reference case. However, it is noticeable that the supply temperature drops sharply for a short time at the end of a period with solar thermal feed-in.

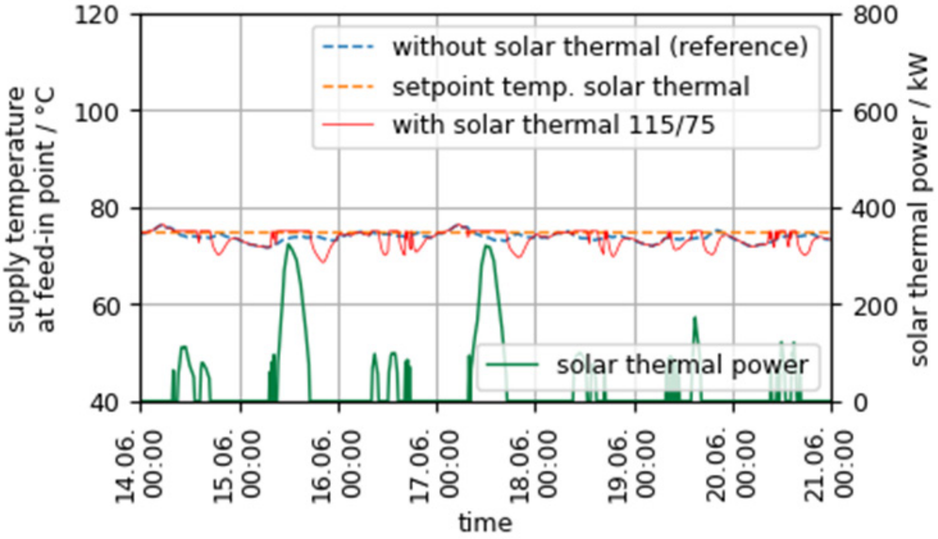

Figure 11: *Temperatures at feed-in location for scenario 115/75*

The effect can be explained as follows: In summer, the solar thermal generates enough heat to supply parts of the upstream network. This means that in some sections of the route upstream of the feed-in location, the direction of flow is reversed, resulting in a temperature drop in the opposite direction compared to the reference case (see the left part of Figure 12). If the flow direction is reversed *again* back to the reference case, water that has already cooled down is pushed *back* in the direction of the feed-in point. On this path, it cools down even further, so that it then has a particularly low temperature at feed-in location (in the right part of Figure 12, for example, 68.1 °C). Whether these short-term effects lead to undersupply at the consumers would have to be examined on a case-by-case basis in a real application. The sharp temperature drops could possibly be avoided by increasing the target flow temperature of the solar thermal at the end of the feed-in process. This would require forecasts of solar irradiation for the next few hours.

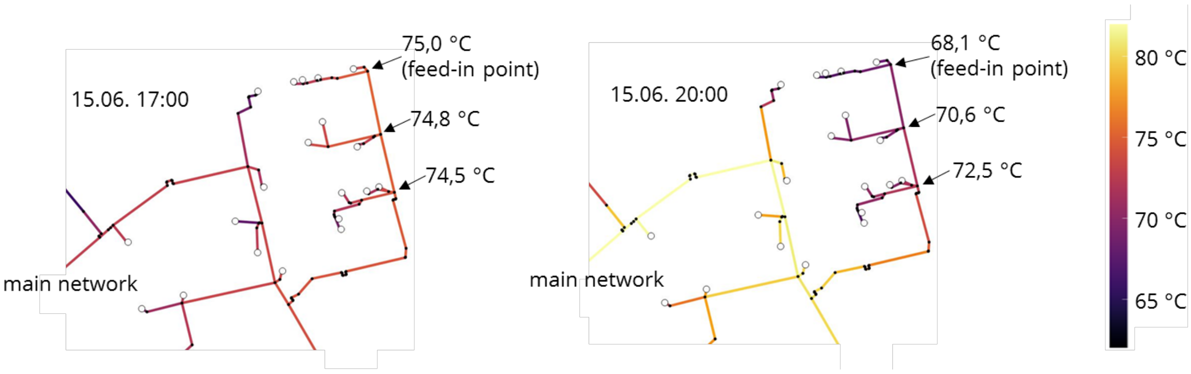

Figure 12: *Temperature distribution near the solar thermal feed-in point at the end of the feed-in process for scenario 115/75. Left: During solar thermal feed-in. Right: Shortly after feed-in stopped*

In addition to the supply temperatures at the feed-in point, the temperatures at the more distant consumers, which are temporarily supplied by the solar thermal system, are also of interest. The fluid cools down up to these consumers, which raises the question of whether a sufficiently high temperature level can be achieved at all consumers, especially for scenario 115/75. As already mentioned, fixed temperature requirements are not included in the consumer models, so that the simulation cannot provide a conclusive statement here. Nevertheless, the temperature distributions in a network section and at a selected consumer are analyzed below and evaluated by comparing them with the reference case.

Figure 13 shows the temperature distribution of the supply lines near feed-in location on 14th June at 12:00. The feed-in of the solar thermal with a 125/85 curve leads to an increase in the flow temperature at the consumers located near the feed-in point. The decreased setpoint temperatures lead to significantly lower supply temperatures at some consumers. One of the consumers that is most affected by cooling is marked as an example. The temporal curves of the supply temperature at this customer are shown in Figure 14 for a summer week, starting on 14th June at 00:00. The setpoint supply temperature reduced by 5 K (120/80) leads to a flow temperature that is up to 4 K lower, while the temperature reduced by 10 K (115/75) leads to a maximum difference of around 7 K compared to the reference case without solar thermal. An undersupply could occur here, at least temporarily. Whether this is of a relevant magnitude would have to be checked in each individual case.

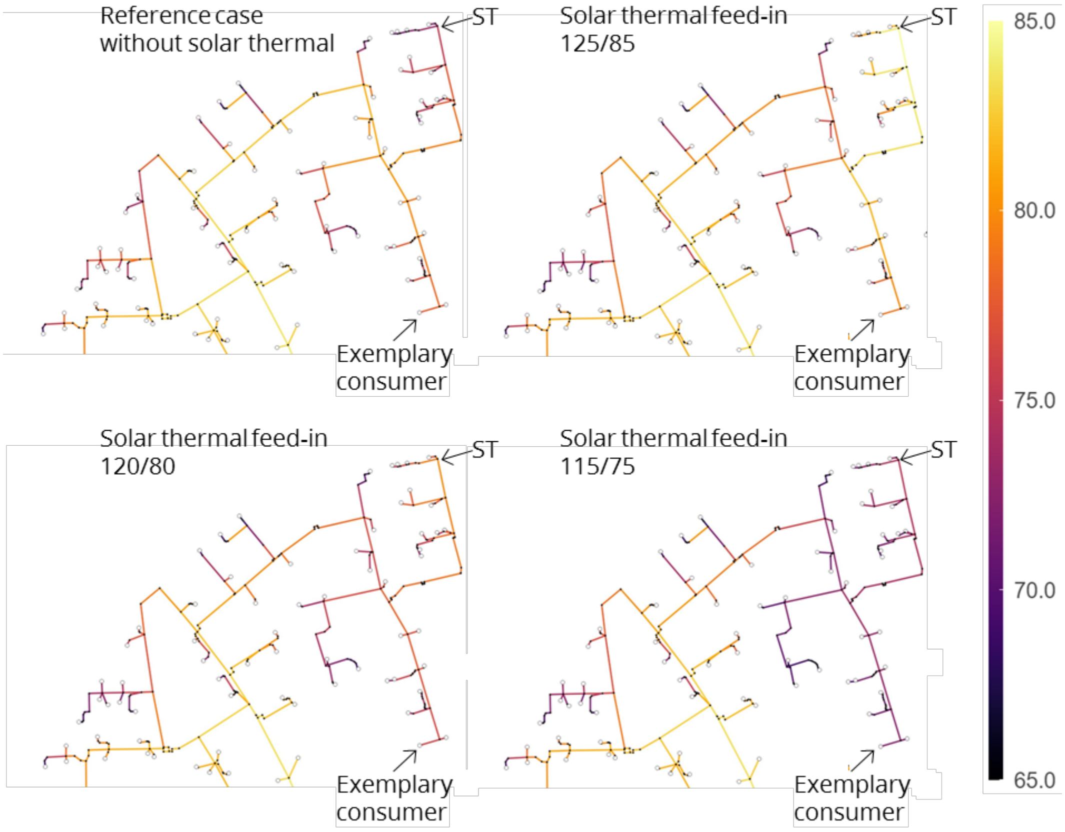

Figure 13: *Supply temperature distribution near the solar thermal feed-in point (ST), 14th June, 12:00*

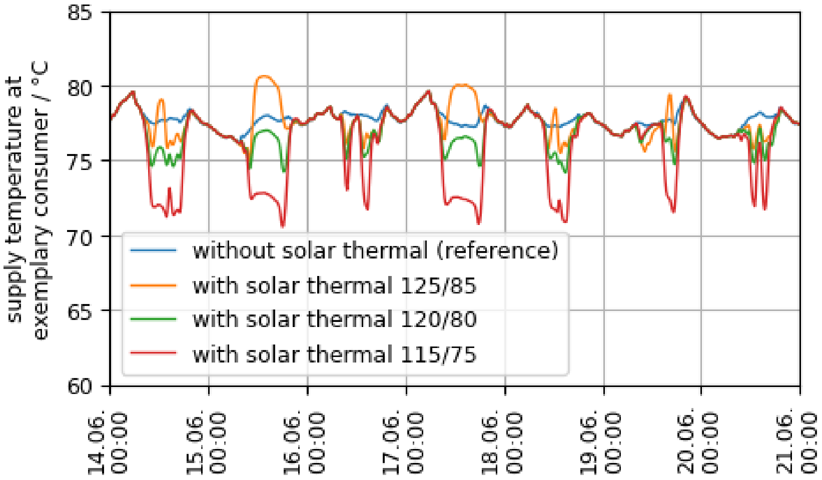

Figure 14: *Temporal curve of supply temperature at exemplary consumer during a summer week*

An interesting effect occurs at the selected consumer especially in scenario 125/85 on 15th and 17th June: At the beginning of the solar thermal feed-in period, the supply temperature at the consumer drops briefly before it then rises to a higher value compared to the reference case. The drop is because the consumer is *not yet* supplied by the solar thermal, but the mass flow from the upstream main network is already lower than in the reference case (as fewer consumers have to be supplied by the central heat producer). This reduces the flow velocity on the way to the consumer and increases temperature loss. On the other days of the week under consideration, on which the solar yields are lower, the temperature falls below the reference case temperature almost all the time for curve 125/85. The consumer does not appear to be supplied by the solar thermal (or only very rarely), while the mass flow from the main grid is often lower and therefore the temperature loss is higher.

The temperature drop at the beginning of the feed-in period on 15th and 17th June can also be observed in the 120/80 and 115/75 scenarios, although the temperature thereafter remains below the temperature in the reference case.

A further drop in temperature can be seen on 15th and 17th June at the end of the feed-in process. This is due to the previously described effect that part of the fluid is first transported from the feed-in point towards the main network and then back again, whereby the temperature loss is particularly high.

The largest negative temperature differences compared to the reference case therefore occur at the exemplary consumer when they are not yet or just not anymore no longer supplied with heat by the solar thermal. However, in the summer week under consideration, curve 115/75 in particular also leads to relatively low flow temperatures at the two consumers over a longer period of time (for a few hours at a time).

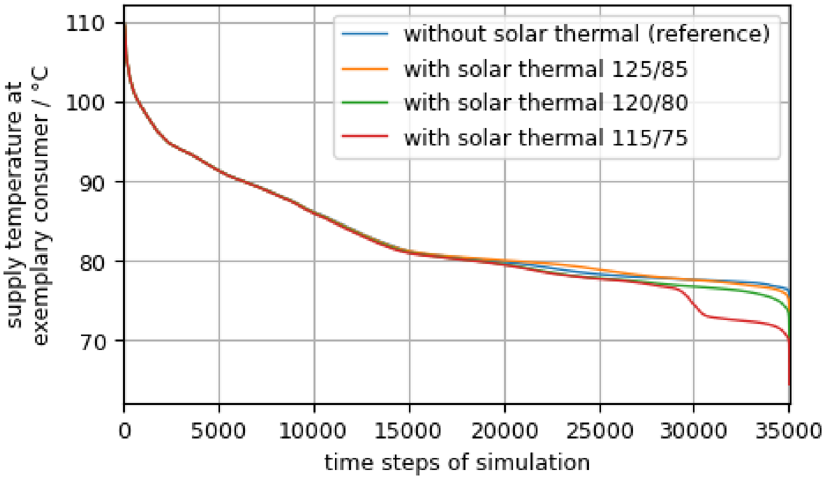

Figure 15: *Duration curve of supply temperature at exemplary consumer*

The question arises as to how high the supply temperature is for the rest of the year under consideration and how often it is significantly below the temperature in the reference case. The annual duration curves of the supply temperatures (see Figure 15) can be used for this purpose. With the 5 K lowered setpoint supply temperature (120/80), high deviations from the reference case occur only rarely. This is more often the case with the 115/75 curve: At the node considered as example, the reference flow temperature is undercut by at least 4 K in 15 to 20 % of the time steps. As previously seen in the exemplary summer week, these shortfalls often occur for several hours at a time. Using the setpoint temperature curve 115/75 therefore does not seem advisable for reasons of security of supply.

2.2.4 Conclusion

If the flow temperature setpoint for feed-in of the solar thermal system is lowered by 5 K (120/80) compared to the temperature of the central heat producer (125/85), this results in an increase in solar feed-in of around 4 %. A reduction of 10 K (scenario 115/75) leads to around 8 % higher heat feed-in compared to scenario 125/85.

Looking at an exemplary consumer showed that the 120/80 setpoint temperature could be sufficient to supply the consumers in the case of the solar thermal system with 500 m². However, the 115/75 curve often leads to significant temperature underruns compared to the reference case over several hours at a time (15 to 20 % of all time steps), which makes it likely that the temperature requirements of the consumers will not be met.

Additionally, the analysis showed that the lowest temperatures at the consumers often occur right before or just after they are supplied with solar thermal heat. This effect exists even with a solar thermal setpoint temperature just as high as the central heat producer' temperature (125/85).

In any examined case, the feed-in of the solar thermal led to stronger fluctuations of supply temperatures at the consumers. This dynamic behavior makes detailed simulations and analyses of the network operation particularly important to detect possible undersupplies and evaluate them with regard to duration and heat amount.

3 Outlook

The simulation tools FreePlan, FreeSolPy, and FreeTTES are continuously developed further and used on the one hand currently in interaction with the optimization tool flixOpt for several use cases of different future supply strategies of several district heating supplier companies.

On the other hand, when coupled with the TRNSYS-TUD thermal-hydraulic network simulation, they are important tools for determining design parameters and testing control strategies for decentralized feed-in substations, including the positioning of partially centralized heat storage systems.

Data availability statement

Information about the available data for the presented use case can be found in the final report for project ZellFlex [10]. However, the underlying data of existing networks and consumers is to be kept anonymous and is thus not publicly available.

Underlying and related material

Description of optimization framework flixOpt on TU Dresden website:
https://tu-dresden.de/ing/maschinenwesen/iet/gewv/forschung/forschungsprojekte/flixopt

Repository with flixOpt Python code:
https://github.com/flixOpt/

Download FreePlan (Excel tool and description):
https://datashare.tu-dresden.de/index.php/s/EKEKsMoAABwA4cX

Author contributions

To the part of software tool development many authors and several research project results (see references) contributed.

For the presented exemplary use case in project ZellFlex, the authors' contributions according to the CreDIT guidelines are the following:

- Clemens Felsmann: funding acquisition, project administration, supervision
- Vera Boß: conceptualization, formal analysis, visualization, writing – original draft
- Bogdan Narusavicius: software, investigation
- Karin Rühling: writing – review and editing

Please note that these do not represent the authors' contributions in the other parts of ZellFlex project.

Competing interests

The authors declare that they have no competing interests.

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- DELFIN: 03ET1358B
- TWINopt: 03EN6016
- SPICE: 03ET1322A

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