About the Efficiency of District Heating with flexible Heat and Temperature Distribution

Sven Paulick[1], Vera Boß[1] and Clemens Felsmann[1]

[1] Technische Universität Dresden, Institute of Power Engineering,

Chair of Building Energy Systems and Heat Supply, 01062 Dresden, Germany

Abstract

Decentralisation of heat supply is one option to transform and decarbonise district heating (DH) networks. However, the volatility and availability of the diversified heat sources also require a much more flexible operation of the heating networks compared to conventional operation. In a German research project "*ZellFlex*" (www.tud.de/mw/zellflex), various methods for network flexibilisation are being investigated in a simulation study. This paper presents latest results of the project with focus on existing district heating networks with higher temperature demand and centralised heat supply, as these kinds of networks are the most common among Germany und Europe.

Keywords: DH network simulation, flexible operation, cell balancing, decentralised feed-in

1. Introduction

The desire and necessity for flexible operation arise for two reasons: on the one hand, limitations and restrictions in the availability of the increasingly used non-adjustable heat sources and, on the other hand, the possibility of increasing efficiency by minimising distribution losses and increasing efficiency of the heat transport. Essential elements are the demand-driven deployment of heat, the shifting or adaptation of heat load requirements to the heat supply on the heat sink side, and the low-loss transport and distribution of thermal energy.

The locally scattered arrangement of decentralised heat sources as well as the different heat and temperature requirements of the heat consumers in parts of the network will increasingly require the evaluation of flexibility measures regarding smaller network sections (*cells*). The balancing of network sections could be conducted within a cellular approach, which is familiar from the electricity sector in the form of balancing groups and the assigned balance responsible parties.

2. Simulation study and flexibility measures

To quantify the effects of different flexibilisation measures, simulations studies have been done. The flexibility measures considered in this paper are (see Fig. 1, a-c):

(a) Pulsating operation (see section 2):

Cyclic operation of cells, especially in off-peak periods, to reduce heat losses

(b) Decentralised and local heat retention (see section 3):

Integration of decentralized heat generators (e.g., solar thermal, waste heat) in combination with heat storage systems to locally und temporally supply a cell

(c) Local and temporal adaption of supply temperature (see section 4):

Local and, if possible, temporary reduction or increase of the network supply temperature in cells with a different demand compared to the main network

doi:10.18086/eurosun.2022.04.09 Available at http://proceedings.ises.org

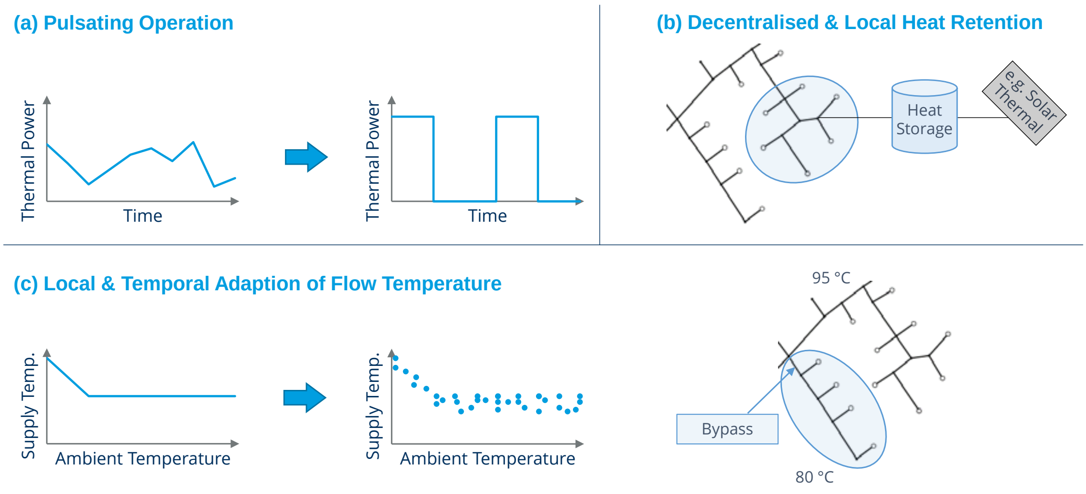

Fig. 1: Flexibility measures considered for selected cells in the DH network

The subject of the investigations is a large heating network with 556 consumer points (Fig. 2), 28.5 MW connected load and approx. 19 % annual heat loss in the district heating network. The network is a 2nd generation, meshed network (following IEA-DHC Annex X Classification). It is a representative real inner-city network in Germany, which was transferred into a simulation model and validated with measurement data. For most of the study, an annual simulation with a time-step of 15 minutes was done with real measurement data for the ambient temperature and solar radiation.

The following flexibility measures were done with a handpicked selection of cells in the heating network, see Fig. 2. The structure, size and number of consumers are different, as well as the distance to the central heat producer. Findings on the selection of a cell area, as well as necessary requirements and challenges, are discussed in section 5.

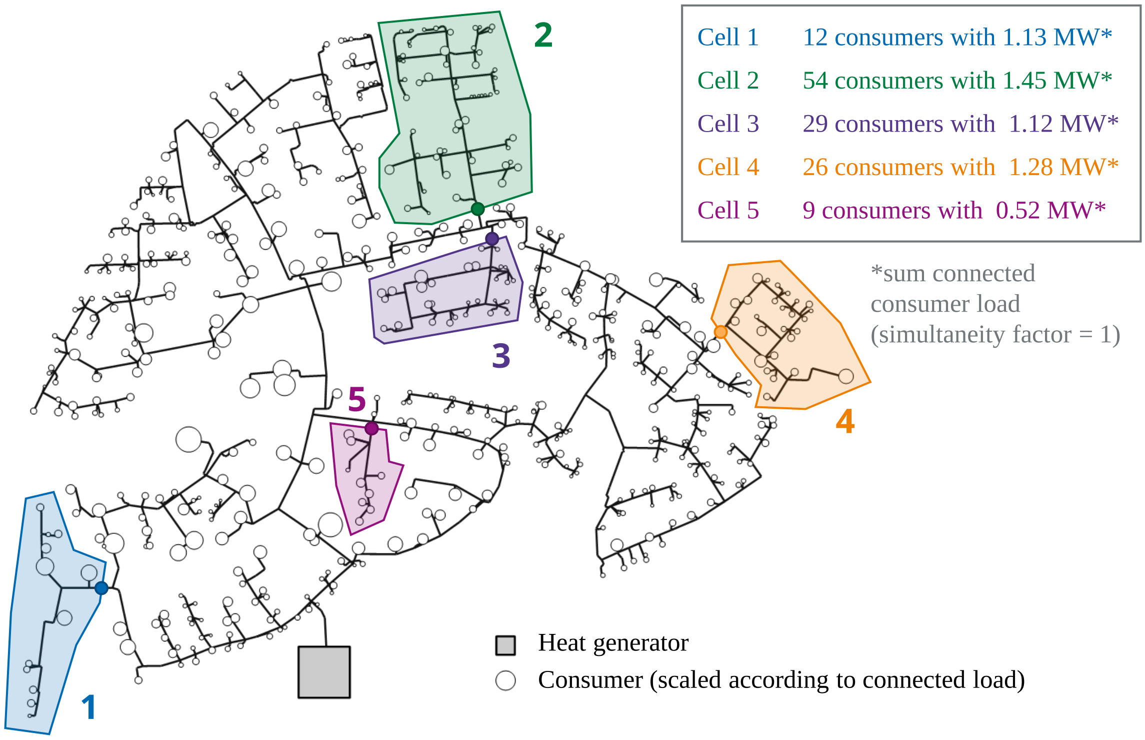

Fig. 2: Structure of the 2nd generation heating network - with central heat producer und the five chosen cells with respective sum of the connected consumer load.

3. Pulsating operation

3.1 Explanation

Especially at off-peak times, the ratio of heat losses to transferred heat output/quantity is particularly unfavourable in heating networks, because as a rule almost the entire network is kept permanently "warm", although the individual consumers have a low heat demand over longer periods of time. Thus, especially in summer and the transition period, the network is permanently in an inefficient partial load range with the consequence of proportionally high network heat losses. This condition could be eliminated by a kind of intermittent operation - here called pulsating operation: a network, respectively a network section (*cell*), is only temporarily flown through and the heat distribution losses can be reduced. However, the heat supplied intermittently (pulsating) must then be stored decentrally and delivered with a time delay without causing further distribution losses. The temporal course of such pulsed operation can be seen as an example in Fig. 3 in comparison with conventional operation (reference).

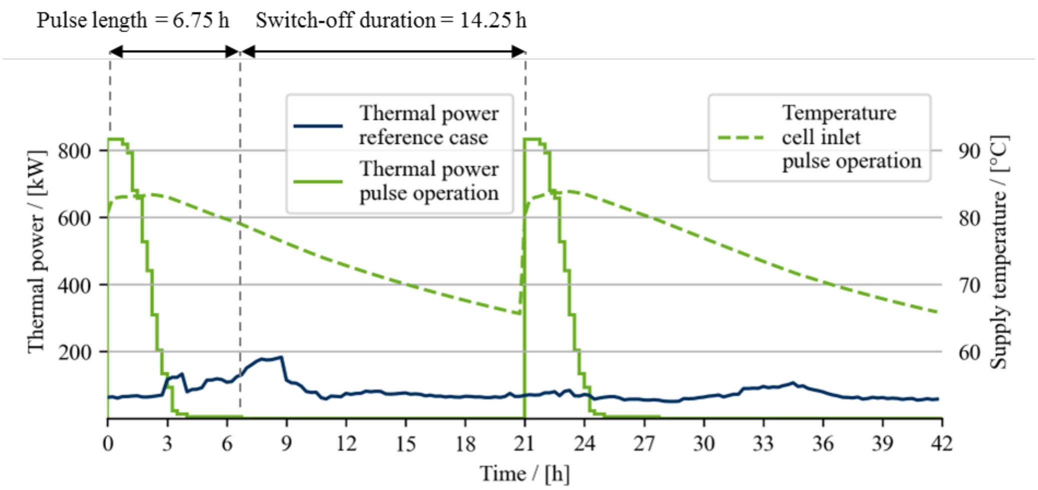

Fig. 3: Pulse operation and reference operation

In pulsating operation, a group of consumers in a cell (defined network area or network section) is considered as a unit and is equipped with decentralized heat storage units (in the building). These are always loaded simultaneously: If one of the heating buffer storages reports a heat demand, all buffer storages within the cell are loaded (pulse - in Fig. 3, for example, from time 0 to 6.75 h). As soon as the last buffer storage is loaded, the cell is "switched off", since for the time being all consumers can cover their heat demand from the heat storage tank assigned to them and thus no heat has to be transported into the cell (switch-off period - in Fig. 3 e.g. from time 6.75 to 21 h). As soon as at least one of the buffer storages in the cell is discharged again, the next pulse starts by fully charging all buffer storages again. The complete shutdown and thus cooling of the cell between the pulses aims at reducing the heat losses. The smaller the pulse length and the longer the switch-off period, the greater is the heat loss reduction.

Enerpipe, a German company that builds innovative local heating networks, has been using this mode of operation for several years, primarily in sparsely populated areas (Euring, 2017, 2020), because pulse operation makes it possible to operate district or local heating networks economically in some cases, even where this would not be possible with conventional operation due to the low density of the heat demand.

3.2 Pulsating Operation in large existing district heating networks

In the German research project “ZellFlex”, this approach is now being applied to a large existing network with urban building density. The aim is to investigate the extent to which pulsating operation in certain cells and at certain times makes heat transport more efficient. The assessment is made with respect to heat distribution losses as well as the hydraulic energy demand of the pump(s), and factors influencing the efficiency of pulsed operation are evaluated.

Five terminal cells in the network were selected, which differ in structure, connected load, location in the network and route length, with the aim of determining influencing factors and restrictions for efficient operation. For an approach to automatic identification of cells, please refer to Mann (2020). In simulation studies, the five cells were each placed in pulsating operation while the rest of the network was in a common operation mode. For a potential analysis, a decentralized heating buffer storage with a volume of 2 m^3 and standby heat losses of 4.5 kWh/d (according to Viessmann (2021)) was assigned to each consumer.

3.3 Heat losses and hydraulic energy

The largest reduction in heat losses in the district heating network was observed in cell 2. The graph in Fig. 4 compares the monthly heat losses for the reference case (without pulse operation) and with pulse operation. The heat losses in pulsed mode are composed of the heat losses of the network and those of the heat storage tanks. The heat losses can be reduced in all months by pulsed operation, whereby the effects are particularly large in summer. In January, 18 % of the network heat losses can be avoided, and up to 52 % in June/July. If the standby heat losses of the distributed storage are added, the relative reduction is still 8 to 36 %.

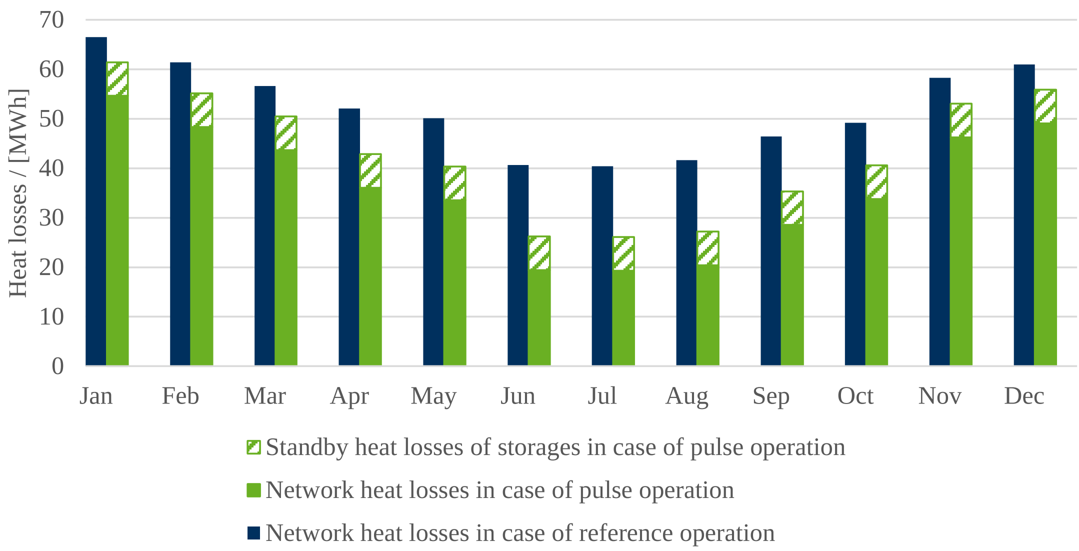

Fig. 4: Heat losses in case of reference and pulse operation for cell 2

This is in line with the expectations that pulsating operation can increase the efficiency of heat transport, especially at off-peak times. This was shown to be true for all cells considered, although to varying degrees. In cell 1, the reduction in network losses is lowest, at 12 to 14 % in summer. This is partly due to the shorter off-time, which is 5 h in summer in cell 1, compared to14.25 h in cell 2 (see Fig. 3). Cell 2 is "switched off" (no heat is supplied) about 68 % of the summertime, compared to 62.5 % in cell 1.

The auxiliary energy demand of the pumps (hydraulic energy) was also considered regarding possible changes due to pulse operation for all periods and cells. A reduction of the hydraulic energy could be determined throughout by the pulse operation, even if to a lesser extent. In all cells, this is in the order of 1 to 2 % in summer.

3.4 Factors influencing the efficiency of pulsating operation

Within the scope of the simulation study, different pulse lengths or switch-off periods were investigated to quantify their influence on the reduction of heat losses. Fig. 5 shows the relative reduction of the network heat losses for each of the five cells in relation to the reference operation for the month of June depending on the length of the switch-off period. (Note: The additional standby heat losses of the storage tanks are not included here). It can be clearly seen that a long interruption of the heat supply (switch-off duration) is advantageous in terms of heat losses. When evaluating the simulations, two factors could be identified that lead to unfavourable switch-off periods and pulse lengths:

- Storage capacity of the decentralised heat storage tank is too low: If the heat demand of the consumer is very high compared to the storage capacity, the storage tank is quickly discharged during the switch-off period. This means that the storage tank must be loaded again early and the length of the switch-off period is thus reduced.

- Volume flow limitation: If a consumer has a rather high heat demand during a pulse, its volume flow limitation might be (almost) reached. Thus, only an extremely low heat flow remains to load the storage tank. This leads to an exceedingly long loading time of the heat storage tank and thus a long pulse length and a short switch-off period.

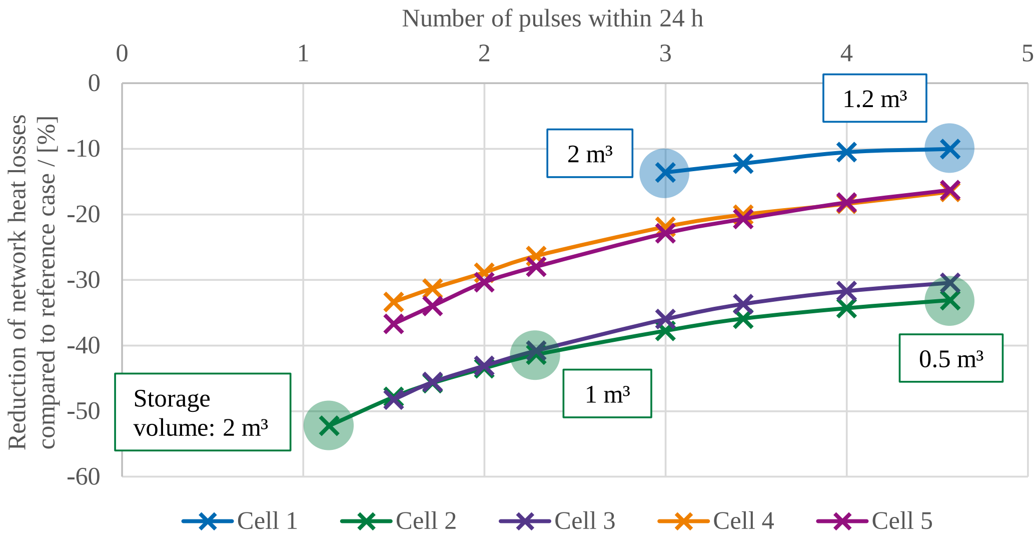

Fig. 5: Reduction of network heat losses compared to reference operation depending on switch-off duration

3.5 Adjustment of the investigated variants

To improve the efficiency of the pulse operation even further, the following measures are now taken - as an example for the month of June in cell 2:

- Measure A: The consumer whose storage is discharged first and thus triggers the start of a new pulse is excluded from the 2 m³ limit, so that it only applies to the other consumers. Therefore, the switch-off time increases from 14.25 to 19.25 hours. The storage volume of the described consumer would have to be increased to 2.50 m^3.

- Measure B: For the consumer, whose storage tank has the longest loading duration, the volume flow limitation is increased by 50 %. This shortens the loading time of the storage tank, and the switch-off period is extended from 14.25 to 17.5 hours.

The original implementation of pulse operation already resulted in a reduction of 52 % of the network heat losses in the month of June in cell 2. With measure A, this value can be increased to 57 %, but with measure B there is almost no improvement. This shows that the switch-off time is only one of several factors that influence the efficiency of pulse operation. In addition, it becomes clear that a significant increase in efficiency can be achieved through relatively simple measures (increasing the size of only one storage unit in the cell). Consequently, the implementation of pulse operation in real DH networks requires careful and extensive planning.

3.6 Summary and outlook – pulsating operation

The results of the simulation study have shown the benefits of pulse operation for certain network areas and under certain conditions. It became apparent that the effects differed greatly for the five cells. Therefore, the development of cell identification characteristics will be taken up again in the further course of the project. In addition, the pipe stress due to the temperature fluctuations caused by the pulsed operation will be investigated. Restrictions could possibly arise here, depending of the type of pipes.

The investigations shown here are only an initial assessment of the potential. For practical implementation, there are some requirements for heating networks that are not (yet) fulfilled everywhere. These include:

- Digitalisation of the house stations (iHAST): It must be possible to control the charge of the storage tanks from a central point (e.g., the control room of the network operator) and track all consumers of a network section (cell). For this purpose, there must be a data connection including write access by the heating netwokr operator to the house side of the house stations (Rapp et. al., 2020).
- Decentralised heat storage: Every consumer participating in pulsed operation needs a sufficiently large heat storage. It is important that this storage also enables buffering of the space heating demand, as otherwise pulsed operation is only possible in times with an exclusive demand for domestic hot water. In the studies shown here, a storage tank size of 2 m^3 was assumed - an optimistic value in practice, which means that the economic efficiency would have to be checked. However, it should be noted that the storage tanks could not only be used for pulsed operation, but also for peak shaving in winter, for decentralised heat retention and for increasing renewable heat shares in the network.

4. Decentralised and local heat retention

Local heat retention is intended to distribute decentrally generated heat locally in a targeted manner. The main objectives are:

- Avoiding hydraulic bottlenecks
- Enable higher decentralised feed-in, if available
- Possible reduction of peak loads in the overall network
- Constant, consumption-dependent supply temperature.

In the case of decentralised heat supply, there is a so-called supply limit. This is the point in the network up to which the heat supply is realised solely by the decentralised feed-in. In Fig. 6, this point is marked by an "X". In conventional operation, the supply limit moves quite strongly in the network depending on the feed-in power and the heat load of the consumers (see Fig. 6, left). Especially at times of high heat feed-in, hydraulic bottlenecks can occur. This is because the pipelines at connection points - especially at the ends of the lines - in existing networks are usually not designed to transmit high heat outputs. This means that a lot of hydraulic energy is needed for heat transport.

Avoiding such hydraulic bottlenecks could be made possible by local heat retention. Here, a decentralised storage is used to keep the supply limit as constant as possible in the heating network (see Fig. 6 right). Demand and local generation combined with the storage capability form a cell.

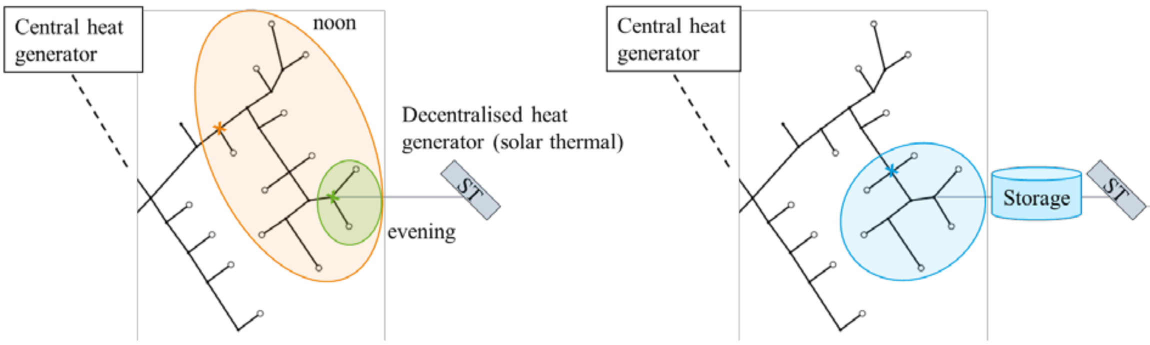

Fig. 6: Decentralised feed-in with moving supply frontiers (left) and local heat retention (right)

In the following, the measure is demonstrated based on decentralised solar thermal feed-in. However, other sources of feed-in, such as waste heat or heat pumps, are also suitable. Cell 1 (see Fig. 1) is equipped with a solar thermal plant of different sizes and is compared with and without large-scale heat storage directly at the solar thermal plant.

In Table 1 the connected load of the consumers in cell 1, as well as the annual consumption is compared to the solar thermal feed-in peak load and the annual heat generation by solar yields.

Table 1: Comparison of connected load/consumption of consumer in cell 1 with solar thermal peak load/yields for different plant sizes

variant	connected load [kW]	consumption [MWh/a]	peak load feed-in [kW]	solar yields [MWh/a]
consumer	1.130	1.757	-	-
ST 500 m²	-	-	315	264
ST 1.000 m²	-	-	630	533
ST 1.500 m²	-	-	945	805
ST 2.000 m²	-	-	1.260	1.076

As seen, the peak load of the feed-in can exceed the connected load of all consumers in cell 1. In the summertime, the daily amount of heat by feed-in of solar thermal power can be the multiple of the required consumer heat. Especially if large open spaces are available for solar thermal plants or industry with waste heat, it can happen that there is a significant surplus of heat available locally. This means that the excess heat must be distributed to the main network without shutting off, which should be avoided for efficiency reasons. For this purpose, it can be suitable to store the heat locally and only/mainly distribute it in a certain area, the cell. Having a look at the impact of variant with 1.000 m² solar thermal plant in cell 1, for hydraulic reasons a useful parameter is the mass flow at the entrance of cell 1. See Fig. 7, one can see the comparison of the nominal mass flow with solar feed-in without storage (orange) and with an additional decentral storage in the cell (dark-red). During the time of higher solar yields, a significantly increased mass flow into the main network can be seen in the variant without storage, due to an excess of heat in cell 1 (negative mass flow according to nominal flow direction). With the integration of a heat storage, the exchange with the main heating network can be reduced to a minimum and the heat is distributed in the cell with a time delay.

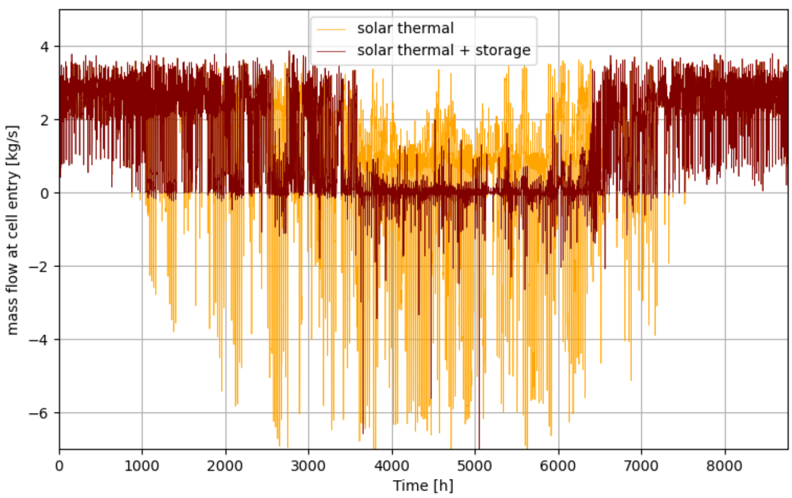

Fig 7: Comparison of mass flow at the entry of cell 1 and solar thermal feed-in with and without storag; positive mass flow means nominal flow (demand in the cell)

The local heat retention can significantly reduce the heat distribution to the main network, which can lead to a reduced effort for feed-in pumps. In addition, a reduction in heat losses is conceivable, since with the help of the feed-in and storage of the heat, the cell is independent of the main network with regard to the flow temperature.

5. Local and temporal adaption of flow temperature

5.1 Temporal adaption of flow temperature

Usually, the central supply temperature (from the central heat generator) in heating networks is controlled by means of a fixed, outdoor temperature-dependent operation mode. The aim is usually to ensure that a minimum supply temperature specified in the Technical Connection Condition (TCC) is maintained at each consumer (on the network side). However, usually the supply temperature actually achieved there is *not* evaluated/measured and accordingly no short-term adjustment of the centrally fed supply temperature takes place. Only longer-term adjustments are relatively common, for example if complaints from customers suggest that the supply temperature achieved at the customer's system is not sufficient. This procedure may lead to higher supply temperatures being operated in heating networks than would actually be necessary to comply with the TCC. If, in the future, real-time data of the network-side temperatures at the consumers become increasingly available due to advancing digitalisation, new types of possibilities for controlling the central supply temperature could arise.

Therefore, a supply temperature operation mode was developed that uses the lowest supply temperature measured at the consumer substation to control the DH network temperature at the central heat generator. The point with the lowest supply temperature is called Temperature Index Circuit (TIC), comparable with the pressure index circuit usually used to control the main pump in the network.

In Fig. 8 the TIC operation mode is illustrated. The temperatures at the TIC are usually above the minimum temperatures according to the TCC (see Fig. 8, left). The difference between the TIC und the required minimum temperature according to the TCC shows the potential for reduction of the network supply temperature. In Fig. 8 (right) the supply temperature at the heat generator is temporally adapted considering the minimum required temperature of the consumers.

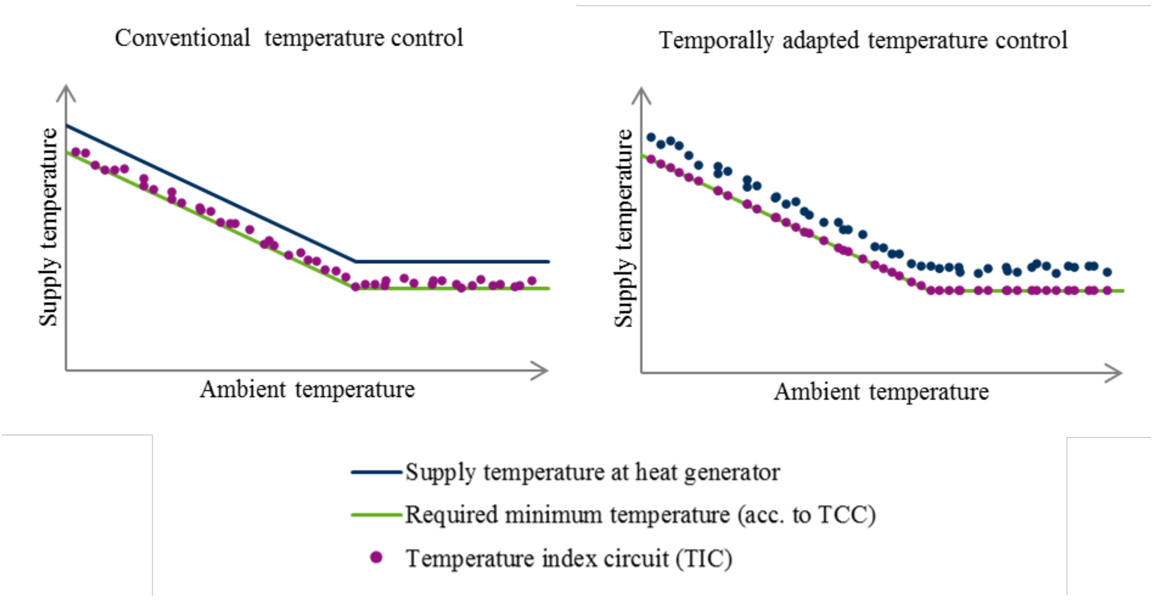

Fig. 8: Schematic diagram of conventional network temperature control (left) and temporally adapted temperature control with respect to the Temperature Index Circuit (right)

The current work deals with criteria and minimum requirements for TIC operation:

- How many metering points are required in the network?
- What type of consumers (e.g. commercial, residential) or consumer size is preferable from a measurement point of view?
- What is the minimum flow rate that the consumer must have after a shut-off period?

Evaluations on this will be published with the completion of the project in 2023.

5.2 Local adaption of flow temperature

Another aspect of flow temperature adjustment is the local decreasing or increasing of the supply temperature. The local increase can be useful if there are network sections that have a higher supply temperature requirement than the main network. Up to now, the supply temperature for the entire network has often been raised centrally in order to guarantee supply. However, this leads to significantly higher network losses and inefficient operation. It would be conceivable to raise the supply temperature in sections, e.g. using a heat pump, waste heat or similar.

More often, however, individual network sections have a significantly lower flow temperature requirement than the main network, e.g. because the network has been extended with more modern buildings. In this case, a local flow temperature reduction is a comparatively simple option. This can be done by mixing the return flow into the supply flow with a pump to overcome the pressure difference. In the case of the example network, cell 2 (see Fig. 2) is lowered in stages. The reduction of heat losses in the network can be seen in Fig. 9. The consumption of the mixing pump can be neglected in comparison to the heat losses.

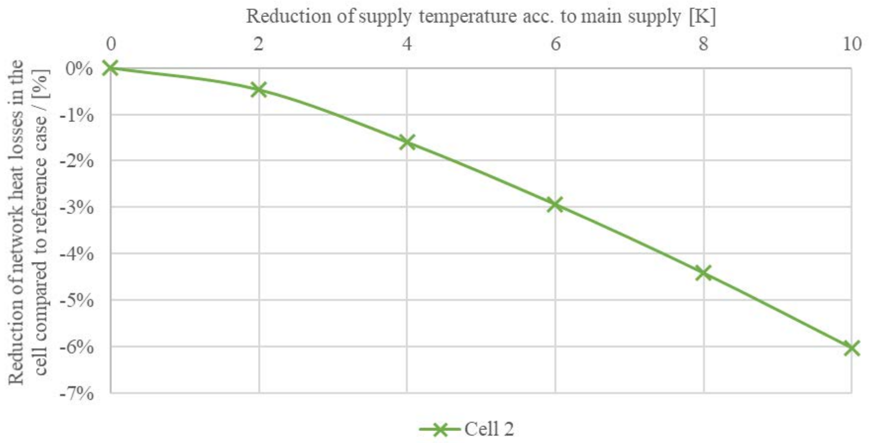

Fig. 9: Reduction of network heat losses by decreasing the supply temperature via a bypass at cell 2

6. Requirements and challenges

The cell boundaries presented in Fig. 1 have been selected manually on the basis of various criteria for the example network and tested and evaluated with the measures presented. However, the aim of the project is to develop generally applicable criteria for defining cell boundaries. As known from the electricity sector, these cells do not necessarily have to be fixed, but can move based on changing boundary conditions.

An important condition for this is the spatially and temporally resolved knowledge of the heat demand and possible heat input. The required flow temperature of the consumers is also relevant. In this regard, studies have already been conducted to evaluate the use of automated clustering methods (Mann, 2020).

Furthermore, the usually installed volume flow limitation in the consumer substations can restrict flexibility measures such as pulsation operation or a reduction of the flow temperature, although the energy-saving effect is obvious.

The necessary measurement data from the networks are often not currently available. Knowledge about the condition of the entire network can often only be estimated on the basis of a few measuring points. For this reason, large-scale digitalisation of the heating networks is an important criterion for efficient, decentralised and flexible operation.

7. Conclusion and Outlook

A decentralised heat supply in the future, especially in existing urban heating networks, poses a major challenge for many energy providers. Network operation must become more flexible, considering the requirements of the consumers. This article has shown the first approaches to flexibilisation, which will be investigated and expanded in more detail. It has been shown that the conventional operation with an overall network view can be replaced by a cellular operation if detailed information about the consumer behaviour is known.

Within the research project, the approaches presented here will be further deepened and necessary requirements will be developed. With the advancing digitalisation of the heating networks, flexibility measures can be put into practice and evaluated in the future.

8. Acknowledgements

This project was founded by the Federal Ministry for Economic Affairs and Climate Action (FKZ: 03EN3001)

9. References

Boß, V. et. al., 2022, Flexibilität der Wärmeversorgung – Untersuchungen zum pulsierenden Netzbetrieb, EuroHeat&Power 4-5/2022. Technische Universität Dresden, Professur für Gebäudeenergietechnik und Wärmeversorgung.

Euring, M., 2020, Wärmenetzplanung 4.0: Quartier ist nicht gleich (Neubau-) Quartier, Netz ist nicht gleich Netz, EuroHeat&Power 7-8/2020. Enerpipe GmbH.

Euring, M., 2017, Smarte Wärmeverteilung in Neubaugebieten reduziert Wärmeverluste auf ein Minimum, EuroHeat&Power 5/2017. Enerpipe GmbH

Mann, L., 2020, Vorlauftemperaturvariable Zellbildungsverfahren für Wärmenetze, Studienarbeit. Technische Universität Dresden, Professur für Gebäudeenergietechnik und Wärmeversorgung.

Rapp, H., Digitalisierung von energieeffizienten Quartierslösungen in der Stadtentwicklung mit intelligenten Fernwärme-Hausanschlussstationen – iHAST (Ohasen 1-2), AGFW, Frankfurt a. M.

Viessmann, 2021, Datenblatt Vitocell 100-E und 100-W, Steinhaus bei Wels und Allendorf, Viessmann GmbH & Co. KG