Measurement Results of a District Heating System with Decentralized Incorporated Solar Thermal Energy for an Energy, Cost Effective and Electricity Grid Favorable Intermitting Operation

Axel Oliva[1], Youmi Kim[1], Manuel Lämmle[1], Sebastian Herkel[1],
Alexander Ripka[2] and Christoph Gebele[2]

[1] Fraunhofer Institute for Solar Energy Systems ISE, Freiburg i.Br. (Germany)

[2] Badenova Wärmeplus GmbH & Co. KG, Freiburg i.Br. (Germany)

Abstract

An overall measurement analysis of a district heating system with distributed decentralized solar thermal systems is given for the period of in total one year. Due to the solar thermal yield of each building supply system the district heating system results in an intermitting operation especially during summer period of time. By implementing intelligent operation modes developed by Elci (2018) and Elci et al. (2015) DH supply of each building connection unit are to harmonize over time to enlarge periods of intermitting operation of the DHN especially by taking periods of a high share of PV in the electricity grid into account. Focus in the analysis carried out is put to energy efficiency and temperature levels of each building supply system and it is shown that the energetic design key data are met. Operational performance instead is related on the analyzed high return temperatures of the systems due to hydraulic unbalanced issues and is therefore away from the expected based on the concepts for energy and cost efficient operation modes by Elci (2018) and Elci et al. (2015).

Keywords: decentralized solar district heating system, economic optimal operation, decentralized feed-in, intermitting district heating operation modes, Freiburg-Gutleutmatten

---

1. Introduction

During the course of an inner-city development the housing estate with 500 apartments, a heated floor area of 40.000 m² in a development area of 82.000 m² and a heat demand of 2.900 MWh/a is being realized. Within the frame of this project decentralized solar thermal systems are installed in each building and will be integrated in a heat supply concept based on a combined heat and power (CHP) district heating (DH) system. The idea is that during periods with high irradiation in summer heat demand is covered by solar thermal systems and during winter by the CHP unit. The assumption is that this kind of design and operation management will be constructive to supply an urban area on a medium and long-term perspective. Central objectives of the project are to implement a concept for the operation management and to derive general rules for comparable urban areas. This will be carried out considering the ongoing massive transformation process of the overall energy system.

2. Demonstration site of “Freiburg Gutleutmatten” and its realization

In this concept, the total heat demand is covered by 38 decentralized solar thermal units including its decentralized storages and the heat produced by the central CHP unit and boiler. The total area of collectors amounts to 2.000 m² (1.400 kW_{th}) and the specific storage volume is approximately 80 litres/$m^2_{aperture}$. It is expected that this leads to a total heat coverage of about 30 % and enable a self-sustaining supply by solar thermal for long periods during summer. The remaining heat demand is supplied by the central CHP unit and boiler. The heat losses of the network (1.540 m) are designed to about 260 MWh/a where the reduced operation time is not taken into account. The aim is to reduce the distribution losses by more than 30 %.

2.1. Objectives of the project

Firstly, the role of solar thermal technology in supplying heat to urban areas is evaluated. This is done by considering prospective conditions of the energy business. The focal point is thereby put on an integral consideration of power and heat consumption and the corresponding supply network systems. Secondly, an innovative and economically promising solution is demonstrated for investors, for the operator and finally for the clients in the integration of solar thermal technology to take the district heating network (DHN) for

doi:10.18086/eurosun.2020.02.06 Available at http://proceedings.ises.org

some periods of time during summer out of operation. The approach is a decentralized implementation of solar thermal into the supply systems of each connection unit to deactivate the CHP operated district heating network for time periods with high irradiation and hence a high fraction of photovoltaics in the electricity grid. During these periods the operation of the CHP is expected to be uneconomical due to the low corresponding feed in tariff.

2.2. Basic features

2.2.1. Key data

The urban development area has the key data as shown in Table 1. It is characterized by a wide variety of system sizes and architectural feature that is due to the fact that the development planning intents to cover a wide range of individual aspects and each property has different ownerships.

Table 1: Basic design values for heat supply of the district of Freiburg-Gutleutmatten

Urban scale of area:	81.500 m²
Accommodation units:	525 (1 ... 42)
Heated floor area:	40.000 m² (3 to 9 floors)
Total heat demand: (~10 % losses DH)	2.900 MWh/a
DHW and circulation:	30 kWh/m²$_{hf}$
Specific heating demand:	35 kWh/m²$_{hf}$
Supply- / Return temp.:	75 °C / 40 °C
Trench length:	1.540 m
Building DH substations:	38 (5 kW$_{th}$ … 100 kW$_{th}$)
ST-system:	2.200 m² (7 m² … 145 m²)
Specific area of ST:	0.05 m²$_{Aap}$/m²$_{hf}$
Specific ST yield:	17.5 kWh/m²$_{hf}$
Solar thermal fraction:	30 %

Due to the scientific focus of operation periods in summer, the size of solar thermal systems installed in each unit is demonstrated in Figure 1. Systems with heat transfer stations at each apartment (HTS) are indicated separately as well as systems with vacuum tube collectors instead of flat-plate collectors.

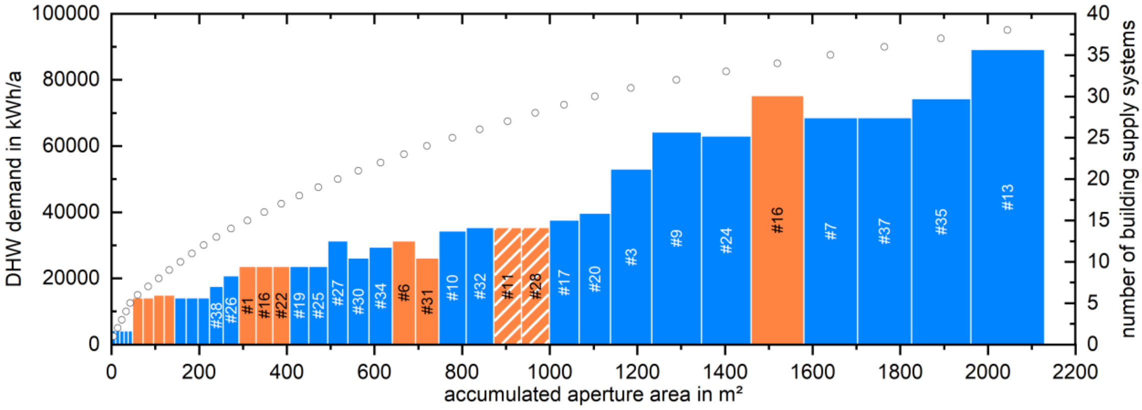


Figure 1: Dimensioning of all building supply systems regarding aperture area and the related DHW demand. Bars in orange stand for decentralized DHW systems with apartment heat transfer stations, crosshatched bars stand for evacuated tube collector systems.

The high range of dimensioning of the resulting connection units becomes clear. The hydraulic layout of the DHN and the related aperture areas of the DH connection units are shown in Figure 2.

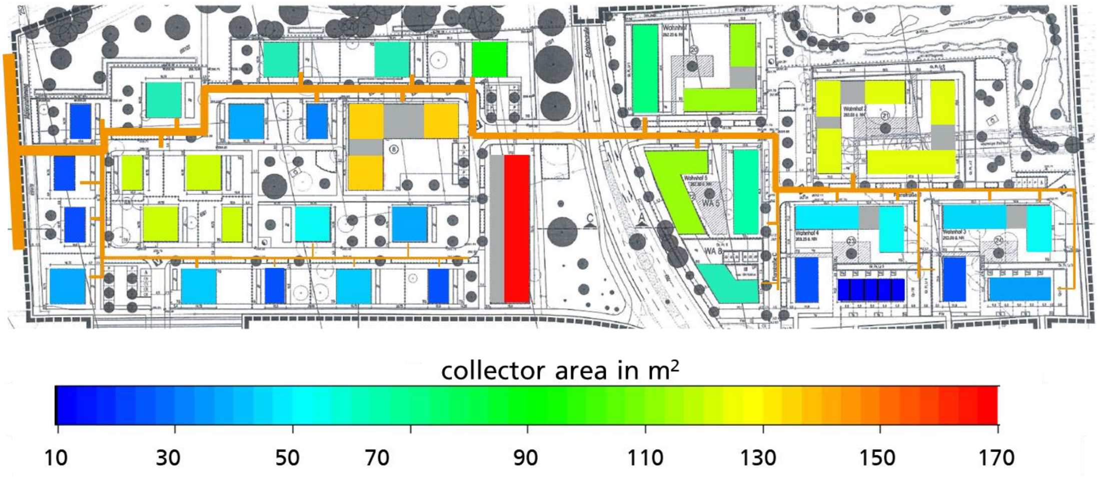
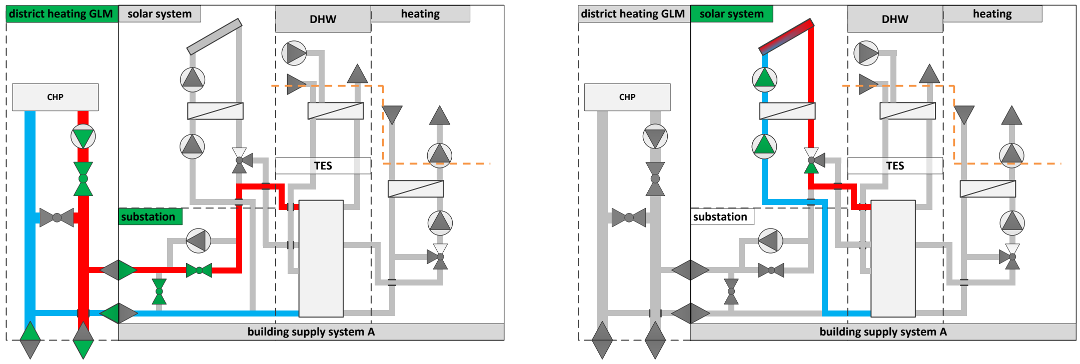


Figure 2: Distribution of aperture area related to the hydraulic distribution system of DH in "Freiburg-Gutleutmatten"

Special attention has to be put on the detached houses connected at the end of the DHN, because those units are the smallest in size and are at the point that is the farthest way from the feed-in point of the DHN.

2.2.2. System layout

The following Figure 3 illustrates the basic system layout for a general decentralized heat supply system for the case of heat supply from a) the DHN or b) from the ST system. The scientific investment includes standard pumps for the decentralized ST-feed as option for smart DHN operation modes described in Elci 2018 and Elci et al. 2015 (compare Figure 4).



a) Heat supply from DHN **b) Heat supply from decentralized ST system**

Figure 3: Basic hydraulic layout of a DH connection unit for one building including the solar thermal system. The boundary for the investment of the heat supplying company does include the hot water storage tanks as well as the solar-thermal system and is indicated by the orange dashed line.

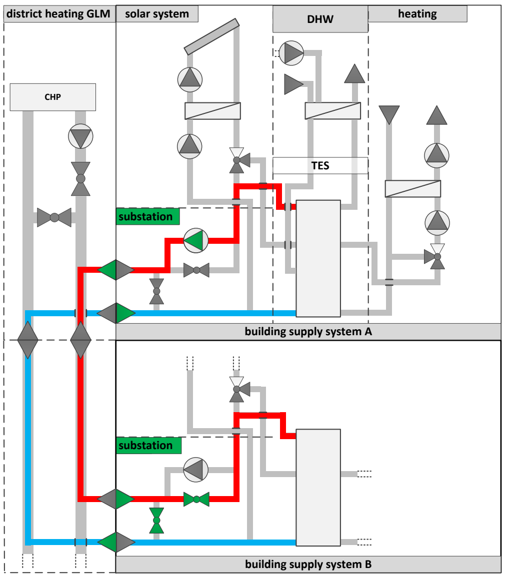


Figure 4: Decentralized ST-feed in for cooperation modes of neighbored connection units described in Elci 2018 and Elci et al. 2015.

In the district of “Freiburg-Gutleutmatten” the heat supply system for each building is quite unique due to the fact of separate ownership. Basically, three different hydraulic schemes have been installed. These different layouts result in three different general measurement schemes (Table 2):

- Scheme 1: Decentralized apartment heat transfer stations with two piping distribution system, one heat meter at load side
- Scheme 2: Centralized DHW preparation with two separate heat meters for distribution of DHW including circulation and another for distribution of space heating
- Scheme 3: Centralized DHW preparation with three separate heat meters for distribution of DHW, circulation and distribution of space heating

Table 2: Measurement schemes in district of “Freiburg-Gutleutmatten” for different DH connection units and the resulting installation of heat meters

System measurement scheme	DHW	Circulation	Space heating	Total load side
1				×
2	×		×	×
3	×	×	×	×

2.3. Realization process

The construction started in 2016 by taking the first solar-thermal system in operation and is still an ongoing process. By August 2020 one solar thermal system has not yet been commissioned, and another one has just been taken in operation. Several typical operational optimizations have been carried out to that point of time. The following issues are most significant:

- It has been observed that the dynamics of solar thermal system are much higher than the dynamics the system control is able to handle. Especially the temperature measurement at the collector field has caused a lot of work for optimization. At the moment the collector fields are driven by a method used by vacuum tube collectors to ensure that the temperature sensors constantly reads correct values
- The ability of data transmission and dynamic parametrization of the installed controller is far from the demanded possibilities.

- The volume flows for primary and secondary circuits of the solar thermal system used are not balanced efficiently.
- Some valves used to get stuck so that they had to be replaced.

3. Heat balances and energy efficiency

In the first step, energy balances for the entire district heating network are shown. In the second step, analysis is done for the system of DH connection units.

3.1. District heating

The heat balance for the entire district is analyzed with the restriction of ongoing work in progress at the site.

3.1.1. Heat balances for entire district

The entire heat transferred to the district heating network Q_{DHN} is at 2 311 MWh in the period of 15th August 2019 to 14th August 2020. There was a period of missing measurement data from 27th January 2020 to 1st March 2020. For this period, missing values are interpolated based on the average slope of the adjacent missing period. This value puts against the sum of all heat meters of the DH connection units $\sum Q_{\mathrm{DHN,CU,i}}$ of 2,101 MWh. Here, there existed several small missing data periods as well. For this period, data interpolation has fulfilled as well. Heat losses of DHN $Q_{\mathrm{DHN,loss}}$ during that period of time account to 210 MWh. This means relative losses of 9.07 %. Furthermore, the solar thermal yield over all systems $\sum Q_{\mathrm{ST,i}}$ achieved a value of 686 MWh. The sum of all heat meters that account for distribution supply of DHW, circulation and space heating of the building supply system as useful supplied heat output to the distribution system of the connected building $\sum Q_{\mathrm{bui,cons,i}}$ amounts to 2,440 MWh. When taking that value into account, including the losses of the building supply systems $\sum Q_{\mathrm{bui,loss,i}}$ of 131 MWh and the losses of the DHN $Q_{\mathrm{DHN,loss}}$ and putting the transferred heat of district heating against Q_{DHN}, a solar thermal fraction $f_{\mathrm{sol,DH}}$ of 17 % is being calculated based on equation 1 for the entire district heating system. Resulting from the heat balance, the heat losses of building supply system $\sum Q_{\mathrm{bui,loss,i}}$ are calculated. The balance and the corresponding losses are shown in Figure 5.

$$f_{sol,DH} = 1 - \frac{Q_{DHN}}{\sum Q_{\mathrm{bui,cons,i}} + \sum Q_{\mathrm{bui,loss,i}} + Q_{\mathrm{DHN,loss}}} \qquad \text{(eq. 1)}$$

$$Q_{bui,cons,i} = Q_{DHW} + Q_{circ} + Q_{SH} \qquad \text{(eq. 2)}$$

where Q_{DHW} is domestic hot water, Q_{circ} is circulation losses of DHW distribution and Q_{SH} is space heating.

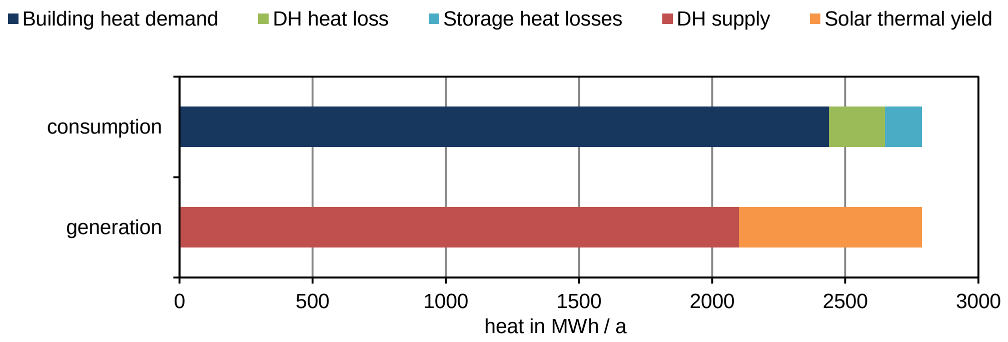


Figure 5: Heat balance for the heat supplying systems and heat consumption systems in the district of "Freiburg-Gutleutmatten" for the period of 15th August 2019 to 14th August 2020

3.1.2. Daily mean power and temperatures at district heating substation system

The daily mean of the power at district heating substation system and the sum of the power of the DH connection units are shown in the Figure 6. The plot is not in order of time but is sorted by the order of the power at district heating substation system. Any day with missing point is excluded. The maximum value of the daily mean power at district heating substation system is at 848 kW. Due to heat losses in the DH network the power at DH level is mostly larger than the sum value of DH connection units. Some exceptional cases seem to be caused by outliers or unexpected malfunctions from supply side considering the supply temperature. The area under the line can be interpreted as a heat in kWh. Therefore, the area between the green and blue line is expected loss for the district heating system. For the entire period, the supply temperature maintains similar values with an average of 70.7 °C while the return temperature shows a trend having low temperatures when power is high. That is due to the fact of too high volume flows at low loads at the DH primary side and indicates hydraulic unbalanced systems.

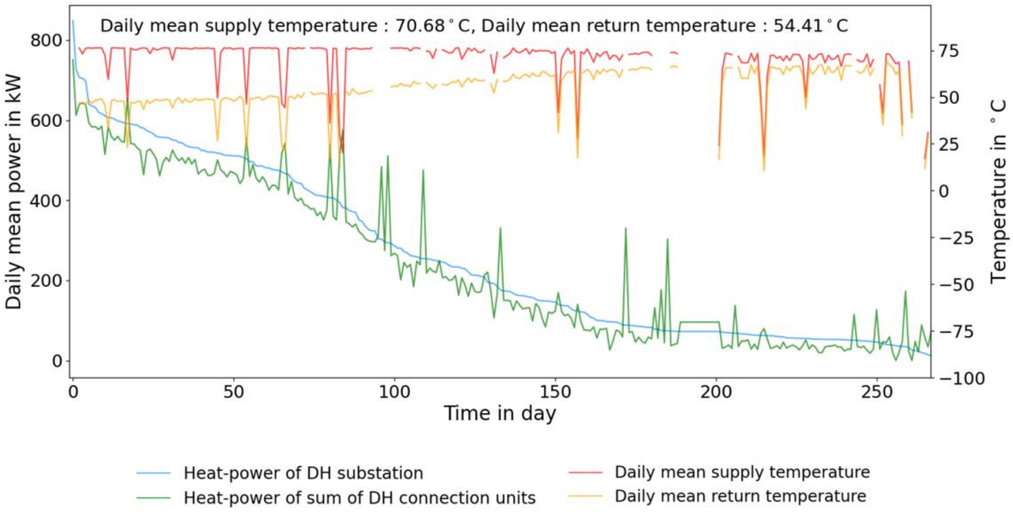


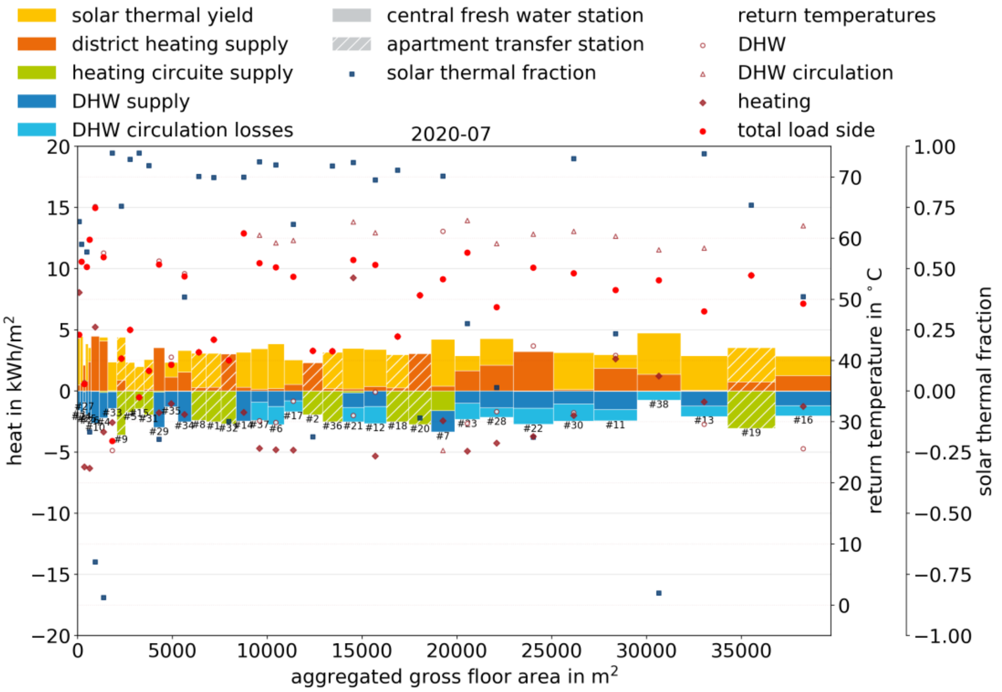
Figure 6: Daily mean for heat and power at district heating system of "Freiburg-Gutleutmatten"

3.2. DH connection units and building heat supply systems

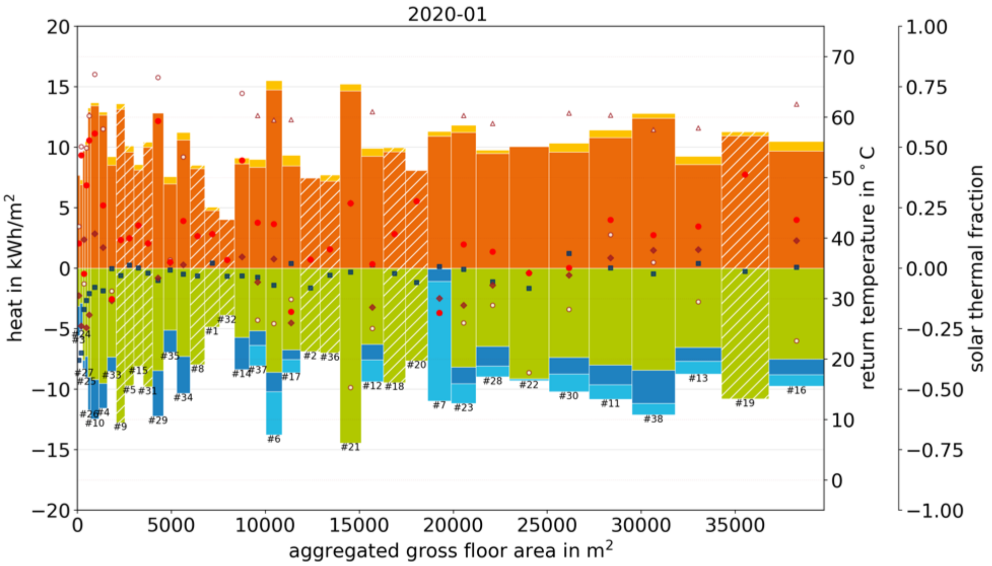
In this chapter, the connection units and its related building heat supply systems are analyzed. The distribution of heat supplies (solar thermal and district heating), heat consumptions for various usages (DHW and circulation and space heating), return flow temperatures and solar thermal fraction are plotted altogether in Figure 7 and Figure 8. Each bar represents each DH connection unit and those are in ascendant order of corresponding floor area. The heat values are calculated as kWh per square meter of heated floor area of each DH connection units. Figure 8 shows the average values for one year of 15th August 2019 to 14th August 2020. Figure 7 shows the seasonal representations with July 2020 in Figure 7a and January 2020 in Figure 7b.

3.2.1. Total heating supply to the distribution system of the building heat supply systems

The demand for domestic hot water was designed at 15 kWh/(m^2_{hfa} a) considering each connection unit. Circulation losses were taken into account with another 15 kWh/(m^2_{hfa} a). In Figure 7a, monthly values for the period of July 2020 are shown, where space heating operation is supposed not to occur due to the related ambient temperatures. By that it becomes clear that design and measured values do not differ much from each other.



a) Summer (July 2020)



b) Winter (January 2020)

Figure 7: Specific heat supply and consumption, return flow temperatures and solar thermal fraction for each unit for summer (July 2020) and winter (January 2020) period. The specific heat is calculated based on floor area. Each building is represented as a bar

The heat demand for space heating was designed to 35 kWh/(m^2_{hfa} a). Regarding the thermal insulation standard KfW-Effizienzhaus 55 (EnEV2014) has been applied under additional requirements of the city of Freiburg i.Br. Thereby heat recovery from ventilation was not a mandatory feature. It can be shown that during the period of 15th August 2019 to 14th August 2020 heat demand is in a range of 33.4 kWh/(m^2_{hfa} a) to 85.4 kWh/(m^2_{hfa} a) at a mean of 57.7 kWh/(m^2_{hfa} a).

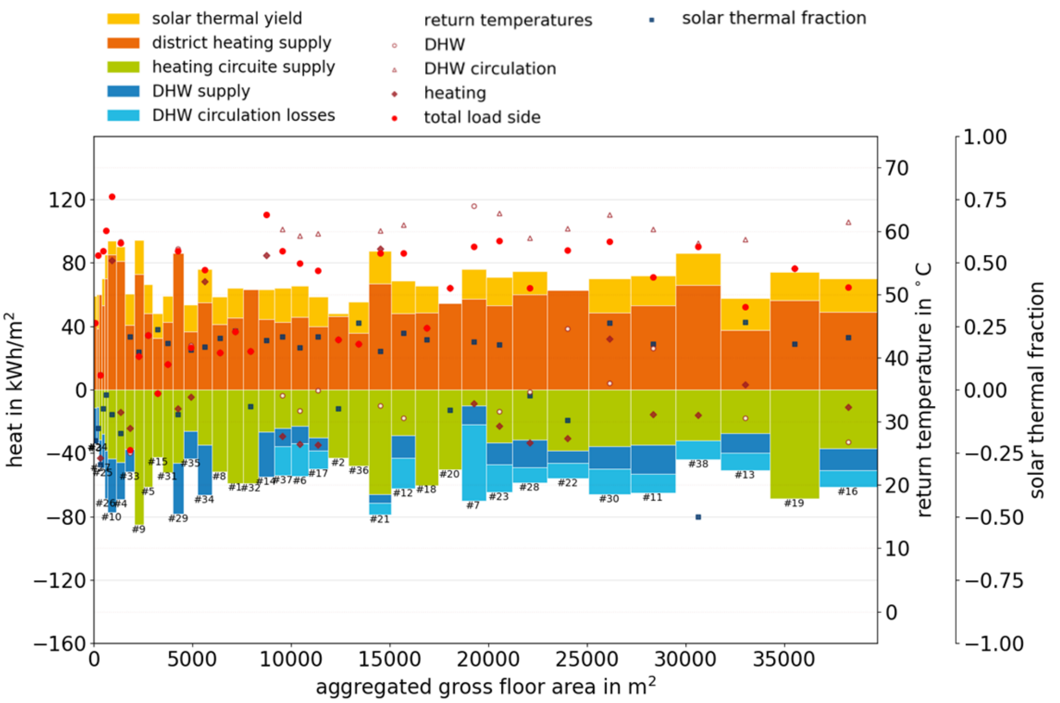


Figure 8: Specific heat supplies and consumptions, return flow temperatures and solar thermal fraction for each unit for one year. The specific heat is calculated based on floor area. Each building is represented as a bar ascendant ordered by the floor area

3.2.2. Solar thermal yield

The same analysis is carried out for the solar thermal yield corresponding to each connection unit. Solar thermal yield has been designed to 350 kWh/(m^2_{Aap} a) by taking 0.05 m^2_{Aap}/m_{hfa} into account. The real installation differs regarding area especially for those two connection units where evacuated tube collectors have been installed instead of flat plate collectors. These systems were designed with 0.036 m^2_{Aap}/m_{hfa}. This means a specific solar thermal yield of 1/3 higher is expected compared to flat plate collectors. The range for the measured yield is in between 8.8 kWh/(m^2_{hfa} a) and 21.5 kWh/(m^2_{hfa} a) with a mean value over all connection units of 18.1 kWh/(m^2_{hfa} a).

3.2.3. Solar thermal fraction

The solar thermal fraction $f_{sol,DH}$ has already been stated for the entire DHN in equation 1. The same relation can be used for each DH connection unit in the district as following equation 3.

$$f_{sol,i} = 1 - \frac{Q_{DHN,i}}{Q_{bui,cons,i}} \qquad \text{(eq. 3)}$$

Looking at Figure 7 it becomes obvious that some systems run on elevated temperatures at the set point temperature sensor of the hot water storage tank and additionally on a high level of effective operating return temperature. This leads to even negative values for f_{sol} for 14 out of 38 systems examined in the stated period of time.

For seasonal comparison, the solar thermal fractions in summer are much higher than the ones in winter as we can clearly see in Figure 8a and 8b. In summer, the heat supply as well as the demand are already very low which would be expected to be no space heating demand any more. Furthermore, the absolute contribution of solar thermal high caused by high solar irradiation. Those factors are resulting larger than 75% of solar thermal fraction for most of buildings. Meanwhile during the winter, both heat supply and demand are increased by two to three times. Most contributions are coming from the space heating expressed as green color. As a result the solar fraction is dramatically decreased.

3.2.4. Temperatures of distribution systems of the building supply systems

As shown in Figure 7 and Figure 8, four categorized return flow temperatures are analysed as below.

- Return flow temperature of distribution for DHW supply ($T_{\mathrm{DHW,ret}}$)
- Return flow temperature of circulation for DHW supply ($T_{\mathrm{DHW,cir,ret}}$)
- Return flow temperature of distribution of space heating supply ($T_{\mathrm{SH,ret}}$)
- Effective return flow temperature of overall consumption circuits of the building supply systems ($T_{\mathrm{load,ret}}$)

For the following analysis it is important to keep in mind the measurement schemes stated in Table 2 that does indicate the hydraulic circuits related to that temperatures.

$T_{\mathrm{DHW,ret}}$ can be observed for the measurement schemes of Type 3 of Table 2. Considering Figure 8 most significant are some quite high values of T_{DHW} at values of more than 40 °C at #22 and close to it in #11. It can be shown that most heat meters detect temperatures in a range of 20 °C to 30 °C.

Considering again measurement schemes of Type 3 of Table 2 temperature of circulation flows can be taken into account as well. Remarkable high temperatures $T_{\mathrm{DHW,circ,ret}}$ can be analysed. Especially in some smaller dimensioned systems this temperature can reach values of about 65 °C. This means that there is no temperature difference of the set-point temperature for DHW preparation and the return flow temperature of DHW circulation. It can be stated that circulation return flow temperatures are far from energy efficient operation.

The operative temperature of return flow for space heating supply $T_{\mathrm{SH,ret}}$ can be analysed for Type 3 and Type 2 of Table 2. By looking at Figure 8 it is shown that this temperature is in a range of about 25 °C to 35 °C. That is about in the expected range due to the fact that most of these buildings include radiator heating systems as well. But also very small buildings like #29 and #35 show quite high temperatures although floor heating systems are installed.

Finally the effective total load operative return temperature for the demonstrated period of one year in Figure 8 can be examined by considering $T_{\mathrm{load,ret}}$. For that value quite a high level is shown at a range of about 60 °C. The analysed values seem to represent quite a contemporary standard DHN system without any measures for energy efficiency.

The return temperatures for DHW, circulation and for some extend space heating can be also compared in different seasons as shown in Figure 7a and Figure 7b. Overall, these DHW related temperatures are basically not related to seasonal effects. In Type 1 of Table 2 the temperatures are effected of the space heating system and so show the characteristics of higher values during summer period of time than during winter periods, where the space heating system does dominate the energy consumption by lower return temperatures.

3.2.5. Temperatures of hot water storage tanks

The hourly mean temperatures of the top of the hot water storage tanks of each DH connection unit can be examined in Figure 9. It becomes obvious that some systems operate at temperatures over the set point of the hot water storage tank sensor for quite long periods of time and others do not do so and so depend on heat supply of the DHN. By that, a shift of solar thermal energy by solar thermal feed in seems to be an attractive option to reduce standard heat supply by DHN as much as possible.

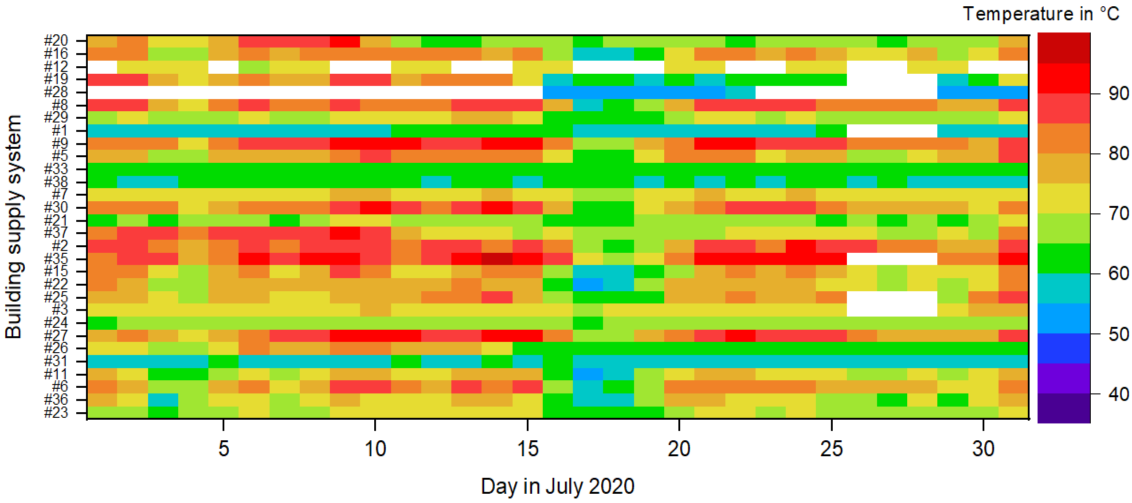


Figure 9: Daily mean temperatures at the set point sensor for district heating supply of the hot water storage tanks of each connection unit for the period of July 2020

4. Intermitting operation of the district heating network

In this section, the heat demand of each building supply system through the connection unit to the DHN is analyzed. In the following Figure 10, the heat demand for the month of July in 2020 is visualized in a time step of 15 minutes. Missing data occurred constantly over all systems and is grey colored.

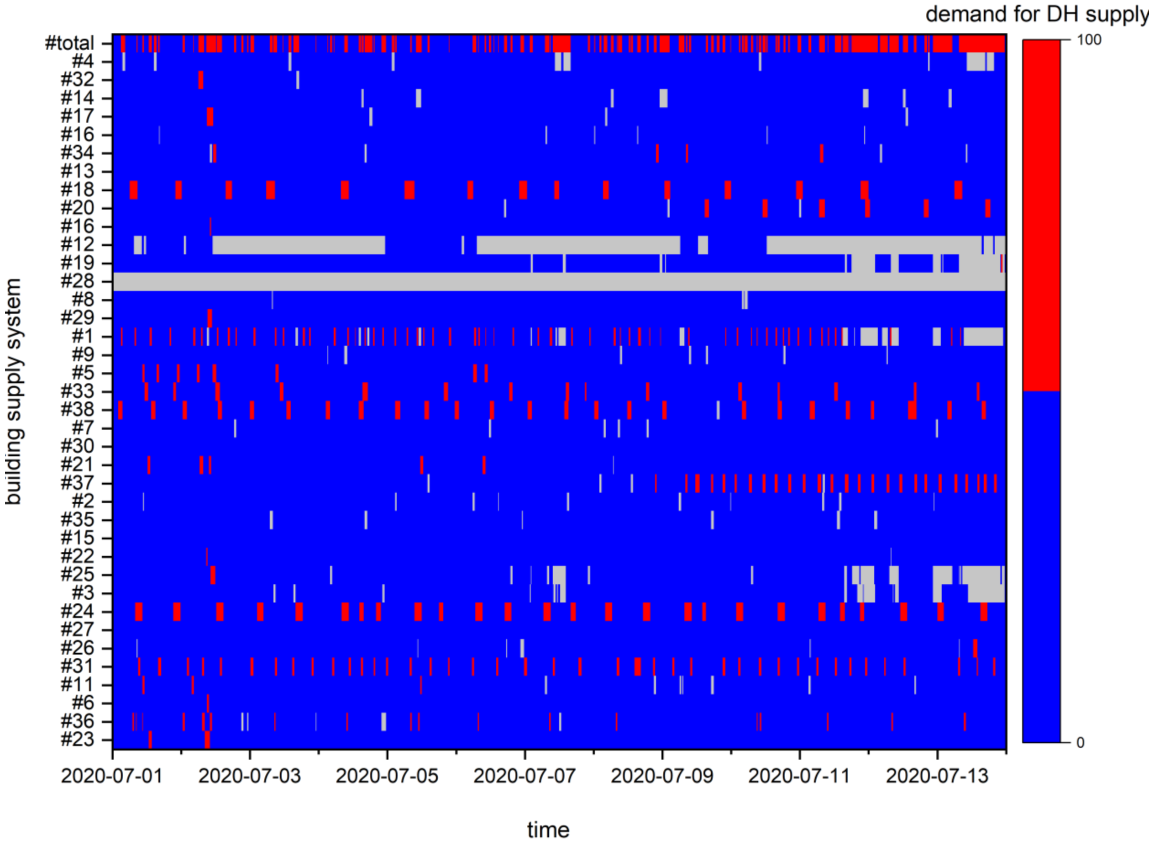


Figure 10: Demand of each building supply system for DH supply in the month of July of 2020 in time steps of 15 min. Heat demand is in red, missing data in grey and no demand for DH supply in blue color. For the consideration of #total the connection units of the

It becomes clear that there are only small periods of time where all building supply systems have no DHN heat demand. Furthermore, missing data at least two of the 38 building supply system (#12 and #28) affects the analysis significantly. In addition, it has to be considered that in the related period of time, three solar thermal systems were not in operation (#18, #24, #28). With the assumption, that the "nan" values have a heat demand (red), 1.5 % of the entire time of that period has to be considered without heat demand of the entire building supply systems connected to DHN. This is a reasonably low number. By taking the three systems out of the analysis and eliminating the two systems with missing data, the result changes to 25 % of time. For that consideration the fictive value "#total" is shown in the graph by its resulting development over time.

5. Conclusions and outlook

The DHN and 38 building supply systems meet in general the energy design parameters ($Q_{\mathrm{DHN,loss}}$ = 9 %, Q_{ST} = 340 kWh/m²$_{\mathrm{Aap}}$, $Q_{\mathrm{bui,cons}}$ = 56 kWh/m²$_{\mathrm{hfa}}$). Due to the large range of dimensioning and different ownership of the 38 building supply systems, it is challenging to establish a district wide standard of concept of control and hydraulic layout. The installation processes and the operation are therefore considered as quite "unhandy". This is resulting in a reasonable energy efficiency ($\bar{T}_{\mathrm{bui,DHN,return}}$ = 46°C) and the effective solar thermal yields do not achieve the optimum temperature levels as originally designed.

Typical malfunctions are caused by hydraulic components (e.g. stuck valves), the sensor system (e.g. temperature measurement), data transmissions and insufficient and not adequate standard control algorithms. Thereby they seem not to be appropriate to be integrated in recent "standard" digital processes.

Around 50 % of the building supply systems do not operate as designed with regards to its "temperature efficiency". This results in more operation time of the DHN during summer than expected (e.g. only 25 % time with intermitting operation in July 2020).

The "solar thermal feed in" to support neighboring supply systems and to obtain a more robust DH system regarding DH supply will be taken into operation in a scientific approach by implementing both rule based control and model predictive control algorithms. This sophisticated approach, however, currently suffers from "real world" implementation issues. Results of that will be shown in further future analysis.

The future research will focus on increasing the robustness of the digital systems and to gather further insights into the dynamics of the related hydraulic systems. A centrally managed, digitalized control may increase the robustness of the hydraulic system as demonstrated in the concept developed (Elci, 2018; Oliva et al.,2019).

To achieve this, more research on how to transfer "real world" hydraulic installations into digitalized systems has to be conducted. The challenges should focused along the entire system starting from measurement equipment, hydraulic components, software solutions, data transmission, treatment methods to data analysis and visualization algorithms. Therefore, more insights into the characterization of components and dynamics of hydraulic systems have to be gathered to establish robust MPC or rule based control methods.

Acknowledgments

The project has been partially funded by the German Federal Ministry of Economic and Energy and Badenova Wärmeplus GmbH und Co. KG. The authors take responsibility for the stated issues.

References

Elci, Mehmet (2018): Smarte und Dezentrale Solare Fernwärme. Dissertation. Fraunhofer Verlag.

Elci, Mehmet (2018): Wärmeverteilnetz und Verfahren zur Wärmeverteilung. Deutschland Patent DE102017201197A1.

Oliva, Axel; Herkel, Sebastian; Elci, Mehment; Hemling, Sebastian; Wapler, Sebastian; Ripka, Alexander (2019): EnWiSol. Soarthermie in der städtischen Energieversorgung – Energiewirtschaftliche Analyse und Demonstrationsvorhaben „Freiburg-Gutleutmatten". http://publica.fraunhofer.de/documents/N-549554.html.