Two case studies for renewable district heating with solar fraction ≥ 70 %

Paul Volk, Christoph Schmelzer, Oleg Kusyy, Janybek Orozaliev, Ulrike Jordan, Klaus Vajen

University of Kassel, Department of Solar and Systems Engineering, Kassel (Germany)

Abstract

Two case studies of renewable district heating in rural areas with high solar fraction are presented. The first solar district heating system is currently under construction. Here, an approximately 8 km heating network will supply heat to 180 households. The main heat supply components are a large collector field (11,700 m²), a seasonal pit storage tank with 26,600 m³, two internal heat pumps (combined 1.5 MW thermal) to discharge the storage tank and raise the temperature for district heating, and a biomass boiler. The total energy demand of 3.6 GWh/a is supplied by solar thermal (67%) and biomass (26%). The rest is supplied by the internal heat pump (electricity 6%). The second district is smaller, with a total energy demand of 2.3 GWh/a for 100 buildings and a 5 km heating network. The demand is covered exclusively by solar thermal energy (87%) and an internal heat pump (electricity 13%). The main components of the second case study are 5,700 m² of collectors (flat plate and evacuated tube), one 15,000 m³ storage tank and the large heat pump (1 MW thermal). Both systems were modeled in TRNSYS and optimized by using numerical algorithms to achieve the lowest levelized cost of heat (LCoH).

Keywords: Solar District Heating, High Solar Fraction, Renewable District Heating

1. Introduction

Around 57 % of Germany's final energy consumption in 2022 was used to provide heating and cooling (33 % for space heating and hot water) with a renewable share of 17.5 % (German Association of Energy and Water Industries 2024; Umweltbundesamt 2024). In order to achieve a climate-neutral heat supply, local authorities in Germany are obliged to develop heating plans by 2028 (municipalities with more than 10,000 inhabitants by 2026) (German Federal Government 2023). These plans shall define how a climate-neutral heat supply for citizens and companies can be achieved in the respective municipalities by 2045 at the latest.

Based on previous experience and the guidelines of Baden-Württemberg (KEA Baden-Württemberg 2020) and Hesse (Landes Energie Agentur Hessen 2020), a special focus is put on heating networks. Various nationwide studies (Blesl and Eikmeier 2015; Gerbert et al. 2018; Gerhardt 2019) also predict a significant expansion of heating networks, as this can reduce the transformation costs and speed up the process for achieving a climate-neutral heat supply. Local heat sources (solar energy and environmental heat for heat pumps) are generally not sufficiently available to guarantee a comprehensive regenerative heat supply, especially in large cities with dense development (Hess et al. 2019). Fossil-free heating networks are therefore an important prerequisite for decarbonizing the heat supply in these areas. For rural areas, the main focus lies currently on extensive energy-efficient building refurbishment and a building-specific heat supply with individual heating systems (especially heat pumps). The share of heating networks in the future heat supply is less than 20% in the study of Gerhardt (Gerhardt 2019), for example. The reason for this is the low heat density of rural areas, which makes the implementation of heating networks more difficult. However, extensive building refurbishment is generally very cost intensive and also very time-consuming due to low refurbishment rates. In rural areas, this is exacerbated by the fact that the buildings have significantly lower market values compared to urban areas and the refurbishment costs increase relative to the value of the building, which makes implementation less likely. As a result, the challenges for the heating transition in rural areas are particularly large. On the other hand, there are also opportunities. For example, rural areas generally have larger undeveloped areas that represent

10.18086/eurosun.2024.03.07 Available at http://proceedings.ises.org

an important resource for the provision of renewable heat and can be used, for example, for large solar thermal fields, storage facilities and heating centers. Furthermore, the laying of pipelines in rural areas is significantly cheaper than in cities.

This paper examines initiatives to decarbonize the local heating supply in German villages based on two case studies in Rauschenburg-Bracht and Amöneburg-Rüdigheim. Decentralized solutions that include building-specific refurbishments and heat pumps are compared with centralized solar local heating systems that include extensive use of solar fields and thermal energy storage. The results of existing feasibility studies, simulation analyses and cost assessments will be analyzed to identify the most effective strategies to significantly reduce CO_2 emissions. The investigations will form the basis for the implementation of climate-neutral heat supply systems that are economically viable and can cover both current and future energy needs in order to show other villages possible future scenarios for a regenerative heat supply.

2. Case Study 1: Rauschenberg-Bracht

2.1. Boundary Conditions

The first case study focuses on the German village called Rauschenberg-Bracht (or in short "Bracht") in northern Hesse. The village with around 860 inhabitants consists of 2 districts, which are around one kilometer apart, and has a total of 294 buildings. In 2013, a feasibility study was presented for solar local heating (solar coverage rate 100%) for the village at a citizens' meeting in order to make the village's heating supply CO_2 neutral and independent of fossil resources (Solarwaerme Bracht eG 2024). This concept envisaged a 12,000 m² solar field with a 45,000 m³ above-ground tank thermal energy storage (TTES) and did not include any other heat generators. As this concept turned out to be very costly and funding from the state of Hesse or the federal government was ruled out, the Department of Solar and Systems Engineering at the University of Kassel was asked to optimize the solar district heating system and to investigate whether an individual building refurbishment with decentralized heat supply (mainly via air-to-water heat pumps) or a central heat supply via a regenerative heating network would be the more cost-effective solution for a CO_2 saving of at least 80 %. To coordinate (and later finance) the implementation of a regenerative heat supply in the village, the people of Bracht have founded a citizens' cooperative that collected data on the heat supply and the conditions of the cooperative members' buildings. Based on current data, approximately 180 out of the 294 buildings in Bracht will be linked to the local heating network. This includes 156 current buildings and 24 new ones that are being built in the next years.

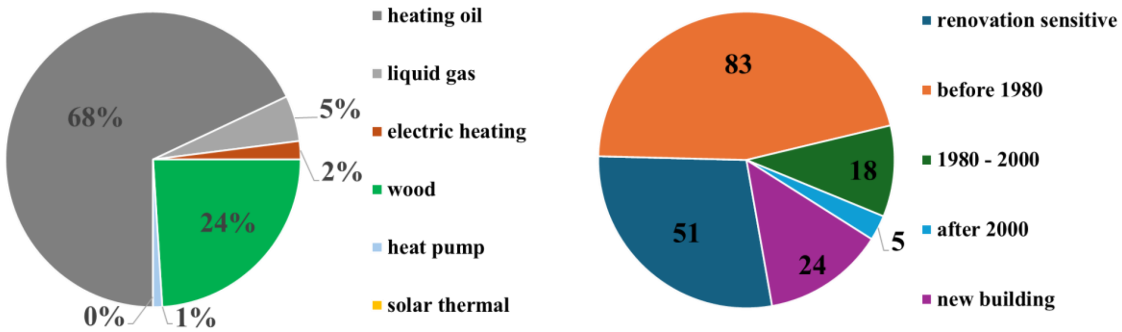

Figure 1: Relative distribution of heat generators in the analyzed buildings (left) and years of construction of the buildings divided into 5 categories (right) (Kelch et al. 2023).

Figure 1 shows the relative distribution of heat generators and the age structure of thes buildings in Bracht. More than 80 % of the buildings were constructed before 1980, with some being half-timbered. The category "renovation sensitive" refers to those half-timbered houses and buildings constructed before 1919. Additionally, a significant part of these predominantly single-family homes is heated using oil heaters or wood stoves, as Bracht is not connected to a natural gas network .

2.2. Centralized vs. dezentralized solution

Kelch et al. (Kelch et al. 2024) examined the refurbishment of buildings with decentralized supply via mainly air source heat pumps or the creation of a regenerative heating network as more cost-effective solution. Here, several assumptions were initially made to make them comparable. Firstly, in both scenarios, 180 potential consumers had to be supplied with heat, including space heating and hot water. Furthermore, the heat supply had to be achieved without the local use of fossil fuels and the use of biomass was not allowed to exceed level of the original state.

In the decentralized renovation scenario described in the paper, decarbonization is targeted through specific insulation measures in individual buildings. This involved using reference buildings in the village, for which detailed information was available, to estimate when building renovation measures would be necessary. For example, it was determined that all buildings that exceed a certain limit value in the heat transfer coefficient must be renovated in such a way that limit values for current funding programs are achieved. The number of underfloor and panel heating systems already installed in the buildings was also investigated. For the new buildings, it was assumed that these would be fitted exclusively with panel heating systems. In addition, new biomass boilers were only proposed for buildings with the highest heat demand that are difficult to renovate (half-timbered houses) or for buildings that already heat with biomass. All other buildings should be equipped with air heat pumps in that scenario. The result of these calculations was that once the insulation measures have been implemented, the total heat consumption of the buildings examined can be reduced by an average of 18%. This, coupled with heat generation using only biomass boilers and heat pumps, meant that CO_2e emissions in the buildings concerned could be reduced by 95%. The proportion of heat provided after the renovation measures is finally shown in Figure 2.

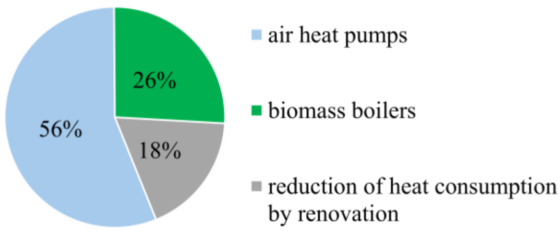

Figure 2: Reduction of heat consumption and shares of heat supply for decentralized renovation scenario in Bracht (Kelch et al. 2024).

The solar district heating scenario focused on a significant reduction in CO_2e emissions through the integration of renewable energy sources, primarily by solar thermal energy. This approach targeted the 156 existing buildings and focused on minimal renovation measures in the buildings (such as insulation of basement ceilings etc.). In this scenario, these measures reduced the heating requirement by around 2 %. The core components of the heating network scenario included an extensive solar thermal collector field coupled with a seasonal pit thermal energy storage system (PTES), coupled with an electric heat pump to cool the storage to about 31°C during the heating season. This cooling significantly reduces both the size and cost of the storage system compared to maintaining it at the higher temperatures traditionally required. As it was assumed that the proportion of biomass can remain the same compared to the original situation, but must not exceed this in future solutions, the concept also provided for the use of biomass boilers to cover the remaining heat demand. The system sizing was optimized using TRNSYS simulations over a period of 3.5 years, with a focus on the last year in which the system reached thermal equilibrium. The optimization aimed to achieve the lowest levelized cost of heat and involved configuring the sizes of the system components using GenOpt software. Of the various possible variants, all of which had similar costs, the variant that offered the greatest flexibility for the future, such as additional consumers connected to the heating network, was favored. This variant comprised a 13,000 m² flat-plate collector field, a PTE storage volume of 26,600 m³, 2 biomass boilers with a total power of 600 kW_{th} and a heat pump with 1.300 kW_{th}, which supply the network with heat via a 250 m³ short-term storage tank (Kelch et al. 2024). Taking into account the practical boundary condition, a collector area of around 11,700 m², a heat pump output of 1.200 kW_{th} and a total biomass boiler output of 550 kW_{th} working on a 400 m³ buffer storage tank turned out to be the best solution, achieving net levelized costs of heat after subsidies of 104 $€_{net}$/MWh (213 $€_{net}$/MWh before subsidies) (Kelch et al. 2022). With this system (see Figure 3), which would have a solar fraction of almost 70 %, a CO_2 reduction of approx. 97 % could also be achieved.

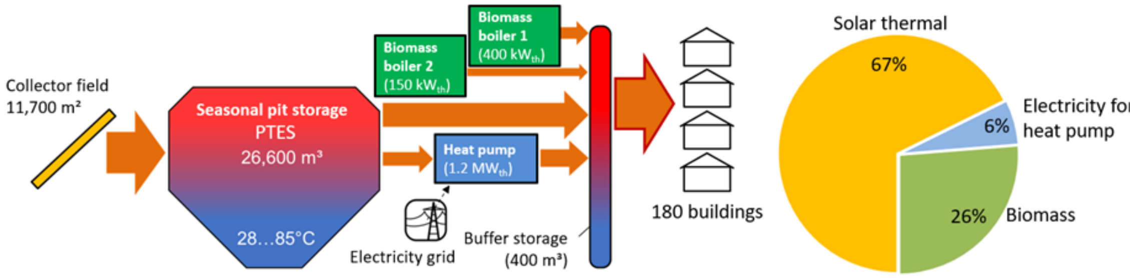

Figure 3: Components, their dimensioning and their share of the heat supply in the district heating solution for Bracht.

In a comparison of the two possible solutions for CO_2-neutral heat supply, Kelch et al. found that centralized solar heating and decentralized building refurbishment achieve the same full heating costs per building within the scope of the calculation accuracy (see Figure 4). However, the main difference between the two variants is that the centralized solution achieves the full CO_2 reduction in just a few years after commissioning, while the decentralized refurbishment takes significantly longer, considering realistic refurbishment rates of 2-3 %/a at most (figure 4, right).

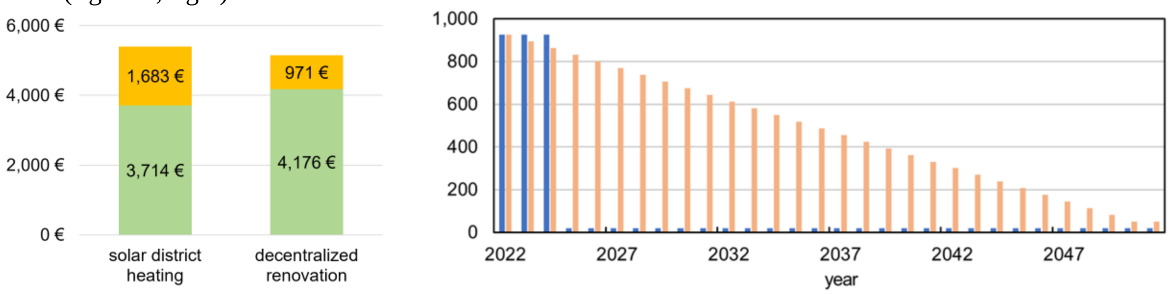

Figure 4: Annual heat costs per average building from solar district heating vs. decentralized solution in Bracht (left) and comparison of annual CO_2e emissions in t_{CO2}/a (right) (Kelch et al. 2024).

These investigations reinforced the citizens' cooperative's original goal of installing a renewable heating network in their village, so that they finally entered the implementation phase with the aim of setting up the system shown in Figure 3.

2.3. Implementation, current design and status

In the original concept developed by Kelch et al. (Kelch et al. 2024), all heat generators initially worked on the buffer storage tank. One of the reasons for this was that the heat pump did not have to provide heat at the network supply temperature. The goal was to increase the efficiency of the heat pumps by connecting them to the center of the storage tank, effectively pre-heating the water of the biomass boiler. In the project currently being implemented (Figure 6), however, the storage tank with a volume reduced to 200 m³ has more the function of a hydraulic switch. Both the biomass boiler (only one boiler in this concept) and the heat pumps can operate directly at the grid supply temperature. In addition, a total heat pump output of 1.5 MW is planned, which is slightly more than in the originally planned variant. This system is currently being modeled and investigated using simulations. However, no results are yet available.

Construction of the PTES (Figure 5) began in November 2023. The process was interrupted several times due to adverse weather conditions. However, the pit will be completely covered with liners by the end of July 2024, meaning that the PTES is likely to be filled by fall 2024. The availability of sufficient water to fill the PTES quickly continued to prove problematic in this area, but has now been resolved.

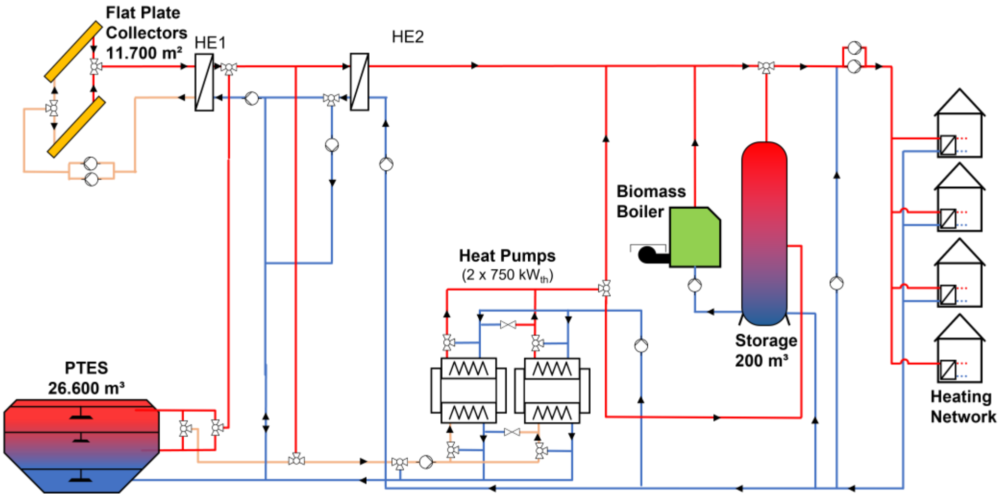

Figure 6: Schematic representation of the hydraulics in Bracht of the system expected to be implemented.

Figure 5: Construction progress of the PTES (image as of July 2024).

In order to check the technical performance of the system, the PTES is to be measured at several points. In addition to the sensors for monitoring the water temperature inside of the PTES, sensors for measuring the wall temperature and the ground temperature in the immediate vicinity of the PTES are also planned to be able to estimate the heating of the ground around the storage. There are also plans to measure the solar thermal field as well as all generators and the heating network to monitor the system and draw conclusions for similar, future projects.

3. Case Study 2: Amöneburg-Rüdigheim

3.1. Boundary Conditions

The second village considered in this paper is Amöneburg-Rüdigheim (Rüdigheim for short), located about 17 kilometers south of Bracht. A citizens' co-operative has also been set up to build a renewable heating network in the village and to provide district heating for about 100 houses, which corresponds to a connection rate of around 60 %. The initial aim was to achieve 100 % solar coverage using a seasonal storage system, mainly to be independent of biomass and fluctuating fuel prices. For this purpose, a planning office, together with a plant constructor and a manufacturer of tank thermal energy storages (TTES), has developed a concept in which the 100 houses with an estimated annual heat demand of 2,250 MWh/a can be supplied via a 5 km heating network. The concept, as shown in Figure 7, envisages a 7,000 m² solar thermal evacuated tube collector (ETC) field and two 15,000 m³ seasonal TTES. Special heat transfer stations, which can enable a return temperature of 40 °C according to the manufacturer (supply temperature approx. 68 °C), are intended to increase the storage capacity in this concept.

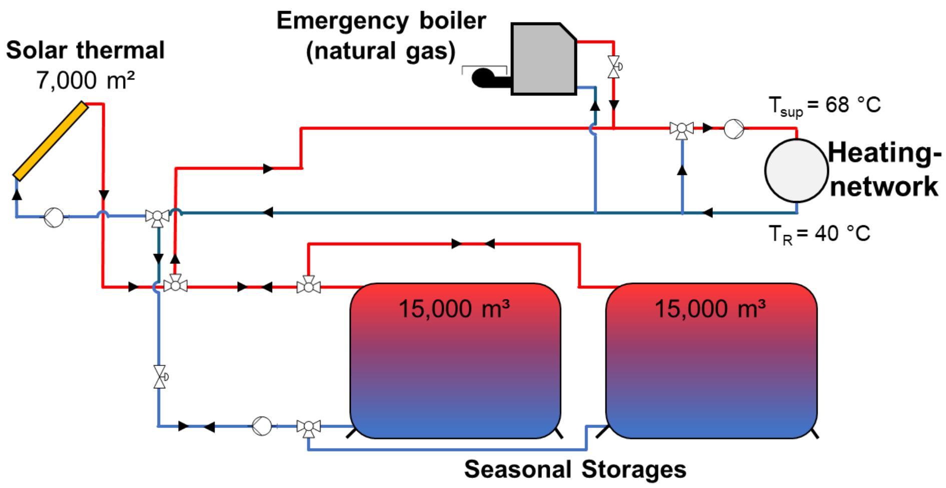

Figure 7: Schematic representation of the original concept in Rüdigheim with 2 TTES and a 7,000 m² evacuated tube collector field.

3.2. Re-simulation of the original variant

The federal subsidies used for the manufactures calculation are not offered any more and the assumed costs were based on rather low investment and operating costs. Additionally, a 100 % solar-powered heating network for the full supply of existing buildings has not yet been realized. For this reason, the University of Kassel, financially supported by the Energy Agency of Hesse (LEA), carried out an extended simulation study. The aim was to examine the technical feasibility and economic viability of the existing concept in more detail and, if necessary, to optimize it.

To ensure the technical functionality, the manufacturer's simulation model in the Polysun software (Vela Solaris), including the technical boundary conditions, was transferred to the TRNSYS simulation program as a first step, so that potential optimizations could be carried out using generic algorithms with GenOpt and Python. For its calculations, the manufacturer has assumed that the storage tanks and the collectors are connected directly to the network without heat exchangers. Furthermore, it was assumed that the heat consumption profile is constant over one month, with a constant demand (including network losses) between April and September and a constant demand from October to March. In the manufacturer's simulations, a value of 1,162 kWh/m²a was used as the annual irradiation at the collector level and the supply temperature of the solar field was simulated at 90 °C in matched flow operation, which has led to additional heat losses in the storage tank of 360 MWh/a. Assuming that the return temperature of 40 °C specified by the manufacturer can be achieved, the manufacturer's specifications regarding the energy balances could be confirmed in the TRNSYS calculations of the University of Kassel, as shown in Figure 8.

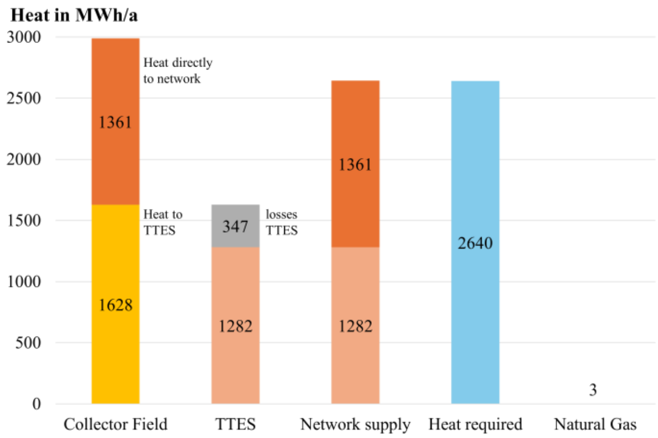

Figure 8: Results of the TRNSYS simulations for the energy balances of the manufacturer's concept.

In the second step, the costs of the original variant were updated and adapted to new subsidy schemes in Germany according to the new funding for efficient heating networks (German Federal Office for Economic Affairs and Export Control 2024), only the investment costs of the collectors can be subsidized in this concept. For example, the cost functions for the storage tank and the collectors were adjusted, the operating costs were increased and a price increase (for electricity consumption) was taken into account in the calculations. All other investment costs and cost functions were assumed by the manufacturer and updated to new boundary conditions as required. With these boundary conditions, an LCoH of 378 €$_{net}$/MWh (237 €$_{net}$/MWh after subsidies) was calculated for the original system design with 100 % solar fraction. This are relatively high costs compared to other regenerative heating networks, which, however, are mainly biomass-based. As implementation is unlikely under these circumstances and the function of a flagship project for other municipalities would be jeopardized, a simulation study was carried out with the aim of reducing costs. The simulations were also based on the assumption that the supply and return temperatures can be maintained as in the original concept and that TTES are used for heat storage. In addition, the heat requirement should still be covered without using fossil fuels, as favored by the citizens' cooperative.

3.3. Economic optimization of the system

Table 1 shows the results calculated with TRNSYS and GenOpt regarding the sizing of the main system components for the different variants studied. However, in variant 1b, without optimization in GenOpt, an attempt was first made to reduce costs by replacing two-thirds of the collector area with less expensive flat-plate collectors (FPC). The total collector area of 7,000 m² was to remain unchanged. Nevertheless, the simulations for this variant showed that the heat demand could not be covered, so the LCoH were not calculated for this variant.

Table 1: Results for collector area, storage tank size, thermal output of the heat pump of the optimized variants based on the initial variant 1 and the resulting LCOH according to Baez and Larriba Martinez (Baez and Larriba Martinez 2015).

Nr.	Variant description	Storage Size in m³	Collector Field (%ETC / %FPC) in m^2_{gross}	Thermal Power Internal Heat Pump in kw_{th}	LCoH before funding in €$_{net,2022}$/MWh
1	original concept manufacturer	2 x 15,000	7,000 ETC only	-	378
1b	original concept, mix of collector types	2 x 15,000	7,000 (33 % / 67 %)	-	heat demand not covered
2	original concept, optimized in TNSYS GenOpt	2 x 14,600	7,600 (43 % / 57 %)	-	363
3	1 Storage	1 x 30,000	7,200 (29 % / 71 %)	-	327
4	1 storage, internal heat pump	1 x 24,000	6,500 (29 % / 71 %)	337	326
5	1 storage, internal heat pump (T_{sup} HP 69 °C)	1 x 23,800	6,600 (26 % / 74 %)	337	325
6	1 storage with manufacturers limitation, internal heat pump (T_{sup} HP 69 °C)	1 x 15,000	5,700 (23 % / 77 %)	1026	323

Starting with variant 2, the system was then optimized in the simulations. For this purpose, an hourly profile was used instead of a monthly, constant load profile. In addition, heat exchangers were included between the collector field and the TTES as well as between the TTES and the network, and the control of the overall system was adapted in order to optimize potential variants with internal heat pumps. The TRNSYS simulations were carried out over 2.5 years in six-minute increments, with only the last year being evaluated. The balance limit was the heating central including heat generators and TTES. The target function in GenOpt was the LCoH per kWh with full coverage of the heat demand, for which the global optimum was determined iteratively. The dimensioning of the main components, the proportion between flat-plate and evacuated tube collectors, the heat pump connection heights to the TTES and, in some cases, the control of the heat pumps, such as the switch-on temperature of the heat pumps, were varied.

Variant 2 shows the optimum LCoH for the case in which 2 TTES are still used in the system. The optimization for this case showed that the storage tanks can be slightly smaller than in the manufacturer's original variant, but the area of the solar thermal system must be around 9 % larger with a flat-plate collector share of around 60 %. In this case, the LCoH would fall by around 4 %, which still corresponds to a relatively high heat price.

To further reduce the costs, in variant 3 was that only one TTES (with twice the volume) used instead of the two originally planned. Due to economies of scale, this results in lower storage costs per m³ of storage volume. In addition, the use of only one storage tank reduces the volume-to-surface ratio, which decreases the storage losses. The result for this variant was that, as originally, 30,000 m³ of storage volume is required with a 3 % higher total collector area. However, this would be able to provide the necessary heat with 70 % flat-plate collectors, so that the heat price (with a solar fraction of still 100 %) could be reduced by around 10 % to a value of 327 $€_{net}$/MWh. An internal heat pump was integrated into the concept from variant 4 onwards. This is intended to cool the TTES below the return temperature of the heating network and thus increase the storage capacity due to the greater temperature spread. The storage volume can be reduced in this way, which may make realization easier due to lower construction heights and reduced space requirements. Under these boundary conditions, variant 4 resulted in a storage volume that is around 20 % smaller than variant 3 and a collector field that was 10 % smaller if a heat pump with 337 kW_{th} is used to cool the TTES. Similar dimensioning resulted for variant 5, in which the heat pump control was selected so that it feeds heat into the storage tank at a maximum of 1 K above the supply temperature of the heating network, which leads to an average supply temperature of the heat pump of 69 °C. The LCoH for these variants are similar to variant 3 with a smaller area requirement and a smaller storage size, but a solar coverage rate of 100 % is no longer achieved here.

As the simulations are based on the boundary conditions of the manufacturer's special house transfer stations and the manufacturer is also expected to supply the TTES in this context, no TTES larger than 15,000 m³ can be provided (manufacturers limitation). Therefore, in variant 6, lowest costs were determined for a system in which the heat demand of the network can be covered with only one storage tank of the maximum size with an internal heat pump. In this system, around 15 % less collector area is required compared to variants 4 and 5 with about the same LCoH. However, the thermal heat pump capacity triples, which leads to a significantly higher electricity requirement and thus to a further reduction in the solar coverage rate. Since this variant nevertheless achieves one of the most cost-effective heat supplies and further dispenses with the use of fuel-based heat generators, this variant is currently being favored by the citizens' co-operative and has been submitted for funding.

3.4. Details of the favored concept

In order to be able to provide sufficient heat with the reduced collector area, the collectors in this variant are connected in series. The 4,400 m² (around 3/4 of the area) of flat-plate collectors are used to preheat the heat transfer fluid, which is then reheated in the 1,300 m² of evacuated tube collectors to the required temperature. Between November and May, the collectors are regulated to a maximum of 75 °C to increase collector efficiency. Despite the smaller collector field, the calculations show that stagnation cannot be prevented in this variant towards the end of the summer, so that stagnation protection is required. Assuming that the collector field losses amount to 3 %, the energy balance of the overall system can finally be taken from figure 9. As can be seen at 3 MWh/a, the fossil reheating requirement is negligible and the heat losses in the TTES, at 9 %, are only a third of the storage losses than in the originally planned variant.

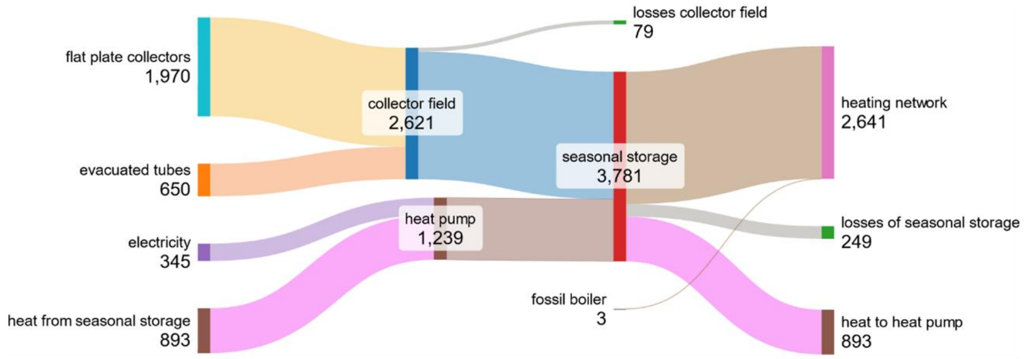

Figure 9: Energy balances of optimized system in Rüdigheim (numbers depict energies in MWh/a).

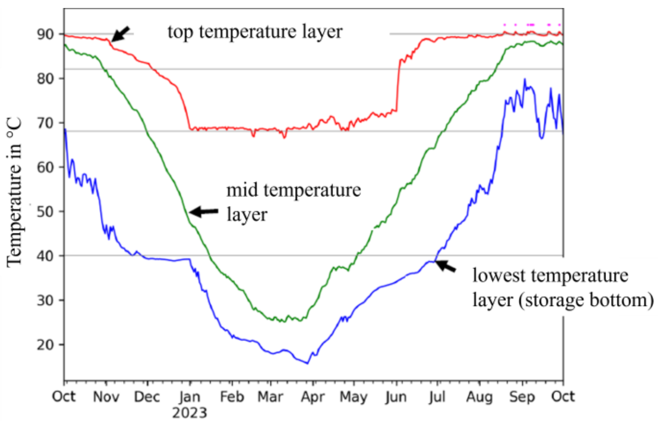

Figure 10: Simulated storage temperatures in 3 layers of the TTES.

As can be seen in figure 10, the average storage tank temperature over the course of a year ranges between around 88 °C and 25 °C. The top storage layer, on the other hand, is only for a few time steps below the network flow temperature. This indicates that the concept was designed to be cost-optimized, the solar fraction reaches almost 90 percent. Figure 11 shows in summary how the optimized system in Rüdigheim is schematically structured. Renewable district heating can be provided for existing buildings with only two different regenerative heat generators in combination with a TTES.

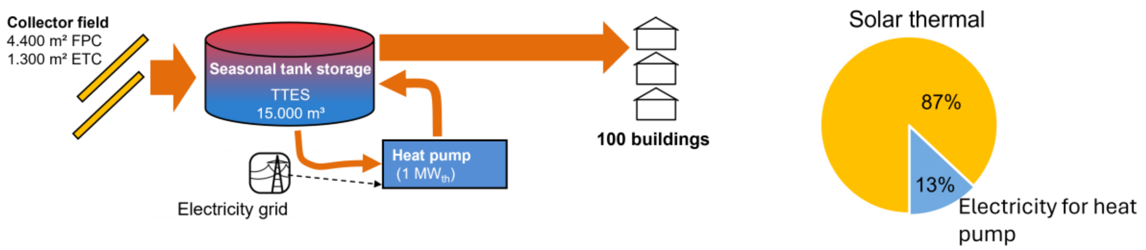

Figure 11: Components, their dimensioning and their share of the heat supply in the optimized system (variant 6) of Rüdigheim.

Table 2 summarizes once again how the Rüdigheim heating network will differ from the Bracht network. The high proportion of solar coverage is currently unique for existing areas. In contrast, however, Bracht has more competitive heating costs.

Table 2: Summary of the data from both case studies (network length incl. house connection pipes).

Locality	Heat Demand in GWh/a	Network length in km	Connected Households	Collector Field in m^2_{gross}	Solar fraction in %	Storage Size in m^3	LCoH before funding in $€_{net,2022}$/MWh
Bracht	3.6	8	180	11,700	70	26,600	213
Rüdigheim	2.3	5	100	5,700	87	15,000	323

4. Conclusion

This article showed that district heating can, despite low heat densities, lead to practicable and sustainable solutions for a climate-friendly central heat supply in rural areas in Germany due to existing open spaces and low infrastructure costs. Through the investigations in Rauschenberg-Bracht and Amöneburg-Rüdigheim, viable models were identified that maximize the use of renewable energies and minimize reliance on fossil resources. Using the example of Rauschenberg-Bracht, it was shown that central solar thermal heating networks in combination with seasonal thermal energy storages can compete economically with the individual heat supply of buildings, while reducing CO_2 emissions to almost zero after a very short time. In addition, the example of Amöneburg-Rüdigheim was used to show how such simulation-based system optimization can be used to reduce the high initial costs of 100 % renewable heating networks. The implementation of these solutions highlights the importance of dedicated citizen initiatives and government funding, which play a critical role in the implementation of renewable heating networks.

5. Acknowledgment

The authors would like to thank the Hesse State Ministry of Economy for long term committed support of the two solar district heating projects and for directly funding several studies as well as measurement equipment (FKZ: E/611/71690944). We also thank the Federal Ministry of Economics and Technology (BMWi) for funding the accompanying scientific research (“ruralHeat”, FKZ: 03EN6031). We are furthermore grateful to the respective energy cooperatives Sonnenwärme Rüdigheim eG and Solarwärme Bracht eG as well as cupasol GmbH and the associated project partner Viessmann Deutschland GmbH for the great co-operation.

References

Baez, M. J., Larriba Martinez, T., 2015. Technical Report on the Elaboration of a Cost Estimation Methodology. Work Package 3 - Estimating RHC energy costs. Madrid, Spain: Creara, URL: https://www.front-rhc.eu/wp-content/uploads/2014/11/FROnT_D3.1_elaboration-of-a-cost-estimation-methodology_2015.07.22.pdf, accessed November 14, 2020.

Blesl, M., Eikmeier, B., 2015. Die 70/70-Strategie. Konzept und Ergebnisse. URL: https://www.agfw.de/strategien-der-waermewende/perspektive-der-fw-7070-4040, accessed July 30, 2024.

Gerbert, P., Herhold, P., Burchardt, J., Schönberger, S., Rechenmacher, F., Kirchner, A., Kemmler, A., Wünsch, M., 2018. Klimapfade für Deutschland: The Boston Consulting Group (BCG); Prognos AG. URL: https://web-assets.bcg.com/e3/06/1c25c60944a09983526ff173c969/klimapfade-fuer-deutschland.pdf, accessed July 30, 2024

Gerhardt, N., Ganal, I., Jentsch, M., Rodriguez, J., Stroh, K., Buchmann, E.K., 2019. Entwicklung der Gebäudewärme und Rückkopplung mit dem Energiesystem in -95% THG-Klimazielszenarien. URL: https://www.iee.fraunhofer.de/content/dam/iee/energiesystemtechnik/de/Dokumente/Veroeffentlichungen/2019/2019_Feb_Bericht_Fraunhofer_IEE_-_Transformation_Waerme_2030_2050.pdf, accessed July 30, 2024

German Association of Energy and Water Industries (BDEW), 2024. Statusreport: Wärme. URL: https://www.bdew.de/service/publikationen/statusreport-waerme/, accessed July 9, 2024.

German Federal Government, 2023. Act for heat planning and the decarbonization of heating networks. URL: https://www.bmwsb.bund.de/SharedDocs/gesetzgebungsverfahren/Webs/BMWSB/DE/Downloads/waermeplanung/wpg-bgbl.pdf?__blob=publicationFile&v=2, accessed July 16, 2024.

German Federal Office for Economic Affairs and Export Control, 2024. Information sheet: Federal funding for efficient heating networks (BEW). URL: https://www.bafa.de/DE/Energie/Energieeffizienz/Waermenetze/Effiziente_Waermenetze/effiziente_waermenetze_node.html, accessed July 30, 2024

Hess, S., Vollmer, R., Wapler, J., Kleinstück, M., Bongs, C., Henning, H.-M., 2019. Ambient Heat Source Availability for Low-Ex Heating of Multi-Family Buildings. *ISES Solar World Congress 2019.* Santiago, 3-7 November

KEA Baden-Württemberg, 2020. Leitfaden Kommunale Wärmeplanung. URL: https://www.kea-bw.de/fileadmin/user_upload/Publikationen/094_Leitfaden-Kommunale-Waermeplanung-022021.pdf, accessed July 16, 2024.

Kelch, J., Kusyy, O.,Orozaliev, J., Vajen, K. 2022. Weiterentwicklung und Optimierung des Konzepts einer solaren Nahwärmeversorgung für ländliche Gebiete am Beispiel von Bracht-Dorf. Abschlussbericht eines Forschungsvorhabens, gefördert durch das Land Hessen und den Europäischen Fonds für regionale Entwicklung; FKZ: EF960 0039/2021 20008503. URL: https://www.uni-kassel.de/maschinenbau/index.php?eID=dumpFile&t=f&f=4844&token=5882c5c8243e420723571b4d64b2773b3579081b, accessed July 30, 2024

Kelch, J., Kusyy, O., Zipplies, J., Orozaliev, J., Vajen, K., 2023. Solar District Heating versus Renovation of Buildings as Measures for Decarbonization of Heat Supply in Rural Areas. *EuroSun 2022*. Kassel, 25-29 September

Kelch, J., Kusyy, O., Zipplies, J., Orozaliev, J., Vajen, K., 2024. Comparison of solar district heating and renovation of buildings as measures for decarbonization of heat supply in rural areas. Solar Energy Advances, 4:100060.

Landes Energie Agentur Hessen, 2020. Die Wärmewende voranbringen. Kommunale Wärmeplanung in Hessen gemeinsam gestalten, URL: https://redaktion.hessen-agentur.de/publication/2021/3443_LEA_Broschuere_Kommunale_Waermeplanung_212018.pdf, accessed July 16, 2024.

Solarwaerme Bracht eG, 2024. Aktueller Stand und Historie Solarwaerme Bracht. URL: https://www.solarwaerme-bracht.de/aktueller-stand-und-historie-solarw%C3%A4rme-bracht/, accessed July 15, 2024.

Umweltbundesamt, 2024. Erneuerbare Energien in Zahlen. URL: https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen#waerme, accessed July 9, 2024.

VDI-Gesellschaft Bauen und Gebäudetechnik (GBG),2012. VDI 2067 Blatt 1/ Part 1: 2012-09, Wirtschaftlichkeit gebäudetechnischer Anlagen Economic efficiency of building installations. Grundlagen und Kostenberechnung, Fundamentals and economic calculation (2067 Blatt 1/ Part 1). Düsseldorf