Solar district heating versus renovation of buildings as measures for decarbonization of heat supply in rural areas

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Abstract

In this study two different decarbonization strategies for rural heat supply are compared on the example of 180 buildings located in a german village called Rauschenberg-Bracht. The comparison shows that erection of a solar district heating system with solar fraction of about 67% leads to similar heating costs as a profound energy efficient renovation followed by installation of decentralized air heat pumps for most buildings. Both concepts aim to achieve a heat supply that is free from the local use of fossil fuels. While the solar district heating system can probably be realized within a few years and therefore achieves the full CO_2e savings promptly, this would take decades for the implementation of energy rehabilitation and heat pumps due to low renovation rate. To reach climate-neutrality for the heat supply could thus be accelerated significantly by the construction of a solar district heating system. Moreover, the two decarbonization approaches do not appear to be fundamentally exclusive: subsequent steady renovation of connected buildings will either increase solar share in heat supply or enable connection of new consumers at similar solar coverage rate. However, it should be also noted that with solar district heating not the same thermal comfort as with profound energy efficient building renovation is achieved.

Keywords: decarbonization strategy, rural heating, solar district heating, energy efficient renovation

1. Introduction

About 150 million tones (BDEW 2021) or about 18% of the total annual CO_2e emissions in Germany are attributed to the heating and cooling of buildings, with heating having the largest share. Especially against the backdrop of the climate crisis, the question arises how the decarbonization of building heat can be achieved as fast as possible and at lowest possible costs. This study focuses on rural areas and develops two different heat supply scenarios for 180 buildings in a German village called Rauschenberg-Bracht as an example. A solar district heating system with 67% solar fraction and basic renovation measures (centralized solution) is compared to profound renovation combined with the installation of air heat pumps for most of the buildings (decentralized solution). The primary target is to achieve a heat supply which is free from the local use of fossil fuels. The annual costs of heat for an average building are used as key figure. Furthermore, the annual CO_2e emissions for the next three decades are compared.

2. Current state analysis

At present, about two thirds of the village heat is generated by heating oil and one quarter comes frombiomass (wood logs, wood chips and pellets). Almost all buildings are single or two-family houses, about 90% were built (some of them in half-timbered construction) before 1980. The village is not connected to the natural gas grid. Inhabitants of Bracht grounded a local energy initiative to implement the solar district heating system. According to current information about 180 buildings will be connected to the local heating network. This building stock comprises 156 existing and 24 planned buildings that will be erected in a few years. All 180 buildings are classified in five categories based on construction year and renovation needs:

- renovation sensitive
- before 1980

- 1980 till 2000
- after 2000
- new building

The category “renovation sensitive” includes the buildings erected in a half-timbered construction and additional buildings built before 1919. The underlying assumption of this category is, that the facades of these buildings are worth to prevent or they are even under monumental protection, thus, they can be insulated only internally. Because the region around Bracht is densely wooded, short transportation routes are assumed and, thus, a CO_2e emission factor of 0 g_{CO2e}/kWh for wood is chosen. Based on survey database, the current overall heat consumption (4,082 MWh/a), CO_2e emissions (926 t_{CO2e}/a) and wood consumption (1,526 MWh/a) are estimated for the 180 buildings. A second data set based on the results of brief energy consultations conducted by the energy agency of Hessen (LEA), contains detailed information for 27 building: firstly, heat transfer coefficient and area for each building component of the thermal building envelope which are later used to estimate the necessary insulation measures for the decentralized renovation, and, secondly, recommended minimum-investment renovation measures like insulation of the top or basement ceiling which are applied when considering solar district heating.

3. Comparability of two scenarios

To ensure comparability, the following framework conditions are defined for both scenarios "solar district heating" and "decentralized renovation":

- Supply of heat (space heating and domestic hot water) for the 180 potential consumers
- Supply of heat without local use of fossil fuels
- No more biomass is allowed than in the present

The emission factor of 366 g_{CO2e}/kWh is taken for the consumed electricity at the current state, while, for the scenario period from 2025 until 2044, the estimated average value of the emission factor is 62 g_{CO2e}/kWh based on the Germany’s policy goal of reaching 80% renewable share for power generation in 2030 and emission factors by Luderer et al. 2021.

4. Solar district heating scenario

In this scenario the CO_2e emissions are mainly reduced by the implementation of renewable energies, especially solar thermal energy. Only minimum renovation measures, such as insulation of upper floor and basement ceilings are exploited to reduce the initial investment costs. The potential reduction of heat demand due to these measures is estimated at about 2 % based on detailed recommendations for 27 buildings by the LEA, estimations on the reduction of heat consumption by the method of tabula according to Loge et al. 2015 and following extrapolation on the rest of the 156 existing buildings with account of building category. The total net cost of minimum renovation is about 631 k€. The most important components of the central heating concept are a large solar thermal collector field (12,900 m^2) and a seasonal heat storage (26,600 m^3), which is designed as a pit storage filled with water, covered with a foil on the ground side and insulated with a floating thermal insulation on the top. An electric heat pump (1,190 kW_{th}) is used to cool the storage in the heating period down to about 30°C. This enables to reduce the storage size and, thus, the investment costs, compared to the direct storage discharge down to the return temperature of the district heating network of about 50°C only. The remaining heating load is covered by two wood chipping fired boilers (150 and 400 kW_{th}), which serve as auxiliary heating to increase the heat pump’s efficiency.

The solar thermal heating system, illustrated in figure 1, has the following operating states listed in decreasing priority. For simplification in figure 1 the heat flow of the first operation state is not illustrated seperatly and added to the second operation state.

- Direct heat supply from solar collector
- Direct heat supply from seasonal storage tank

- Simultaneous heat supply from heat pump and wood chipping boilers

The heating system is simulated in TRNSYS with the modified type 343 "ICEPIT" as pit storage for 3.5 years. Only the last year when the ground around the storage tank has warmed up and, apart from the temperature changes within the annual cycle, has reached a thermal equilibrium, is used for energetical and economical evaluation. For the optimization TRNSYS is coupled with the GenOpt software (Generic Optimization program) to determine the component sizes that yield minimum levelized costs of heat.

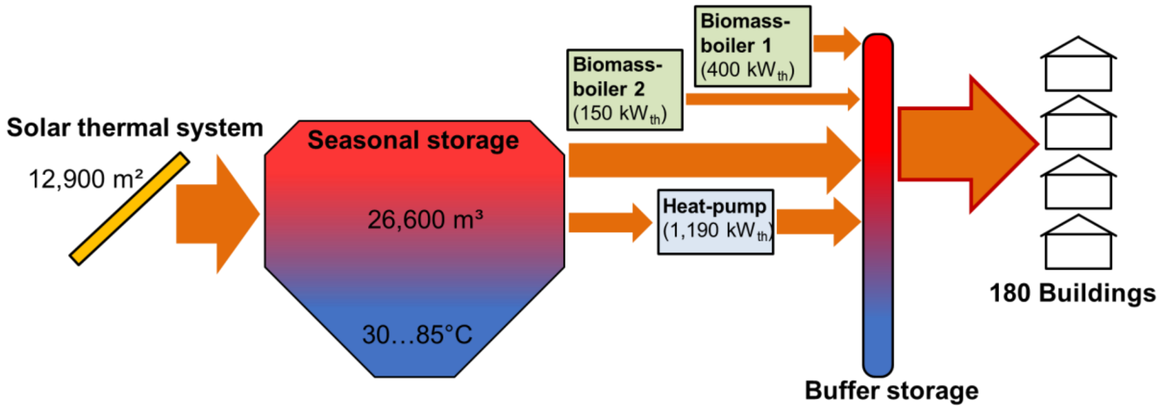

Figure 1: Solar district heating system

The shares of heat supply by different energy sources are shown in the figure 2 for the optimized system. With 67% solar thermal energy has the highest share. The heat pump is working with a SCOP of about 4.7 and the seasonal storage tank is operated in a temperature range of 30 till 85°C. Due to solar district heating the CO_2e emissions are reduced by -98% compared to current state.

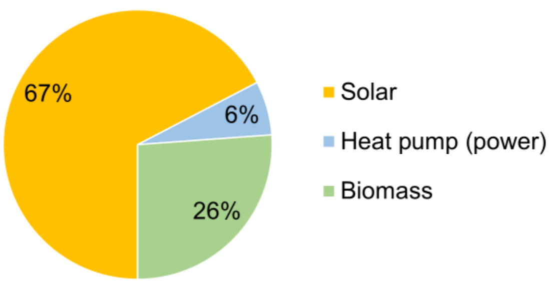

Figure 2: Distribution of heat sources feeding into the district heating network

5. Decentralized renovation scenario

In this scenario the decarbonization is achieved with decentralized measures in the buildings only. The estimation of the measures is based on evaluation of 27 buildings for which detailed data are available. To estimate the extent of the measures the aproach is as described:

- To determine necessary measures for improving the building's thermal envelope, insulation thresholds are defined, which means that all components of the 27 buildings with heat transfer coefficients higher than the chosen thresholds will be insulated.
- It is assumed, that the existing insulation remains and the new insulation is implemented on top (except for windows, which must be replaced).
- If a measure is necessary, it will be dimensioned to reach the minimal heat transfer coefficient required

by federal funding for efficient buildings (BEG) for individual measures (BMWi 2021).

The thresholds and minimum requirements for funding are presented in table 1.

Table 1: Heat transition coefficients for the scenario decentralized renovation

Building component	Assumed thresholds for the existing insulation in $W/m^2 \cdot K$	Minimum requirement of funding if new measures are done in $W/m^2 \cdot K$
roof	0.4	0.14
top ceiling	0.3	0.14
basement ceiling	1.0	0.25
basement wall	0.5	0.25
base plate	1.0	0.25
outer wall (external)	0.4	0.20
outer wall (internal)	0.7	0.65
windows	2.6	0.95

The reduction of heat consumption for each of the 27 buildings is calculated by the method of tabula with considering the rebound effects caused by changing resident's behavior in buildings with increased efficiency. For this a correction factor determined by the Institute for Housing and the Environment (IWU) (Loge et al. 2015) is used.

For the 180 buildings that should be supplied by the district heating network, the estimated distribution by building category is presented in table 2. The building categories are known only for 132 existing and 24 new buildings but not for the remaining 24 existing buildings. For that reason, the categories of existing buildings are scaled up from 132 to 156 resulting in decimal numbers. This distribution serves for the extrapolation of the identified measures as well as specific heat consumption (per m² living area) from 27 to 180 buildings.

Table 2: Estimated distribution of 180 buildings into five building categories

	1	**2**	**3**	**4**	**5**	
	renovation sensitive*	**before 1980**	**1980 till 2000**	**after 2000**	**new building**	$\sum$
Number of buildings	50.8	82.7	17.7	4.7	24.0	180

The estimated insulation measures for 180 buildings shown in figure 3 indicate that insulation of the outer wall and replacement of windows are quite often required for buildings constructed before 2000. It will be shown later that this has a large influence on the total investment costs. It is assumed that architect's services are necessary for buildings for which roof or outer wall are to be insulated and blanket costs for that services are considered later in the economic evaluation.

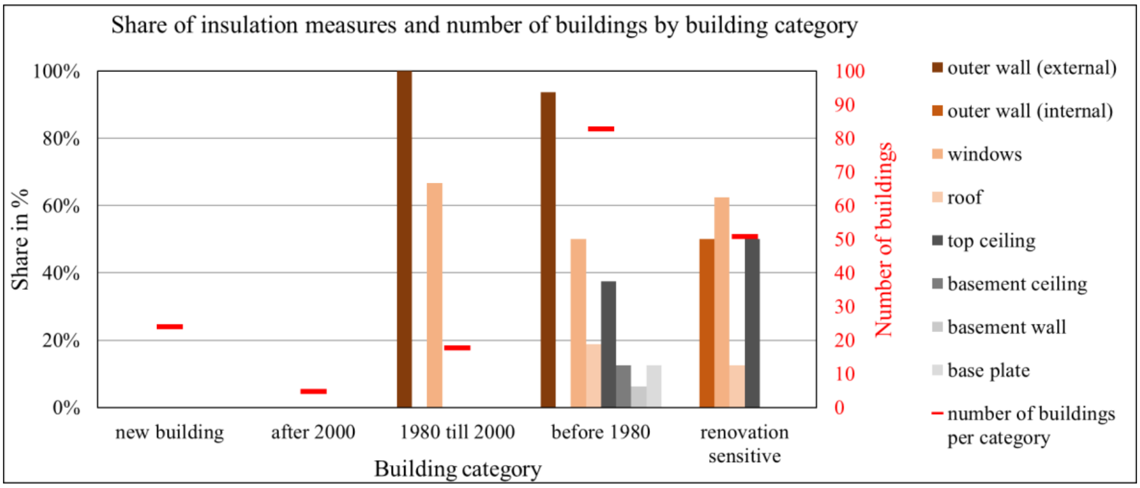

Figure 3: Estimated insulation measures for 180 buildings in decentalized renovation scenario

The figure 4 presents the shares of heat pumps and wood fired boilers by building category. This distribution is a result of the assumptions that new wood fired boilers will be implemented in the buildings with highest specific heat consumption and only either in the renovation sensitive buildings or in the buildings which heat with the wood at present. The wood amount is enough to heat around 55 buildings, while the rest is heated by air heat pumps. To ensure a high SCOP for the buildings heated with air heat pumps the underfloor heating systems are implemented, what is probably not always reasonable (or possible) and could overestimate the investment costs.

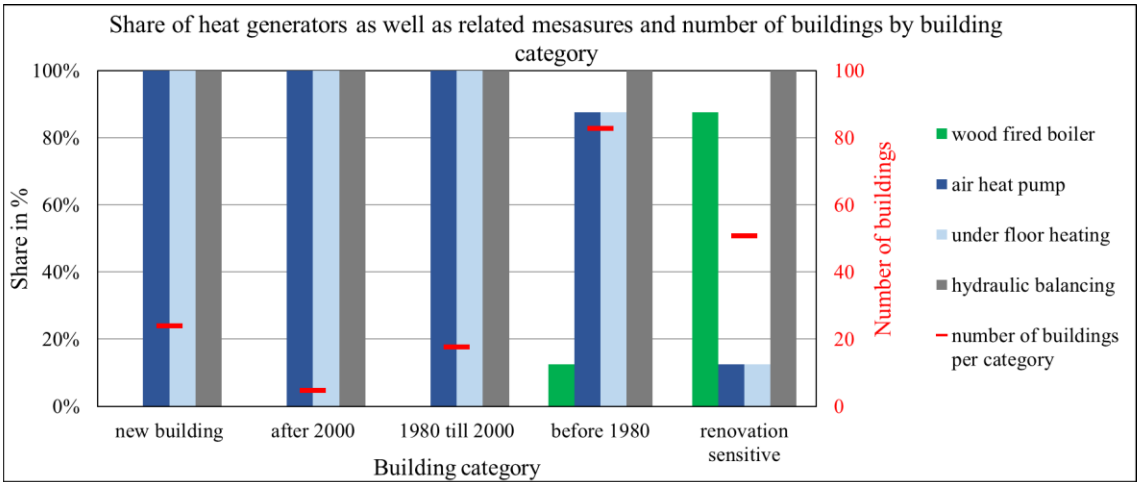

Figure 4: Estimated measures for 180 buildings concerning heat generation and distribution inside the building in decentralized renovation scenario

By the implementation of all measures presented in figure 3 and 4 the heat consumption decreases by about -22% and the CO_2e emissions by -95% in total for all 180 buildings. The shares of heat supply by air heat pumps and wood fired boilers as well as the reduction of heat consumption are shown in figure 5.

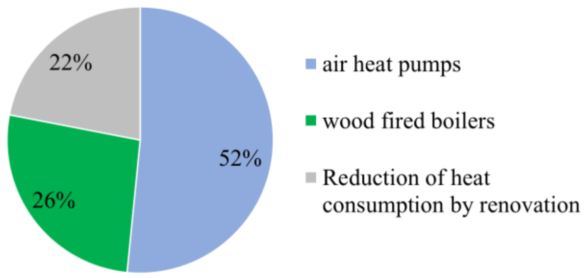

Figure 5: Reduction of heat consumption and shares of heat supply for decentralized renovation

6. Comparison of two scenarios

Figure 5 shows, that the largest investments for solar district heating are the solar thermal system, the heating network and the seasonal storage. The federal funding by the German program KfW EE Premium (BMWK 2022) is around 42% of the total investment. Especially the solar thermal system and seasonal storage gain high subsidies of around 58%.

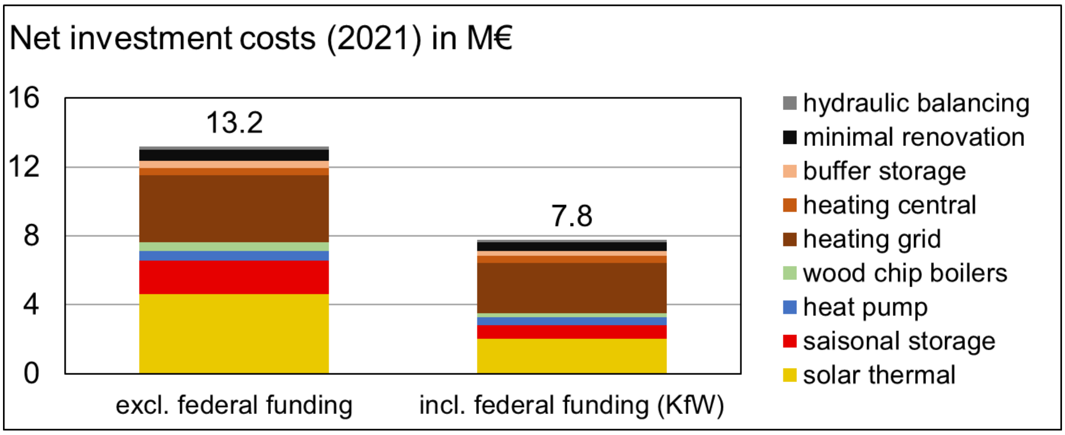

Figure 6: Investment costs for solar district heating

The total investment costs for decentral renovation presented in figure 7 are very similar to those for solar district heating. The constructional measures with the highest investment costs are outer wall insulations, replacement of windows and underfloor heating systems. Funding by BEG (15. August 2022) is considered (BAFA 2022).

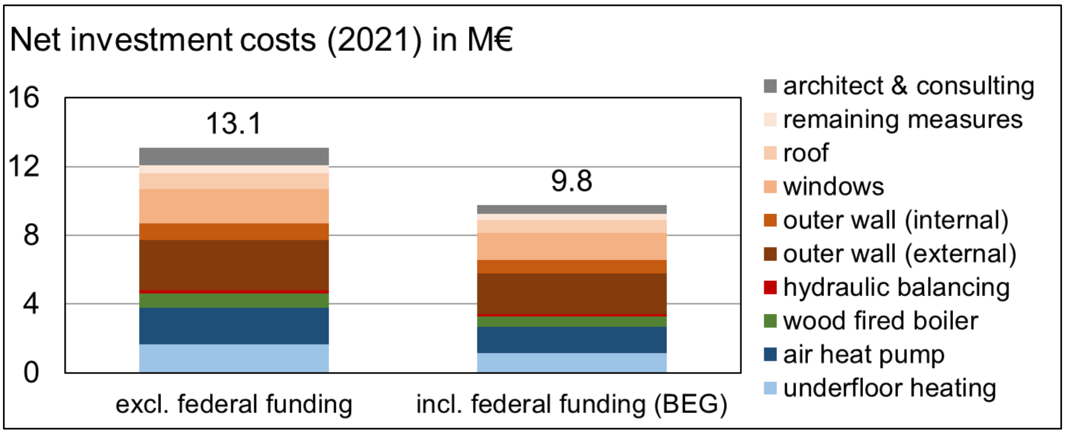

Figure 7: Investment costs for decentralized renovation

The operation costs presented in figure 8 are similar for both scenarios in total. Differences are the higher maintainance and repairs costs for solar district heating explained by higher investments for components that need to be maintained (heat generators, heating network and storages), and the higher electricity consumption of air heat pumps for decentralized renovation. Although the amount of wood is the same in both scenarios, the costs for biomass differ because of the higher prices for log wood used in decentralized renovation scenario compared to wood chippings used in solar district heating scenario (Carmen 2021). Costs for maintenance and repairs of the building's envelope have still to be investigated for both scenarios. In this study these costs have been neglected.

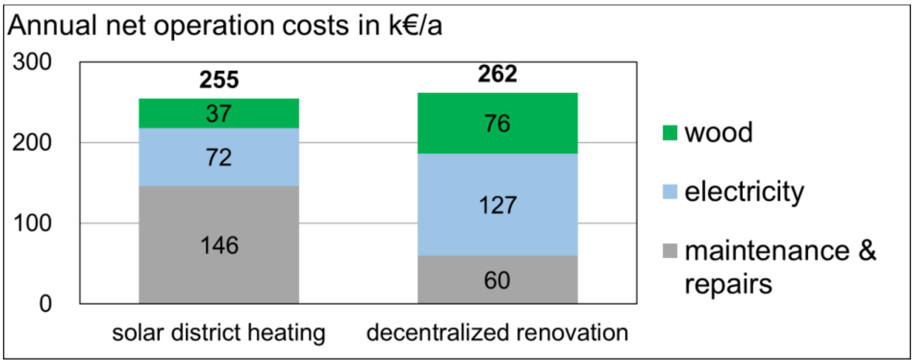

Figure 8: Annual net operation costs of both scenarios (annuity) during observation period of 20 years

A calculation is done with the annuity method under the following assumptions:

- observation period: 2025 until 2044 (20 years)
- interest rate: 3.0 %/a
- inflation rate: 1.8 %/a

Figure 9 shows the comparison of the annual net cost per average building in total. While the costs without federal funding are a bit lower for the decentralized renovation (5,147 €/a) compared to solar district heating (5,421 €/a), this changes after applying the federal funding resulting in solar district heating costs (3,734 €/a) slightly lower than costs for decentralized renovation (4,176 €/a). Considering the calculation accuracy both scenario's costs are on a similar level.

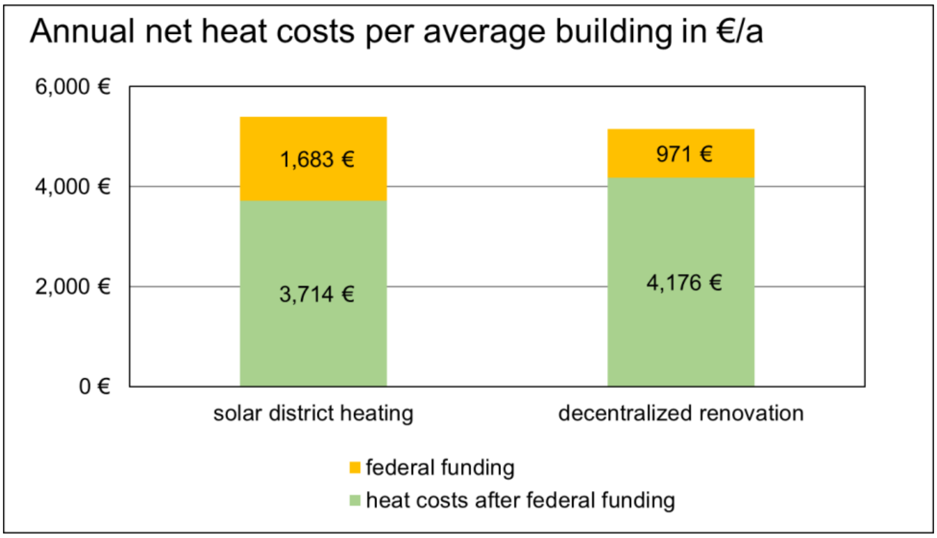

Figure 9: Comparison of annual heat costs per average building for solar district heating and decentralized renovation

The main difference between the two scenarios is illustrated in figure 10. While solar district heating can reach the full reduction of annual CO_2e emissions already at the start of operation (after a few years of planning and construction), this will take decades for decentralized renovation because of the low renovation rates. The accumulated CO_2e amount for the next three decades would be about 3,318 t_{CO2} with solar district heating and 14,202 t_{CO2} with decentralized renovation, which is an increase of 328%.

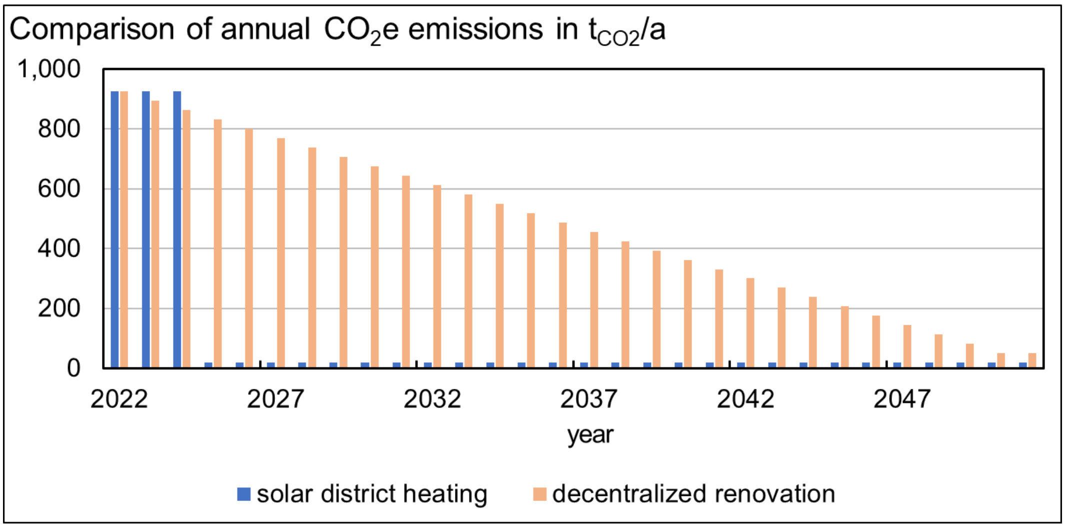

Figure 10: Comparison of the annual CO_2e emissions for both scenarios assuming a renovation rate of 3%/a to implement the measures for decentralized renovation

It should be mentioned that there should be still a cost reduction potential for the decentralized renovation scenario, because an economical optimization was implemented for solar district heating only.

7. Conclusion and Outlook

It is possible to significantly accelerate the decarbonization of heat supply in rural areas with solar district heating systems, while the heating costs are not increased compared to the alternative strategy of profound building renovation and use of heat pumps. The main advantage of profound building renovation on the other hand is higher living comfort (e.g., foot warmth thanks to underfloor heating, more even temperatures and fewer draught). It should be also mentioned that decentralized renovation scenario is not economical optimized. However, synergies between the two decarbonization strategies are possible: renovation of buildings connected to a heating network can still be carried out later, which leads to free capacities concerning heat generation and distribution which could be used for connecting further consumers.

8. Acknowledgment

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