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# Comparison of solar district heating and 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 small village in Germany with about 860 inhabitants and typically mainly old buildings, partly in half-timbered construction. The comparison shows that erection of a solar district heating system with solar fraction of about 67 % leads to similar heating costs as an energy efficient renovation followed by installation of decentralized air source heat pumps for most of the 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 $CO_2$ savings promptly, this would take decades for the implementation of energy efficient renovation and heat pumps due to low renovation rate. Reaching 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 mutually 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 alone, not always the same thermal comfort as with reinforced building renovation is achieved.

## 1. Introduction

About 150 million tons or about 18 % of the total annual greenhouse gas emissions, measured in tons of $CO_2$, are attributed to the heating and cooling of buildings in Germany [1], with heating having the largest share. Because 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 existing buildings in rural areas and develops two different heat supply scenarios for 180 buildings in a small German village called Rauschenberg-Bracht (or in short “Bracht”) as an example. The village with a total of 294 buildings and about 860 inhabitants is divided into two districts, which are about one kilometer apart. The 180 buildings to be supplied are distributed over both districts. There is no industry in Bracht and only a small amount of commerce. A solar district heating system with 67 % solar fraction and just a few basic renovation measures (centralized solution) is compared to more profound renovation combined with the installation of air source 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 and whose wood demand is limited to the current use, since wood is a limited resource [2]. The annual costs of heat for an average building are used as key figure in the evaluation of the two solutions. Furthermore, the annual $CO_2$ emissions for the next three decades are compared.

In the following, studies with relevant basic knowledge are presented. A basic precondition for an efficient heat pump operation in existing buildings is to bring the heating circuit supply temperatures to a sufficiently low level, what can be achieved by sufficient heating surface. To achieve this, either the heating surface can be increased or the required heating surface can be reduced by additional insulation measures on the building that lead to a reduction in the heating load [3–6]. In an extensive field test, Günther et al. [5] investigated the use of heat pumps in existing buildings in Germany analyzing heat pump efficiency, energetic condition of building and installed heating surface. In the study air source heat pumps were able to achieve high seasonal coefficients of performance (SCOP) of 3.1 on average ($n = 32$) even in only partially renovated buildings. The mean value of the temperatures for space heating for the majority of the air source heat pumps ($n = 29$) was

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36.9 °C and the mean value for the maximum supply temperatures was 43.6 °C. The latter were measured at average outside air temperatures of -3.0 °C, which is relatively warm in view of standard design outside air temperatures of -12 °C to -16 °C. In colder weather conditions, it can be assumed that the required heating circuit temperatures are correspondingly higher, while the SCOP decreases. However, it should be mentioned that within this field test the warm weather conditions of the test period (2018/2019) were favorable in terms of heat pump efficiency and moreover the buildings had been proposed by heat pump manufacturers, which in total suggests an above-average performance of the investigated heat pumps. Gerard et al. [7] also mention that heat pumps can be integrated into partially renovated existing buildings although they limit its use to high-temperature heat pumps or hybrid solutions (gas-fired peak load boiler and heat pump), which differs from the statement of Günther et al.

With regard to building renovation and the resulting energy savings, the results from Sunikka-Blank and Galvin [8] are important to consider. They found that the estimation of heat consumption based on the theoretical heat demand in comparison to the real consumption tends to be overestimated for inefficient buildings and underestimated for efficient buildings. In the first case they call it “prebound-effect” (overestimation) and in the second case “rebound-effect” (underestimation) and quantify as an example that the prebound-effect leaded to an overestimated heat consumption of about 30 % regarding German buildings ($n = 3{,}400$). The authors point out that predictions of energy and $CO_2$ emissions savings through renovation tend to be overestimated because of these two effects. Even though the necessary renovation efforts on the European level are estimated quite differently, as an example the range of heat demand reduction for buildings in 2050 compared to 2015 are specified in different studies between 28 % and 47 %, it is certain that significantly higher efforts are required in view of current renovation rates of about 1 %/a [7]. Hummel et al. [9] calculated specific savings costs for six European countries and for a heat demand reduction of the building stock by 50 % in each case and they arrive at a range between 0.014 €/kWh (Romania) and 0.093 €/kWh (Denmark) while Germany is in the midfield with 0.053 €/kWh. According to their study, the rebound-effect after renovation is considered in the calculations and the savings costs are below the respective net district heating price for all six countries. However, it remains unclear whether the prebound-effect, which has a significant impact, was considered too.

Case studies for dealing with the research question “expansion of renewable energies versus increased efficiency through renovation” are presented below. Francisco Pinto and Da Carrilho Graça [10] come to the result that for 10,000 buildings in Groningen (Netherlands) the heat costs, including investment and operating costs for a review period of 40 years, are about 12 % higher with deep geothermal fed district heating (226 M€) compared to decentral gas boilers combined with building renovation reducing the gas consumption by -86 % (202 M€), while at the business as usual case the costs are almost twice as high (390 M€). However, the question arises how the reduction of -86 % can be achieved with the measures used in the study in particular with 50 mm additional external wall insulation (thermal conductivity of 0.03 W/m•K). To a slightly different result arrive Liu et al. [11] for 162,000 buildings in Utrecht (Netherlands), after which a heat demand reduction of -7 % and a high district heating share of 75 % accompanied with 83 M€/a additional costs are more cost-effective than -17 % heat demand reduction and 21 % district heating share (otherwise use of individual heat pumps) associated with 228 M€/a additional costs compared to the reference scenario in both cases. In contrast to Bracht, the rural village investigated in this study, both case studies examine urban and much larger supply areas. Two other case studies compare costs for individual heating with district heating with the same state of building renovation in each heating solution. Wang [12] comes to the result that for an average British household the heat production costs are quite similar if using a heat pump individual as well as central for district heating. The SCOPs set for individual heat pumps (3 for air source and 4 for ground source heat pump) appears relatively high because additional renovation measures of the building, required for efficient heat pump operation as described before, are not mentioned and therefore probably not taken into account. In their case study Brum et al. [13] compare the costs for heating and cooling of low-energy houses in California by individual solution (electricity heating and air conditioning) and by district heating and cooling (ground source heat pump) coming to the result that the individual solution is cheaper. The framework conditions, in particular little low-energy houses in all variants, consideration of heating and cooling supply and low number of buildings (max. 12) appear in total unfavorable for centralized solution and differ significantly from the conditions in Bracht. Three other case studies focus on existing rural district heating providing heat mainly with biomass in the current state. While Lepiksaar et al. [14] and Terreros et al. [15] investigate switching the heat supply from biomass heat to a heat pump, Bücker et al. [16] investigate the operation of six heating networks in Germany over one year to identify optimization potentials and to develop a standardized monitoring. Compared to the first two studies, solar district heating can still be seen as a further development, since not only the biomass demand is reduced, but also the demand for peak load electricity. Other case studies for rural district heating networks were carried out from Le Guen et al. [17] investigating the electricity and heat supply of 150 buildings in Hemberg (Switzerland) and Huang et al. [18] investigating different measures to improve an existing district heating and cooling network supplying 181 buildings in Wangjiapu village (China). However, the latter studies do not seem to be easily comparable with the present study, because, for example, the focus is extended to electricity or cooling supply. Trabert et al. [19] consider the expansion of an existing district heating network of a village in Germany and calculate heat production costs for several constellations of heat generators (e.g., solar thermal system together with seasonal storage) as well as for an individual business as usual scenario without high ambitions to decarbonize. Even if the costs are not directly comparable to Bracht, because the heat network is partly already in place, a relevant result is that the heat costs for a solar district heating (38 % solar share) are only 14 % higher than the business-as-usual scenario but the spec. $CO_2$ emissions are 4-times less. A comparison between an increased use of renewable energies with the use of individual heat pumps and corresponding building renovation to decarbonize a village’s heat supply could not be found in literature so the present study aims to close this gap.

According to Bonk et al. [20], about 10 solar district heating networks with seasonal storage have been built as pilot systems in Germany, while similar systems are already used commercially and on a much larger scale in Denmark [21]. The present study is largely based on the previous work Kelch et al. [22]. An important novelty is, that the renovation measures of the decentralized solution are based now on the initial conditions of the buildings of the heat pump field test by Günther et al.. Furthermore, the dimensioning of components for the solar district heating is optimized under different conditions compared to the pre-work, now for example the current federal funding for efficient heat networks in Germany is considered.

## 2. Current state analysis

At present, in Bracht about two thirds of the heat is generated by heating oil and one quarter comes from biomass (wood logs, wood chips and pellets) while the remaining heat comes from liquid gas, electric heating and to a lesser extent from solar thermal domestic hot water systems. Almost all buildings are single or two-family houses, about 90 % were built (some of them in half-timbered construction) before 1980. The village with an area of about 28 km$^2$ is not connected to the natural gas grid. Strongly committed inhabitants of Bracht formed a local citizen energy cooperative to implement a solar district heating system which was supported among others by the city of Rauschenberg and the Hessian Ministry of Economics, Energy, Transport and Housing. According to current information about 180 buildings of a total of 294 buildings in Bracht will be connected to the district heating network, consisting of

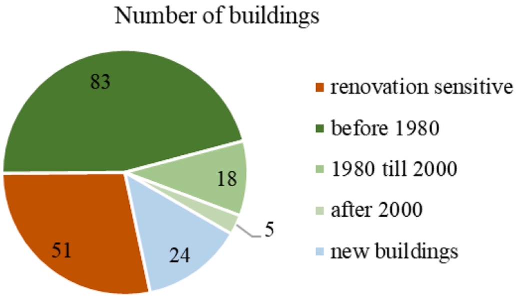

**Fig. 1.** Estimated distribution of 180 buildings into five building categories, "new buildings" include an already planned area in the community that will be built on in the near future.

residents with a connection request and planned new buildings with mandatory district heating connection. The connection rate of around 60 % initially seems quite high for a rural 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 as shown in Fig. 1. The category "renovation sensitive" includes the buildings erected in a half-timbered construction and in addition 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.

A data set based on the results of brief energy consultations conducted by the energy agency of Hesse (LEA) contains the following information for 27 buildings:

1) heat transfer coefficients and areas for building components of the thermal building envelope (both used later to estimate the necessary insulation measures for the decentralized renovation)
2) recommended low-investment renovation measures like insulation of the top floor or basement ceiling (applied when considering solar district heating)
3) annual consumption of various energy sources (oil, biomass, liquid gas, electricity) for heating purposes

Furthermore, for the 24 new buildings, yet to be built, the following assumptions have been made:

- heated living area: 200 $m^2$
- room temperature: 21 °C
- heat supply: air source heat pump for space heating and domestic hot water preparation (circulation of domestic hot water assumed)
- efficiency standard: KfW40, which is a German standard (Kreditanstalt für Wiederaufbau (KfW) 2023)

These assumptions result in a specific heat consumption of 68 kWh/($m^2$·a) (heated living area) and a building heat consumption of 13.6 MWh/a for the new buildings including space heating and domestic hot water. Because the region around Bracht is densely wooded and biomass is mainly used in wood fired stoves, short transportation routes are assumed and, thus, a $CO_2$ emission factor of 0 $g_{CO2}$/kWh is chosen for biomass. Based on the distribution shown in Fig. 1 and on calculated average values per building category the today's current overall heat consumption (4,518 MWh/a), $CO_2$ emissions (989 $t_{CO2}$/a) and biomass consumption (1,493 MWh/a) are estimated for the 180 buildings.

## 3. Comparability of two scenarios

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

- heat supply including space heating and domestic hot water for 180 potential consumers
- no greater use of biomass than in the present and no local use of fossil fuels
- review period: 2025 to 2044

The emission factors for consumed electricity from the grid during the review period are estimated by defining three anchor points and the assumption of linear decrease in between these points: 438 $g_{CO2}$/kWh from before corona pandemic in the year 2019 [23], 61 $g_{CO2}$/kWh in 2030 based on the Germany's policy goal of reaching 80 % renewable share in combination with emission factors by Luderer et al. [24] and 0 $g_{CO2}$/kWh in 2045 by reaching climate neutrality. The emission factors over the review period are illustrated in Fig. 2 while the average value of this period is 65 $g_{CO2}$/kWh.

In Fig. 3 the limit of energy balance for the heat consumption is illustrated which means depending on scenario the output heat of the house transfer station (a) or the heat generator (b).

## 4. Solar district heating scenario

In this scenario the $CO_2$ emissions are mainly reduced by the implementation of renewable energies, especially solar thermal energy. Only low-investment renovation measures, such as insulation of top floor and basement ceiling are exploited to reduce the heat demand and thus the initial investment costs for the heat supply system. The potential reduction of heat consumption due to these measures is estimated at about 2 % for the 156 existing buildings based on detailed recommendations for 27 buildings by the LEA, estimated heat consumption reductions with the method of tabula according to Loga and Diefenbach [25] and following extrapolation on the number of 156 existing buildings. The total net costs of the minimum renovation are about 631 k€.

The most important components of the central heating concept are a large solar thermal collector field and a seasonal heat storage, which is

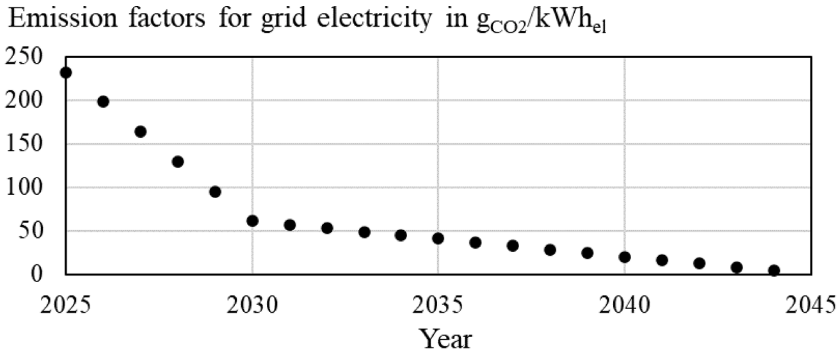

**Fig. 2.** Assumed emission factors for grid electricity during review period.

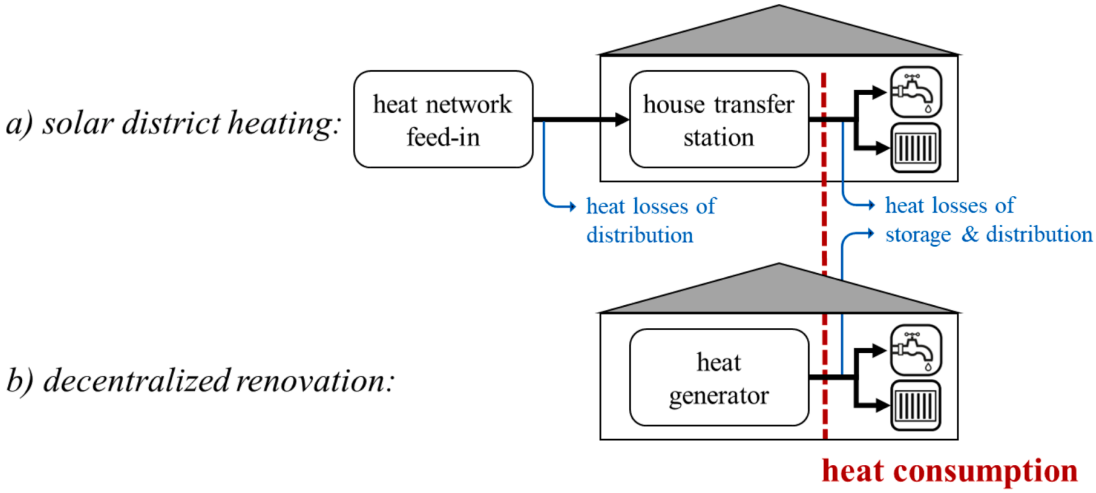

**Fig. 3.** Limit of energy balance for heat consumption (dashed red line) in the scenarios solar district heating (a) and decentralized renovation (b).

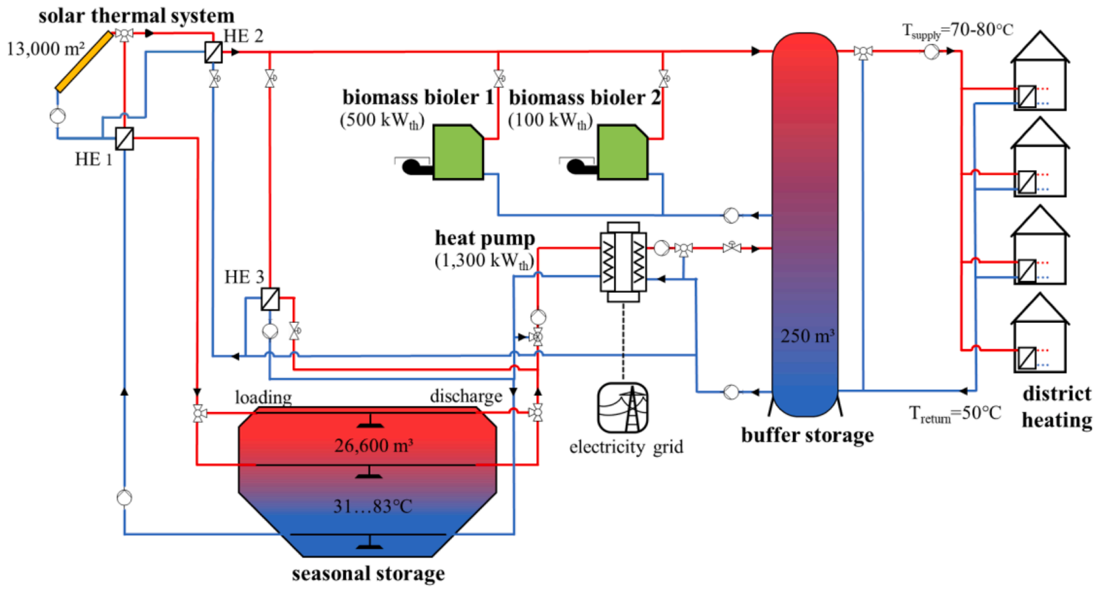

**Fig. 4.** Solar district heating system.

designed as a pit storage filled with water, covered with a foil on the ground and slopes and insulated with a floating thermal insulation on the top. An electric heat pump is used to cool down the storage in the heating period to about 31 °C. This enables to reduce the storage size and, thus, the investment costs, compared to the limitation of the storage discharge down to the return temperature of the district heating network of about 50 °C. The remaining heating load is covered by two biomass boilers, which can also use moist biomass (e.g., green cuttings) and serve as auxiliary heating of the heat pump to increase its efficiency.

The solar thermal heating system, illustrated in Fig. 4, has the following operating states listed in decreasing priority:

1. direct heat supply from solar collector
2. direct heat supply from seasonal storage tank
3. simultaneous heat supply from heat pump and biomass boilers

The heating system is simulated in TRNSYS with the modified type 343 "ICEPIT" as pit storage for 3.5 years with the same weather conditions for each year. Based on the temperature profiles in Fig. 5, it is assumed that the ground around the storage tank has reached after 2.5 years a thermal equilibrium, apart from the temperature changes within the annual cycle. The difference in the average minimum storage temperature compared to the previous year is 1.24 K in the second year and 0.33 K in the third year, which is already very small. Only the last year of the simulation is used for energetical and economical evaluation. It has not been investigated to which extent this approach could be transferred to other climatic conditions and soil properties.

For the optimization TRNSYS is coupled with the software GenOpt (Generic Optimization program) to determine the component sizes that yield minimum levelized costs of heat [26]. The heating load profile for the simulation is created according to the procedure of Hellwig [27] based on the annual heat consumption of the buildings. The heat loss profile of the heating network is determined by a calculated network heat loss coefficient based on a heat network design in STANET (Fischer-Uhrig Engineering GmbH) and an estimated ground temperatures profile.

The results of the heat cost optimization show that with different system configurations, either enlargement of collector area and seasonal storage with lower cooling of the seasonal storage or larger heat pump with deeper cooling of the seasonal storage, similar low costs can be achieved in certain dimensioning ranges with regard to the calculation accuracy of the determined cost minimum. The advantage of the first

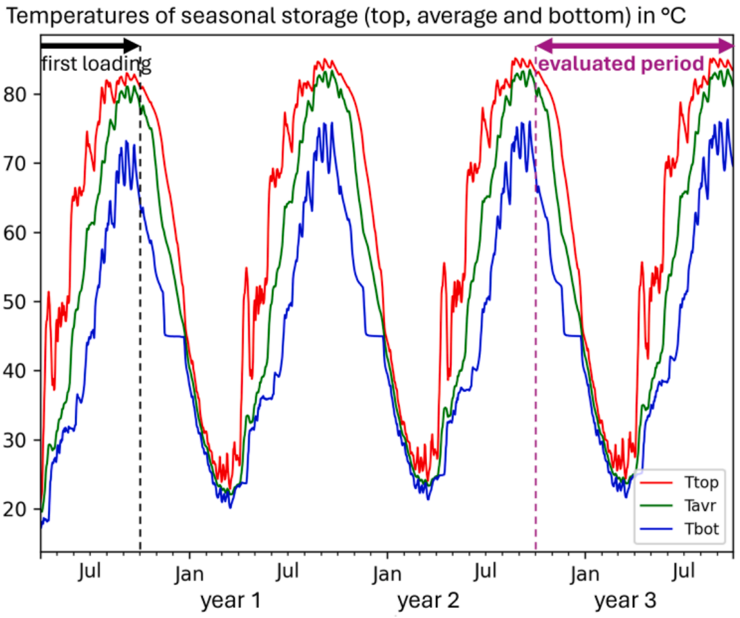

**Fig. 5.** Temperature profiles of seasonal storage tank.

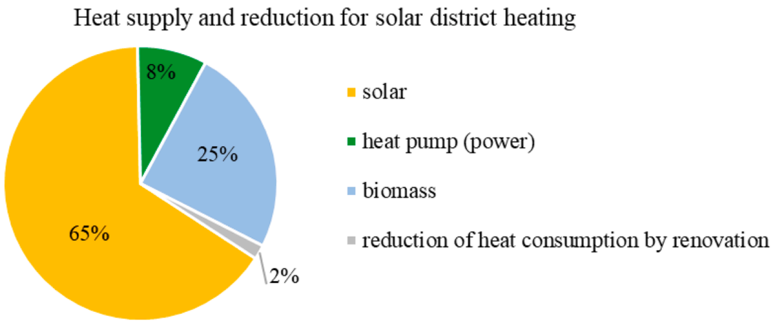

**Fig. 6.** Distribution of heat sources (at house transfer station) and reduction in heat demand through renovation.

configuration, which tends to have a larger solar system and a larger seasonal storage tank, is that if additional heat consumers were subsequently connected, it would be easy to cool down the seasonal storage tank further, e.g., by adding heat pump capacity. Therefore, such a configuration is chosen, and the associated plant sizes are shown in Fig. 4. The levelized costs of heat (net amount) for the selected configuration are 146 €/MWh with federal funding and 219 €/MWh without funding related to the heat purchased at the house transfer stations. The cost optimization with and without funding leads to almost the same dimensioning of the system because the considered federal funding for efficient heating networks in Germany provides the main incentive in the form of investment cost funding and all components of the concept are funded with the same percentage of 40 %. Therefore, both results are not presented separately.

The shares of heat supply from different energy sources (regarding heat consumption at the house transfer stations) and the reduction in heat demand through renovation are shown in the Fig. 6 for the optimized system. With 65 %, respectively 67 % regarding only the heat supply, solar thermal energy has the highest share. The heat pump is working with a SCOP of about 4.2 and the seasonal storage tank is operated in a temperature range of 31 to 83 °C. Due to solar district heating the $CO_2$ emissions are reduced by -97 % compared to current state.

## 5. Decentralized renovation scenario

In this scenario the decarbonization is achieved with individual measures in the buildings only. The estimation of the measures is based on the evaluation of the already mentioned 27 buildings for which detailed data are available. To estimate the extent of the measures the approach 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 are replaced). The building renovation might often not be practically feasible throughout in this way, but the consideration of the minimum required insulation thickness ensures that costs for decentralized renovation are in tendency underestimated and calculated conservatively
- If a measure is necessary, it is dimensioned so that the heat transfer coefficients meet the requirements of the federal funding for efficient buildings (BEG) in Germany [28].

Since, as already described, building insulation (u-values), heating surface and heat pump efficiency are closely related by the achievable

**Table 1**
Thermal transmittance (U-value) of build elements for the derivation of insulation measures in the scenario decentralized renovation.

| Building component | Assumed thresholds for the existing insulation in $W/m^2 \bullet K$ | Minimum requirement of funding if new measures are done in $W/m^2 \bullet K$ |
|---|---|---|
| roof | 0.4 | 0.14 |
| top ceiling | 0.3 | 0.14 |
| basement ceiling | 0.6 | 0.25 |
| basement wall | 0.8 | 0.25 |
| base plate | 0.6 | 0.25 |
| outer wall | 0.8 | 0.20 |
| outer wall (renovation sensitive) | 1.2 | 0.65 |
| windows | 2.6 | 0.95 |

heating circuit flow temperature, this work is orientated to the results from the field test of Günther et al. [5] who investigated heat pumps operated in existing buildings. The SCOP for an electric driven heat pumps can be described as quotient of heat supply and electricity consumption. Thus, the average SCOP for air source heat pumps of 3.1 is considered that was determined in the field test under the following conditions:

- considered heat supply: thermal storage loading for space heating and domestic hot water by heat pump and heating rod minus thermal energy for defrosting the air source heat pump
- considered electricity consumption: all consumers inside the heat pump, the electric heating rod and the ventilator (heat source drive on primary side) without the pump(s) on secondary side (heat sink)

Minimizing insulation costs as far as possible while still achieving high SCOPs was the main challenge in the design of the decentralized renovation scenario in this study. It is assumed that the efficiency measures of the existing buildings from the field test [5], which had been pre-selected by heat pump manufacturers, are well balanced in this respect, because the average SCOP seems to be quite high.in view of the fact that most of the buildings are only partially renovated. Therefore, the assumed thresholds for the upper building envelope (roof and top floor ceiling), the external walls (internal and external insulation) and windows are orientated (read from figures) to the thresholds from 45 buildings energetical analyzed in the field test. The threshold values of the building elements were selected so that they correspond to the highest thermal transmittance (U-value) that occurs among the buildings from the field test for this element. This ensures that the buildings from this study are at least as well insulated as the worst insulated building from the field test. The thresholds for the basement ceiling, base plate and basement wall shown in Table 1, on the other hand, correspond to own assumptions. All assumed thresholds are presented together with minimum requirements for funding in Table 1.

The share of living space heated with underfloor heating in existing buildings is estimated with 40 % on average based on the results of the field test together with own assumptions. For the new buildings which are all heated by heat pumps it is assumed that there is only panel heating installed. Furthermore, it is assumed that new biomass boilers (wood logs) are preferentially used in the buildings with the highest specific heat consumption and moreover, only in buildings sensitive to renovation or currently heated with biomass. Under the assumptions made, the available biomass is sufficient to heat 42 buildings (23 %), while the remaining 138 buildings (77 %) are heated with air source heat pumps. The share of living space heated with panel heating is 38 % of the total living space of all buildings, while a large part of it is accounted to the new buildings.

It is assumed that new biomass boilers fired by wood logs are implemented in the buildings with the highest specific heat consumption and only either in the renovation sensitive buildings or in the buildings that are currently heated with biomass. So, it results that the biomass amount from the current state suffices to heat 42 buildings (23 %), while the remaining 138 buildings (77 %) are heated by air source heat pumps and the living area with underfloor heating is 38 % of the total living area of all buildings.

The reduction of heat consumption for each of the 27 buildings is calculated by the tabula method, a standard reference calculation procedure for determining delivered energy demand at which the prebound and the rebound effect are considered both with a single correction factor (Loga and Diefenbach [25] and Loga et al. [29]). Fig. 7 presents the estimated shares of measures for the 180 buildings. It is noticeable that the three measures windows exchange, insulation of outer walls and insulation of buildings envelope top are implemented in a similar frequency of 44 % to 47 % while the insulation of the building's envelope base is implemented more often with 68 %.

Results show that by the implementation of the presented insulation measures the total heat consumption including space heating and domestic hot water preparation decreases by about -18 % and the average specific total heat consumption is reduced from 124 $kWh/(m^2{\cdot}a)$ to 103 $kWh/(m^2{\cdot}a)$ related to the heated living space. Simultaneously $CO_2$ emissions for all 180 buildings are reduced in total by -95 %, in particular by displacing fossil fuels through the use of heat pumps and

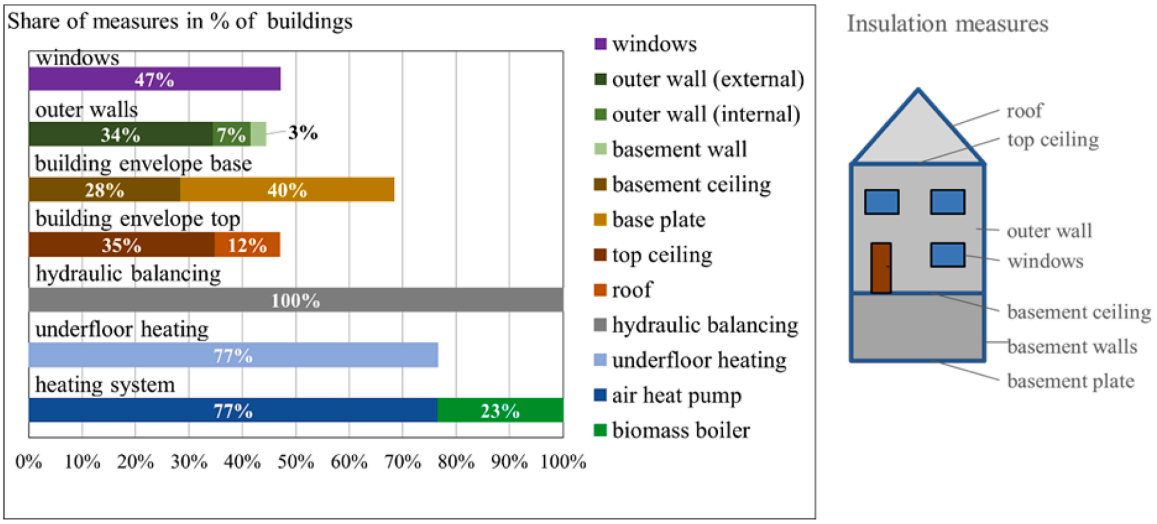

**Fig. 7.** Estimated measures for 180 buildings in decentralized renovation scenario.

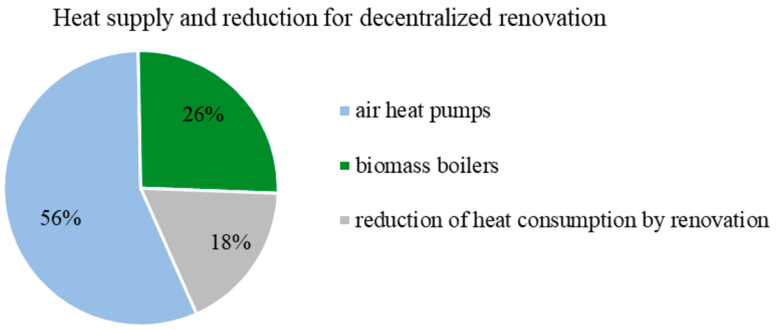

**Fig. 8.** Reduction of heat consumption and shares of heat supply for decentralized renovation.

wood boilers with the assumed spec. emissions for electricity of 65 $g_{CO2}$/kWh (average value for the review period) and for biomass of 0 $g_{CO2}$/kWh. The shares of heat supply by air source heat pumps and biomass boilers as well as the reduction of heat consumption are shown in Fig. 8.

Based on the results in Fig. 7 it can be roughly assumed that renovation measures are implemented at half of the thermal building envelope area. An explanation that the other half of the area is not renovated is that among the 180 buildings, there are 24 planned and 5 existing new buildings that do not require a renovation. In addition, the renovation thresholds used reduce the number of required measures, since no additional renovation is carried out for sufficiently efficient existing building parts. If approximately the half of the thermal building envelope area is renovated, the reduction of the total heat consumption of -18 % seems to be low at first sight, but there are several reasons for that:

- The prebound and the rebound effect are considered resulting in lower reductions which are closer to measured values. Without taking these effects into account, the reduction of the total heat consumption would be -30 % (instead of -18 %), and thus 40 % higher.
- Besides space heating also domestic hot water preparation is considered in the heat consumption but latter does not change due to the renovation measures. Without domestic hot water preparation the reduction of the total heat consumption would be approximately -21 % (instead of -18 %).
- The reduction in heat consumption is highest for the first cm of insulation. Since many buildings in Bracht are already partially insulated but not sufficiently efficient in view of the renovation thresholds set, the additional insulation of these buildings has less effect compared to buildings in completely unrenovated condition.
- In renovation sensitive buildings, which account for 28 % of all buildings, outer walls are insulated only internal and relatively few (thermal transmittances (U-values) of threshold-value and minimum requirement are higher compared to the rest of the buildings as shown in Table 1).

As a rough check, the calculated reduction of total heat consumption for Bracht is compared with that of an individual building, calculated using the tabula webtool by Loga et al. [30]. In both cases the reduction refers to the total heat consumption including space heating and domestic hot water and furthermore rebound as well as prebound effects are taken into account. For the individual building an initially unrenovated single-family house in Germany with a construction year between 1958 and 1968 is selected (building name in tabula webtool: DE.N.

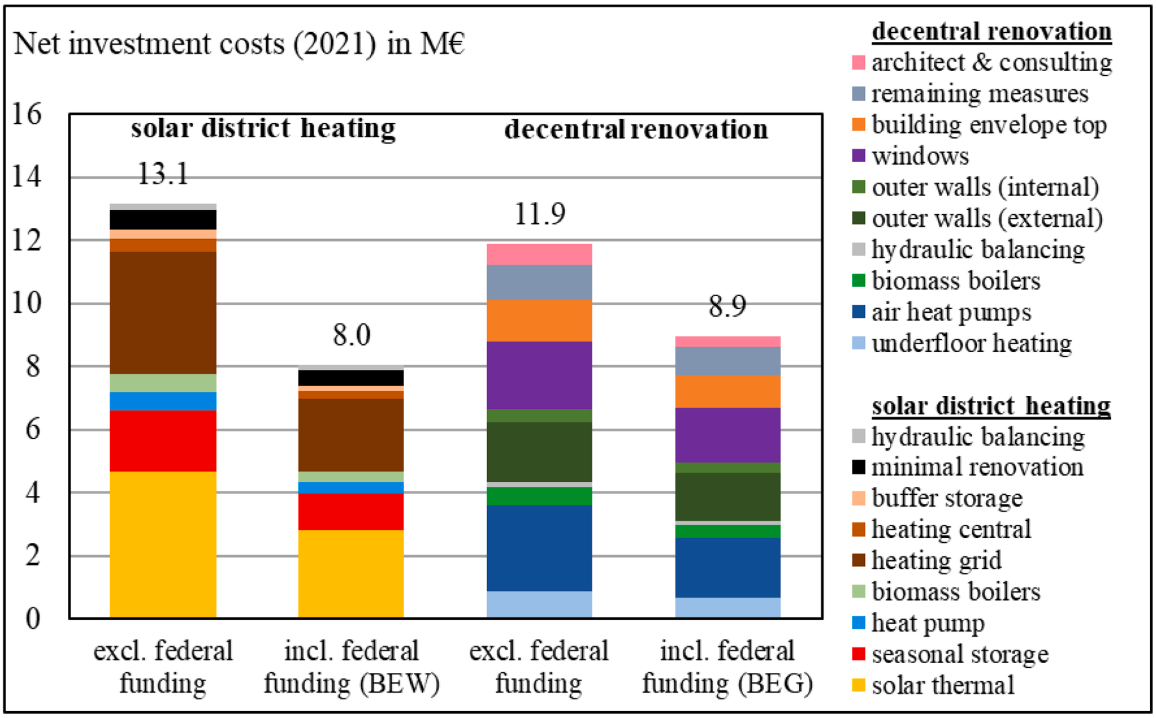

**Fig. 9.** Investment costs of both scenarios, each with and without federal funding.

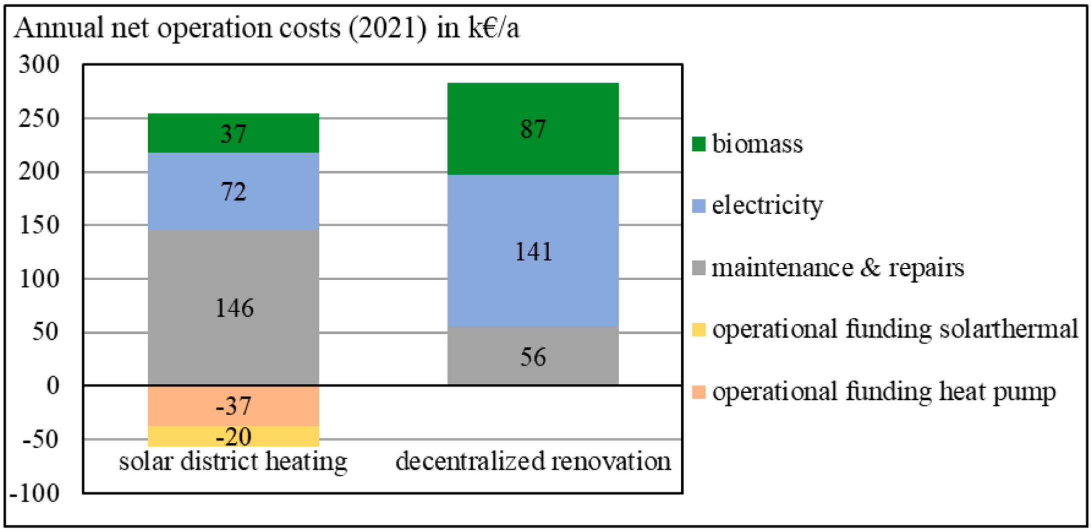

**Fig. 10.** Annual net operation costs of both scenarios (annuity) during observation period of 20 years. The total costs are therefore 255 k€/a (198 k€/a incl. funding) for the centralized and 283 k€/a for the decentralized solution.

SFH.05.Gen). With ambitioned renovation and the use of a ground source heat pump the total heat consumption is reduced by -41 % (without ventilation and heat recovery) for the individual building. Assuming that within the renovation scenario for Bracht about half of the thermal envelope building area is renovated, the heat consumption reduction should be about twice as high if the whole area was renovated, and thus approx. -36 %. The difference to -41 % achieved for the renovation example can be explained by the fact that many buildings in Bracht have already been partially renovated but are still less efficient than the renovation thresholds. Therefore, the additional renovation measures result in lower heat consumption savings. It should be mentioned that ventilation with heat recovery could be used as a further effective measure to reduce the heat consumption. However, this measure, which would also be associated with additional costs, was not considered for the renovation scenario.

## 6. Comparison of two scenarios

All assumptions of costs and useful life are listed for both scenarios in the annexes A to G. In the following, the results of the economic feasibility study are presented, and the funding is briefly discussed. Like it is illustrated in Fig. 9, the largest investments for solar district heating are the solar thermal system, the heating network, and the seasonal heat storage. A funding program for district heating in Germany that has been in place since September 2022 is the so called federal funding for efficient heating networks (BEW). The funding percentage for investment by the BEW is 40 % [31].

The total investment costs for decentralized renovation are similar to those for solar district heating as also presented in Fig. 9. The measures with the highest investment costs are heat pumps, outer wall insulations and replacement of windows. Funding is considered by federal funding for efficient buildings (BEG), a funding program for the renovation of buildings in Germany [32]. In the scenario decentral renovation, the estimated amount of underfloor heating (38 % of total heated living area) and the corresponding costs are considered. As a rough estimation costs for architect's services are only set in form of a lump sum per building if roofs or outer walls have to be insulated. However, additional investment costs for new radiators, according to Günther et al. an important prerequisite for increasing heat pump efficiency in existing buildings, are neglected because these costs are difficult to quantify. For solar district heating engineer costs are included in the investment costs.

The operation costs presented in Fig. 10 show differences between both scenarios such as higher maintenance and repairs costs for solar district heating that can be traced to higher investments for components that need to be maintained (heat generators, heating network and storages), and the higher electricity consumption of air source heat pumps for decentralized renovation. Another difference is the operating cost funding in Germany by the funding program BEW for solar thermal

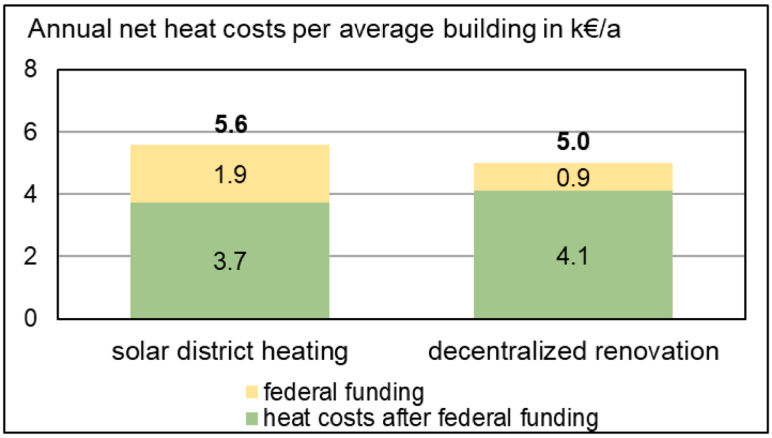

**Fig. 11.** Comparison of annual heat costs per average building for solar district and decentralized renovation.

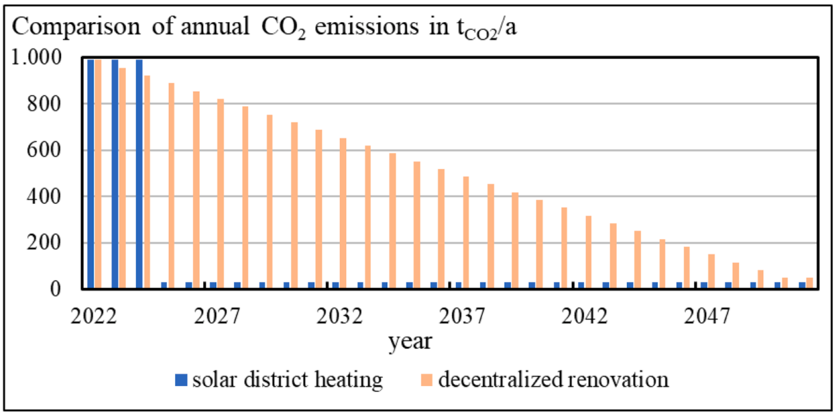

**Fig. 12.** Comparison of the annual $CO_2$ emissions for both scenarios assuming a renovation rate of 3 %/a to implement the measures for decentralized renovation.

systems and heat pumps that feed into a district heating network, however the exact application is not explained in this study, as it is only relevant for Germany. Although the amount of biomass is nearly 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 chips used in solar district heating scenario. Costs for maintenance and repairs of the building's envelope have still to be investigated for both scenarios. Hence, in this study these costs have been neglected for both scenarios.

The calculation of the annual heat costs is done with the annuity method [33] under the following assumptions:

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

The comparison of the annual net cost per average building in Fig. 11 (heated living space of 202 $m^2$) shows that while the costs without federal funding are about 11 % lower for the decentralized renovation (4,995 €/a) compared to solar district heating (5,597 €/a), this changes after applying the federal funding resulting in solar district heating costs (3,730 €/a) now around 9 % lower than costs for decentralized renovation (4,117 €/a). Considering the uncertainty of the cost assumptions made to calculate the heating costs of both scenarios, solar district heating and decentralized renovation, the sensitivities are greater than the difference between the two results. Since an economic optimization with numerical methods was only carried out for the solar district heating, for the costs of the decentralized renovation there should still be a certain cost reduction potential. On the other hand, the following costs have been neglected in the decentralized solution:

- The costs for new or additional radiators haven't been considered. Costs would have to be expected after the field test by Günther et al. [5] as of the 44 existing buildings heated with heat pumps, radiators had been retrofitted in 26 buildings, often with larger dimensions, while just in 13 buildings only original radiators were operated.
- The costs for necessary electricity grid reinforcements as well as additional low-voltage transformers have not yet been considered in the decentralized solution, in order not to jeopardize the general validity of the statement.

With regard to the macro-economic costs, it can therefore be assumed that the centralized solution will in general be cheaper to implement than the decentralized one.

The further main difference between the two scenarios is illustrated in Fig. 12. While solar district heating can reach the full reduction of annual $CO_2$ emissions already at the start of operation (after a few years of planning and construction), this will take decades for decentralized renovation even with an assumed renovation rate of 3 %/a. The accumulated $CO_2$ emissions over the next three decades would be 4-times higher with decentralized renovation (15,100 $t_{CO2}$) than with solar district heating (3,750 $t_{CO2}$).

## 7. Conclusion

Solar district heating can significantly accelerate the decarbonization of heat supply in rural areas. The heat costs of solar district heating and increased building renovation with the use of heat pumps are very similar within the calculation uncertainty. However, depending on the capacity of local power distribution lines, centralized solar heat supply would become the clearly most economically favorable solution. The main advantage of building renovation, on the other hand, is increased living comfort (e.g., foot warmth thanks to underfloor heating, more even temperatures, fewer drafts). However, synergies between the two decarbonization strategies are possible: renovation of buildings connected to the heating network can lead to free capacities in heat generation and distribution and enable the connection of additional consumers.

## CRediT authorship contribution statement

**Jan Kelch:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Oleg Kusyy:** Conceptualization, Data curation, Formal analysis, Software, Visualization, Validation. **Johannes Zipplies:** Conceptualization, Data curation, Formal analysis, Software, Validation, Visualization. **Janybek Orozaliev:** Funding acquisition, Supervision. **Klaus Vajen:** Funding acquisition, Methodology, Resources, Supervision, Writing – review & editing.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Jan Kelch reports financial support was provided by State of Hesse Ministry of Economics Energy Transport and Housing. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Annex A: Assumed net prices of energy carriers in both scenario (reference year is 2021)

| energy carrier | net price | source | price increase | source |
|---|---|---|---|---|
| *Solar district heating:* | | | | |
| electricity | 23,2 Ct/kWh | commercial electricity price according to Bundesnetzagentur and Bundeskartellamt [34] | 0,0 %/a | own assumption |
| wood chips | 2,2 Ct/kWh | manufacturer A (2021) | 1,0 %/a | own assumption |
| *decentral renovation:* | | | | |
| electricity for heat pump | 20,0 Ct/kWh | heat pump electricity price according to Bundesnetzagentur and Bundeskartellamt [34] | 0,0 %/a | own assumption |
| Auxiliary electricity (boilers) | 26,8 Ct/kWh | domestic customers electricity price according to Bundesnetzagentur and Bundeskartellamt [34] | 0,0 %/a | own assumption |
| wood logs | 5,4 Ct/kWh | CARMEN [35] | 1,0 %/a | own assumption |

## Annex B: Assumed net investment costs for solar district heating incl. normalization to the year 2021 with the consumer price index (bold font) if reference year is older than 2021

| component | value / formula | unit | reference year | source |
|---|---|---|---|---|
| solar thermal system | $1535 \text{ x } {A_{\mathrm{col},\ m^2}}^{(-0.165)} \text{ x } 1.091$ | €/$m^2$ | 2015 | Grosse et al. [36] |
| land area | 2.3 | €/$m^2$ | 2022 | energy cooperative Bracht |
| biomass boiler | 870.5 | €/$kW_{th}$ | 2021 | manufacturer A (2021) |
| biomass storage | $21 \times 1.096$ | €/$m^3$ | 2014 | Eltrop et al. [37] |
| heat pump | $(349.5 \text{ x } \dot{Q}_{\mathrm{HP},\ \mathrm{kW\_th}}^{0.912} \text{ x } 1.25 \times 1.8) / \dot{Q}_{\mathrm{th,HP}} \text{ x } 1.031$ | €/$kW_{th}$ | 2020 | Schlosser [38] |
| frequency inverter for heat pump | 20,000 | € | 2022 | own assumption |
| seasonal storage | $1900 \text{ x } {V_{\mathrm{St},\ m^3}}^{-0.33} \text{ x } 1.091$ | €/$m^3$ | 2015 | Grosse et al. [36] |
| hydraulic seasonal storage | 50,000 | € | 2021 | manufacturer A (2021) |
| buffer storage | 1000 | €/$m^3$ | 2021 | manufacturer A (2021) |
| district heating route | 360 | €/m | 2021 | manufacturer A (2021) |
| house transfer station | 3250 | € | 2021 | manufacturer A (2021) |
| network technology | 280,000 | € | 2021 | manufacturer A (2021) |
| control technology | 120,000 | € | 2021 | manufacturer A (2021) |
| heating centre | 1875 | €/$m^2_{FA}$ | 2021 | manufacturer A (2021) |

## Annex C: Assumed annual net maintenance and repair costs for solar district heating

| component | net maintenance and repair costs | Source |
|---|---|---|
| heat generator | | |
| solar thermal system | 3 €/$MWh_{th}$ (incl. costs of auxiliary electricity) | manufacturer A (2021) |
| heat pump | 2,7 €/$kW_{th}$ (fix) and 1,7 €/($MWh_{th}$•a) (variable) | Grosse et al. [36] |
| biomass boiler | 4,0 %/a related to investment costs | Eltrop et al. [37] |
| thermal storage | | |
| seasonal storage | 1,25 %/a related to investment costs | Mangold et al. [39] |
| *hydraulics of seasonal storage* | 2,0 %/a related to investment costs | VDI (2012) |
| buffer storage | 2,0 %/a related to investment costs | VDI (2012) |
| district heating network | | |
| district heating route | 0,5 %/a related to investment costs | VDI (2012) |
| house transfer stations | 3,0 %/a related to investment costs | VDI (2012) |
| network technology | 3,0 %/a related to investment costs | VDI (2012) |
| control technology | 3,0 %/a related to investment costs | VDI (2012) |
| heating centre | 2,0 %/a related to investment costs | VDI (2012) |

## Annex D: Assumed useful life of the components for solar district heating

| component | useful life in years | source |
|---|---|---|
| solar thermal system | 30 | Grosse et al. [36] |
| biomass boiler | 20 | Eltrop et al. [37] |
| biomass storage | 30 | own assumption |
| heat pump | 20 | Wolf [40] |
| seasonal storage | 30 | own assumption |

(*continued on next page*)

(*continued*)

| component | useful life in years | source |
|---|---|---|
| hydraulic of seasonal storage | 20 | VDI (2012) |
| buffer storage | 20 | Grosse et al. [36] |
| district heating pipes | 50 | manufacturer A (2021) |
| house transfer station | 20 | own assumption |
| network technology | 20 | own assumption |
| control technology | 20 | VDI (2012) |
| heating center | 50 | VDI (2012) |

## Annex E: Assumed net investment costs for decentralized renovation incl. normalization to the year 2021 with the consumer price index* and building price index** (bold font in each case) if reference year is older than 2021

| | value / formula | unit | reference year | source |
|---|---|---|---|---|
| *heat generators:* | | | | |
| air heat pump | (0.657 x $\dot{Q}_{th,HP,kW}$ ˆ 2 - 55.886 x $\dot{Q}_{th,HP,kW}$ + 2191) x 1.03*<br>(formula created from graphic) | €/$kW_{th}$ | 2020 | Bürger et al. [41] |
| biomass boiler | (1.5 x $\dot{Q}_{th,pellet\ boiler,kW}$ ˆ 2 - 94.5 x $\dot{Q}_{th,\ pellet\ boiler,kW}$ + 2040) x 1.03*<br>(formula created from graphic) | €/$kW_{th}$ | 2020 | Bürger et al. [41] |
| *insulation measures:* | | | | |
| roof | (2.33 x $d_{insulation,cm}$ + 126.9) x 1.27** | €/$m^2_{component}$ | 2015 | Lambrecht and Jungmann [42] |
| roof dormer | 397.5 × 1.27**<br>(11 $m^2$ of roof dormer for each insulated roof assumed according to Hinz 2015) | €/$m^2_{component}$ | 2015 | Lambrecht and Jungmann [42] |
| top ceiling | 0.5 x (1.5 x $d_{insulation,cm}$ + 23.55 + 0.89 x $d_{insulation,cm}$ + 3.13) x 1.27**<br>(50 % walkable and 50 % non-walkable assumed) | €/$m^2_{component}$ | 2015 | Lambrecht and Jungmann [42] |
| base plate | (0.87 x $d_{insulation,cm}$ +42.16) x 1.27** | €/$m^2_{component}$ | 2015 | Lambrecht and Jungmann [42] |
| basement ceiling | 0.5 x (1.05 x $d_{insulation,cm}$ + 25.84 + 1.3 x $d_{insulation,cm}$ + 45.59) x 1.27**<br>(50 % clad and 50 % non-clad surface assumed) | €/$m^2_{component}$ | 2015 | Lambrecht and Jungmann [42] |
| basement wall | 124.07×1.09**<br>(assumed fix value is related to 8–10 cm of insulation) | €/$m^2_{component}$ | 2020 | Dahlhaus et al. [43] |
| outer wall (internal) | 124.07×1.09**<br>(assumed fix value is related to 8–10 cm of insulation) | €/$m^2_{component}$ | 2020 | Dahlhaus et al. [43] |
| outer wall (external) | (2.36 x $d_{insulation,cm}$ +81.41) x 1.27**<br>(thermal insulation composite system) | €/$m^2_{component}$ | 2015 | Lambrecht and Jungmann [42] |
| scaffolding costs | 63.56 x $A_{heated\ living\ area}$ ˆ −0.32×1.27** | €/$m^2_{heated\ living\ area}$ | 2015 | Lambrecht and Jungmann [42] |
| windows | 396.92 x $A_{window}$ ˆ −0.32×1.27** | €/$m^2_{component}$ | 2015 | Lambrecht and Jungmann [42] |
| *remaining costs:* | | | | |
| underfloor heating | 50.4 x (1.12* / 2 + 1.34** / 2) | €/$m^2_{component}$ | 2012 | Hempel et al. [44] |
| hydraulic balancing | 15.17 x $A_{heated\ living\ area}$ ˆ −0.22×1.12* | €/$m^2_{heated\ living\ area}$ | 2012 | Hempel et al. [44] |
| architect | 616.16 x $A_{heated\ living\ area}$ ˆ −0.599×1.09* | €/$m^2_{heated\ living\ area}$ | 2015 | Lambrecht and Jungmann [42] |
| energy consulting | 1345×1.09* | € | 2015 | Lambrecht and Jungmann [42] |

## Annex F: Assumed net maintenance and repair costs for decentralized renovation

| component | maintenance and repair costs | Source |
|---|---|---|
| *heat generators:* | | |
| air heat pump | 173 €/a | own assumption |
| biomass boiler | 397 €/a | own assumption |

## Annex G: Assumed useful life of the components for decentralized renovation

| component | useful life in years | source |
|---|---|---|
| *heat generators:* | | |
| air heat pump | 20 | Lambrecht and Jungmann [42] |
| biomass boiler | 20 | Lambrecht and Jungmann [42] |
| *heat distribution:* | | |
| underfloor heating | 50 | Lambrecht and Jungmann [42] |
| *insulation measures:* | | |
| roof | 30 | Lambrecht and Jungmann [42] |
| top ceiling | 50 | Lambrecht and Jungmann [42] |
| base plate | 50 | Lambrecht and Jungmann [42] |
| basement ceiling | 50 | Lambrecht and Jungmann [42] |
| basement wall | 50 | Lambrecht and Jungmann [42] |
| outer wall (internal) | 50 | Lambrecht and Jungmann [42] |
| outer wall (external) | 30 | Lambrecht and Jungmann [42] |
| windows | 50 | Lambrecht and Jungmann [42] |

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