DECARBONIZING BUILDING STOCK WITH RENEWABLE DISTRICT HEATING – A CASE STUDY FOR A RURAL AREA IN GERMANY

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Abstract

District heating can present an opportunity to increase the share of renewable energies in the German heating sector, which is currently stagnating at around 14 % (Umweltbundesamt 2018). The aim of this paper was to develop heat supply concepts for the year 2030 for mainly residential settlements in rural areas. For this purpose, a village in central Germany was examined with regard to its heat demand and supply structure. As heat supply technologies, large solar collector fields with a seasonal storage, woodchip boilers and combinations of CHP-units and heat pumps for sector coupling were investigated. The tool energyPRO by EMD International A/S was used to simulate three concepts with high shares of renewable energies in order to determine Levelized Cost of Heat and ecological indicators. Finally, the concepts were compared with a reference case scenario based on current trends for decentralized heat supply.

Keywords: Solar district heating, rural areas, existing buildings, Levelized Cost of Heat, key ecological indicators

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Abbreviations

BAU	Business as usual	LCoH	Levelized cost of heat
CHP	Combined heat and power	PTES	Pit thermal energy storage
COP	Coefficient of performance	SPF	Seasonal performance factor
DH	District heating	TTES	Tank thermal energy storage

1. Introduction

Following the Paris Climate Agreement, the German government set the target of an almost climate-neutral building stock in 2050. As an intermediate goal, CO_2-emissions in the building sector are supposed to be reduced by 40 % until 2030 compared to 2014 (BMUB 2016). Consequently, it is necessary to lower the total heat demand on the one hand, but also to transform heat supply using new technologies for domestic hot water and space heating on the other. However, the share of renewable energies in the final energy consumption for heating and cooling in Germany is stagnating at around 14 % in recent years (Umweltbundesamt 2018). While there are legal requirements regarding energy efficiency and the use of renewable energies for new buildings, the decision to renovate building stock generally remains with the owners. In rural areas, where most buildings are in private ownership, it is common to observe renovation backlogs. This is most likely caused by relatively high investment costs for renovation, whereas the operating costs for conventional heat supply systems are stable. In this respect, this paper deals with the possibilities and perspectives to decarbonize heat supply through local heating networks with high shares of renewable energies, despite low renovation rates of the connected buildings. The heat generation of three different district heating (DH) concepts was simulated with the tool energyPRO by EMD International A/S. The central question is how the economic efficiency of DH concepts in rural areas relates to decentralized heat supply systems. In this context the holistic approach of calculating Levelized Cost of Heat (LCoH) was chosen in order to consider all costs related to heat supply. The economic comparison is supplemented by key ecological indicators. Those cover the share of renewable energies, specific CO_2-emissions and primary energy factors. The comparison is based upon a case study about the heat supply in 2030 for a village called Heinebach, which is located close to Kassel in Germany.

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2. Heat supply area

2.1 Building stock

During an on-site inspection with a local expert, detailed information on the building stock in Heinebach could be gathered. The area under consideration consists of 416 buildings of which 89 % are residential buildings with single-family houses as the dominant type. The remaining 11 % are commercial buildings and mainly located in the south of the village. Some of the buildings in this commercial area are already connected to a small existing heating network that is currently supplied by excess heat of a biogas plant. The village has grown historically, so that diverse building typologies can be found. Residential buildings were classified into 12 different categories concerning their year of construction according to Loga et al. (2017). The commercial buildings were classified into 9 categories considering year of construction as well as their predominant use. Up to 75 % of the building stock was built before 1980 and the center of the village is even characterized by historic houses.

2.2 Heat demand

Since actual energy consumption data for the heat supply of the designated area was not available, a method to estimate the current heat demand was applied. First of all, the heated (living) area of each building was determined. In total, it amounts to approximately 75,000 m² for residential and 22,500 m² for commercial buildings. Specific values for space heating and domestic hot water demand were then assigned to the buildings using the age structure (see section 2.1). On average, this results in an annual specific useful energy demand of 540 MJ/(m²·a) or 150 kWh/(m²·a) for residential and 346 MJ/(m·a) or 96 kWh/(m²·a) for commercial buildings. Considering in-house heat losses of approximately 11 %, a total heat demand of 55.12 TJ/a or 15.31 GWh/a was determined. In order to predict the heat demand for 2030, it was assumed that about 1 % of the buildings built before 1978 are renovated per year and in consequence their heat demand is reduced by around 38 %. This assumption reflects current trends in building renovation according to Diefenbach and Clausnitzer (2010) and Loga et al. (2017). It results in a total reduction of 3.28 % until 2030, so that heat demand for the concept comparison amounts to 53.32 TJ/a or 14.81 GWh/a.

2.3 Current heat supply

In the course of the investigation multiple data sets (i.e. subsidies databases, chimney sweep data) could be used concerning the locally installed heat generation technologies. Those included information about the year of construction, fuels used, installed thermal power and collector area for solar thermal systems. With the help of typical technology-specific full load hours and typical collector yields for solar thermal systems the contribution of each technology to cover the current heat demand could be determined. Fossil fuels (natural gas, fuel oil, LNG) account for the largest share of the total heat supply (76 %), while solid biomass is the largest renewable heat source (18 %) (see also Fig. 2).

2.4 Heating network

In order to assess linear heat densities of different sections of the area as well as costs for the heating network, a preliminary design for the network was defined. The fact that a small network already exists was neglected for the design, since the corresponding specifications were unknown. Due to given local circumstances like the fully developed gas network, a connection rate of only 50 % was assumed as a basis for the comparison. Therefore, the network consists of 208 buildings in total. Connecting pipes were considered with a length of 10 m_{route} per building on average, resulting in route lengths of 8.2 km with transportation pipes and 2.1 km with connecting pipes. Under these conditions, the linear heat density amounts to 2.56 GJ/(m_{rroute}·a) (0.71 MWh/m_{route}·a). According to Persson and Werner (2011) the mean nominal pipe diameter DN_a can be estimated as a function of linear heat density. The resulting DN_a of about 46 mm is approximately met by selecting DN 50 for transportation pipes and DN 20 for connecting pipes according to Best et al. (2018). Heat distribution losses as a percentage of the total heat feed-in were also determined depending on linear heat density. In line with an approach by Nussbaumer and Thalmann (2014) that is based on data about existing heating networks in Germany, Denmark, Austria, Finland and Switzerland those amount to 20 % of the total heat feed-in. In terms of the design temperature level a conservative approach was chosen in order to address temperature requirements of existing in-house heating systems and domestic hot water supply. Therefore, a supply temperature of 80 °C and return temperature of 60 °C was assumed.

2.5 Heat load profiles

The simulation of the heat generation of the DH concepts required to generate heat load profiles. The annual heat demand was allocated to the hours of the year depending on ambient temperatures of the reference year 2016. The allocation relies on standard load profiles according to Hellwig (2003) that originate from the gas sector. The used profiles correspond to old single-family houses (before 1978), new single-family houses (from 1979), old multi-family houses (before 1978), new multi-family houses (from 1979) and commercial buildings for retail and wholesale. The resulting heat load profiles for the residential and commercial buildings connected to the designated heating network can be seen in Fig. 1.

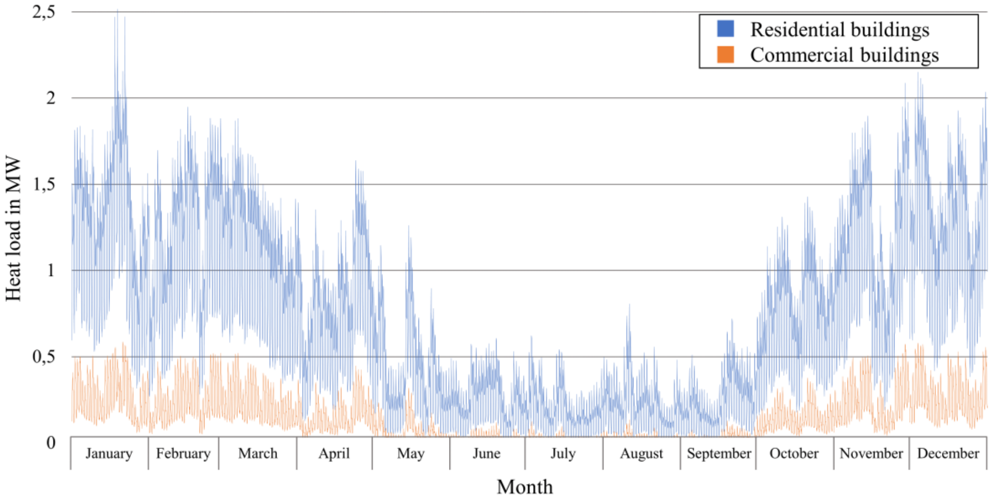

Fig. 1: Heat load profiles

The load profile for the compensation of heat distribution losses was created within the simulation tool energyPRO. The load was modelled to be partially constant and partially dependent on soil temperatures. This is supposed to reflect the annual profile of the temperature difference between supply temperature and soil temperature, which is decisive for the level of heat distribution losses.

2.6 Peak load

Dimensioning heat generators for heating networks requires to determine the peak loads of the potential consumers. The relevant load types within the case study include the heating load of the buildings, the load for supplying domestic hot water as well as the load for compensating heat distribution losses. The calculation of the peak load of the residential buildings was based on methods according to the German national standards DIN EN 12831 Suppl. 2 for space heating (Deutsches Institut für Normung e.V., 2012) and DIN 4708 for domestic hot water demand (Deutsches Institut für Normung e.V., 1994). The used building typology data for the commercial sector was less detailed, so that the peak load had to be derived from heat demand and characteristic full load hours for decentralized heat generators. Since peak loads of the individual consumers are staggered in time, so-called simultaneity factors can be considered when determining the peak load for the whole heating network. They are dependent on the number of connected consumers. In the case at hand they were applicable to the heating loads of residential and commercial buildings as well as domestic hot water demand of the commercial buildings. Regarding the compensation for heat distribution losses the maximum value of the modeled load profile described in section 2.5 was considered for the peak load. Taking renovation measures as well as a connection rate of 50 % into account, a total peak load of 3.8 MW was determined for the designated heating network in 2030.

3. Heat supply concepts for 2030

3.1 Reference case scenario – business as usual

A reference case scenario was developed expecting the continuation of business as usual (BAU) regarding heat supply in the area. It is based upon data about the current heat supply described in section 2.3. In order to project the current technological composition of decentralized heat supply onto the year 2030, technology-specific change rates were assumed according to Adolf et al. (2013) and local circumstances (i.e. fully developed gas network, German Emission Control Act). In conjunction with a supposed replacement of existing heat generators after a useful life of 25 years as well as the years of construction from the given data, the technological composition for 2030 is outlined. The results for the equivalent heat demand supplied by a potential heating network (connection rate 50 %) are shown in Fig. 2. The shares of heat pumps (+4 %), solar thermal systems (+1 %), solid biomass (+3 %) and natural gas (+9 %) are increasing, while the shares of fuel oil (-14 %) and LNG (-0.5 %) are decreasing. It is assumed that the biogas plant will not exist anymore in 2030 due to ceasing subsidies.

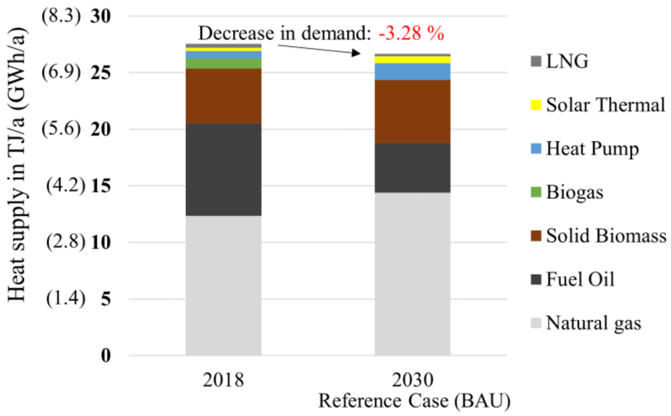

Fig. 2: Decentralized heat supply in Heinebach

3.2 District heating concepts

The heating network described in section 2.4 presents the basis for all three DH concepts. The systems and the chosen components are described in the following.

Concept 1 Solar Seasonal

The first concept is aimed at achieving a high solar share in the heat supply. Therefore, a pit thermal energy storage (PTES) is included as a seasonal storage. An electric heat pump is used to discharge the PTES below return temperature of the heating network and consequently expand its capacity. Two woodchip boilers serve as baseload heat generators in the winter. The system is completed by a gas boiler as peak load heat generator and a buffer storage as a flexibility option. A schematic diagram of the system is illustrated in Fig. 3 with the following specifications of the components:

- Solar thermal system: 8,782 m² CPC vacuum tube collectors
- El. heat pump: 679 kW_{th} (2-stage high temperature compression heat pump; COP = 2.6 at W10/W85)
- Woodchip boiler 1 / 2: 650 / 400 kW_{th} (Minimum partial load: 30 % of nominal load)
- Natural gas boiler: 3,400 kW_{th}
- Buffer storage: 200 m³ (Tank thermal energy storage)
- Seasonal storage: 20,000 m³ (Pit thermal energy storage filled with water)

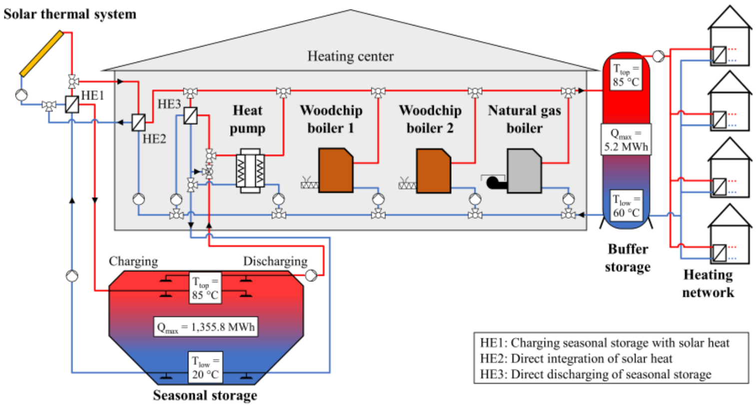

Fig. 3: Schematic diagram of Concept 1 – Solar Seasonal

Concept 2 Solar Classic

The second concept is inspired by local district heating networks that are already installed in rural areas in Germany. The solar thermal system is designed to cover the heat demand during the summer period. Similar to the first concept, two woodchip boilers represent the baseload heat generators for the winter. Whenever possible, those are switched off during summer to avoid unfavorable partial load operation. The buffer storage is designed larger than in concept 1 in order to bridge longer low-radiation periods. A natural gas boiler is added as backup and peak load heat generator. The schematic diagram is shown in Fig. 4 with the following specifications:

- Solar thermal system: 3,842 m^2 CPC vacuum tube collectors
- Woodchip boiler 1/2: 2 x 650 kW_{th} (Minimum partial load: 30 % of nominal load)
- Natural gas boiler: 3,150 kW_{th}
- Buffer storage: 350 m^3 (Tank thermal energy storage)

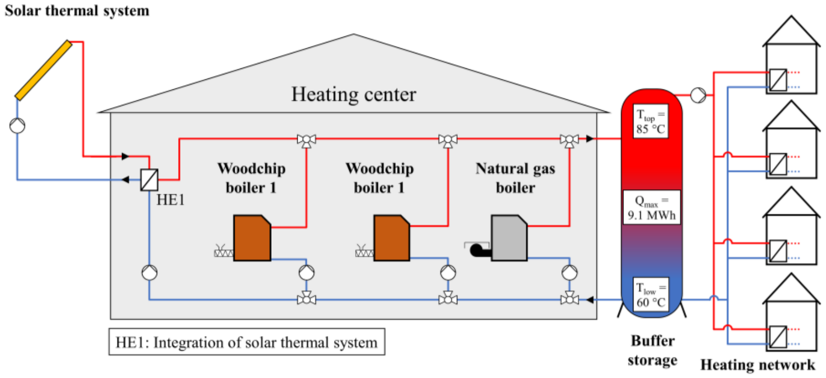

Fig. 4: Schematic diagram of Concept 2 – Solar Classic

Concept 3 Sector coupling

The third concept shown in Fig. 5 is geared towards aligning heat generation flexibly with market prices for electricity. Amid the increasing volatility of the feed-in of renewable energies into the electricity grid, it is expected that spot prices will also fluctuate according to the availability of solar and wind power. Therefore, two electrical heat pumps, that utilize geothermal heat, operate when electricity prices are low, while a gas-fired CHP unit can produce heat and electricity when prices are high. Consequently, electricity market participation is required. The buffer storage enables a flexible operation strategy. The specifications are the following:

- El. heat pumps: 2 x 679 kW_{th} (2-stage high temperature compression heat pump; COP: 2.6 at W10/W85)
- Natural gas CHP unit: 986 kW_{th}; 835 kW_{el} (Minimum partial load: 50 % of nominal load)
- Natural gas boiler: 3,150 kW_{th}
- Buffer storage: 300 m^3 (Tank thermal energy storage)

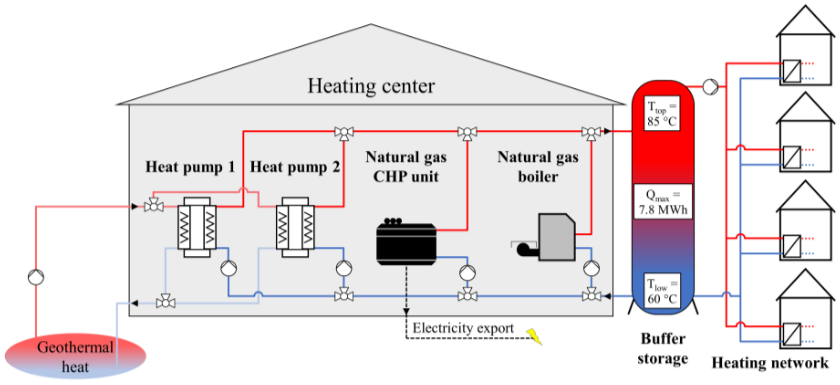

Fig. 5: Schematic diagram of Concept 3 – Sector Coupling

4. Framework for comparison

4.1 Simulation tool energyPRO

The simulation tool uses an analytical optimization method to meet heat demand in every timestep with the component that has the lowest priority, which is usually equal to the lowest heat generation cost at that time. It must be noted that heat demand and transport is simulated independent of corresponding temperature levels. Priorities are determined through component parameters, operating costs and external boundary conditions. Weather data (ambient temperature, solar radiation, soil temperature), a prognosis of electricity spot market prices as well as the heat load profiles described in section 2.5 serve as common boundary conditions for the simulation of the DH concepts. The weather data was taken from the “ERA5 Climate reanalysis dataset” that can be accessed within the simulation tool. For Heinebach the year 2016 has turned out to be an average weather year within a 10-year period, so that it served as reference year. The simulation period spans one year with an hourly resolution. The spot market prognosis for 2030 was created following Wiese (2015). The described basic operation strategy is particularly relevant for CHP units and heat pumps, since in those cases heat generation costs are dependent on variable electricity spot market prices.

4.2 Economic framework

An economic evaluation of heat supply concepts requires an assessment period (T) that reflects on the useful life of the system components. In the case at hand the decisive component that determines the assessment period is the heating network with a useful life of 30 years. In order to account for future developments, the following conditions are considered for the economic evaluation. The most sensitive parameter for the comparison is the discount rate (i), which is assumed with 3 % and enables to refer future payments to the time of calculation. An inflation rate of 1.8 % is applied to the development of maintenance and service costs. Furthermore, trends in the costs for energy carriers are included with annual change rates for natural gas +2.46 %, fuel oil +2.54 %, biomass +1.00 % and electricity -0.33 %.

The relevant expenses in the following evaluation include investments, fuel costs, maintenance and service as well as operation and heat distribution, whereas in-building distribution is excluded. On these grounds the Levelized Cost of Heat (LCoH) for each concept is determined. According to Baez and Larriba Martinez (2015) LCoH is “the constant and theoretical cost of generating one kWh of heat, which is equal to the discounted expenses incurred throughout the lifetime of the investment.” The calculation follows equation 1. The shown variables are discussed in the following.

$$LCoH = \frac{I + \sum_{t=1}^{T} \frac{C_t - S_t - RV}{(1-i)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1-i)^t}} \qquad \text{(eq. 1)}$$

The investment (I) for the decentralized heat supply in the Reference Case (BAU) corresponds to the reinvestment costs that occur when the age of existing heating systems exceeds an assumed average useful life of 25 years. Relying on the data described in section 2.3 and technology-specific reinvestment costs according to Tab. 1, the total investment for each individual year of the assessment period is determined.

Tab. 1: Specific reinvestment costs for decentralized heat generation

Component	Specific investment	Reference
Natural gas boilers	314 €/kW$_{th}$	Hinz (2015)
Fuel oil boilers	379 €/kW$_{th}$	Hinz (2015)
Solid biomass boilers	609 €/kW$_{th}$	Hinz (2015)
Solid biomass ovens	152 €/kW$_{th}$	Assumption
LNG boilers	314 €/kW$_{th}$	Assumption
Heat pumps	1,000 €/kW$_{th}$	Wunderlich (2016)
Solar thermal systems	450 €/m²	Wunderlich (2016)

In case of the DH systems the investment in the heating network is considered with the specific costs according to Tab. 2. The main street of the village Heinebach will be subject to renovation in the foreseeable future, so that costs corresponding to a construction area are used. The heating center is assumed with 4.2 % of the total costs for the pipes and further components (i.e. pumps, control valves, underground cables, control technology) are taken into account with 3.5 % of the total heating network costs.

Tab. 2: Specific investment costs for the heating network

Component	**Specific investment**		**Reference**
Transportation pipes DN 50, inner city areas	380	€/m$_{route}$	Große et al. (2017)
Transportation pipes DN 50, construction area	190	€/m$_{route}$	Große et al. (2017)
House connection			
Connecting pipes DN 20	314	€/m$_{route}$	Große et al. (2017)
House-lead-in	395	€/unit	Best et al. (2018)
Substation	3,600	€/unit	Stuible et al. (2016)

The specific investment costs of the central heat generators vary depending on the installed capacity in the individual concepts. Except for the woodchip fuel storage and the land area for solar thermal systems, all cost assumptions are based on cost functions depending on the size of the component. The costs of the electrical heat pump in the third concept include the exploitation of the heat source. The determined values and the assumed useful life in years are shown in Tab. 3. If the useful life of a component is less than the assessment period of 30 years, a reinvestment is considered for the calculation of LCoH. Finally, the cost of engineering for the DH concepts is estimated with 10 % of the total initial investment.

Tab. 3: Specific investment costs for heat generation in DH concepts

Component	**Specific investment**		**Useful life**	**Reference**
Solar thermal system			30 a	
Solar Seasonal	452	€/m²		Große et al. (2017)
Solar Classic	511	€/m²		Große et al. (2017)
Land area	1.24	€/m²		Destatis (2018)
Natural gas CHP unit	800	€/kW$_{el}$	15 a	ASUE (2014)
Woodchip boiler			20 a	
650 kWth	290	€/kW$_{th}$		Eltrop (2014)
400 kWth	327	€/kW$_{th}$		Eltrop (2014)
Fuel storage	19.3	€/t	30 a	Eltrop (2014)
Electrical heat pump			20 a	
Solar Seasonal	399	€/kW$_{th}$		Wolf (2017)
Sector Coupling	499	€/kW$_{th}$		Wolf (2017), Große et al. (2017)
Natural gas boiler			20 a	
Solar Seasonal	141	€/kW$_{th}$		Große et al. (2017)
Solar Classic / Sector Coupling	143	€/kW$_{th}$		Große et al. (2017)
Buffer storage (TTES)	599	€/m³	25 a	Große et al. (2017)
Seasonal storage (PTES)	72	€/m³	30 a	Große et al. (2017)

The costs of operation for each year (t) result from the operating expenses (C_t) and the income from operation (S_t), which is equal to the income from electricity feed-in. The operating expenses consist of costs for service and maintenance of the components as well as the energy carriers including electricity for auxiliary energy expenditure. Since the available references for service and maintenance costs for each component differ, they are determined either as a percentage of the total investment or as a fixed rate depending on installed capacity and/or heat generation. Specific costs for energy carriers were assumed separately for the Reference Case (BAU) and the DH concepts to account for varying purchased quantities. In the last year of the assessment period, the cost of operation is supplemented by the residual value (RV) of the components registered as an income.

The last variable necessary for calculating LCoH is the amount of heat delivered to the buildings (E_t), which is also equal to the amount decentralized systems must supply.

5. Results

5.1 Simulation

The shares of the individual technologies in the feed-in to the heating network as a result of the simulation are shown in Fig. 6. The solar thermal system in Solar Seasonal fully meets the heat demand during summer and has a significant contribution in the winter as well. Considering the seasonal storage efficiency of 84 %, the total contribution of solar thermal heat is 38 % with a specific solar yield of 1,433 MJ/m^2·a or 398 kWh/m^2·a. It must be noted that the share of the heat pump in Solar Seasonal is equal to its electricity consumption, since the solar heat in the seasonal storage is its heat source. This circumstance also enables a high seasonal performance factor (SPF) of 5.3 for the heat pump. In Solar Classic the solar thermal system covers most of the heat demand during summer with a slightly larger specific solar yield of 1,598 MJ/m^2·a or 444 kWh/m^2·a, since storage losses of the buffer storage system are lower. The biomass boilers show a steady operation during winter with full load hours of 4,000 and 5,700 h/a. In Sector Coupling the geothermal heat pumps only reach a SPF of 3.0 covering the heat demand in summer and the base load in winter. Therefore, full load hours of 4,200 and 5,600 h/a are reached. The CHP unit profits from mainly operating at high electricity market prices with an average deviation of 22 % above mean market price. The heat pumps in Sector Coupling are operating on average at 5 % below mean market price, whereas the heat pump in the concept Solar Seasonal operates at 7 % below mean market price.

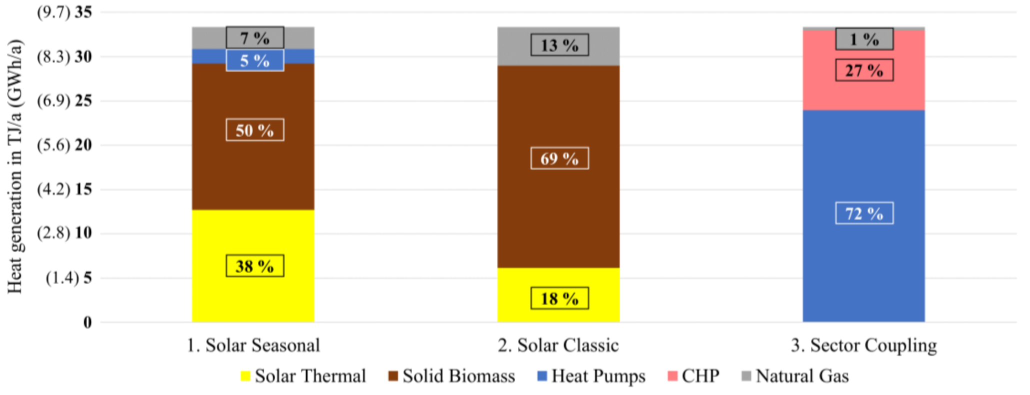

Fig. 6: Heat feed-in into the heating network in the DH concepts

5.2 Economic evaluation

It can be seen in Fig. 7 that the first DH concept Solar Seasonal requires the largest initial investment of about 12.4 Mio € due to the large solar thermal system with 4.0 Mio. € and the seasonal storage with 1.6 Mio. €. In the concepts Solar Classic and Sector Coupling, the heating network with 4.5 Mio. € accounts for more than 50 % of the initial investment volume. In comparison, the nominal investments within the 30-year assessment period in the Reference Case (BAU) are only 3.6 Mio. € in total.

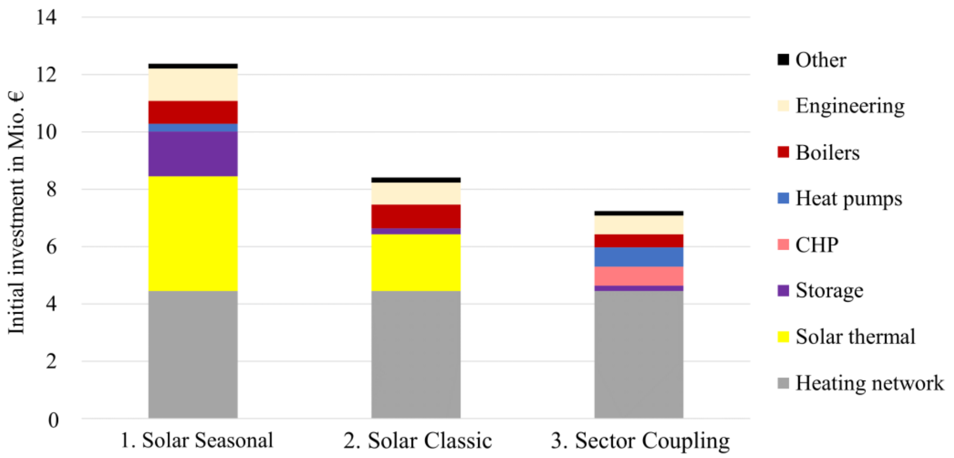

Fig. 7: Economic evaluation – Initial investment for the DH concepts

Fig. 8 shows the cost of operation for the first year, so that the future developments described in the economic framework have no effect yet. The concepts with large solar thermal systems have the lowest cost of operation. In Sector Coupling they are still below the Reference Case, if the income from electricity feed-in is considered. It is also notable that the 20 % higher solar fraction in the DH concept Solar Seasonal is not mirrored in the cost of operation in comparison with Solar Classic. High specific costs for electricity to discharge the seasonal storage with a heat pump in the Solar Seasonal concept in contrast to relatively low-cost woodchips almost level out concerning the operating costs, but service and maintenance costs are higher for the more complex system Solar Seasonal. The income from electricity feed-in in Sector Coupling is composed of variable spot market prices and fixed basic payments that reflect subsidies for electricity from CHP units in Germany.

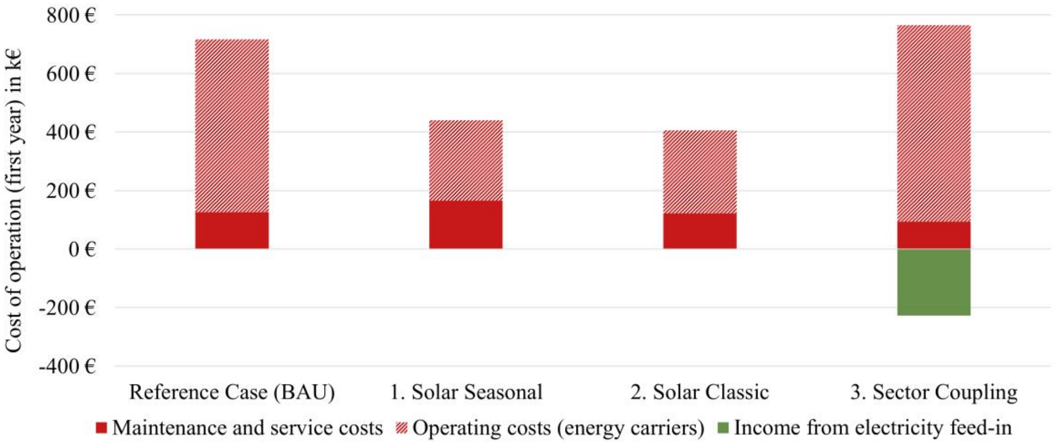

Fig. 8: Economic evaluation - Cost of operation in 2030 (first year of operation)

Assuming a continuous operation according to the first (simulated) year of operation results in the LCoH shown in Tab. 4. Possible subsidies for the investments are neglected. Concept 2 Solar Classic has the lowest LCoH with 35.4 €/GJ (127.5 €/MWh) and is thus 7 % below the LCoH of the Reference Case (BAU) with 38.1 €/GJ (137.0 €/MWh). The LCoH of Solar Seasonal and Sector Coupling are 9 % resp. 14 % higher than the Reference Case (BAU).

Tab. 4: Comparison of Levelized Cost of Heat

LCoH in €/GJ (€/MWh)	**Reference Case (BAU)**	**1. Solar Seasonal**	**2. Solar Classic**	**3. Sector Coupling**
	38.1 (137.0)	43.6 (157.1)	35.4 (127.5)	41.6 (149.8)
Deviation from Reference:		+14 %	-7 %	+9 %

5.3 Discussion of the economic framework

The calculations of the previous chapter were examined for sensitivities to specific costs and economic boundary conditions due to the numerous necessary assumptions. A high discount rate of 6 % favors the Reference Case (BAU), as the investments are spread over the entire assessment period. In contrast, the LCoH of the DH concepts decrease with a low discount rate (1.5 %). In case of Solar Seasonal they drop to 40.0 €/GJ (143.9 €/MWh) and are thus only 5 % above the Reference Case (BAU). Taking economies of scale into account for the specific costs of solar thermal systems (350 €/m²) and seasonal storages (50 €/m³), the LCoH of Solar Seasonal are also approaching those of the Reference Case (BAU) with 40.0 €/GJ (144.2 €/MWh). A variation of annual change rates (50 % and 200 % scenario) for energy carrier prices has a particularly strong effect on the Reference Case (BAU) and the Sector Coupling concept, where costs for energy carriers have a high share in the total cost of operation. On the other hand, only minor effects can be observed in Solar Seasonal due to the high solar fraction. In addition, it can be stated that the LCoH of Solar Classic is still on the same level as the Reference Case (BAU) in the 50 %-scenario with 34.3 €/GJ (123.5 €/MWh). Finally, the LCoH were tested in scenarios with a taxation of CO_2-emissions of 30 €/t and 60 €/t. A CO_2-tax raises the LCoH of all concepts, whereas the Reference Case (BAU) would be affected most with an increase of approx. 1.5 to 3.1 €/GJ (5 to 9 €/MWh). In the concepts Solar Seasonal and Solar Classic the LCoH are relatively stable in the CO_2-tax scenarios with an increase of approx. 0.3 to 0.8 €/GJ (1 to 3 €/MWh).

5.4 Ecological evaluation

The ecological evaluation of the heat supply concepts is carried out using the share of renewable energies f_{RE}, specific CO_2-emissions $e_{CO2,out}$ and primary energy factors $f_{P,out}$ as key figures. Common ground for all calculations is the delivered heat to the buildings. Solar energy, wind, hydropower, renewable biomass and environmental energy are considered as renewable energies. In terms of the consumed electricity (i.e. heat pumps, auxiliary energy) a factor of 58.8 % is applied representing the projected share of renewable energies in the German electricity grid in 2030 as a mean value of several scenarios according to Greiner et al. (2016). It is important to keep in mind that particularly the intended decarbonization of the German electricity sector will have an impact on the ecological evaluation over the entire assessment period. The calculation of CO_2-emissions and primary energy factors is carried out according to standards by the German district heating and cooling association AGFW (AGFW FW 309 part 6 - 2016, AGFW FW 309 part 1 – draft 2017). The primary energy factor $f_{P,out}$ provides the most comprehensive consideration of the ecological effects of heat supply, since, in contrast to $e_{CO2,out}$, it includes the entire upstream chain for the supply of energy carriers. However, it must be noted that it specifically applies to Germany. Fig. 9 depicts that f_{RE} in the Reference Case (BAU) is rising to 28.1 % compared to 23.8 % in 2018. Nevertheless, the DH concepts achieve a significantly larger f_{RE} ranging from 61.9 % in the Sector Coupling concept to 90.6 % in the Solar Seasonal concept. Consequently, $e_{CO2,out}$ is 30 % (Sector Coupling) to 80 % (Solar Classic) lower than in the Reference Case. It is also noticeable that $e_{CO2,out}$ in Solar Classic is higher than in Solar Seasonal despite the higher f_{RE}. This is mainly due to the larger electricity demand caused by the heat pump in Solar Seasonal, as electricity has the highest specific CO_2-emission factor compared to the energy carriers used. Finally, $f_{P,out}$ in the DH concepts is from 25 % (Sector Coupling) up to 59 % (Solar Seasonal) lower than in the Reference Case (BAU).

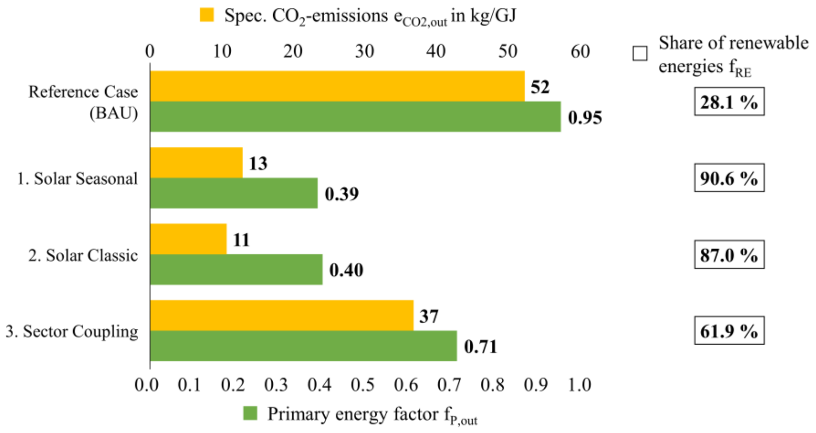

Fig. 9: Ecological evaluation - Spec. CO_2-emissions, primary energy factors and share of renewable energies

6. Discussion

The projection of the current decentralized heat supply in Heinebach onto the year 2030 in the Reference Case (BAU) shows that, without serious changes, only a slight increase in the share of renewable energies in the technological composition is to be expected. In contrast to this, the central heat generation of the heating network offers a variety of possibilities for the integration of renewable energies. Although 20 % more heat has to be generated in the DH concepts to compensate for grid losses, the ecological evaluation of all considered variants is positive compared to the Reference Case (BAU). The goal of the German government to reduce CO_2-emissions in the building sector by 40 % until 2030 compared to 2014 is, in contrast to the Reference Case (BAU), reached in all investigated DH concepts. Considering the progressing decarbonization of the German electricity sector as well as the limited availability of solid biomass, the concept Solar Seasonal has the least ecological impact. The simulation results suggest that existing buildings in rural areas with high temperature requirements do not necessarily present a barrier for the integration of renewable energies. However, the accuracy of simulating a temperature sensitive concept composed of a solar thermal system with a PTES and a heat pump for discharging is limited within the tool energyPRO. So far, the simplifying assumption of a fully mixed storage might impair the performance of the system. Detailed planning of this concept would require an investigation with an additional simulation tool in order to adequately model temperature stratification within the PTES and storage heat losses to the surrounding soil, especially during the first years of operation. This would further have an impact on return flow temperatures to the solar thermal system and supply line temperatures on the heat-source-side of the heat pump. Still, the economic evaluation indicates that heat can be supplied in the DH concepts at comparable costs to the decentralized Reference Case (BAU) even without subsidies. The specific investment costs for the solar thermal systems and the PTES are sensitive parameters for the economic efficiency of the Solar Seasonal and Solar Classic concepts, so that under the condition of sinking costs due to economies of scale or subsidies, these technologies represent important components for cost-efficient heat supply in local heating networks in the future.

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