# Exergy Assessment of Hybrid District Heating Systems Using Resource Exergy Analysis (REA)

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# EXERGY ASSESSMENT OF
# HYBRID DISTRICT HEATING SYSTEMS
# USING RESOURCE EXERGY ANALYSIS (REA)

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## Abstract

In this paper six supply systems for a simulated energy demand scenario are compared using resource exergy analysis (REA). The analysis is complemented with an assessment of greenhouse gas emissions. The six scenarios (S) that are compared are

- S1: decentralized gas boilers,
- S2: low temperature district heating using 50% heat from a block CHP plant and 50% heat from a gas boiler,
- S3: decentralized air-source heat pumps,
- S4: a very low temperature district heating network with a central large heat pump and decentralized electrical boilers,
- S5: a cold district heating network using heat from the ground as a source for decentralized water-water heat pumps and
- S6: deep geothermal low temperature district heating network.

The electricity used in all scenarios is assumed to come from PV panels that are newly built on the district. Thus, all results for hybrid energy systems can be considered best-case scenarios.

Scenario 1 and Scenario 6 are intended to provide reference scenarios for the evaluation of the considered hybrid energy systems. S1 allows a comparison with the current status quo. S6 is there to show how good hybrid energy systems can be if compared to one of the best thermal district heating sources.

The results of the performed analysis show that hybrid energy networks can be among the most resource saving and low carbon heat supply solutions possible. In order to achieve this outcome, it is important to ensure that the electric load generated by these systems is covered by additional GHGE-free power supply.

In comparison to natural gas boilers hybrid energy systems can save more than 70% of resource exergy and over 90% of GHGE. All considered hybrid energy systems produce similar savings, so that the decision on what type of hybrid energy system is best for a given community largely depends on the heat demand density, the potential for heat networks or air-water heat exchangers and the availability of suitable heat sources apart from life-cycle cost considerations.

While hybrid energy networks can be among the top solutions for decreasing resource exergy consumption and GHGE, they are not the only technology suitable for resource saving and climate friendly heat supply. Scenario 6 (Deep geothermal heat) shows that district heating using suitable thermal sources can match or even outperform best case hybrid energy networks. However, since thermal sources that can directly provide heat at the temperature levels required by the building stock can be locally limited, hybrid energy

networks are one of the key technologies to supply heat to areas with high heat demand density.

# 1 Introduction

Space and domestic hot water heating accounts for around 40 percent of final energy consumption in the European Union and holds the key to Europe's energy transition towards a sustainable low carbon future (Zeyen, Hagenmeyer, & Brown, 2021).

**Definitions of hybrid energy systems, hybrid energy networks and hybrid district heating:**

Hybrid energy systems cover a specific type of energy demand such as heating, cooling or fuels by combining thermal, electrical and/or chemical energy carriers.

They can be based on a single or multiple renewable energy sources and can include centralized and decentralized energy conversion and storage processes. (IEA DHC Annex TS3, 2021; IEA EBC Annex 67, 2021; Kallert, 2019).

A hybrid energy network is a combination of electrical, thermal and/or chemical energy carrier networks, which cover a single demand type such as heating or cooling.

A hybrid district heating system is a hybrid energy network that supplies heating.

Hybrid energy networks have the potential to provide space heating and cooling in an exceptionally efficient way. Thereby making a significant contribution to the effective decarbonization of the heating sector.

Additionally, Hybrid Energy Networks that include electrical networks can mitigate the effects of fluctuating electricity feed-in from renewable sources by integrating thermal storage into the electricity system and by providing a connection between the electricity grid and other energy sectors such as heat and gas (IEA DHC Annex TS3, 2021).

District heating systems meet around 12 % of European heat demand in 2018 and cover more than 50% of building heat demand in some European countries (Nuffel et al., 2018). Integrating district heating systems with electrical and/or gas networks therefore can provide substantial storage and balancing capacity to the overall energy system.

To optimize the interaction with the electrical grid, hybrid energy network operation can be more flexible through the integration of optimized energy storage systems and through increasing control of consumption-side heat loads.

Due to the use of PV power, the presented results provide a best-case scenario in terms of GHG mitigation. Since results for hybrid district heating systems depend significantly on the type of power used for heat generation, they are not transferrable to systems where non-PV power is used.

The central goal of this publication is to present and discuss the results of resource exergy analysis (REA) for the considered systems (Jentsch, 2022b). REA can be understood as an upgrade to primary energy analysis and answers the question how much resource exergy is used by a given system to cover the considered supply.

| **Definition of exergy:** |
| --- |
| Exergy associated with a flow of mass or energy is the maximum work obtainable by using an ideal thermodynamic process to bring the flow into equilibrium with a clearly defined reference environment.<br><br>The thermodynamic properties of the reference environment such as temperature, pressure and chemical composition should reflect properties of the ambient environment that do not change noticeably when exchanging energy or mass with the considered flow. The reference environment properties are thus assumed constant.<br><br>For better understanding, the physical property “exergy” can be described as a product of energy and “energy quality”. It thus increases the scope of energy system analysis from energy to include all thermodynamic effects including those on energy quality.<br><br>All non-thermal energy carriers such as fuels or electricity have an energy quality of 100%, which means that in theory they can be fully transformed into electricity or work.<br><br>Thermal energy flows have an energy quality that is usually much lower than 100%. For heat flows above the temperature of the surroundings (reference temperature), a higher temperature means higher energy quality.<br><br>Exergy optimization entails matching the quality levels of energy supply and demand in order to optimize the utilization of high-value energy resources, such as combustible fuels, and minimizing losses of valuable resources.<br><br>(Jentsch, 2010; Rant, 1956) |

It is important to note that a low consumption of resource exergy to cover a demand is equally important as reducing overall greenhouse gas (GHG) emissions when aiming to reach ambitious climate targets. The reasoning behind this statement is that in energy systems which are in the process of transformation to a fully GHGE-free supply all demands that are not covered by GHGE-free supply technologies are covered by technologies that lead to emissions of GHG. If assuming that all GHGE-free capacity is always used any inefficiency in term of resource exergy use leads to increased use of GHG-emitting energy conversion processes such as combustion of coal and natural gas. This is also valid for inefficiencies in GHGE-free energy supply systems. Consequently, it is key to minimize resource exergy consumption in order to minimize overall system GHGE.

In the underlying study, GHGE (GWP100[1]) are considered in addition to resource exergy consumption to allow an estimate of the direct climate impact of the considered systems.

The application of exergy analysis is an essential tool to improve system efficiency regarding thermodynamic potentials and for comparing different energy resources and techniques. It goes beyond energy analysis by considering energy quality in addition to energy quantity. In several studies (Ahmadian & Schmidt, 2020; Falk, 2017; Fitó, Ramousse, et al., 2020; Kallert, 2019; Pompei et al., 2019; Schüwer et al., 2020; Terehovics et al., 2016) exergy analysis of different district heating systems was applied and analyzed. These studies put their focus on the comparison of the performance of district heating systems regarding energy, exergy, economic and environmental aspects.

(Daghsen et al., 2021) have investigated energy, exergy and environmental performances of hybrid low temperature district heating systems in combination with photovoltaic (PV)-units. While their study is based on similar assumptions to those underlying the analysis presented in this paper, they have used a different exergy-based methodology for analysis that does not fulfill the standards of REA.

A multicriteria (energy, exergy, economic and environmental) assessment of several renewable-based solutions with their grid-based counterparts solutions for residential heat production is proposed in (Fitó et al., 2021a). Even in a low-carbon energy market context, the drawbacks of each renewable-based system could be counterbalanced depending on the implementation scale.

Divergence between energy and exergy optimizations were highlighted in e.g. (Fitó, Hodencq, et al., 2020; North & Jentsch, 2021).

Further, the energy, exergy and environmental benefits of District Heating Networks thanks to demand pooling compared to decentralized solutions were discussed in (Fitó et al., 2021b).

## 1.1 Resource exergy analysis

The focus of this paper lies on analysis of different low temperature district heating systems as a part of hybrid energy networks by using resource exergy analysis (REA) (Hertle et al., 2016; Jentsch, 2022b) which can replace primary energy analysis with a more comprehensive and consistent system while still remaining similarly simple.

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[1] Non-$CO_2$ are considered using their global warming potential over a hundred years (GWP100). In addition, it is recommendable to assess these emissions over twenty years (GWP20) as soon as data on them is available. This can help to minimize the risk of reaching tipping points in the climate system. Especially, emissions from natural gas are much higher if considering (GWP20) than when using GWP100, due to methane being a short lived GHG gas.

REA considers aspects beyond the law of energy conservation and considers the second law of thermodynamics (i.e. law of irreversibility). It also includes sensible and proven system boundaries thus ensuring transparent identification of real resource saving solutions. It differs in its system boundary definition and the underlying theory of exergy as a product of energy and energy quality (Jentsch, 2010) from alternative types of exergy analysis.

The methodology of REA has specifically been developed to model physical reality as realistically as possible using the available data and therefore usually leads to more consistent, more comprehensive and more reliable results than energy analysis and other forms of exergy analysis used for overall energy system comparison. It can thereby help to minimize fossil fuel inputs and improve renewable and sustainable systems by findings solutions that cannot be identified based on energy analysis alone (Kallert, 2019; North & Jentsch, 2021).

E.g., Conversion of power to heat is a process that decreases energy quality while having a high energy efficiency. So, while a power to heat transformation might look energy efficient (98%), the efficiency can be much lower (<10%) this shows that only with exergy analysis certain losses can be quantified consistently (North & Jentsch, 2021).

To support decision making REA should be complemented with an analysis of GHGE and life cycle costs. Therefore, the fundamental calculations for this paper have been done comparing energy systems using REA and GHGE analysis. Costs were not considered for this paper as they are not a physical criterion and vary greatly among countries and with time. A cost assessment can always be added once energy systems with desirable environmental characteristics have been identified.

## 1.2 The supply target

In this paper, six different heat supply scenarios are examined based on a new housing settlement in Neuburg on the Danube (Yu et al., 2020). Specifically, two decentralized heat supply systems and four low temperature district heating systems are considered. On the demand side, the new housing settlement presented in this work consists of 31 single family houses and one multi- family house (see Figure 1), which are planed according to the German Energy Saving Ordinance (EnEV 2016, 2016). The calculated annual heat demand for space heating amounts to 324 MWh/a and for domestic hot water supply to 110 MWh/a (Holway, 2021).

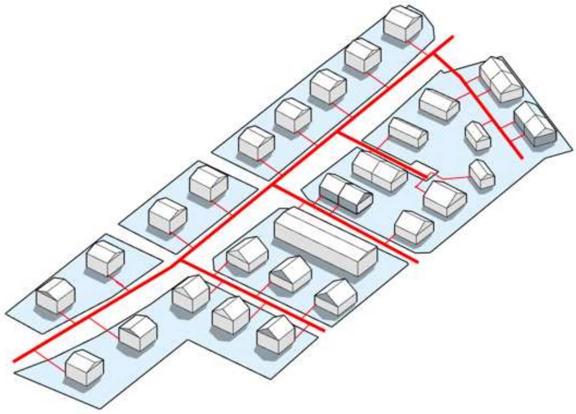

*Figure 1: perspective drawing of the new housing settlement (Yu et al., 2020)*

Against this background, this paper aims to highlight the potential of hybrid district heating networks regarding energy and exergy aspects by using REA (Jentsch, 2022b) to compare six selected heat supply systems. The exergy-based analysis in this report considers only effects of the operation of the heat supply system scenarios for the considered district and the Cumulated Energy Consumption for PV electricity, geothermal heat and natural gas. The analysis does not consider the resource exergy of the material resources used or the resource exergy of the energy required to build the local systems and recycle them later.

# 2 Energy supply scenarios

In this study, six energy supply scenarios were analyzed using resource exergy analysis (REA) (Jentsch, 2022b). Table 2 shows an overview of the energy supply scenarios analyzed. All the specific data used for the scenarios considered are given in section 8.4. Scenario 1 (individual natural gas boilers in each house) serves as a reference system to compare different energy supply systems from a resource utilization point of view. The considered heat supply systems include decentralized heat supply with air-source heat pumps, district heating based on CHP and boilers, cold district heating, district heating with a centralized heat pump and district heating using deep geothermal energy. Deep geothermal district heating has been added to the analysis in order to provide a benchmark for district heating based non-hybrid thermal sources. Due to the common size involved of deep geothermal wells, it was assumed that the district heating network extends beyond the considered supply target.

In order to avoid the dependency of the results on the grid power mix of specific countries, electricity needs are assumed to be fully satisfied by domestic PV production. The assumption is based on an annual electric balance considering sufficient PV production on site which is made possible by the large roof surface in the studied area. Even if this hypothesis can only be satisfied thanks to balancing temporal mismatch by the electric grid, it allows generalization of this study to any country. As a consequence, the GHGE and REC for electricity production are significantly underestimated in comparison to using power sources with more resource use and GHGE than PV.

If the supply target and its supply system are covered by dedicated PV production, the hybrid energy systems are powered by electricity from the local grid. Following the REA guideline (Jentsch, 2022b) the current grid power mix needs to be considered that considers all energy im- and exports. The values for the grid power mix need to be current and match the time frame of the analysis in order to avoid neglecting aspects of power demand increase by hybrid energy systems. For REA the grid power mix is characterized by the average Cumulated Energy Consumption and GHGE within a timestep of the analysis (e.g. a year, month, week etc.).

A description on how to adapt the results of this analysis to a system using the grid power mix can be found in the results section in chapter 6.

The reference temperature for exergy assessment is set to 7 °C to reflect the average ambient temperature in Germany during the heating season.

*Table 2 overview of the energy supply scenarios*

| Scenario | Heat supply | Electricity supply | Grid temperature of the district heating system |
|---|---|---|---|
| **Scenario 1** | individual natural gas boilers | | - |

| | | | |
|---|---|---|---|
| **Scenario 2** | District heating system (DHS) with a centralized CHP | decentralized PV-modules for grid pumps | Supply temperature: 70 °C<br>Return temperature: 40 °C |
| **Scenario 3** | decentralized heat supply with air-water heat pumps | decentralized PV-modules for heat pumps | - |
| **Scenario 4** | DHS with a centralized ground source heat pump | decentralized PV-modules for heat pump + grid pumps | Supply temperature: 45 °C<br>Return temperature: 25 °C |
| **Scenario 5** | Cold district heating system (CDHS) with decentralized water-water heat pumps | decentralized PV-modules for heat pumps + grid pumps | Supply temperature: 10 °C<br>Return temperature: 5 °C |
| **Scenario 6** | DHS based on deep geothermal energy | decentralized PV-modules for grid pumps | Supply temperature: 70 °C<br>Return temperature: 40 °C |

According to the technical assumptions, the energy standard of the buildings is identical for all scenarios to the German Energy Efficiency Building Code EnEV 2016 (EnEV 2016, 2016). Further general assessment parameters are the minimum required room temperature (20 °C), the minimally required hot water temperature of 43°C (DIN, 2005) and a cold-water temperature of 10°C as well as a heat demand of domestic hot water (110 MWh/a) and heat demand for space heating (324 MWh/a). The heat demand was assessed based on a simulation of the building source.

Since the supply target is to be newly built, the internal heat distribution systems are assumed to be adapted to the supply temperatures of the considered scenarios. That means floor heating and decentralized heat exchangers for all systems involving heat pumps to allow higher annual performance factors (APF) and conventional convection heating and hot water storage tanks for the systems that supply 70 °C forward flow. The specifics of the analyzed scenarios are outlined in the following chapters.

## 2.1 Scenario 1: Decentralized natural gas boiler

The first scenario represents the reference decentralized heat supply, which consists of individual natural gas boilers. The energy efficiency relating to the lower heating value of the natural gas boilers is assumed to be 96 % (Jagnow, 2004). In this scenario, the heat demand of domestic hot water and space heating is covered by individual natural gas boilers. This scenario sets the base line for the comparison as individual natural gas boilers are the most common type of heating systems in Germany in 2021.

## 2.2 Scenario 2: District heating system with a centralized CHP coupled with a natural gas peak load boiler

The second scenario considers district heating with a centralized CHP-unit and a natural gas boiler. This system consists of a district heating system with CHP covering 50 % of the annual heat load (base load) and an additional natural gas boiler covering another 50 % of annual heat load (peak load). The efficiency of the CHP is assumed to be 37 % (electricity production) and 46 % (heat production) (Heizungsfinder.de, 2014). In this case, the district heating system with a supply temperature of 70 °C covers both domestic hot water heat and space heating demand. The heat is distributed by a district heating system that causes distribution losses of 32 MWh/a (ca. 7 % of the total heat demand). The pumps of the thermal network require 1,5 % power in relation to the annual heat generated (AGFW, 2014). The electricity demand for grid pumps is covered with electricity from decentralized roof-top PV-modules on an annual balance in order to be consistent with the other scenarios.

## 2.3 Scenario 3: Decentralized heat supply with air-water heat pumps in combination with decentralized PV-modules

The third scenario considers the decentralized heat supply system with air-water heat pumps. The SPF (Seasonal Performance Factor) of the heat pumps is assumed to be 3.07 (Günther et al., 2020) including the use of an electric auxiliary immersion heater for peak demand. In this scenario, the air-water heat pumps can cover the heat demand for space heating (supply temperature: 40 °C) and domestic hot water supply (supply temperature: 60 °C). Furthermore, it was assumed that the total power demand of the air-water heat pumps is covered with electricity from decentralized roof-top PV-modules on an annual balance.

## 2.4 Scenario 4: district heating system with a centralized ground source heat pump coupled with an electric peak load boiler

This scenario considers a centralized district heating system, which consists of a large central heat pump and decentralized individual electric boilers to support domestic hot water supply and the covering of heat loads. The supply temperature of the low temperature district heating grid is designed to be 45 °C, the heat supply for space heating is preferably done via floor heating systems or via low temperature radiators. A hygienic preparation of domestic hot water is realized by freshwater stations that include decentralized immersion heaters, which raise the temperature from 45 °C to 60 °C for domestic hot water demands. The SPF of the centralized heat pump is estimated to be 4.86 based on the ideal COP and a degree of perfection (ratio of real to ideal COP) of 54%[2]. The SPF is higher than for decentralized heat

[2] Calculated based on a flat SPF of 2.7 (AGFW, 2020) for a large heat pump operating between 10 and 80 °C and the ideal Carnot COP (5.045) for this kind of heat pump assuming it has to provide 80°C on the heating side.

pumps due to efficiency improvements with heat pump size. The heat source is assumed to be geothermal collectors that provide 10°C water in the forward flow. The pumps of the thermal network require 2.03 %[3] of the annual heat generated. The low temperature district heating system reduces heat losses of distribution grids. Consequently, the distribution losses of the system amount to ca. 4 % of the annual heat demand. The electricity demand for the centralized heat pump, grid pumps as well as decentralized electric heater for the domestic hot water supply is covered with electricity from decentralized roof-top PV-modules on an annual balance.

## 2.5 Scenario 5: cold district heating system with decentralized water-water heat pumps in combination with decentralized PV-modules

In this scenario, a cold district heating system is investigated, which provides both space heating and cooling at low temperature level (under 25 °C). In this study, the supply temperature of the cold district heating is 10 °C and the return temperature is assumed to be 5 °C. Thereby, geothermal heat collectors, e.g. collecting heat from under a crop field such as in Wüstenroth (M. Brennenstuhl, personal communication, 2017)are assumed as the heat source. Due to the low supply temperature, the heat losses within the district heating network are neglected. Decentralized water-water heat pumps realize the temperature increase to the required temperature level (space heating: 40 °C and domestic hot water supply: 60 °C). The SPF of heat pumps is 4.2 for space heating and 3.2 for domestic hot water supply including back up immersion heaters and other auxiliary demands (Günther et al., 2020). The electricity demand of grid pumps amounts to 2.6 % (M. Brennenstuhl, personal communication, 2017) of the annual heat generated. The electricity demand for the heat pumps as well as grid pumps is covered with electricity from decentralized roof-top PV-modules on an annual balance.

## 2.6 Scenario 6: district heating system based on deep geothermal energy

Scenario 6 considers a district heating system using deep geothermal energy. The analyzed district heating system is operated with a supply temperature of 70 °C. The district heating system with the central geothermal energy system provides both domestic hot water heat and space heating demand. The electricity demand of the grid pumps amounts to ca. 1,5 % (AGFW, 2014) of the annual heat generated. An additional 0.5% of the heat demand are assumed to be used as additional electricity to operate the geothermal well (Winsloe, 2021). The distribution losses of the system amount to ca. 7 % of the annual heat demand. The electricity demand for grid pumps is covered with electricity from decentralized roof-top PV-modules on an annual balance. While this heating system realistically will not be built for the rather small set of considered buildings it is assumed that the buildings are connected to a

[3] Calculated based on (AGFW, 2014).

larger grid supplied by deep geothermal energy. If unavoidable waste heat at 70 °C were used instead of deep geothermal heat the results for this scenario would be similar.

# 3 Results

## 3.1 General

The methodology of REA[4] aims at evaluating two resource exergy criteria: the resource exergy consumption (REC) and the resource exergy efficiency (REE). REE is the ratio of resource exergy demand (RED) and REC. RED therefore is not an independent but an additional informative indicators.

Additionally, greenhouse gas emissions (GHGE) in $CO_2$ equivalents ($CO_{2e}$, 100 years horizon[5]) were evaluated.

Furthermore, in chapter 3.2 results on PEC (cumulated, total and fossil)[6] are provided to allow comparison with the results from REA and underline the importance of an exergy-based assessment.

More examples of how REA results differ from conventional energy assessment have been discussed in (North & Jentsch, 2021). Examples on how results differ from LCA can be found in (Jentsch, 2016).

Due to the use of PV power the results shown in this article can be considered best-case scenarios for hybrid energy systems assuming the current global PV production system. These results can only be achieved if policy makers make sure that the use of electricity for heating does not lead to additional use of non-GHG free fuels in the overall grid. The rationale behind choosing a realistic assumption for power that hybrid energy systems use can be found in (Jentsch, 2022b).

The results of the analysis are shown in Table 1 and Table 2. These tables do not only show the results of REA but also GHGE and three PEC indicators meant to allow a discussion of the benefits of REA over PEA.

The results for the Primary Energy Indicators are discussed in chapter 3.2 on page 25 and following.

[5] The 100-year horizon for evaluating $CO_2$ equivalents is a convention that underrepresents the effect of short-lived GHG gases such as methane. If significant amounts of natural gas are used it is recommended to also consider a 20-year horizon for the calculation of $CO_2$ equivalents. On this time scale natural gas combustion contributes similarly to climate change as coal combustion. The mid-term GHG gas mitigation is very important in order to avoid triggering tipping points in the climate system (Traber & Fell, 2019).
[6] Calculated using Cumulated Energy Consumption ratios for the total column instead of the conventional primary energy factors.

*Table 1: Summary of analysis results for the compared heat supply scenarios.*

| | | Cumulated Primary Energy Consum-ption (CPEC) | Total Primary Energy Consum-ption [7] (TPEC) | Fossil Primary Energy Consum-ption (FPEC) | Resource Consum-ption (REC) | Resource exergy efficienc y (REE) | GHG emission s (GHGE) |
|---|---|---|---|---|---|---|---|
| | | **MWh/a** | **MWh/a** | **MWh/a** | **MWh/a** | **%** | **$t_{CO2e}$/a** |
| **S1: NGC B** | **Natural gas condensing boiler (NGCB)** | 582 | 552 | 552 | 582 | 3,7% | 112 |
| **S2: DH CHP/ NGB** | **District heating with CHP base load (50%) & Natural gas** | 598 | 577 | 434 | 455 | 6,2% | 86 |
| **S3: ASHP** | **Air-source heat pump (mono** | 468 | 377 | 0 | 175 | 12,2% | 9 |
| **S4: DH LHP** | **District Heating with large heat pump + peak** | 493 | 397 | 0 | 171 | 17,3% | 8 |
| **S5: DH Cold** | **Cold district heating system (W-W heat pump)** | 464 | 374 | 0 | 153 | 19,9% | 9 |
| **S6: DH Geo** | **District Heating with heat from deep geothermal** | 506 | 462 | 0 | 110 | | 7 |

The results obtained for REC and REE and GHG cover the full production chain of from resource to natural gas, PV electricity and geothermal heat from the ground respectively. REC for construction of combustion systems and district heating networks and for the recycling of the considered energy systems have been neglected due to a lack of available data. This seems justified due to the fact that for combustion systems the exergy used for construction is very small compared to exergy used in operation (Bejan et al., 1996).

However, if the required data is available, it might be of interest to assess the considered energy systems based on Cumulated Exergy Consumption for all process steps and all materials.

The detailed results for each scenario are given in (Jentsch, 2022a), using exergy passes, an advanced visualization of REA. For comparison purposes, the results are summarized in

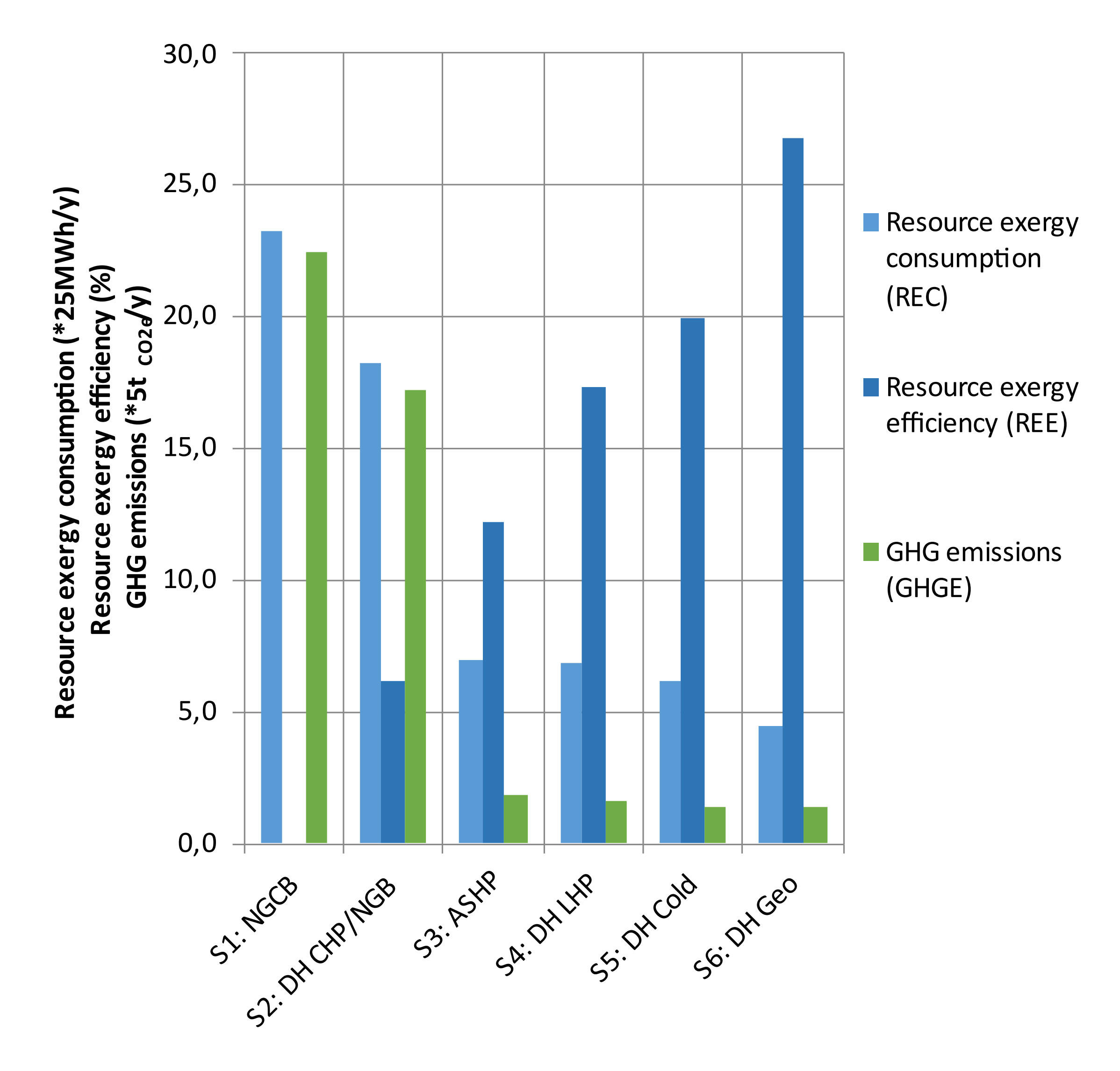


Figure 2.

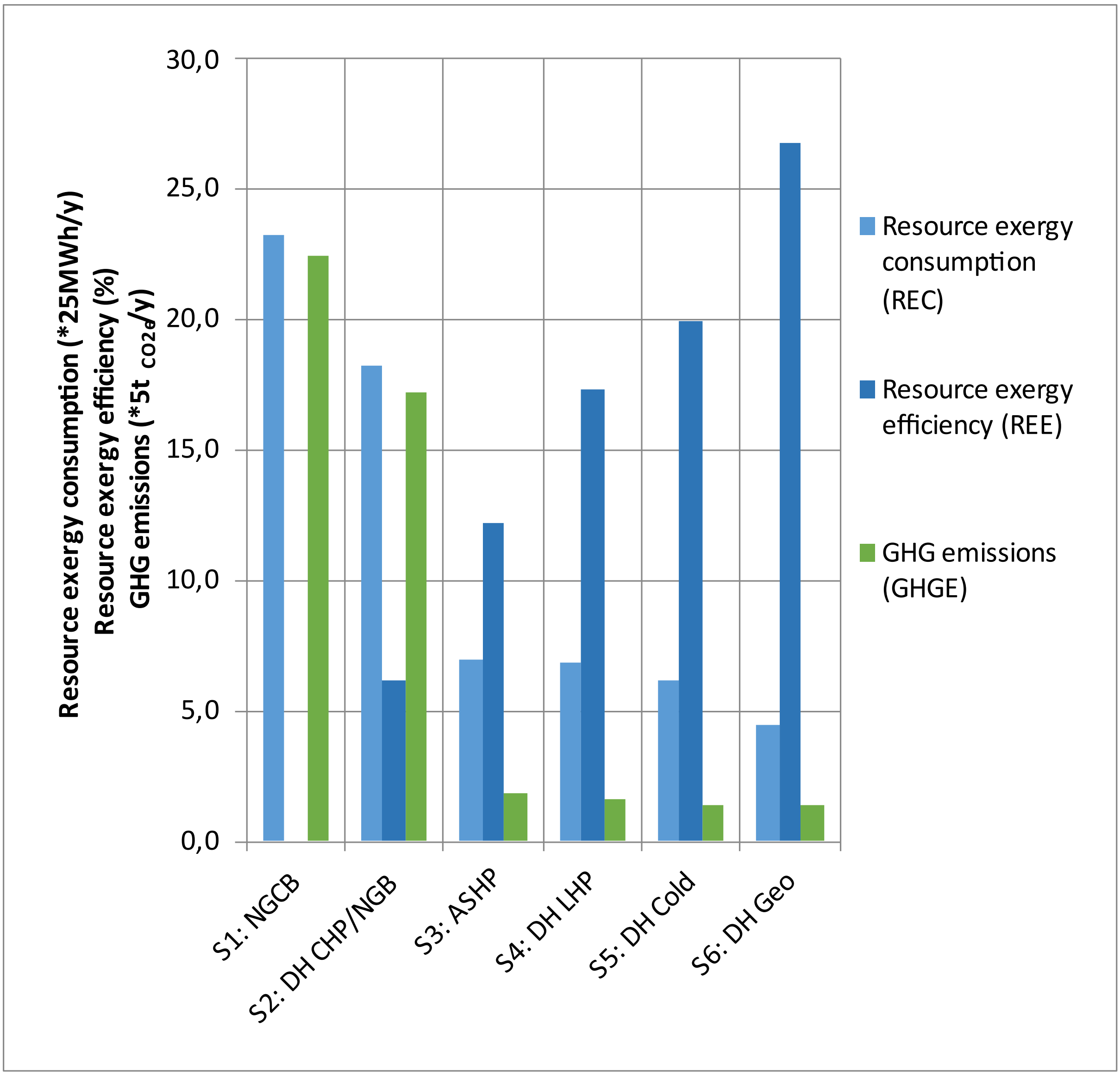


*Figure 2: Comparative results for resource and GHG indicators of the considered scenarios*

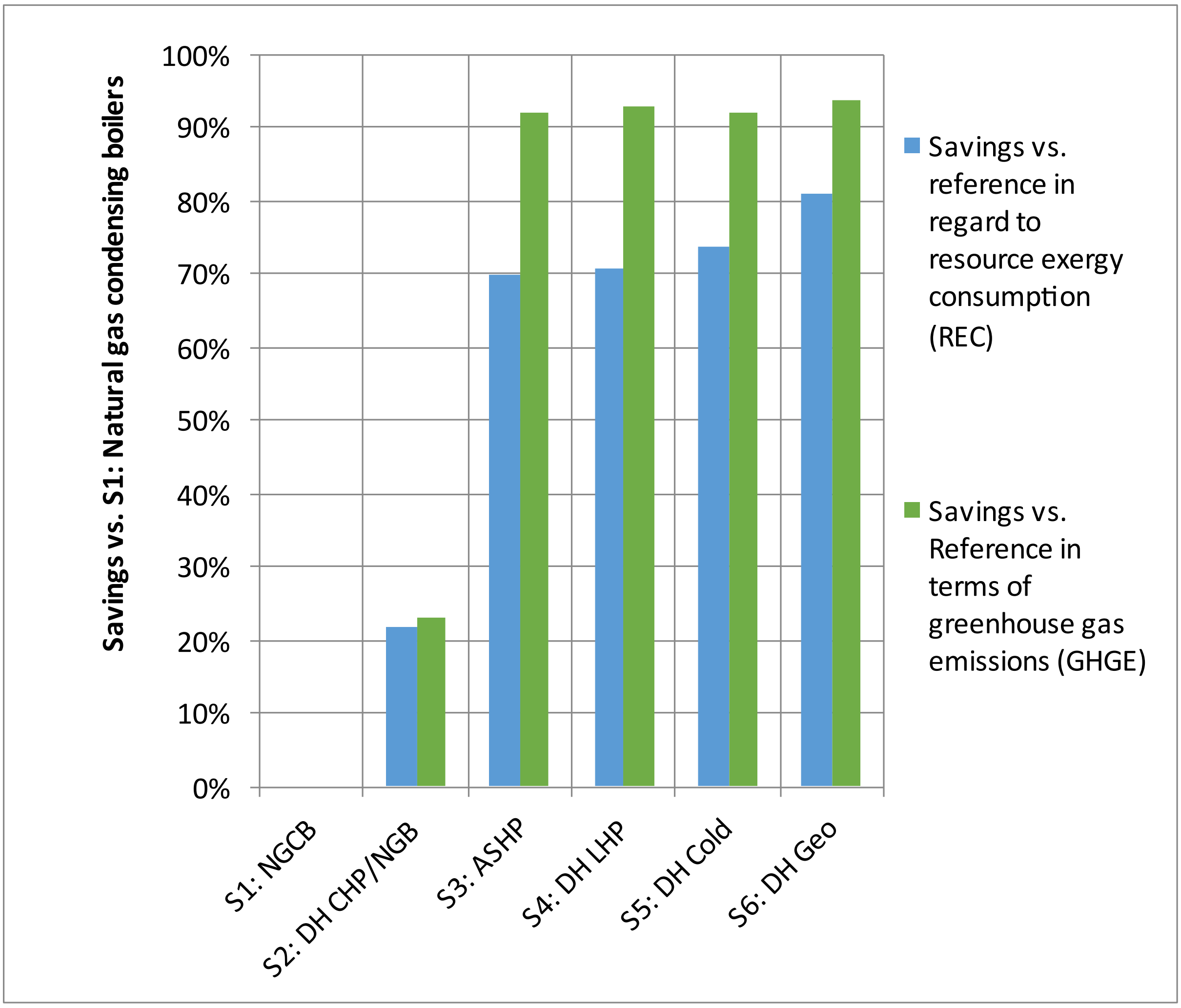


*Figure 3: Savings versus a decentralized gas boiler achieved with the considered scenarios*

Table 1 and

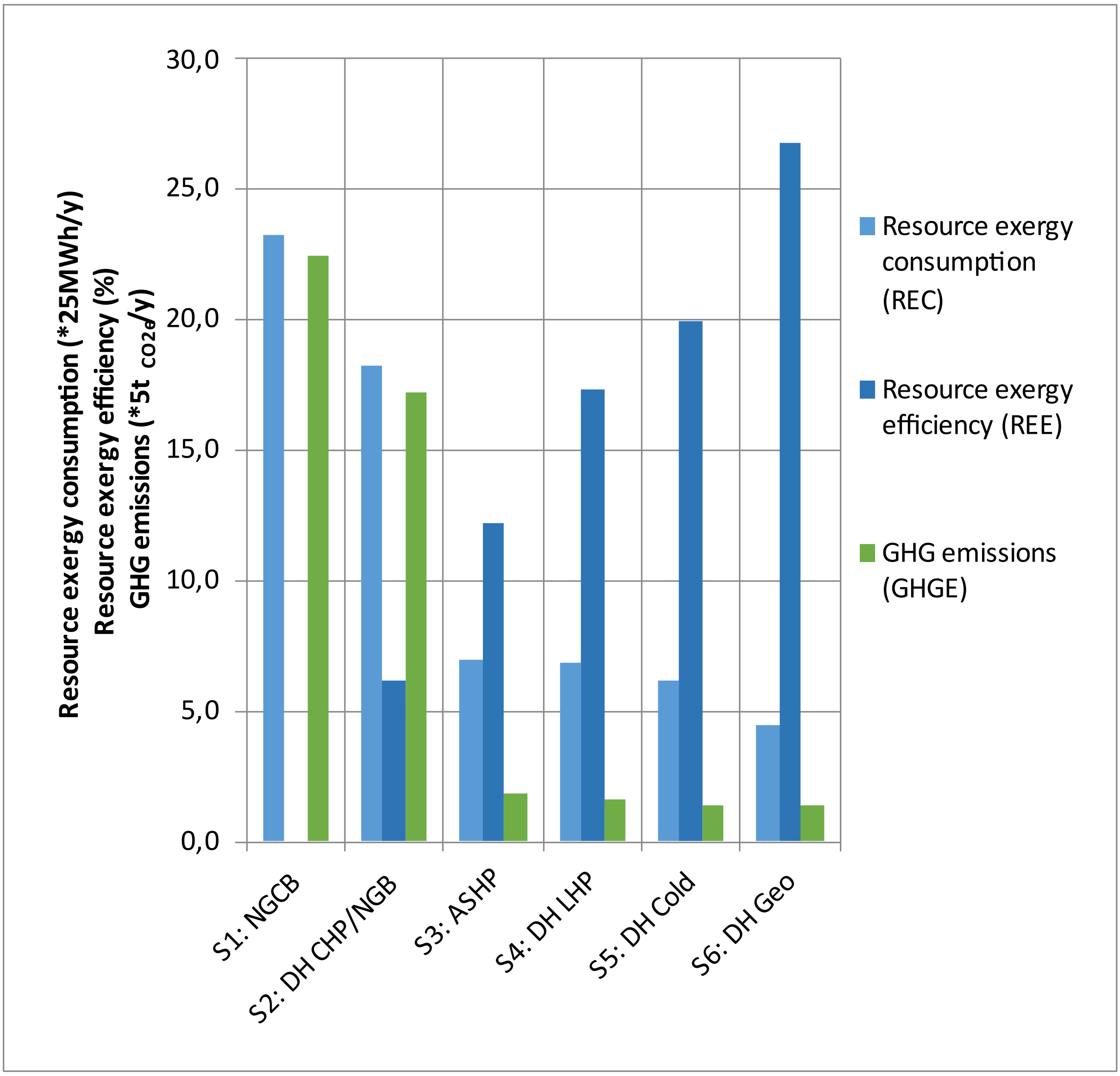


Figure 2 show that the efficiency improvements are not proportional to the reductions in REC. E.g., while for the decentralized air-source heat pump (S3) the REE is 12.2% leading to a REC of 175 MWh/a, S4 (Heat network supplied by a large heat pump and electric backup boilers) shows an efficiency of 17.3% while consuming 171 MWh/a of resources (a reduction of REC of about 2%).

This is caused by the different goals that both indicators have. While REE shows how sophisticated a technical solution is, REC is an indicator how much resource exergy is consumed to provide the final demand. So, while REE can clearly indicate how well a given technical solution reaches its potential for perfection it does not indicate how friendly it is to the environment. Even a highly efficient solution can be a poor choice if the demands that are needed to be covered (final demand, auxiliary demand) are high. A solution low in REC however is always a desirable choice even if its efficiency is rather low, since it indicates the resulting impact on the surroundings is rather low.

As a consequence, REE can be considered as an auxiliary indicator but should not be used to directly compare solutions that have different auxiliary demands. For systems that have exactly the same RED, REE does not provide additional insights to REC. Consequently, all conclusions concerning the choice of energy systems should be based only on REC (as the exergy indicator) and other useful indicators such as GHGE and life cycle costs. REE can only provide an indicator on the improvement potential of a given technology.

Table 2 shows the savings achieved with the considered scenarios in comparison to S1 – decentralized natural gas condensing boilers. Savings in terms of efficiency were not assessed since efficiency can only be an auxiliary criterion and should not be used for direct comparison.

The results for the Primary Energy Indicators are discussed in chapter 3.2 on page 25 and following.

*Table 2: Savings in comparison to Scenario 1 (S1) an individual natural gas boiler*

| | | Cumulated Primary Energy Consum-ption (CPEC) | Total Primary Energy Consum-ption [8] (TPEC) | Fossil Primary Energy Consum-ption (FPEC) | Resourceexergy consum-ption (REC) | GHG emissions (GHGE) |
|---|---|---|---|---|---|---|
| | | MWh/a | MWh/a | MWh/a | MWh/a | $t_{CO2e}/a$ |
| **S1: NGCB** | **Natural gas condensing boiler (NGCB)** | 0% | 0% | 0% | 0% | 0% |
| **S2: DH CHP/ NGB** | **District heating with CHP base load (50%) & Natural gas boiler (NGB)** | -3% | -5% | 21% | 22% | 23% |
| **S3: ASHP** | **Air-source heat pump** | 20% | 32% | 100% | 70% | 92% |
| **S4: DH LHP** | **District Heating with large heat pump + peak e-boiler** | 15% | 28% | 100% | 71% | 93% |
| **S5: DH Cold** | **Cold district heating system (W-W heat pump)** | 20% | 32% | 100% | 74% | 94% |
| **S6: DH Geo** | **District Heating with heat from deep geothermal heat** | 506 | 462 | - | 110 | 7 |

Regarding the final user heating demand, space heating accounts for almost 75% (324 MWh/year) of the total energy demand and DHW for 25% (110 MWh/year), for all scenarios. However, exergy-wise, 67.1% (14.4 MWh(exergy)/year at 20 °C) of the final exergy demand is dedicated to space heating and 32.9% (7.1 MWh(exergy)/year to heat water from 10 °C to 43 °C) for DHW, because of their respective energy quality.

For the centralized solutions, additional heating demand is considered to include compensation of heat losses through distribution pipes. The heat losses were estimated at 32 MWh/year for a 70/40 °C heating network (S2 and S6), 18.9 MWh/year for a 45/25 °C (S4) and null for a cold district heating operating at 10/5 °C (S5), considering the reference temperature of 7 °C. The auxiliary power required for circulating pumps, fed by PV panels, is also considered. It accounts for 1.5 % (S2 and S6), 2 % (S4) and 2.6 % (S5) of the total heat generated.

As expected, the reference scenario (individual natural gas condensing boiler, S1) is the worst for the three criteria considered, as it relies on fossil fuel as primary energy which has a high energy quality factor (100%) and uses combustion without coproduction or integration of ambient heat to generate heat. Consequently, the use of high-quality energy to satisfy low quality needs results in significant REC (582 MWh/year) and large inefficiencies (low REE, 3.7 %), in spite of the high final energy efficiency of the boiler (96 %). In general, the REE (defined in (Jentsch, 2022b) as the specific resource exergy demand divided by the specific resource exergy consumption) for DHW production is always higher than for space heating (of 3.3% and 4.8% respectively, for this case), because exergy destruction is greater if the temperature level required for the energy service is lower and the supply is the same. Furthermore, natural gas combustion implies significant GHGE, of up to 112 t/year.

Similarly, coupling a block combined heat and power plant and a centralized gas boiler (S2) in a conventional district heating network, both fed by natural gas, to satisfy the residential heat demand still involves high REC (455 MWh/year) and GHGE (86 t/year). It needs to be noted however that all characteristics could be significantly improved by shares of CHP that are higher than the 50% assumed. The resulting resource savings and GHG savings, compared to the reference scenario account for 22 % and 23 %, respectively. Although additional heat losses related to the distribution losses due to the 70/40 °C heating network are taken into account, the use of the cogeneration process allows to reduce the REC and GHGE thanks to the fact that heat is the byproduct of electricity production and therefore only carries a comparably small, temperature-dependent share of the resources used for the combined process (Jentsch, 2022b). For this case study, the resources used coming from the cogeneration with natural gas have an average energy quality of 42 % in comparison to 100 % if using natural gas in the boiler. Finally, the REE reaches 6.2 % for this scenario.

Considering the use of individual air source heat pumps (scenario 3), all the three criteria significantly improve despite the comparably low SPF of the system (SPF=3.07). The relatively low average energy quality of the consumed resources (a mixture of heat from air and electricity from PV: 37.5 %) leads to a REE of 12.2 % and a REC of 175 MWh/year, saving 70 % of the resource compared to the reference case. Thanks to the electricity produced via local PV, the GHGE drop to 9 t/year, with savings of 92 %.

It must be noted that using a grid power mix mainly consisting of power from fossil fuels easily could triple the resources consumed and significantly increase GHGE from hybrid energy systems and therefore would lead to very different results for these technologies.

Therefore, to ensure a maximum benefit from hybrid energy systems it is necessary to build additional dedicated GHGE-free power generators that can cover the demand of the heat pumps in the time frame considered.

(Jentsch, 2022b) explains what needs to be considered to make realistic assumptions about the power used in hybrid energy systems. Chapter 6 shows how an estimate for different power sources can be obtained.

Implementation of a centralized water/water heat pump (S4) to satisfy heat demand via a low temperature heating network (45/25 °C) leads to slightly higher performance than for individual air-source heat pumps in scenario 3 (REE of 17.3 %; REC of 171 MWh/year and GHGE of 8 t/year), thus 71 % of the REC and 93 % of the GHGE are saved compared to the reference case. Thanks to the water/water heat pump technology, the lower temperature differential between the hot and cold sources and the efficiency improvements that come with heat pump size, the Seasonal Performance Factor reaches 4.86 (compared to 3.07 for individual air-source heat pumps) and the average energy quality of the consumed resources decreases to 25 %. However, the use of decentralized electric boilers to satisfy peak Domestic Hot Water demand (accounting for 34 MWh/year) plus the distribution losses through the networks (18.9 MWh/year) counterbalance these gains.

The considered cold district heating network[9] with semi-centralized water-water heat pumps (S5) shows a comparably high REE (19.9 %). Although the seasonal performance factor of the decentralized water-water heat pumps is set to 4.2, leading to an average energy quality of the supplied energy of 29 %, the avoidance of heat distribution losses contributes to decrease the REC to 165 MWh/year (saving 74 % resources compared to the reference). However, the additional electricity consumption to boost temperature up to 60 °C for DHW (8 MWh/year) and the comparably high amount of electricity required to operate the cold district heating network (2.6% of the heat generated) counterbalances these effects so that no significant improvement over decentralized air-source heat pumps is achieved in terms of REC or GHGE. Similarly to scenario 3, the GHGE are estimated to 9 t/year (saving 92 % compared to the reference), thanks to local PV production. It has to be noted though that this solution avoids the need for noisy air – water heat exchangers and can potentially supply areas with higher heat demand density.

The last scenario can be considered as a best-case reference and is rather prospective. It relies on the use of deep geothermal heat allowing to supply a 70/40 °C heating network (S6). The direct use of low-grade energy and the avoided use of electric boilers for peak demand lead to an energy quality of 20 %, thus reducing the REC to 110 MWh/year (with

[9] These networks are sometimes misleadingly[9] called anergy networks. However, anergy is a very limited concept. While it works for heating above reference temperature, it does lead to confusion when applied to cooling and pressurized air and should therefore be avoided. The background of this fact is that exergy is a property of the considered flow and the environment and their joint potential and not a property of the considered flow alone.

81 % savings). GHGE are lowered to 7 t/year (with 94 % GHGE savings). While not a hybrid energy system this scenario was included in the analysis to show that district heating networks using GHGE-free thermal sources can compete well with the best-case of hybrid energy networks in terms of REC and GHGE. This implies that electrification of district heating in not the only option to decarbonize these systems but that district heating using GHGE-free thermal sources (such as deep geothermal, Solar thermal or unavoidable industrial excess heat) is also an important element to be considered.

## 3.2 Results of REA in comparison to primary energy analysis

In the following the results of three types of primary energy analysis are shown and compared with the results of REA and GHG analysis. The aim of the following comparison is to demonstrate how the choice of analysis methodology influences the results of energy system assessment and the following conclusions and why therefore REA is necessary to ensure a viable path to stopping climate change.

To assess the pre-chain losses of primary energy consumption (PEC) for extraction, construction and transport of the used final energy three different factors were used.

1. Cumulated primary energy consumption (CPEC) uses the specific Cumulated Energy Consumption to represent pre-chain losses. It is the most scientifically accurate factor of the three considered and can be found in databases. It also can be used as an element in a simplified REA if Cumulated Exergy Consumption values are not available (Jentsch, 2022b).
2. Total primary energy consumption (TPEC) is based on industry norms (DIN, 2010) that provide a simplified approach to assess pre-chain losses. It includes renewable and non-renewable energies alike but does not consider primary energy required for construction of the pre-chain infrastructure.
3. Fossil primary energy consumption (FPEC) only considers fossil primary energy. Renewable primary energy is not considered. Like TPEC it is based on industry norms (DIN, 2010) and the most commonly used assessment criterion in German lawmaking at the time of writing.

Figure 4 shows the comparison of indicators from Table 1.

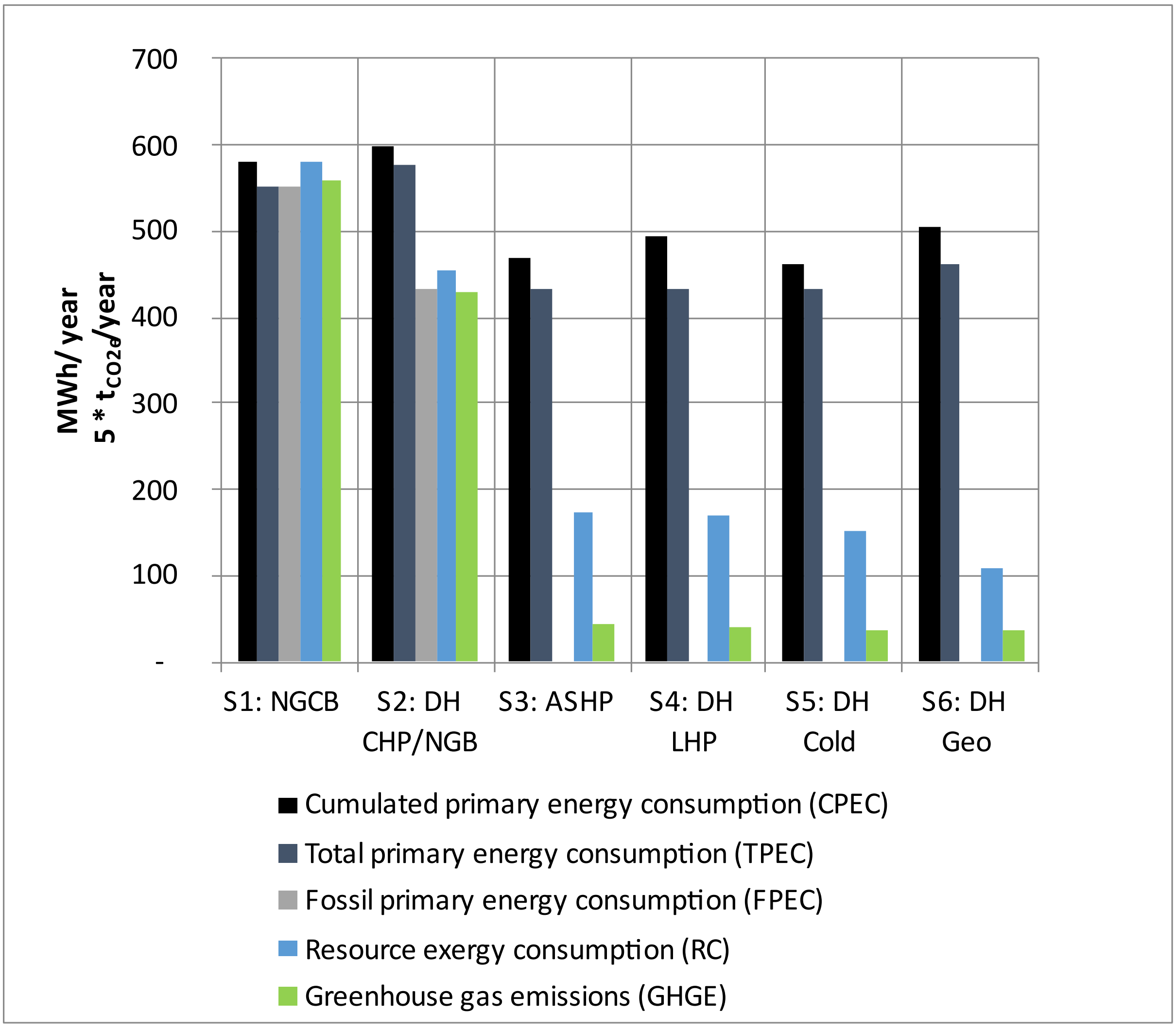


*Figure 4: Comparison of ecological key performance indicators*

While for S1 all indicators show similar results, the results for all other scenarios differ significantly from each other. CPEC and TPEC are always above 434 MWh/year and therefore do not reflect the savings achievable with hybrid energy systems. This can easily be explained as these indicators only consider energy independent of its energy quality or GHGE. Due to the law of energy conservation, the amount of cumulated and total primary energy consumed can never be lower than the demand. However, TPEC does not consider the difference between power from PV and low-value heat from air, ground or water. Also it does not include primary energy used for construction and therefore is clearly the less comprehensive indicator of the two (CPEC and TPEC).

FPEC has been calculated differently than TPEC for S2, based on generic primary energy factors for district heating instead of using the primary energy factors for Natural Gas and the Carnot-Method of fuel allocation. It can clearly be seen that the different calculation approaches for essentially the same indictor (TPEC and FPEC are essentially the same for fossil fuel use) lead to significantly different results. This shows that for the evaluation of CHP neither TPEC nor FPEC are reliable performance metrics but instead provide a means to manipulate results through the choice of assumptions used.

Furthermore, FPEC is zero by definition for four of the six scenarios considered. It therefore does not allow comparison of renewable energy systems. It is closest to GHGE as an indicator but adds no value. On the contrary for many renewable energy systems FPEC is strongly correlated to the GHGE of the system, thus effectively changing from the wastefulness indicator it is for fossil energy systems to one that is essentially a less scientifically grounded GHGE indicator. At the same time FPEC ignores efficiency aspects of renewable energy systems, thus paving the ground for a wasteful use of renewable resources and the resulting increase of GHGE in the overall energy system (see explanation in chapter 1).Figure 5 shows the comparison of the savings from Table 2 achieved by a considered scenario in comparison with a natural gas condensing boiler (S1).

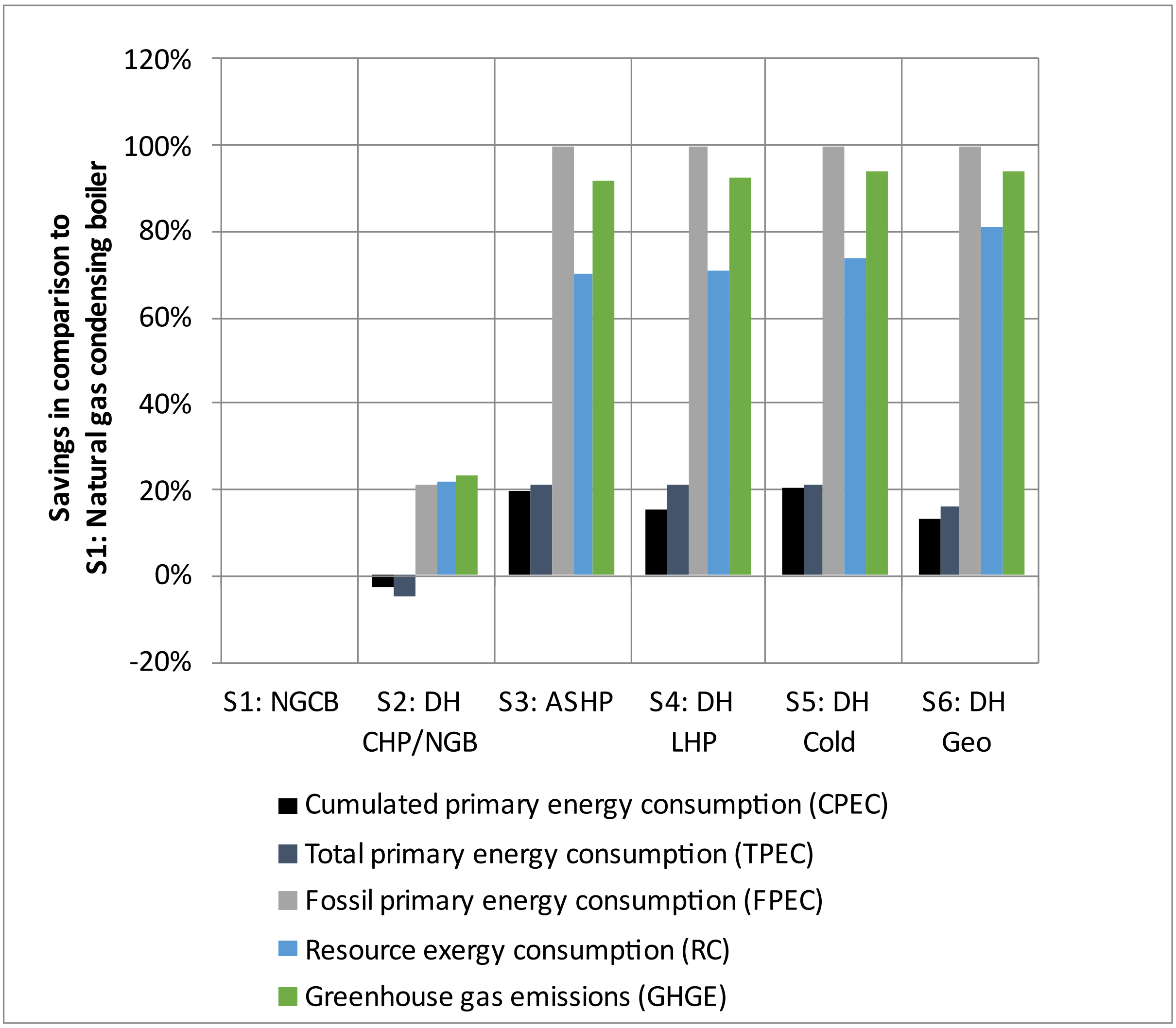


*Figure 5: Comparison of ecological key performance indicators in terms of savings in comparison to S1: Natural Gas Condensing Boiler*

Using TPEC and CPEC S2: DH CHP/NGB - a system with a significant amount of CHP can be deemed less efficient than a natural gas boiler. This illustrates why the consideration of energy quality is so important and underlines the lack of suitability of these indicators for energy system comparison.

Also, the savings for renewable energy systems are systematically underestimated thus making them less attractive than if using REA. Using TPEC and CPEC for renewable energy assessment can thus easily damage climate change mitigation efforts as both indicators fail to provide insights into the loss-reduction benefits of low-GHG systems.

The savings achievable by FPEC using renewable power are always 100% in comparison to S1: NGCB. Thus, FPEC systematically ignores all losses in non-fossil energy systems. For S3, S4 and S5 REC indicates that the savings are 30% - 26% lower for HES than indicated by FPEC.

As explained in (Jentsch, 2022b) minimizing wastefulness in all energy systems is key to avoid an indirect and potentially very significant increase in GHGE in the overall energy system. This is valid not only for fossil but also for the use of low-GHG energy sources in an overall system that still uses fossil fuels.

Consequently, the use of FPEC for the analysis of non-fossil energy systems leads to a systematic underestimation of the overall system effect and thus likely leads to an avoidable increase of climate change. REC provides a viable alternative indicator that is independent from GHGE and allows to identify the most resource saving solutions.

In summary the investigated scenarios show clearly that the three types of primary energy analysis are significantly flawed when it comes to assessing the wastefulness of energy systems. To avoid systematic errors in judgement, decision makers should learn to ignore these commonly communicated indicators and obtain a more realistic assessment of the impact on overall system resources using REA. Which in turn helps to ensure that low-GHG systems do not lead to avoidable increase in GHGE elsewhere in the overall energy system.

Further proof for the need to replace primary energy analysis (CPEC) with a consistent, realistic and more comprehensive methodology such as REA can be found in (North & Jentsch, 2021).

# 4 Discussion

Several scenarios have been considered that allow to meet the heat demand of a simulated residential district. The variety of the technical solutions considered, from fully distributed to fully centralized, involves several primary energy sources. The following main conclusions can be drawn based on the performed analysis.

Regarding the different energy sources considered (natural gas, electricity, heat), scenarios 1 and 2 relying on the use of natural gas show very poor or poor exergy performance due to the combustion of high-quality energy carriers to satisfy low quality energy demand, despite of the high energy conversion efficiency. Similarly, the use of electricity as a complement source for peak demand contributes to decreases in REE and increases the consumption of resources to satisfy the demand. Scenarios 3, 4, 5 and 6 show a much-reduced REC, as they rely on low energy quality resources (Heat from the environment or the ground) minimizing the use of high-quality resources (fuel or electricity).

The comparison of scenarios 3, 4 and 5 provide some insights about the effect of centralized versus decentralized solutions. Distributed air source heat pumps (scenario 3) are a fully decentralized solution that can be compared to centralized large heat pumps (scenario 4), with heat distribution through a conventional low temperature network. An intermediate solution is the implementation of a cold heating network using semi-centralized heat pumps (scenario 5) to satisfy the demand. These three scenarios show similar performance (REC of 165-175 MWh/year and GHGE 8-9 t/year).

The individual air-source heat pumps (scenario 3) are penalized due to their relatively low Annual Performance Factor (3.07 (including hot water boosting) compared to 4.2 for the semi-centralized water-water heat pump associated to cold district heating – scenario 5 and 4.86 for the centralized heat pump – scenario 4). However, district heating involves additional energy consumption, related to heat distribution losses (18.9 MWh/year for scenario 4 and assumed null for scenario 5) and pumping power (8.3 MWh/year and 11.1 MWh/year for scenarios 4 and 5, respectively). Further, the use of electric boilers as auxiliary systems, that account for 10% of the total thermal demand (43 MWh/year) in scenario 4 to satisfy peak-load and to disinfect Domestic Hot Water at 60 °C from the outlet of the heat pump (8 MWh/year) in scenario 5, counterbalance the gains from the higher Annual Performance Factors. Finally, the low reliance on electricity of scenario 6 results in the highest REE of the considered scenarios showing that hybrid energy systems are not the only solution effectively capable of reducing REC and decarbonizing the heating sector.

Concerning the temperature level of the heating network, the conclusions are not straightforward. On the one hand, higher temperature in the forward flows (70/40 °C for scenarios 3 and 6, 45/25 °C for scenario 4 and 10/5 °C for scenario 5) results in higher distribution losses (32 MWh/year, 18.9 MWh/year and 0 MWh/year, respectively). However, they are partially counterbalanced by lowering pumping power, depending on the heat distributed and the temperature difference (7 MWh/year for scenario 3, 7.89 MWh/year for scenario 6, 8.3 MWh/year for scenario 4, 11.1 MWh/year for scenario 5). The main differences observed come mainly from the energy resource used (natural gas, electricity, heat) and the resource exergy performance of each system considered. As a conclusion, conventional low temperature district heating can show comparably low reductions in REC when supplied with heat from natural gas CHP & a large share of boiler heat (50%) compared to a supply by a deep geothermal energy source.

As a conclusion, the most efficient scenario among the compared solutions is the centralized deep geothermal solution (scenario 6), as it favors the direct use of low energy quality resources to satisfy the thermal demand without any energy conversion, thus reducing the exergy destruction in the energy system.
All considered hybrid energy systems (scenarios 2, 3 and 5) show the potential to be only slightly worse in terms of REE and GHGE than this frontrunner. However, they only achieve that if the power comes from additional PV installed on premises and storage losses by the electrical grid (or any other electrical storage) are minimal.

It is therefore an important task for regulators to ensure that any energy system that creates additional electricity demand – such as hybrid energy systems – is supplied as completely as possible with GHGE-free power that would otherwise either not be harvested or not used.

# 5 Conclusion and outlook

In this paper six energy systems that cover the heat demand (space heating and domestic hot water) of a residential district are compared. The comparison is performed by using resource exergy analysis (Jentsch, 2022b, 2022a) and complemented with an assessment of GHGE (GWP100). The three assessment criteria used are: resource exergy consumption (REC), resource exergy efficiency (REE) and greenhouse gas emissions (GHGE).

REE has been shown to be an indicator not well suited for cross-system comparison as it can vary significantly for systems with similar REC. It is an informative criterion to characterize the degree to which a considered system reaches its theoretical potential.

GHGE show the direct reduction of GHGE by using the considered system.

Since less REC means less need to build GHGE-free energy systems, reductions in REC indicate how much a considered system supports the goal of reaching climate targets in time.

The analysis has been performed assuming additional PV power to cover all electrical demands of the considered energy systems. Thanks to the global indicators and the universally applicable assumption about power coming from PV, the results obtained can be generalized to any country, independently of their respective electricity mix.

The results highlight the high influence of the resource exploited. As expected, the use of fossil fuel such as natural gas results in high GHGE, particularly in the case of individual gas condensing boilers and large shares of heat from boilers in district heating networks.

The considered hybrid energy systems (air-source heat pumps) and hybrid energy networks (large heat pumps in a very low temperature district heating network and decentralized water-water heat pumps in a cold district energy network) achieve similar savings in comparison to heat supply from a decentralized natural gas condensing boiler.

The similar performance is caused by the fact that additional energy demands of heat networks, e.g. heat losses and pumping power needed, are counterbalanced by higher energy efficiency of the considered supply technologies (water-water heat pumps instead of air-source heat pumps).

Consequently, all types of hybrid energy systems show a large potential to support the decarbonization of heat, if the supply temperatures are kept as low as possible, additional GHGE-free power is used and the performance factors are optimized.

Furthermore, it is shown that GHGE-free thermal sources (e.g., deep geothermal heat) can reach similar improvements over a natural gas condensing boiler as the best cases of hybrid energy systems even if providing heat at higher temperatures (70/40 °C instead of 40/25 °C).

Finally, the performed analysis demonstrates the importance to shift from primary energy analysis to resource exergy analysis to obtain a realistic picture of system wastefulness and avoid judgment errors when making energy system choices.

In summary, this paper shows that hybrid energy systems, hybrid energy networks and low temperature district heating from thermal sources can all help to significantly reduce GHGE (>90%) and REC (>70%) in comparison to heat supply by decentralized natural gas condensing boilers.

However, to harness the full potential of hybrid energy systems it is key to ensure that any power consumed by them is provided by GHGE-free sources that are built up in addition to the existing GHGE-free generation capacity of the grid.

# 6 Adapting results to other sources of electricity

The results for the investigated hybrid energy systems (S3, S4, S5) strongly depend on the source of electricity that is assumed to supply the considered heat pumps. To obtain an estimate of the REC and GHGE for the considered systems if they use grid power mix the following equations can be applied.

The REC using the grid power mix $(REC_{gm})$ is a function of the REC using dedicated PV power $(REC_{PV})$ (see Table 1), the Cumulated Energy Consumption of the grid power mix $(CEC_{gm})$ and the Cumulated Energy Consumption of PV power $(CEC_{PV})$.

| | | |
|---|---|---|
| **Approximation for the resource exergy consumption of the investigated hybrid energy systems using grid power mix** | $REC_{gm} \approx \frac{CEC_{gm}}{CEC_{PV}} \cdot REC_{PV}$ | *(1)* |

Analogously, the GHGE using the grid power mix $(GHGE_{mpm})$ is a function of the specific GHGE using dedicated PV power $(GHGE_{PV})$ (see Table 1), the specific of the grid power mix $(SE_{GHG,mpm})$ and the specific GHGE of PV power $(SE_{GHG,PV})$.

| | | |
|---|---|---|
| **Approximation for the resource exergy consumption of the investigated hybrid energy systems using grid power mix** | $GHGE_{gm} \approx \frac{SE_{GHG,gm}}{SE_{GHG,PV}} \cdot GHGE_{PV}$ | *(2)* |

The assumptions for PV can be found in Table 5. The results of such an analysis are not being presented here as this would go beyond the scope of this analysis, which is to show the potential of hybrid energy systems. Furthermore, the non-hybrid energy systems would need to be adapted for their power demands as well and would require additional equations to do so. However, since the power demands for Scenarios 1, 2 and 6 are rather small (see Table 3) the results for these scenarios have a low sensitivity to the assumptions concerning power.

# 7 Acknowledgements

The authors would like to than Étienne Saloux for his detailed review of some drafts of this paper. Furthermore, we would like to thank AGFW, IEA DHC and Fraunhofer IEE for their financial support.

# 8 Appendix

## 8.1 Abbreviations

| | |
|---|---|
| ASHP | Air-source heat pump |
| APF | Annual performance factor |
| CEC | Specific cumulated energy consumption |
| CHP | Combined heat and power |
| CPEC | Cumulated primary energy consumption |
| Cold | Cold district heating |
| $CO_{2e}$ | Carbon dioxide equivalents (GWP 100) |
| DH | District heating |
| DHS | District heating system |
| Geo | Geothermal |
| GHG | Greenhouse gases |
| GHGE | Greenhouse gas emissions |
| GWP100 | Global warming potential of non-$CO_2$ emissions averaged over 100 years. |
| FPEC | Fossil primary energy consumption |
| LHP | Large heat pump |
| NGB | Natural gas boiler (without condensing) |
| NGCB | Natural gas condensing boiler |
| PEC | Primary energy consumption |
| PV | Photovoltaic electricity generators |
| S | Scenario |
| $SE_{GHG}$ | Specific greenhouse gas emissions |

| | |
|---|---|
| TPEC | Total primary energy consumption |
| REA | Resource exergy analysis |
| REC | Resource exergy consumption |
| RED | Resource exergy demand |
| REE | Resource exergy efficiency |

## 8.2 List of figures



## 8.3 List of tables

## 8.4 Calculation assumptions

*Table 3: Table of calculation assumptions for the scenarios*

| | Scenario | Unit | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 | Scenario 6 |
|---|---|---|---|---|---|---|---|---|
| General information | **System description for DH (centralized heat supply system)** | | Natural gas boiler (NGB) | District heating with CHP base load (ca. 4,000 operating hours) + e.g. NGB peak load | Air-source heat pump (mono energetic) | District Heating with Large central heat pump + peak e-boiler | Cold district heating system (W-W heat pump monovalent) | District Heating with heat from deep geothermal heat - no peak boiler required |
| | **Reason for considering system** | | Current individual standard | Standard for district heating | Current individual hybrid heating system standard | Centralized hybrid district heating | Semi-centralized hybrid district heating | Likely best case for thermal district heating |
| Building | **Energy standard of buildings** | | EnEV 2016 (Ger.) | EnEV 2016 (Ger.) | EnEV 2016 (Ger.) | EnEV 2016 (Ger.) | EnEV 2016 (Ger.) | EnEV 2016 (Ger.) |
| | **Set room temperature** | °C | 20 | 20 | 20 | 20 | 20 | 20 |
| | **Set DHW temperature in DHW-tank** | °C | 60 | 60 | 60 | 60 | 60 | 60 |
| | **Temp. Heating circuit in buildings** | °C | 40 | 40 | 40 | 40 | 40 | 40 |
| | **Heat demand (space heating)** | MWh/y | 324 | 324 | 324 | 324 | 324 | 324 |
| | **Heat demand (DHW)** | MWh/y | 110 | 110 | 110 | 110 | 110 | 110 |
| | **Heat losses (distribution grid)** | MWh/y | 0 | 32 | 0 | 18,9 | 0 | 32 |
| | **Share of heat losses in centralized heat production** | | | 0,069 | | 0,046 | | 0,069 |
| | **Total heat demand** | MWh/y | 434 | 466 | 434 | 452,9 | 434 | 466 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Heat supply | **Energy efficiency / Seasonal perform-ance factor** | | 0,96 | Efficiency (el.) 37 % / Efficiency (th.) 46 % | 3,07 | 4,86 | "SPF (space heating): 4.2<br><br>SPF (DHW): 3.2 | 0,98 |
| | **Reference for energy efficiency** | | Jagnow et al. 2004: Effizienz von Wärmeerzeugern, TGA Fachplaner 10/2004 | 24.06.2022 15:18:00C HP Only (Assumption based on www.heizungsfinder.de/bhkw/ratgeber/stromkennzahl-wirkungsgrad (accessed on 17.10.2014)) | ISE 2021: Wärme-pumpen im Bestand | Calculation based on Temperatures and AGFW Praxisleit-faden Großwärme-pumpen | Simulation results of Fraunhofer IEE | Only 0.5% pump power will be assumed for a universal geothermal system such as www.eavor.de |
| | **Pump power required by thermal network** | MWh/y | | 1,5 | | 2,03 | 2,6 | 1,5 |
| | **Share of heat generation by peak technology** | | | 50% | included in SPF | 10% | | 0% |
| | **Source temperature for Heat pumps** | °C | | | 5 | 10 | 10 | |
| | **Supply temperature of primary heat generator** | °C | 70 | 70 | 45 | 45 | 10 | 70 |
| Domestic Hot Water (DHW) Supply | **Return temperature to primary heat generator** | °C | 40 | 40 | 25 | 25 | 5 | 40 |
| | **DHW-Supply** | | De-centralized (Boiler) | Centralized (District Heating) | Decentralized (Heat pump and immersion heating) | Centralized (District Heating) & local immersion DHW heaters | Semi-centralized (W-W heat pumps) | Centralized (District Heating) |
| On-site photovoltaic power generation | **de-centralized DHW-Supply** | MWh/y | 110 | 0 | 76 (Het pump) / 34 (Immersion) | 34 | 110 | 0 |
| | **Use of electricity from decentralized PV modules** | Yes/No | YES (auxiliary) | YES (pumping) | YES (heat pump + heaters) | YES (heat pump + heaters + pumping) | YES (heat pump + pumping) | YES (pumping) |

*Table 4: General calculation assumptions for natural gas*

| Parameter | Value | Unit | Description | Reference |
|---|---|---|---|---|
| **specific $CO_2$ emissions for natural gas as final energy** | 0.247 | kg/kWh | Average specific greenhouse gas emissions (related to the calorific value of the final energy and measured in $CO_2$ equivalents) resulting from the combustion of natural gas. This value is not valid for natural gas from fracking. | (IfEU, 2014) |
| **Calorific value / calorific value for natural gas** | 0.901 | kWh/kWh | The ratio of calorific value and calorific value of a fuel \| It is simplified assumed that the exergy of a fuel is identical with its calorific value. | (DIN, 2010) |
| **Cumulative Energy Consumption for Natural Gas** | 1.16 | kWh/kWh | Cumulative Energy Consumption fossil and renewable (CEC_total)\| The cumulative energy consumption indicates how much energy has to be spent to provide one unit of the considered energy | (GEMIS 4.6, 2010a) |

*Table 5: General calculation assumptions for PV power*

| Parameter | Value | Unit | Description | Reference |
|---|---|---|---|---|
| **Specific $CO_2$ emissions for electricity from photovoltaics as final energy** | 0.061 | kg/kWh | Average specific GHGE (related to final energy and measured in $CO_2$ equivalents) resulting from the use of photovoltaics (solar cells) | (IfEU, 2014) |
| **Cumulative energy consumption for end-user electricity from photovoltaics** | 1.24 | kWh/kWh | Cumulative energy consumption fossil and renewable (CEC_total)\| The cumulative energy consumption indicates how much energy must be expended to provide one unit of the energy under consideration | (GEMIS 4.6, 2010b) |

*Table 6: General calculation assumptions for deep geothermal heat*

| Parameter | Value | Unit | Description | Reference |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| **Specific CO2e emissions for geothermal energy without auxiliary power** | 0.014 | kg/kWh | Average specific greenhouse gas emissions (related to final energy and measured in CO2 equivalents) resulting from the use of geothermal energy from deep layers of the earth (2 - 3 km) | (McCay et al., 2019) |
| **specific auxiliary power input for the extraction of geothermal water** | 0.002 | kWh/kWh | Power input (related to the extracted heat) for the transport of hot water from the ground and the injection after cooling on an annual average | assumption based on (BMU, 2007) |
| **Cumulative energy consumption for heat from geothermal energy** | 1.07 | kWh/kWh | Cumulative energy consumption fossil and renewable (CEC_total)\| The cumulative energy consumption indicates how much energy has to be spent to provide one unit of the considered energy | assumption based on (BMU, 2007) |

*Table 7: Calculation assumptions overview for primary energy assessment*

| Parameter | Cumulated Energy Consump-tion (CEC) | References for CEC | Total primary energy factor (TPEF) | Fossil primary energy factor (FPEF) | Reference for TPEF and FPEF |
|---|---|---|---|---|---|
| **Natural gas** | 1.16 | (GEMIS 4.6, 2010a) | 1,1 | 1,1 | (DIN, 2010) |
| **Power from PV** | 1.24 | (GEMIS 4.6, 2010b) | 1,0 | 0,0 | |
| **Geothermal heat** | 1.07 | assumption based on (BMU, 2007) | 1,0 | 0,0 | |

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