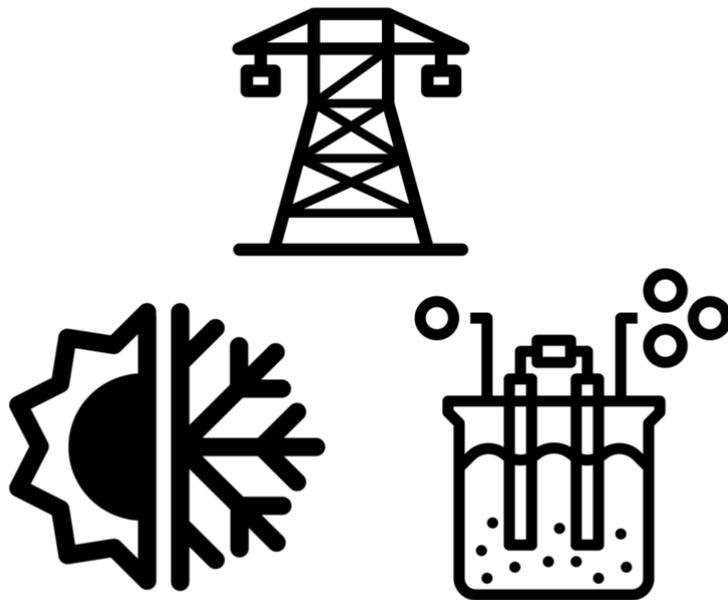




INTERNATIONAL ENERGY AGENCY  
TECHNOLOGY COLLABORATION PROGRAMME ON  
DISTRICT HEATING AND COOLING



IEA DHC ANNEX TS3: HYBRID ENERGY NETWORKS

# APPENDIX I

## RESOURCE ENERGY ANALYSIS OF HYBRID DISTRICT HEATING SYSTEMS

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## Figures and Tables

All figures and tables are included in the document. All figures should be printed in color. Most tables are included in section A.

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## Highlights

- Hybrid energy systems using solar power are efficient tools for decarbonization
- Heat pumps have similar potential in individual and district energy systems
- District heating systems can be more efficient than heat pumps
- Resource exergy analysis provides better results than primary energy analysis
- Resource exergy analysis should complement greenhouse gas emission assessment

## Keywords

District heating, Exergy, Energy, Heat pumps



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## ABSTRACT

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

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. To achieve this outcome, it is important to ensure that the electric load generated by these systems is covered by a photovoltaic power supply that is generated additionally to existing photovoltaic power fed into the power grid.

In comparison to natural gas boilers, hybrid energy systems can save more than 70 % of resource exergy and over 90 % of greenhouse gas emissions. 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 greenhouse gas emissions, they are not the only technology suitable for resource saving and climate - friendly heat supply. The analysis of deep geothermal heat shows that district heating using suitable thermal sources can match or even outperform best-case hybrid energy networks.

However, thermal sources that can directly provide heat at the temperature levels required by the building stock, can be locally limited. Therefore, 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 at least two of the following energy carriers: thermal, electrical and chemical.

They can be based on 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 combines at least two types of energy networks (such as electrical and thermal) to 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 other 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. However, flexibility issues are not considered in this document that is focused on assessing wastefulness and greenhouse gas emissions based on an average annual approach.

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, 2023). REA can be understood as an upgrade to primary energy analysis and answers the question of 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.

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.

For better understanding, the physical property “exergy” can be described as a product of energy and “energy quality” (Jentsch, 2010). It thus increases the scope of energy system analysis from energy to include all thermodynamic effects, including those on energy quality. All non-thermal energy carriers such as fuels or electricity have an energy quality of 100 % in combination with the environment (Jentsch, 2010), which means that in theory they can be fully transformed into electricity or work.

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.

Exergy optimization entails matching the quality levels of energy supply and demand to optimize the utilization of high-value energy resources, such as combustible fuels, and minimizing losses of valuable resources.

(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 (GHGE) when aiming to reach ambitious climate targets. In the following, the reasoning behind this statement is laid out.

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 terms 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 renewable and fossil energy systems to minimize overall system GHGE.



In the underlying study, GHGE (GWP100<sup>1</sup>) 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 and Schmidt, 2020; Falk, 2017; Fitó et al., 2020b; 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 document, they have used a different exergy-based methodology for analysis that does not fulfill the standards of REA.

A multi-criteria (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 et al., 2020a; North and 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 document lies on analysis of different low-temperature district heating systems as a part of hybrid energy networks by using resource exergy analysis (REA) (Hertle

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<sup>1</sup> Non-CO<sub>2</sub> 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.



et al., 2016; Jentsch, 2023) which can replace primary energy analysis with a more comprehensive and consistent system while remaining similarly simple.

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 and Jentsch, 2021).

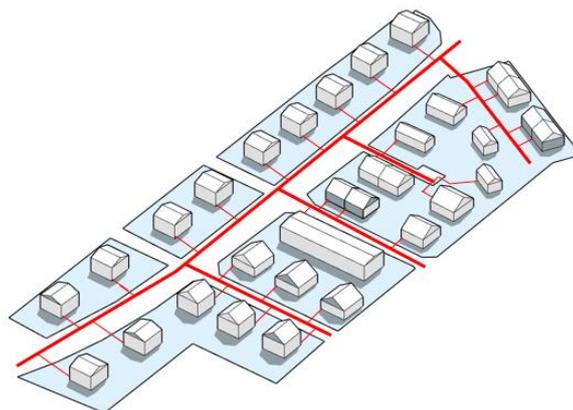
E.g., conversion of power to heat is a process that decreases energy quality while having a high-energy efficiency. So, while a power to heat transformation might look energy efficient (98 %), the efficiency can be much lower (<10 %) this shows that only with exergy analysis certain losses can be quantified consistently (North and 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 document have been done comparing energy systems using REA and GHGE analysis. Costs were not considered for this document 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 document, 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 multifamily house (see Figure 1), which are planned 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 document aims to highlight the potential of hybrid district heating networks regarding energy and exergy aspects by using REA (Jentsch, 2023) to compare six selected heat supply systems. The exergy-based analysis in this report considers only the effects of the operation of the heat supply system scenarios for the considered district and the cumulated exergy consumption for PV electricity, geothermal heat and natural gas. The cumulated exergy consumption is modelled based on the cumulative energy consumption factors of the considered energies, as described in (Jentsch, 2023). Due to a lack of available data, 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, 2023). Table 1 shows an overview of the energy supply scenarios analyzed. All the specific data used for the scenarios considered are listed in section A. Scenario 1 (individual natural gas boilers in each house) serves as a reference system to compare different energy supply systems from a resource utilization perspective. 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 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.

To avoid the dependency of the results on the grid power mix of specific countries, electricity needs are assumed to be fully satisfied by on-site PV production that is delivered directly to the respective electricity consumers such as heat pumps. While this is a simplification, this ensures validity of the results in any country and allows a best-case scenario assessment for hybrid energy systems.

If using power sources with more resource use and GHGE than PV, such as a national grid mix, GHGE and REC for electricity production and hybrid energy systems would be higher than presented in this document. 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 3.3.

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



*Table 1: Overview of the energy supply scenarios*

Scenario	Heat supply	Electricity supply	Grid temperature of the district heating system
<b>Scenario 1</b>	Individual natural gas boilers		—
<b>Scenario 2</b>	District heating system (DHS) with a centralized CHP	Decentralized PV-modules for grid pumps	Supply temperature: 70 °C Return temperature: 40 °C
<b>Scenario 3</b>	Decentralized heat supply with air-water heat pumps	Decentralized PV-modules for heat pumps	—
<b>Scenario 4</b>	DHS with a centralized ground source heat pump	Decentralized PV-modules for heat pump + grid pumps	Supply temperature: 45 °C Return temperature: 25 °C
<b>Scenario 5</b>	Cold district heating system (CDHS) with decentralized water-water heat pumps	Decentralized PV-modules for heat pumps + grid pumps	Supply temperature: 10 °C Return temperature: 5 °C
<b>Scenario 6</b>	DHS, based on deep geothermal energy	Decentralized PV-modules for grid pumps	Supply temperature: 70 °C 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 able to deal with the respective supply temperatures of all considered scenarios. That means floor heating and decentralized heat exchangers for all systems to allow higher annual performance factors (APF) of heat pumps. The specifics of the analyzed scenarios are outlined in the following chapters.



## 2.1 SCENARIO 1: DECENTRALIZED NATURAL GAS BOILER

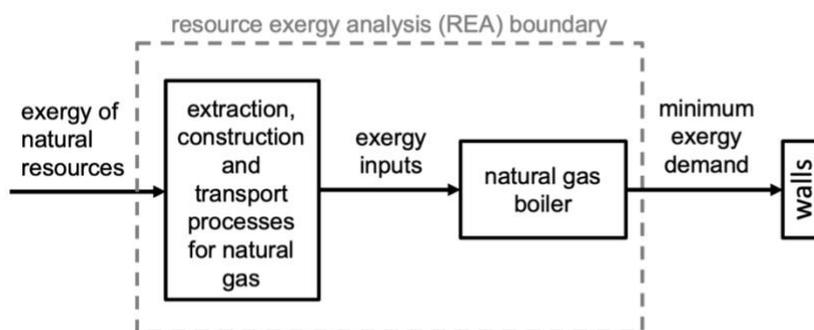


Figure 2: Flow chart and balance boundaries for scenario 1

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 baseline 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

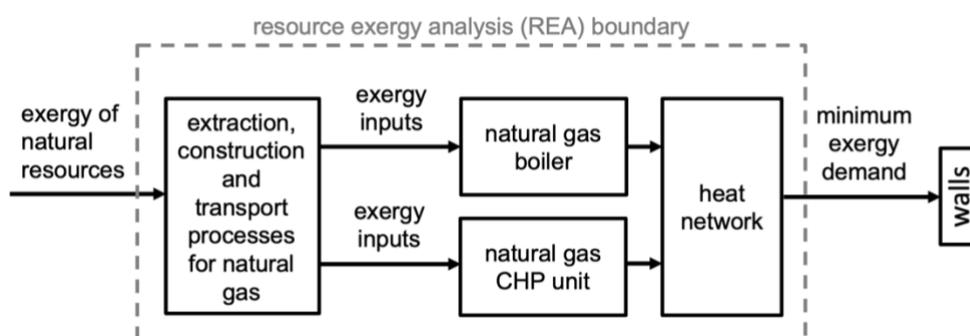


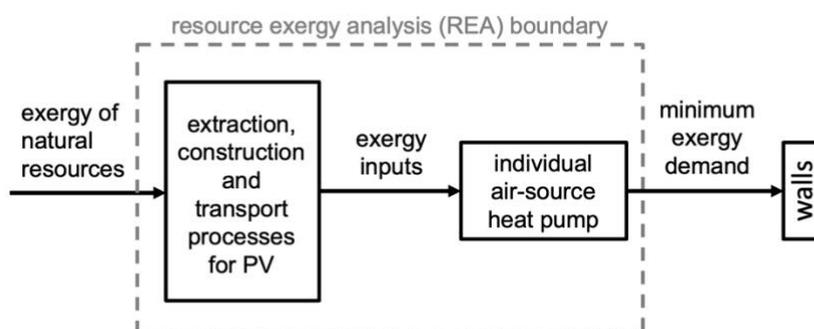
Figure 3: Flow chart and balance boundaries for scenario 2

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 the 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, 2021). The electricity demand for grid pumps is covered with electricity from decentralized rooftop PV-modules on an annual balance 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



*Figure 4: Flow chart and balance boundaries for scenario 3*

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 rooftop 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

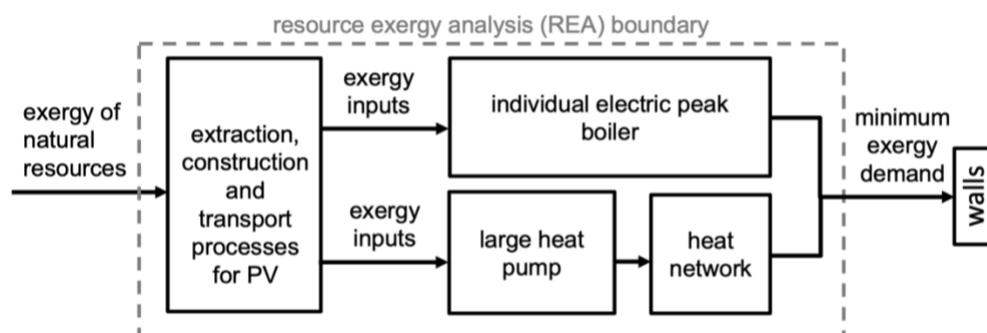


Figure 5: Flow chart and balance boundaries for scenario 4

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 %<sup>2</sup>. The SPF is higher than for decentralized heat 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 %<sup>3</sup> 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 rooftop PV-modules on an annual balance.

<sup>2</sup> 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.

<sup>3</sup> Calculated based on (AGFW, 2021).



## 2.5 SCENARIO 5: COLD DISTRICT HEATING SYSTEM WITH DECENTRALIZED WATER-WATER HEAT PUMPS IN COMBINATION WITH DECENTRALIZED PV-MODULES

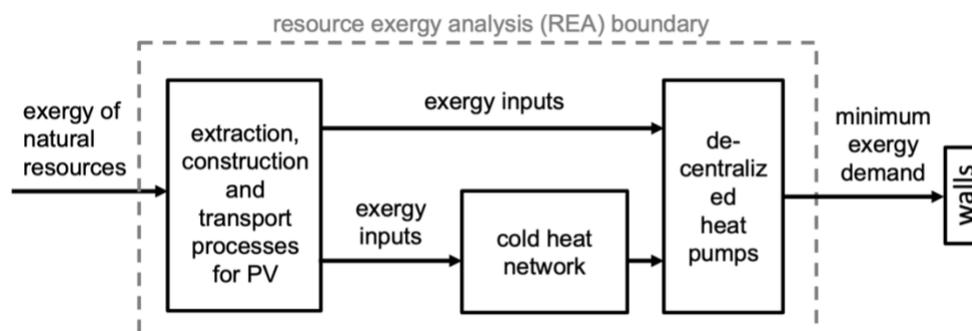
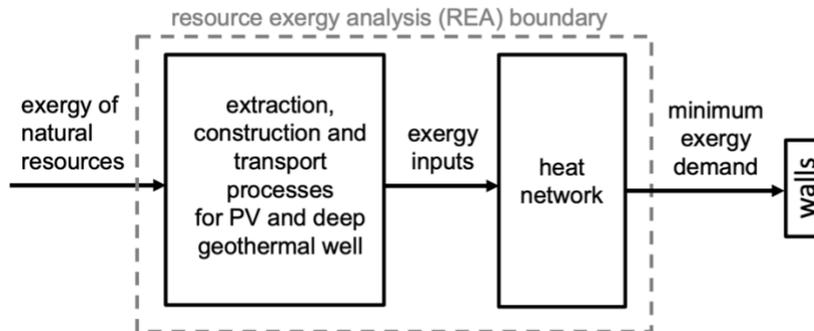


Figure 6: Flow chart and balance boundaries for scenario 5

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 (Brennenstuhl, 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 % (Brennenstuhl, 2017) of the annual heat generated. The electricity demand for the heat pumps as well as grid pumps is covered with electricity from decentralized rooftop PV-modules on an annual balance.

## 2.6 SCENARIO 6: DISTRICT HEATING SYSTEM BASED ON DEEP GEOTHERMAL ENERGY



*Figure 7: Flow chart and balance boundaries for scenario 6*

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, 2021) of the annual heat generated. An additional 0.5 % of the heat demand is 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 rooftop 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 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 following results were obtained by using the assumptions presented in section A in the respective equations presented in (Jentsch, 2023). A more detailed presentation and explanation of the results is found in the comparative study in section B.

The methodology of REA 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. REE therefore is not an independent, but an additional informative indicator.

Additionally, greenhouse gas emissions (GHGE) in CO<sub>2</sub> equivalents (CO<sub>2e</sub>, 100 years horizon) were evaluated. It is important to note that the 100-year horizon for evaluating CO<sub>2</sub> 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<sub>2</sub> equivalents. On this timescale, natural gas combustion contributes similarly to climate change as coal combustion. The midterm GHG gas mitigation is critical to avoid triggering tipping points in the climate system (Traber & Fell, 2019).

Furthermore, in chapter 3.2 results on primary energy consumption (PEC) (cumulated, total and fossil) are provided to allow comparison with the results from REA and underline the importance of an exergy-based assessment. Total and fossil primary energy consumption have been calculated using primary energy factors from German standards. Cumulated energy consumption is based on cumulated energy consumption factors obtained from literature instead of the conventional primary energy factors.

More examples of how REA results differ from conventional energy assessment have been discussed in (North and Jentsch, 2021). Examples of 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 policymakers make sure that the use of electricity for heating does not lead to additional use of non-GHG free fuels in the overall grid. This is best done if the PV power is used independently of the grid, so that potential double counting of PV benefits is avoided.

The results of the analysis are shown Table 2 and Table 3. 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 primary energy analysis (PEA) in section 3.2.



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 because for combustion systems, the exergy used for construction is minimal compared to exergy used in operation (Bejan et al., 1996). It can be assumed that the same is valid for hybrid energy systems.

However, if the required data on the gray energy of energy converters, district heating networks and insulation is available, it might be of interest to assess the considered energy systems based on resource exergy consumption for all process steps and all materials.

The detailed results for each scenario are given in section B using exergy passes, an advanced visualization of REA. The equations used for the calculation of REE and REC are shown and explained in (Jentsch, 2023).

For comparison purposes, the results are summarized in Table 2. The primary energy indicators shown are discussed separately in section 3.2.



Table 2: Summary of analysis results for the compared heat supply scenarios.

		Resource consumption	Resource exergy efficiency	GHG emissions	Cumulated primary energy consumption	Total primary energy consumption	Fossil primary energy consumption
		(REC)	(REE)	(GHGE)	(CPEC)	(TPEC)	(FPEC)
		MWh/a	%	tCO <sub>2</sub> e/a	MWh/a	MWh/a	MWh/a
<b>S1:</b>	<b>Natural gas NGCB condensing boiler (NGCB)</b>	582	3.7 %	112	582	552	552
<b>S2: DH CHP/ NGB</b>	<b>District heating with CHP base load (50 %) &amp; Natural gas boiler (NGB) (50 %)</b>	455	6.2 %	86	598	577	434
<b>S3:</b>	<b>Air-source heat ASHP pump (mono energetic)</b>	175	12.2 %	9	468	377	0
<b>S4: DH LHP</b>	<b>District heating with large heat pump + peak e-boiler</b>	171	17.3 %	8	493	397	0
<b>S5: DH Cold</b>	<b>Cold district heating system (W-W heat pump)</b>	153	19.9 %	9	464	374	0
<b>S6: DH Geo</b>	<b>District heating with heat from deep geothermal heat</b>	110	26.7%	7	506	462	0

The results show why REE is not a suitable indicator for technology comparison regarding environmental impacts. 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. This means for a reduction of REC of about 2 % REE is improved by 42 %.

This is caused by the different goals that both indicators have. While REE shows how sophisticated a technical solution is, REC is an indicator of 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 need 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 that 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 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 of the improvement potential of a given technology.

Table 3 shows the savings achieved with the considered scenarios in comparison to S1 – decentralized natural gas condensing boilers. To obtain the savings, the indicator value of the considered scenario was divided by the respective value of the reference scenario. The resulting ratio was then subtracted from 100 %. Savings in terms of efficiency were not assessed, since efficiency can only be an auxiliary criterion that should not be used for direct comparison. Savings regarding primary energy consumption are discussed in section 3.2.



Table 3: Savings in comparison to Scenario 1 (S1) an individual natural gas boiler

		Resource consumption	GHG emissions	Cumulated primary energy consumption	Total primary energy consumption	Fossil primary energy consumption
		(REC)	(GHGE)	(CPEC)	(TPEC)	(FPEC)
		MWh/a	t <sub>CO2e</sub> /a	MWh/a	MWh/a	MWh/a
<b>S1:</b> <b>NGCB</b>	<b>Natural gas condensing boiler (NGCB)</b>	0 %	0 %	0 %	0 %	0 %
<b>S2: DH CHP/ NGB</b>	<b>District heating with CHP base load (50 %) &amp; Natural gas boiler (NGB) (50 %)</b>	22 %	23 %	-3 %	-5 %	21 %
<b>S3: ASHP</b>	<b>Air-source heat pump</b>	70 %	92 %	20 %	32 %	100 %
<b>S4: DH LHP</b>	<b>District heating with large heat pump + peak e- boiler</b>	71 %	93 %	15 %	28 %	100 %
<b>S5: DH Cold</b>	<b>Cold district heating system (W-W heat pump)</b>	74 %	93 %	20 %	32 %	100 %
<b>S6: DH Geo</b>	<b>District heating with heat from deep geothermal heat</b>	81%	94 %	13%	16%	100%

It becomes obvious that savings in terms of GHGE do not exactly match REC savings. While the GHG savings for scenarios S5 and S6 are both 94% the REC savings are significantly different (74% and 81% respectively). While in this comparison, this does not change the “ranking” of the technologies, for other technologies the results could be very different, e.g., heating systems that use biomass-based or synthetic fuels. Furthermore, in an all-renewable world, GHGE savings in comparison to fossil fuel technologies can become 100% while still consuming significant amounts of renewable resources. REC savings, on the other hand, are only 100% if no resources – neither fossil, nuclear nor renewable – are used at all. Therefore,



REC adds valuable information, especially for the comparison of GHGE-free systems, where GHGE fails to be an instructive indicator.

The following detailed results assessment for the three main criteria considered (REC, REE, GHGE) is based on results presented Table 1, Table 2 and the assumptions presented in the section A.

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, 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 in terms of the three main criteria considered, as it relies on fossil fuel as primary energy which has a high-energy quality and uses combustion without cogeneration 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 %), despite the high final energy efficiency of the boiler (96 %). In general, the REE (defined in (Jentsch, 2023) 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 (CHP) 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 considered, the use of the cogeneration process allows reducing the REC and GHGE thanks to the fact that heat is the byproduct of electricity production by combustion and



therefore only carries a comparably small, temperature-dependent share of the resources used for the combined process (Jentsch, 2023). 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 including significant shares of power from fossil fuels would significantly increase the REC and GHGE from hybrid energy systems. To avoid double accounting of REC and GHGE savings, hybrid energy systems need to be assessed using the local grid mix or the power that is fed in directly without using the national grid as an intermediary. Thus, to ensure a maximum benefit from hybrid energy systems in the transition phase towards carbon neutrality, it is necessary to build additional dedicated GHGE-free power generators that can cover the demand of the heat pumps directly. Chapter 3.3 shows how an estimate for hybrid energy systems using different power sources than PV can be obtained based on the results presented in Table 2.

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 difference 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). 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<sup>4</sup> 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, the avoidance of heat distribution losses

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<sup>4</sup> These networks are sometimes misleadingly<sup>4</sup> 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.



contributes to decreasing the REC to 153 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 reduce the REC to 110 MWh/year (with 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 is 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 scientific databases.
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.
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.

In addition to REC, REE and GHGE Table 2 shows the primary energy indicators mentioned above (CPEC, TPEC, FPEC).

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 effect is generated by energy quality and GHGE respectively. Due to the law of energy conservation, the amount of cumulated and total primary energy consumed can never be lower than the demand. Since TPEC is more simplified than CPEC it does not consider the difference between power from PV and low-value heat from air, ground, or water. Furthermore, 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 indicator (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 8 shows the savings of the considered scenarios in comparison with a natural gas condensing boiler (S1) that are provided in detail in Table 3.

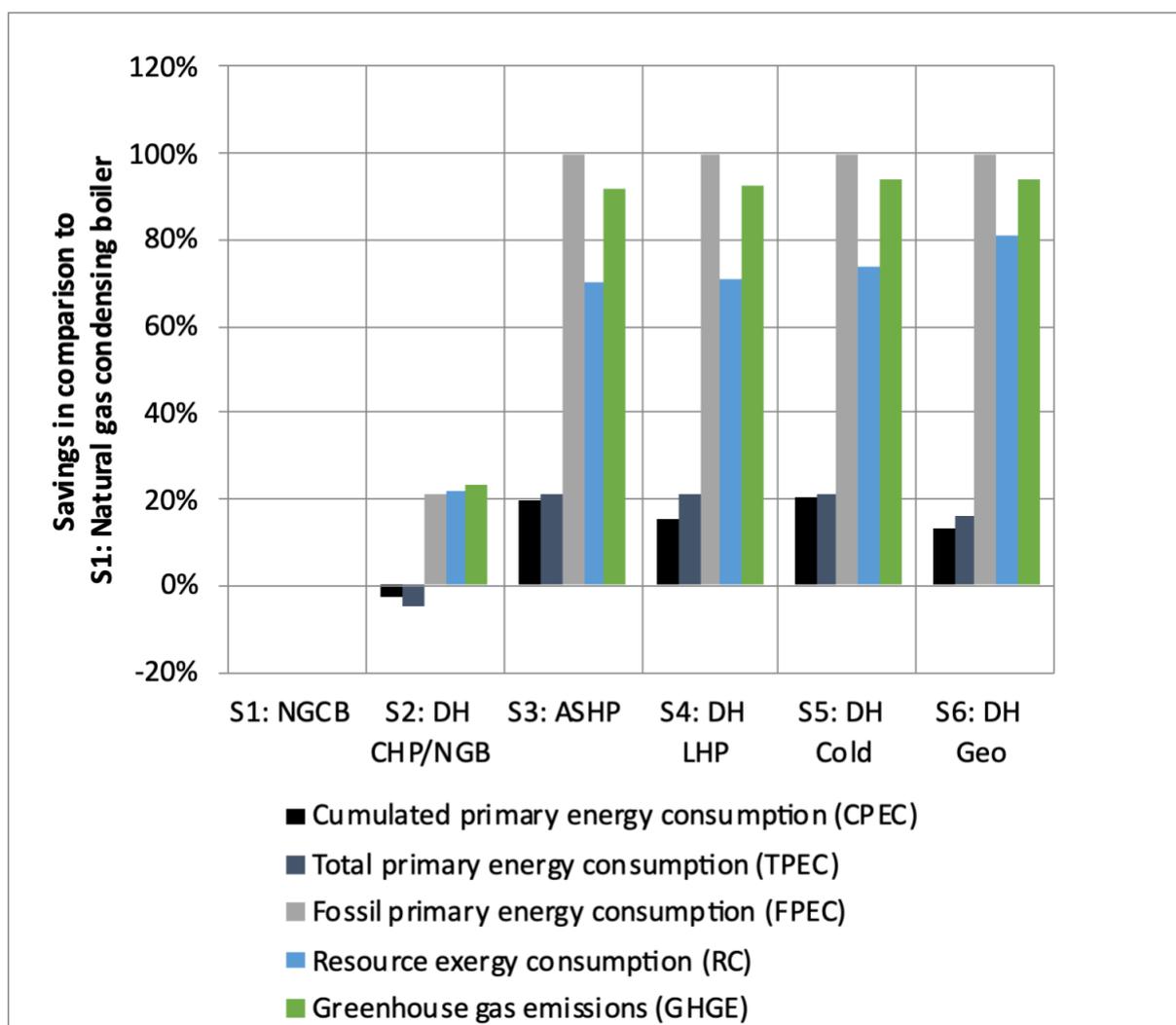


Figure 8: Comparison of ecological key performance indicators in terms of savings in comparison to S1: Natural gas condensing boiler

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.

Furthermore, 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, 2023) minimizing wastefulness in all energy systems is key to avoiding 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 contribution to climate change. REC provides a viable alternative indicator that is independent of GHGE and allows identifying the most resource saving solutions. If FPEC is mandatory, the addition of REC can help decision makers to avoid suboptimal 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 or at least expand primary energy analysis (CPEC) with a consistent, realistic and more comprehensive methodology such as REA can be found in (North and Jentsch, 2021).

### 3.3 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. While the results for hybrid energy systems can be directly obtained by performing the presented analysis using assumptions for the power mix instead of PV power, there is also an easier way to obtain an estimate of the REC and GHGE for the considered hybrid energy systems if they use grid power mix. For this the following equations can be applied.

The REC of the considered systems using the grid power mix ( $REC_{gm}$ ) is a function of the REC using dedicated PV power ( $REC_{PV}$ ) (see Table A.3), the cumulated energy consumption of the grid power mix ( $CEC_{gm}$ ) and the cumulated energy consumption of PV power ( $CEC_{PV}$ ).

$$REC_{gm} \approx \frac{CEC_{gm}}{CEC_{PV}} \cdot REC_{PV} \quad (1)$$

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 A.3), the specific of the grid power mix ( $SE_{GHG,mpm}$ ) and the specific GHGE of PV power ( $SE_{GHG,PV}$ ).



$$GHGE_{gm} \approx \frac{SE_{GHG, gm}}{SE_{GHG, PV}} \cdot GHGE_{PV} \quad (2)$$

The assumptions for PV can be found in Table A.3. 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.

For comparison purposes, the non-hybrid energy systems could be adapted in respect to their power demands as well but would require additional equations to do so. However, since the power demands for Scenarios 1, 2 and 6 are rather small (see Table A.1) the results for these scenarios have a low sensitivity to the assumptions concerning power.



## 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 various 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 poor exergy performance due to large shares of non-cogeneration combustion of high-quality energy carriers to satisfy low-quality energy demand, despite high-energy conversion efficiencies. Scenarios 3, 4, 5 and 6 show a much-reduced REC, as they rely largely 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 provides 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 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 153-175 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). Furthermore, 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 Factor. 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 compared to 18.9 MWh/year and 0 MWh/year, respectively). However, they are partially counterbalanced by lowering auxiliary power consumption (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 result 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 shows comparably low reductions in REC when supplied with heat from natural gas CHP & a large share of boiler heat (50 %) compared to supply from 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-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 front-runner. However, they only achieve these benefits if the power comes from directly connected PV and if storage losses are minimal.

Therefore, it is 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 that is not accounted for in the grid mix.



## 5 CONCLUSION AND OUTLOOK

In this document, 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, 2023, 2022) and complemented with an assessment of GHGE (GWP100). The three main 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 of environmental impacts, 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, low REC reduces indirect GHGE emitted from the overall energy system. Thus, reductions in REC indicate how much a considered system supports the goal of reaching climate targets in time.

The analysis has been performed assuming directly used 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, dedicated 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 document 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 GHGE-free generation capacity that is accounted for in the grid mix.



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### 6.2 COMPETING INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this document.

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## 7 REFERENCES

AGFW, 2021. Arbeitsblatt AGFW FW 309 Teil 1: Energetische Bewertung von Fernwärme - Bestimmung spezifischer Primärenergiefaktoren von Wärme- und Kälteversorgungssystemen.

AGFW, 2020. Practical guide - large-scale heat pump technology, 1. ed.

Ahmadian, A., Schmidt, R.-R., 2020. Exergy analysis of district energy systems and comparison of their exergetic, energetic and environmental performance.

Bejan, A., Tsatsaronis, G., Moran, M.J., 1996. Thermal Design and Optimization. John Wiley and Sons Inc.

BMU, B. für U., Naturschutz und Reaktorsicherheit (Ed.), 2007. Tiefe Geothermie in Deutschland (Deep geothermal energy in Germany).

Brennenstuhl, M., 2017. Messdaten zu „Kommunale netzgebundene Energieversorgung – Vision 2020 am Beispiel der Gemeinde Wüstenrot“.

Daghsen, K., Lounissi, D., Nahla, B., A., K., Yu, Y.J., 2021. Energy, exergy and environment analyses of a hybrid PV-system district heating system for a new household settlement in Germany.

DIN, 2010. DIN 18599 2010: Beiblatt 1.

DIN, 2005. DIN EN 806 “Technische Regeln für Trinkwasserinstallationen.”

EnEV 2016, 2016. Energieeinsparverordnung (EnEV).

Falk, P.M., 2017. Evaluation of district heating systems based on exergy analysis.

Fitó, J., Dimri, N., Ramousse, J., 2021a. Competitiveness of renewable energies for heat production in individual housing: A multicriteria assessment in a low-carbon energy market. Energy and Buildings 242, 110971. <https://doi.org/10.1016/j.enbuild.2021.110971>

Fitó, J., Dimri, N., Ramousse, J., 2021b. Improving Thermo-economic and Environmental Performance of District Heating via Demand Pooling and Upscaling. Energies 14, 8546. <https://doi.org/10.3390/en14248546>

Fitó, J., Hodencq, S., Ramousse, J., Wurtz, F., Stutz, B., Debray, F., Vincent, B., 2020a. Energy- and exergy-based optimal designs of a low-temperature industrial waste heat recovery system in district heating. Energy Conversion and Management 211, 112753. <https://doi.org/10.1016/j.enconman.2020.112753>

Fitó, J., Ramousse, J., Hodencq, S., Wurtz, F., 2020b. Energy, exergy, economic and exergoeconomic (4E) multicriteria analysis of an industrial waste heat valorization system



through district heating. Sustainable Energy Technologies and Assessments 42, 100894. <https://doi.org/10.1016/j.seta.2020.100894>

GEMIS 4.6, 2010a. Ergebnistabelle August 2010 / Tabelle: heat-end 2005.

GEMIS 4.6, 2010b. Ergebnistabelle August 2010 / Tabelle: Strom-DE 2005.

Günther, D., Wapler, J., Langner, R., Helmling, S., Miara, M., Fischer, D., Zimmermann, D., Wolf, T., Wille-Hausmann, B., 2020. WPSMART IM BESTAND: Felduntersuchung optimal abgestimmter Wärmepumpenheizungssysteme in Bestandsgebäuden beim Betrieb im konventionellen sowie im intelligenten Stromnetz (Smart Grid).

Heizungsfinder.de (Ed.), 2014. Strom & Wärme in einem Gerät: das BHKW.

Hertle, H., Jentsch, A., Eisenmann, L., Brasche, J., Brückner, S., Schmitt, C., Sager, C., Schurig, M., 2016. Die Nutzung von Exergieströmen in kommunalen Strom-Wärme-Systemen zur Erreichung der CO<sub>2</sub>-Neutralität von Kommunen bis zum Jahr 2050 (No. 35/2016), Climate Change.

Holway, S., 2021. Simulation based analysis of low temperature district heating system concepts for a planned new housing development in Neuburg.

IEA DHC Annex TS3, 2021. Hybrid energy networks.

IEA EBC Annex 67, 2021. Energy-flexible buildings.

IfEU, 2014. Empfehlungen zur Methodik der kommunalen Treibhausgas- bilanzierung für den Energie- und Verkehrssektor in Deutschland.

Jagnow, K., 2004. Effizienz von Wärmeerzeugern. TGA Fachplaner.

Jentsch, A., 2023. REA: resource exergy analysis - Calculation guide for energy systems, including district heating and cooling. <https://www.agfw.de/rea/en>

Jentsch, A., 2022. IEA DHC Annex TS3, Appendix I - Exergy pass: Comparative study for planning options for IEA DHC Annex TS3.

Jentsch, A., 2016. SUSMILK - Re-design of the dairy industry for sustainable milk processing: Del. 7.3 Report on life cycle assessment, economic assessment, potential employment effects and exergy-based analysis - part 2: Exergy-based analysis.

Jentsch, A., 2010. A novel exergy-based concept of thermodynamic quality Development of a novel thermodynamic concept and its application to energy system evaluation and process analysis. Suedwestdeutscher Verlag fuer Hochschulschriften, Saarbrücken. <https://doi.org/10.14279/depositonce-2399>

Kallert, A., 2019. Modelling and simulation of low-temperature district heating systems for the development of an exergy-based assessment method.



McCay, A.T., Feliks, M.E.J., Roberts, J.J., 2019. Life cycle assessment of the carbon intensity of deep geothermal heat systems: A case study from Scotland. *Science of The Total Environment* 685, 208–219. <https://doi.org/10.1016/j.scitotenv.2019.05.311>

North, P., Jentsch, A., 2021. A circular economy approach to building heating: The role of exergy in policymaking. *Energy Reports* 7, 334–342. <https://doi.org/10.1016/j.egy.2021.08.098>

Nuffel, L.V., Dedecca, J.G., Smit, T., Rademaekers, K., 2018. Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise?

Pompei, L., Nardecchia, F., Mattoni, B., Gugliermetti, L., Bisegna, F., 2019. Combining the exergy and energy analysis for the assessment of district heating powered by renewable sources.

Rant, Z., 1956. Exergie - ein neues Wort für technische Arbeitsfähigkeit. *Forschung auf dem Gebiete des Ingenieurwesens* 1.

Schüwer, D., Warburg, A., Buchholz, M., Freier, A.N., Jentsch, A., Pauschinger, T., Verheyen, O., Witte-Humperdinck, N., 2020. LowEx Herten: innovative interkommunale Wärmeversorgung für die Neue Zeche Westerholt in Herten/Gelsenkirchen: Endbericht. Wuppertal Institut für Klima, Umwelt, Energie, Wuppertal.

Terehovics, E., Veidenbergs, I., Blumberga, D., 2016. Exergy analysis for district heating network.

Winsloe, R., 2021. Eavor - Presentation for AGFW on 11.02.2021.

Yu, Y.J., Kallert, A., Kneiske, T.M., Cronbach, D., Doderer, H., Hoppe, F., 2020. Strom-Wärme Versorgung im Quartier – eine Analyse zukunftsfähiger Versorgungsoptionen unter technischen, wirtschaftlichen und regulatorischen Gesichtspunkten.



## 8 ABBREVIATIONS, FIGURES AND TABLES

### 8.1 LIST OF 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 <sub>2e</sub>	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 <sub>2</sub> 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 <sub>GHG</sub>	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



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## A. ASSUMPTIONS

Note: All assumptions that are provided without references have been obtained from simulation or experience-based estimations by the authors. The presented assumptions were made in 2021. Some more current values are presented in (Jentsch, 2023).

*Table A.1: Table of calculation assumptions for the scenarios*

Scenario	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
<b>System description for DH (centralized heat supply system)</b>		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
<b>Reason for considering system</b>		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
<b>Energy standard of buildings</b>		EnEV 2016 (Ger.)	EnEV 2016 (Ger.)	EnEV 2016 (Ger.)	EnEV 2016 (Ger.)	EnEV 2016 (Ger.)	EnEV 2016 (Ger.)
<b>Set room temperature</b>	°C	20	20	20	20	20	20
<b>Set DHW temperature in DHW-tank</b>	°C	60	60	60	60	60	60
<b>Temp. Heating circuit in buildings</b>	°C	40	40	40	40	40	40
<b>Heat demand (space heating)</b>	MWh/y	324	324	324	324	324	324
<b>Heat demand (DHW)</b>	MWh/y	110	110	110	110	110	110



Scenario	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
<b>Heat losses (distribution grid)</b>	MWh/y	0	32	0	18.9	0	32
<b>Share of heat losses in centralized heat production</b>			0.069		0.046		0.069
<b>Total heat demand</b>	MWh/y	434	466	434	452.9	434	466
<b>Energy efficiency / Seasonal performance factor</b>		0.96	Efficiency (el.) 37 % / Efficiency (th.) 46 %	3.07	4.86	"SPF (space heating): 4.2 SPF (DHW): 3.2	0.98
<b>Reference for energy efficiency</b>		(Jagnow, 2004)	12/08/2023 06:09:00C HP Only: Assumption based on (Heizungsfinder.de, 2014)	(Günther et al., 2020)	Calculation based on Temperatures and (AGFW, 2020)	Simulation results of Fraunhofer IEE	Only 0.5 % pump power will be assumed for a closed-loop geothermal system like eavor.com
<b>Pump power required by thermal network</b>	MWh/y		1.5		2.03	2.6	1.5
<b>Share of heat generation by peak technology</b>			50 %	included in SPF	10 %		0 %
<b>Source temperature for Heat pumps</b>	°C			5	10	10	
<b>Supply temperature of primary heat generator</b>	°C	70	70	45	45	10	70



Scenario	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
<b>Return temperature to primary heat generator</b>	°C	40	40	25	25	5	40
<b>DHW-Supply</b>		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)
<b>De-centralized DHW-Supply</b>	MWh/y	110	0	76 (Heat pump) 34 (Immersion)	34	110	0



Scenario	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
<b>Use of electricity from decentralized PV modules</b>	Yes/ No	YES (auxiliary)	YES (pumping)	YES (heat pump + heaters)	YES (heat pump + heaters + pumping)	YES (heat pump + pumping)	YES (pumping)

*Table A.2: General calculation assumptions for natural gas*

Parameter	Value	Unit	Description	Reference
<b>Specific CO<sub>2</sub> emissions for natural gas as final energy</b>	0.247	kg/kWh	Average specific greenhouse gas emissions (related to the calorific value of the final energy and measured in CO <sub>2</sub> equivalents) resulting from the combustion of natural gas. This value is not valid for natural gas from fracking.	(IfEU, 2014)
<b>Calorific value / calorific value for natural gas</b>	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)
<b>Cumulative energy consumption for natural gas</b>	1.16	kWh/kWh	Cumulative energy consumption fossil and renewable (CEC <sub>total</sub> )   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 A.3: General calculation assumptions for PV power*

Parameter	Value	Unit	Description	Reference
<b>Specific CO<sub>2</sub> emissions for electricity from photovoltaics as final energy</b>	0.061	kg/kWh	Average specific GHGE (related to final energy and measured in CO <sub>2</sub> equivalents) resulting from the use of photovoltaics (solar cells)	(IfEU, 2014)
<b>Cumulative energy consumption for end-user electricity from photovoltaics</b>	1.24	kWh/kWh	Cumulative energy consumption fossil and renewable (CEC <sub>total</sub> )   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 A.4: General calculation assumptions for deep geothermal heat

Parameter	Value	Unit	Description	Reference
<b>Specific CO<sub>2e</sub> emissions for geothermal energy without auxiliary power</b>	0.014	kg/kWh	Average specific greenhouse gas emissions (related to final energy and measured in CO <sub>2</sub> equivalents) resulting from the use of geothermal energy from deep layers of the earth (2 – 3 km)	(McCay et al., 2019)
<b>specific auxiliary power input for the extraction of geothermal water</b>	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)
<b>Cumulative energy consumption for heat from geothermal energy</b>	1.07	kWh/kWh	Cumulative energy consumption fossil and renewable (CEC <sub>total</sub> )   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 A.5: Calculation assumptions overview for primary energy assessment

Parameter	Cumulated energy consumption (CEC)	References for CEC	Total primary energy factor (TPEF)	Fossil primary energy factor (FPEF)	Reference for TPEF and FPEF
<b>Natural gas</b>	1.16	(GEMIS 4.6, 2010a)	1.1	1.1	(DIN, 2010)
<b>Power from PV</b>	1.24	(GEMIS 4.6, 2010b)	1.0	0.0	(DIN, 2010)
<b>Geothermal heat</b>	1.07	assumption based on (BMU, 2007)	1.0	0.0	(DIN, 2010)



## B. EXERGY PASS: COMPARATIVE STUDY FOR PLANNING OPTIONS FOR IEA DHC ANNEX TS3

In the following a comparative study with exergy passes is attached that provided the basic results discussed in this document. It has been created with a modified version of a prototype version of the software [exergypass.com](http://exergypass.com). As it is essentially a standalone document, the page numbers begin anew.



# Comparative study for planning options

for IEA DHC Annex TS3



On behalf of



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## Imprint

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## Disclaimer

The contents of this study have been prepared to the best of our knowledge and checked several times.

However, all people and companies involved cannot assume legal liability or warranty for this study and the accuracy of the results contained therein.

If you have a compelling need for a warranty or limited assumption of liability and are prepared to accept additional costs for this, please contact us in writing at

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## Exergy pass studies

For comparative studies of planning variants with exergy passes, a particularly well-founded comparison procedure is used. This is based on a strictly physical foundation. This makes it possible for the results to accurately reflect the actual situation. The comparison results are made transparent in the form of exergy passes. The exergy passes enable a more comprehensive and accurate assessment than energy certificates.

Comparative studies of planning variants with exergy passes help to avoid costly mistakes and really protect the climate. In this way, investments with maximum benefits for the budget and the environment can be reliably identified.

## Background

The first exergy pass was developed in 2009 under the name *ExergyFingerprint* at the *Fraunhofer Institute for Environmental, Safety and Energy Technology UMSICHT* in Germany. The theoretical basis for the representation of resource efficiency and resource consumption as an exergy pass has been published in the PhD thesis of Dr. Andrej Jentsch.

In 2010, Dr. Andrej Jentsch founded the consulting company Richtvert. Since then, the concept of the exergy passes has been applied and further developed in dialogue with clients and project partners. Clients who have commissioned comparisons with the exergy pass include the German Federal Environmental Agency, Municipal Utilities of Munic, ThyssenKrupp Nirosta and the City of Dortmund.



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## Preface

This comparative study of planning options helps you to comprehensively assess possible planning alternatives within the scope of your transformation project. This gives you the opportunity to decide not only economically, but also in a sustainable manner.

One of the main objectives of this study is to convey difficult facts in a way that is easy to understand. Therefore, the texts in this study are aimed to align with the recommendations of the “simple language” network. In some cases, this leads to unusual but easily comprehensible spellings and sentence structures.

## Environmental impact and cost savings

This comparative study looks at environmental impacts: Resource consumption and CO<sub>2</sub> emissions. In addition, the cost savings of energy consumption and resource utilization are evaluated.

Resources are the raw materials and energy carriers extracted from the environment, such as crude oil and natural gas. The concept of resources used here is therefore limited to material and energy resources.

Greenhouse gas emissions measure the contribution to climate change. All greenhouse gases are converted into CO<sub>2</sub> equivalents or CO<sub>2</sub>e.

Due to the availability of data, the present analysis is limited to the effects of energy consumption during the service life of the finished building, district or city. Strictly speaking, the results only apply if the underlying calculation bases reflect the real situation accurately enough. The assumptions are listed in the appendix. On average, the calculation bases represent the state of the art well. Thus, the results can be considered to be guidelines for the transformation project under consideration.



## Being able to read exergy passes

The central diagram of the exergy pass shows the resource requirements and resource consumption of a planning variant for a building project. The resource consumption is thereby evaluated by the amount of consumed "primary exergy". Resource demand is also represented as exergy. Resource utilization is the ratio of resource demand to resource consumption.

## What is exergy?

Exergy, just like energy, is a quantity from physics.

Measured in energy, all forms of energy have the same value. However, this does not correspond to human experience. For example, electric current can be converted very well into almost all other forms of energy, such as work in household appliances, light or heat. Heat, on the other hand, can only be converted into electric current and most other forms of energy with great effort and incompletely.

An exclusively energetic evaluation thus neglects the important aspect of usability. For a complete evaluation, however, it is essential to consider the diversity of energy forms comprehensively.

Exergy includes energy. In addition, however, exergy also takes into account energy quality. In this context, energy quality is a physically based measure of usability.

**To illustrate:** Imagine that a unit of energy is an energy coin. The energy quality is the value of this coin. For example, there are energy coins worth 10 ct and energy coins worth 100 ct. The amount of energy results from the number of energy coins. The amount of exergy results from the number of energy coins multiplied by their respective value. If one has thus 3 energy coins, of which 2 have the value of 10ct and 1 the value of 100 ct, then this corresponds to an exergy of 120 ct. So the exergy here is equal to the value of the energy coins. The average value of the energy coins in this case corresponds to 40 ct.

Conservation of resources means conservation of value. This means that it is not only about saving the amount of energy. It is equally important to make sure that the value of the energy decreases as little as possible for any given task. For comprehensive comparisons, exergy is therefore a more suitable evaluation parameter than energy.

The exergy makes it possible to convert all forms of energy into electrical energy without arbitrary assumptions. A unit of energy multiplied by its energy quality is exergy. The energy quality is a measure of how well the energy under consideration can be converted into electricity in the best case.

Exergy can thus be translated as "electricity that can be extracted in the best case".

For example, 100 units of heat at 20°C against a background of 9°C outdoor temperature can be used to generate 4 units of electricity in the best case. Thus, this heat has an energy quality of 4%.

Heat can only be partially converted into electricity and therefore always has an energy quality of less than 100%. Electricity has an energy quality of 100%. The same applies to any energy from fuels, which also has an energy quality of 100%.

Exergy makes it possible to convert all material and energetic resources into units of "ideally recoverable electricity". Thus, exergy makes it possible to evaluate all resources using the same unit. This allows a unified comparison of all material and energy resources necessary for the operation of a building or building complex.

Since exergy includes energy quality and makes it possible to evaluate all raw materials consistently, it is a particularly well-suited basis for scientific studies. It makes it possible to compare all resource streams and facilities comprehensively in terms of their key environmental impacts.

## The exergy pass - an introduction

In order to understand the structure of the exergy pass, the elements it is made up of are shown below. The starting point of the comparison is always a supply task. In the case of buildings, this consists of providing a defined level of comfort to the users.

This means that the rooms in the building under examination must be heated or cooled as required, as well as ventilated and illuminated. In addition, domestic hot water needs to be provided. Other needs such as washing, dishwashing, cooking and the operation of televisions, computers and music systems can also be considered.

The services that a building provides for the user can be specified in terms of the amount and type of energy they require. The basis of the exergy pass is thus the knowledge of the energy demand, which arises from the different types of demand such as electricity demand, heating demand and cooling demand. These can be represented as colored bars, as in Fig. 1.

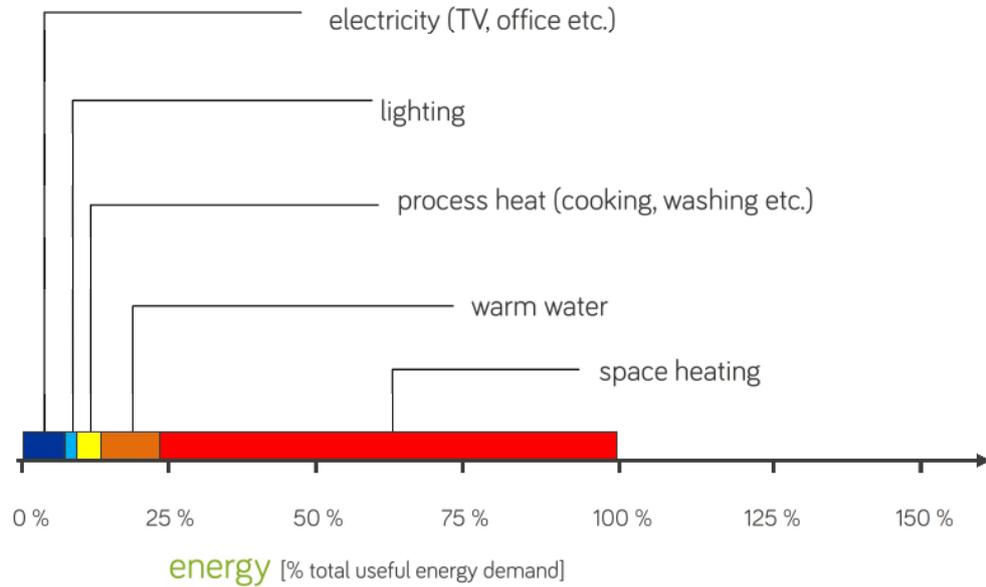


Figure 1: Energy demand of a typical residential building.

In addition to the quantity of energy requirements, Figure 2 also shows the corresponding energy quality. The resulting colored areas correspond to the exergy demand. Exergy allows all resources to be measured in a unified way. Thus, exergy here is a measure of resource demand.

By considering the energy quality, the characteristics of heat and electricity demand become clear. While electricity requires a high energy quality, space heating requires only a low one. In the present example, the amount of resources required for electricity and light is about the same as the amount of resources required for heating. And this is despite the fact that the energy requirement for heating being much higher.

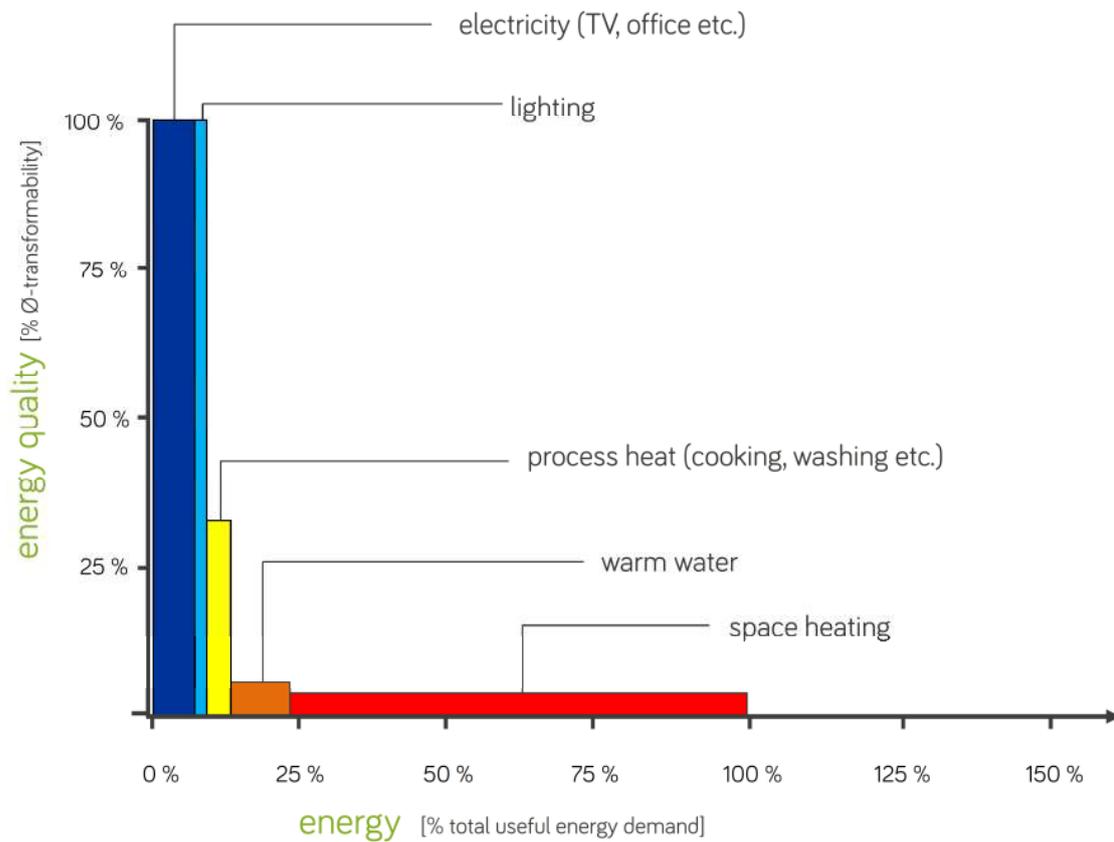


Fig. 2: Resource demand of a typical residential building.

In Fig. 3, the resource demand is compared with the resource consumption. The resource consumption is always greater than the resource demand. The difference between resource consumption and resource demand is the loss that occurs. It is represented by the gray area.

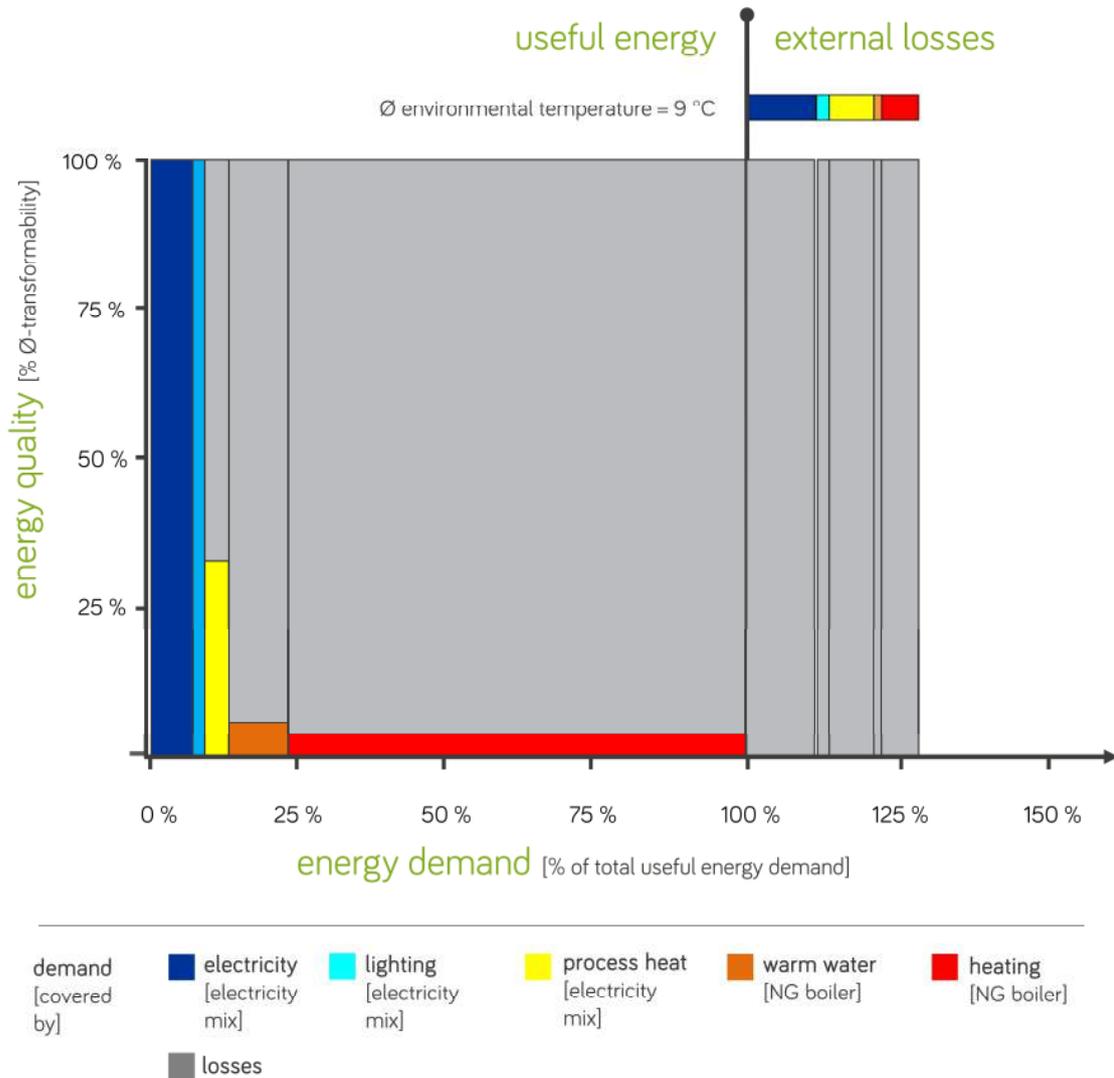


Figure 3: The central diagram of the exergy certificate

In the example shown, it can be seen that a large part of the losses occur in the area of heating. These arise in particular from the use of an energy source with a high energy quality to meet a demand with a low energy quality. This type of loss cannot be detected with energy analysis.



The losses in meeting resource needs arise from two different effects. On the one hand, these are "energy losses," for example in pipelines or in the conversion of one form of energy into another. On the other hand, losses also occur through energy devaluation. Both types of losses occur, among other things, when fuels such as natural gas or wood are converted into heat.

To make the nature of the losses clear, resource consumption is divided into "external losses" and "useful energy" in Fig. 3. The losses occurring in the useful energy area make it clear where energy devaluation occurs. The losses in the "External losses" area show how many resources are lost before they are put to use. A colored bar is placed above the area for External Losses. Together with the division of the External Losses by fine lines, it allows an allocation of the losses to the respective resource demands.

The exergy pass makes three types of improvements visible. These are shown in Figure 4.

Each energy saving shortens the useful energy area in the exergy certificate. Higher energy efficiency shortens the "External losses" section. In addition to these commonly known improvement measures, the exergy pass also shows the suitability of the energy consumed to meet demand. This can be increased in particular by energy recycling. It reduces the energy quality of the gray area at the corresponding points.

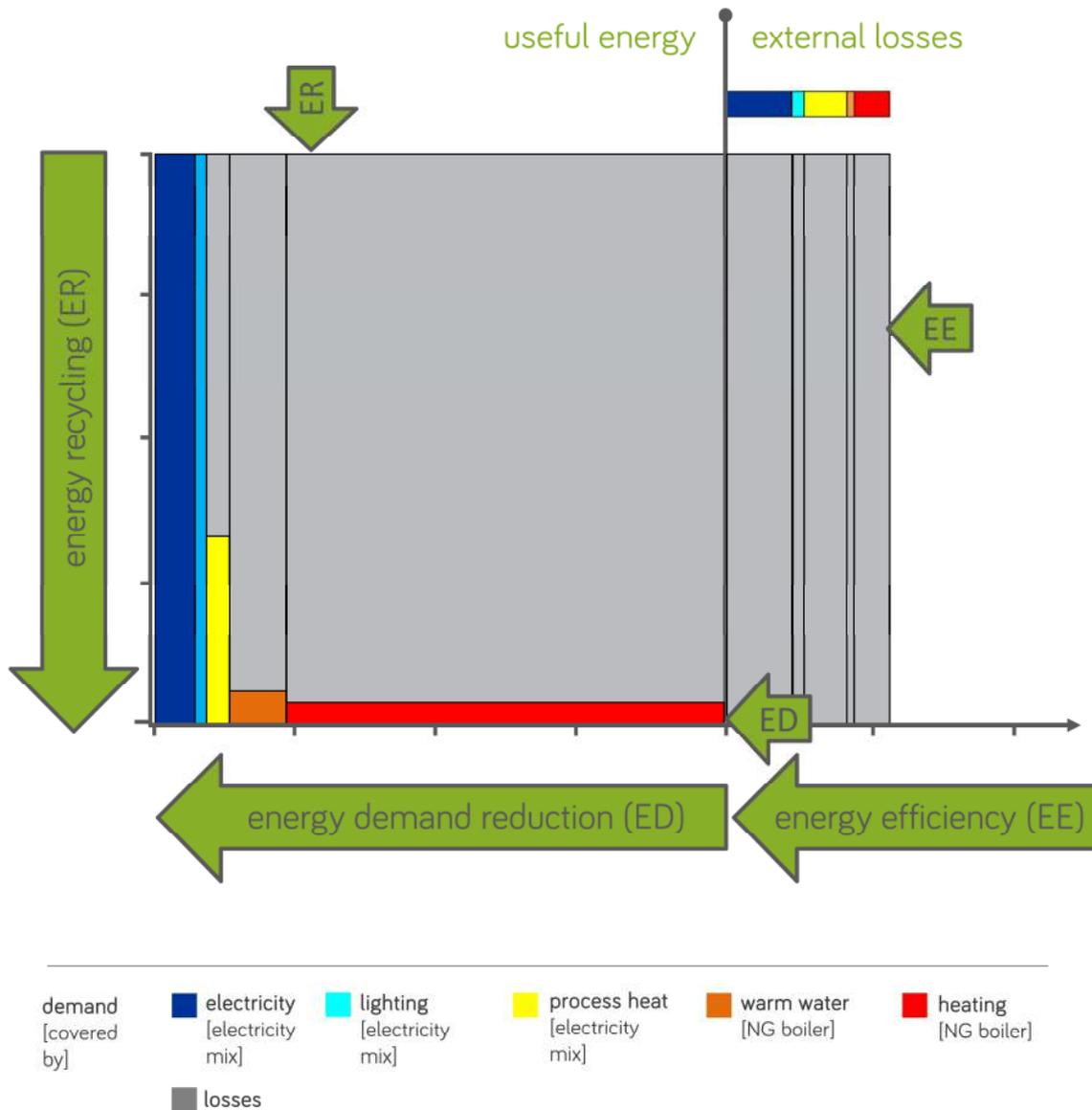


Fig. 4: The effects of energy savings, energy efficiency and energy reuse on the exergy certificate.

Several important assessment variables can be seen from the plot in Figure 5. The width of the colored area corresponds to the energy demand. The width of the gray area corresponds to the energy losses. The width of the colored and the gray area together corresponds to the energy consumption. The area of the colored area corresponds to the resource demand. The gray area corresponds to the resource losses. The sum of the colored and the gray area corresponds to the resource consumption.

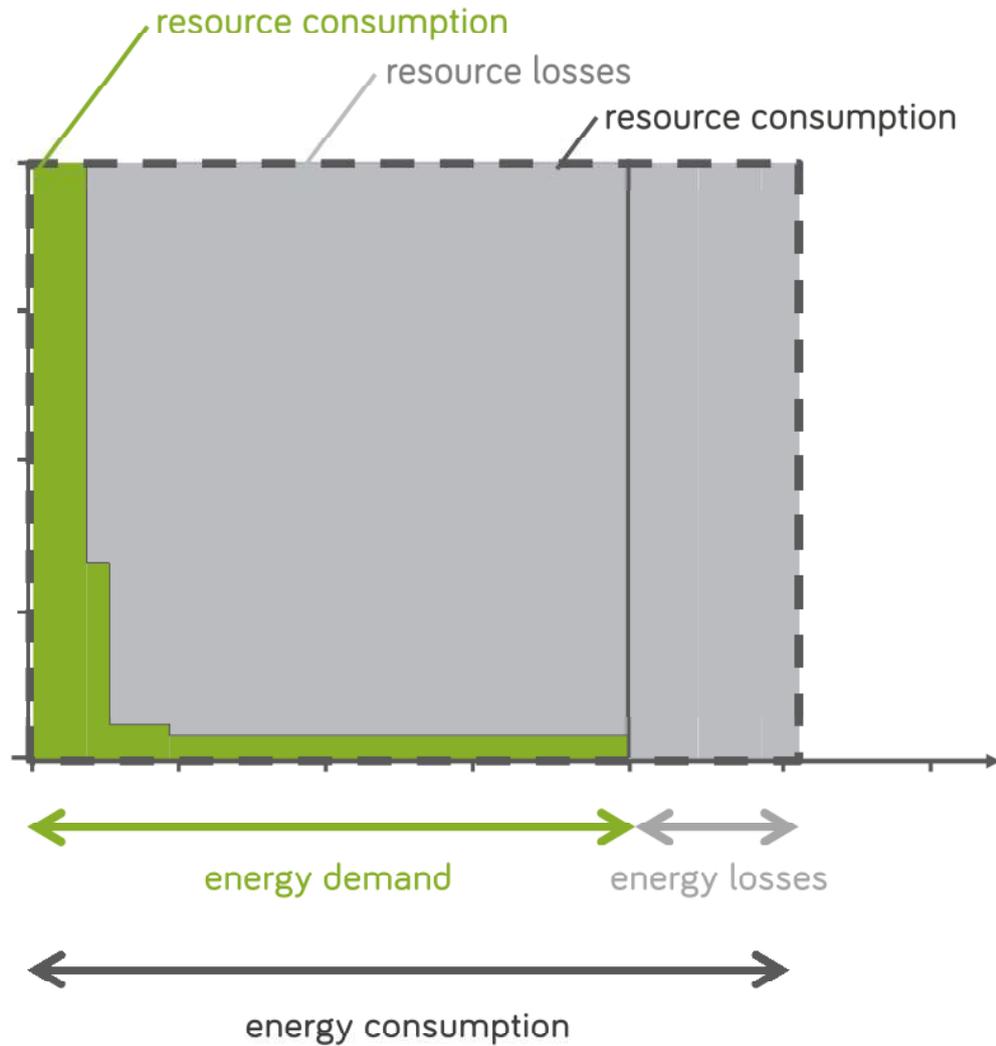


Fig. 5: Assessment variables that are visualized in the exergy pass

The ratio of energy demand to energy consumption is the energy efficiency, which can also be called energy utilization. This says something about how well the energy extracted from the environment is used.

The ratio of resource demand to resource consumption is resource utilization. It is a measure of how well the extracted resources are used. Resources consider both energy and its energy quality. Therefore, an assessment of resources is more comprehensive than an assessment of energy.

In addition to the central certificate diagram, the exergy certificate consists of several other elements.

Thus, in addition to the visual representation in the exergy certificate, the numerical values for resource consumption, resource utilization, CO<sub>2</sub> emissions and costs of energy purchase are also given. Since the costs of energy purchase do not represent the total costs important for the decision, they are given in brackets. An example of a reference exergy certificate can be found on page 17.

A promising planning option has low resource consumption, low CO<sub>2</sub> emissions, and low energy purchase costs. All three variables are interrelated. In this context, resource consumption is the basis for the other two variables. The consumption of resources usually causes CO<sub>2</sub> emissions. The amount of CO<sub>2</sub> emitted depends on the type and amount of resources consumed.

The costs for the energy purchase result from the final energy consumption as well as other economic influencing factors. The final energy consumption is included in the resource consumption.

In addition to the figures mentioned above, the exergy certificate also makes it possible to read how well an examined scenario compares to a previously defined reference state. For this purpose, the savings compared to the reference are shown in traffic lights. An example of an exergy certificate for a planning variant can be found on page 18.

The traffic light turns red if the investigated variant is worse than the reference. In this case, the savings are marked with a minus sign because nothing is saved. Instead, more is consumed or emitted.

The traffic light remains gray if there is no difference between the compared variants. And it turns yellow if a considered variant leads to savings of 1% to 32%. For all savings of 33% or more, the traffic light turns green.

In the exergy certificate "Current state" on page 17, cooling and lighting are marked with an "x". This means that these demands have been enlarged to improve visibility. This happens when the demand is below 1.5% of the useful energy demand (here for light) or below 1.5% energy quality (here for cooling). If there is an increase on both the energy axis and the energy quality axis, the corresponding demand is marked with "xx". The enlargement keeps the exergy certificate fully readable even with a very small partial demands. While this makes the diagram less accurate. the traffic light values as well as the other information in the header of the exergy certificate are calculated correctly despite the enlargement. Thus, the magnification does not affect the exact comparison of the alternatives.

The accuracy of the calculations in the background becomes clear when the costs between the two following alternatives are compared. They amount to 19 €/m<sup>2</sup>\*a each. For the second exergy certificate, however, a saving of -4% is indicated. This means that the costs are 4% higher than for the reference variant. This makes it clear that the figure of 19 €/m<sup>2</sup>\*a is rounded to full currency amounts. The indicated savings of 4% shows that in the background calculations were made on the basis of non-rounded values.

This principle can also be applied to resource and CO<sub>2</sub>e values. Here, too, the values displayed are rounded to whole numbers, while more precise values are calculated in the background. The rounding of the displayed values makes it easier to read the exergy certificates and to focus on significant differences.



## Understanding results

A healthy environment is an important prerequisite for a healthy and fulfilling human life. Investment decisions become more sustainable the less the environment is impacted. There are practical limits to the decision maker due to the available funds and the expected costs. Within these limits, however, variants with particularly high savings are to be preferred.

The exergy pass makes it possible to understand visually where the calculated savings are achieved. In the exergy pass on page 18, the area between the dashed line and the filled area makes the savings compared to the reference variant obvious. In this exergy pass, the dashed line between useful energy and external losses shows the higher demand. This could result, for example, from higher interior temperatures. In this case, the savings are caused by a better adapted energy quality. Overall, the resource and CO<sub>2</sub>e savings are greater than the effects of the additional energy demand for space heating.

The exergy certificate on page 18 further shows that it is also possible to include systems with multiple producers in the comparison. For example, in this variant, 90% of the heat is generated using district heating from cogeneration in a city network (FW SN) and 10% using a natural gas boiler in the district heating network (FW HK EG).

In addition to the heat supply, the source of the cooling supply was also changed. Instead of an electric chiller (KMEL RK), district cooling from direct cooling (FK DK) was used. Direct cooling is a label for the use of cool water freely available in the environment, for example groundwater or lake water, for cooling purposes.

The resource consumption made transparent via the exergy pass diagram is considerably lower than the resource consumption of the reference, with 33% savings. However, the much lower savings in CO<sub>2</sub> emissions of only 15% indicates that a fuel mix was used which causes more emissions per unit of energy. This may be due to the use of coal, for example.

At 4%, the cost of purchasing energy is only slightly higher than in the "Current state" reference. This is mainly caused by the higher energy demand assumed here for increased comfort. Thus, the variant "+4°C & city grid" is in principle very interesting from an ecological point of view. CO<sub>2</sub>e emissions and resource consumption can be significantly reduced, while the cost of energy purchases hardly increases. However, this small increase is due to the 4°C higher room temperatures.

The resource utilization of the "+4°C & city grid" variant is almost twice that of the reference on page 17, so the package of supply technologies is almost twice as well matched to the supply task as the reference. In this case, this is entirely due to the change in heating and cooling supply.



## Adding life cycle costs

Energy consumption costs are only a part of the costs important for the final decision. All significant costs can be summarized in life cycle costs. These can be integrated into the exergy pass as an alternative to the energy consumption costs. The life cycle costs take into account construction, operation, maintenance and dismantling of the studied scenarios, as well as capital costs over the life of the transformation project. Since some of these costs can only be determined after the system design is completely known, the life cycle costs for the exergy certificate must be calculated manually.

Unlike energy consumption costs, life cycle costs are presented without brackets. They represent the most comprehensive economic decision criterion.

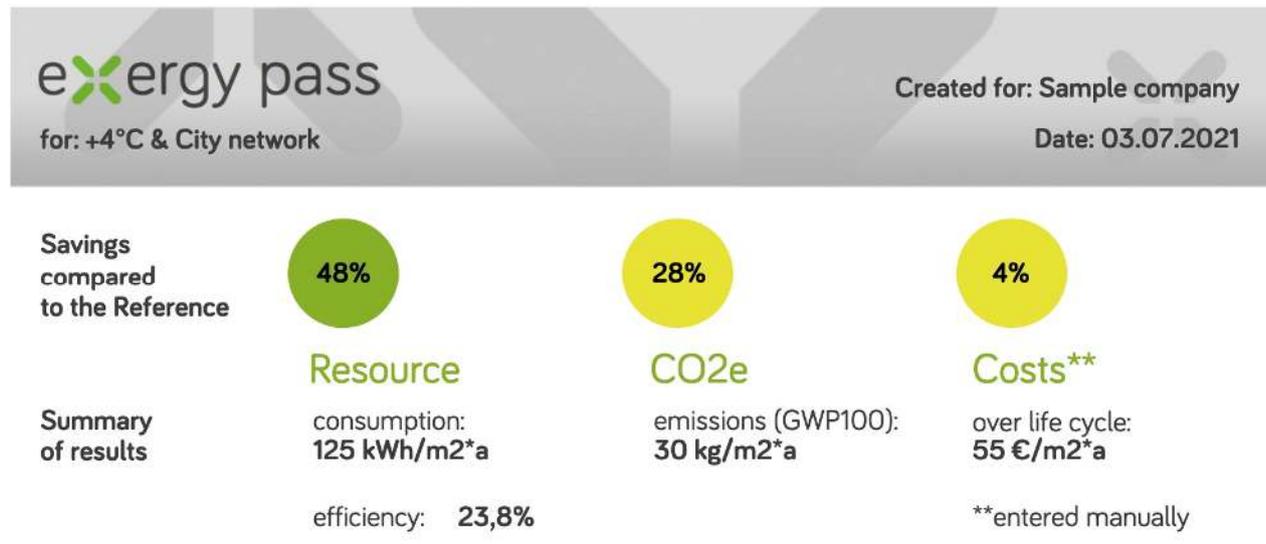


Figure 7 : Header of the exergy pass for a reference building with life cycle costs.



## Exergy passes for the studied options

Table 1: Overview of the abbreviations for demands and final energies

BC	Brown coal
BG	Biogas
BM	Biomass
CDH	Cold district heating
DC	District cooling
DF	Deep freezing
DH	District heating
EL	Electricity
FC	Food cooling
HC	Hard coal
HO	Heating oil
LST	Large solar thermal
NG	Natural gas
SC	Space cooling
ST	Solarthermal
Wood	Wood



Table 2: Overview of abbreviations for supply technologies

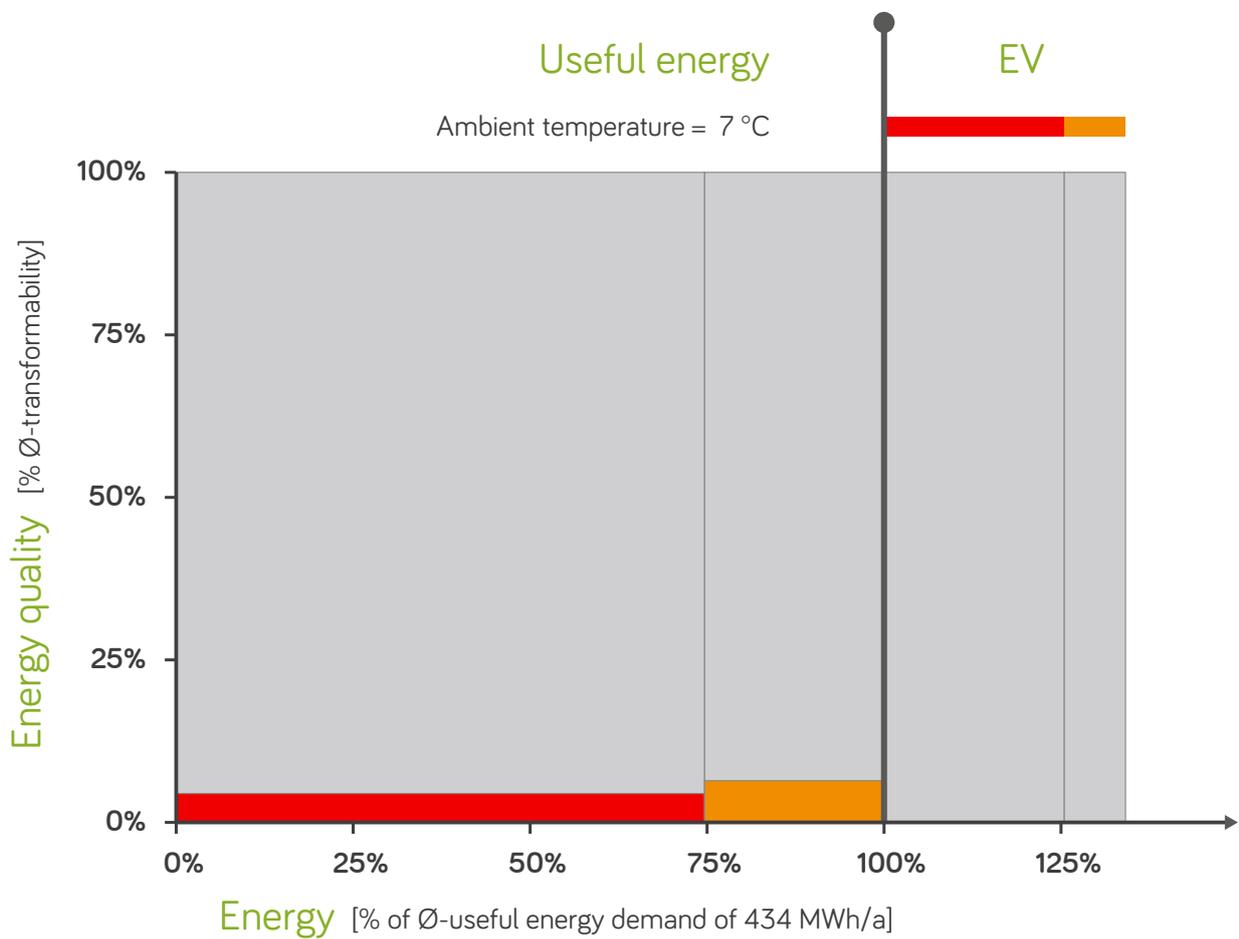
B	Boiler
BCHP	Standard Block CHP plant
BCHPE or BCP	Efficient Block CHP plant
BCHPM	Block CHP plant (micro)
BCHPS	Block CHP plant used on-site power production
BSF	Boiler for solid fuels
CB	Condensing boiler
CHP	Large cogeneration plant
CN	City network – average thermal grid
CNC	City network used for cooling
CNE	City network – efficient thermal grid
DGT	Deep geothermal
DirC	Direct cooling with lake or sea water
DirH	Direct heating
EC	Electrical chiller
EH	Excess heat
GC	Gas-driven chiller
Gen.	Generator without heat utilization
Grid mix	Power grid mix
HP	Heat pump (air-source)
HPE	Efficient heat pump (ground-source)
LHP	Large Heat pump
PV power	PV cells that produce power for local use
St.	Stove

This is the Reference scenario.

Summary of results	Resource	CO2e	Costs**
	consumption: <b>582 MWh/a</b>	emissions (GWP100): <b>112 t/a</b>	over life cycle: not specified
	efficiency: <b>3,7%</b>		**entered manually

Demand: Standard

Supply: Natural gas cond. boiler



Demand [covered by] ■ Space heat [CB NG] ■ Hot water [CB NG]

■ Losses  Consumption of the reference

Savings compared to the Reference



22%

Resource

Summary of results

consumption: 455 MWh/a

efficiency: 6,2%



23%

CO<sub>2</sub>e

emissions (GWP100): 86 t/a



n.s.

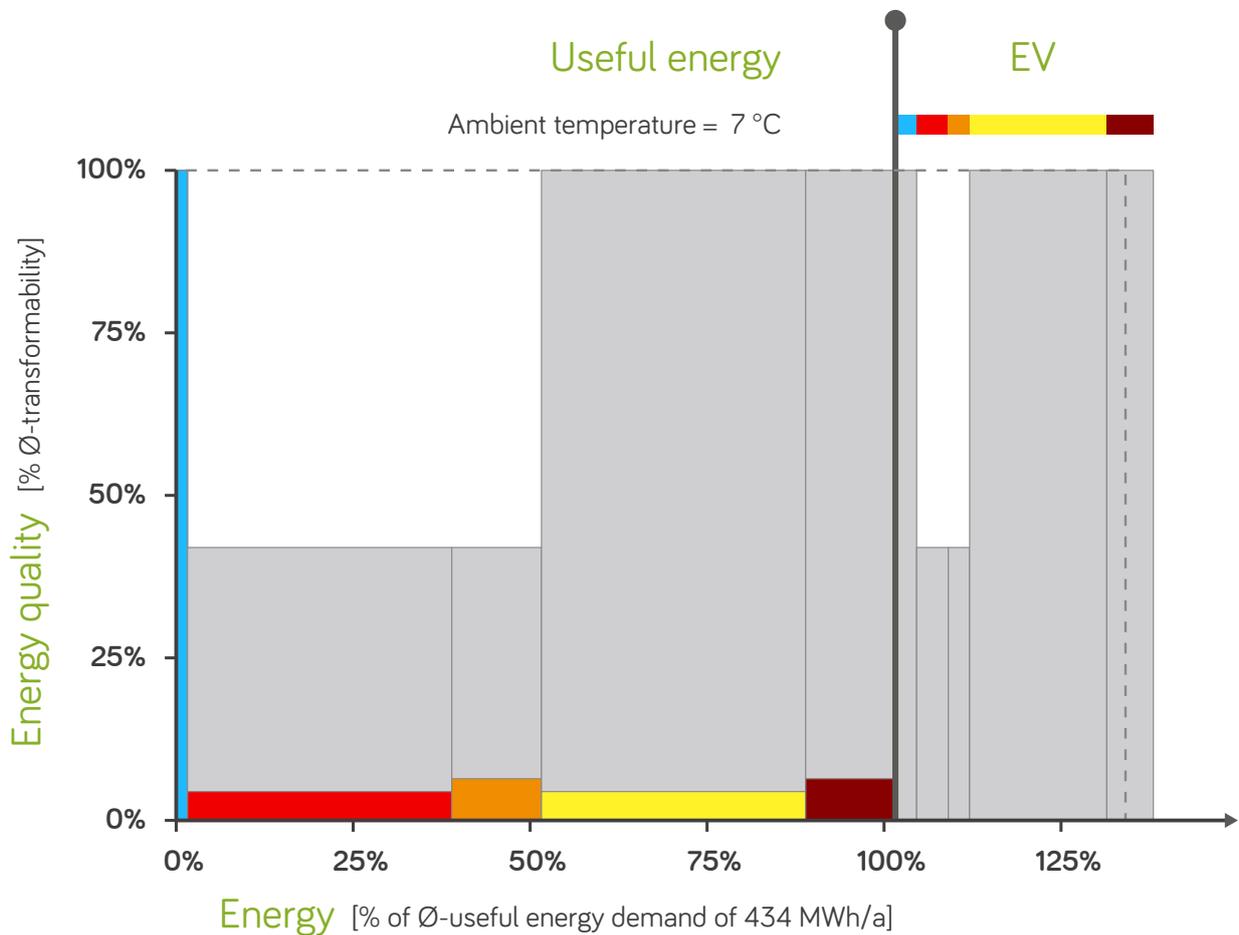
Costs\*\*

over life cycle: not specified

\*\*entered manually

Demand: Standard

Supply: DH NG CHP & boiler



Demand [covered by] ■ Aux. power [PV power] ■ Space heat [DH BCP NG] ■ Hot water [DH BCP NG] ■ Space heat [DH CB NG] ■ Hot water [DH CB NG]

■ Losses    Consumption of the reference

Savings compared to the Reference



Resource

Summary of results

consumption: 175 MWh/a

efficiency: 12,2%



CO<sub>2</sub>e

emissions (GWP100): 9 t/a



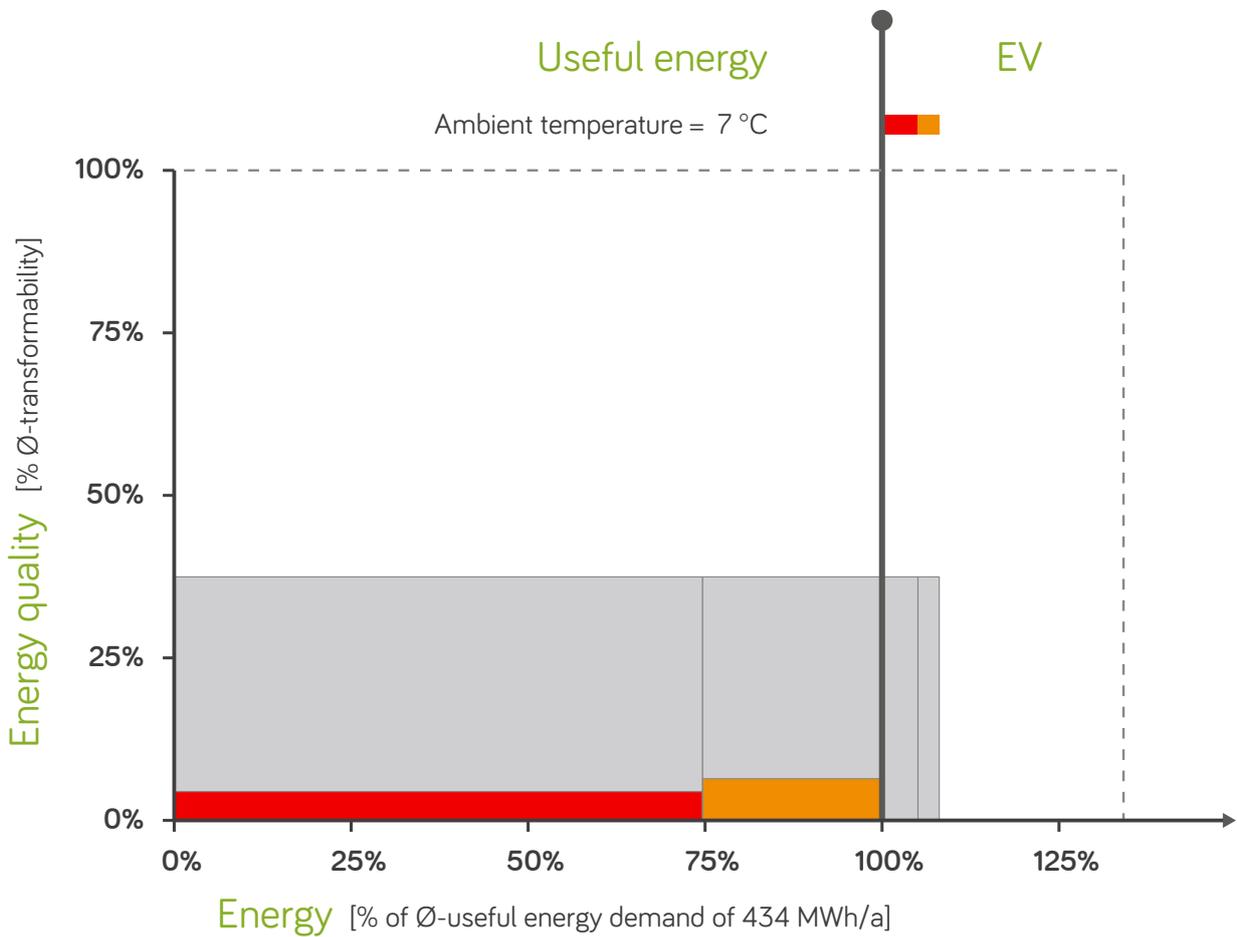
Costs\*\*

over life cycle: not specified

\*\*entered manually

Demand: Standard

Supply: Decentral AS HP



Demand [covered by] ■ Space heat [HP EL] ■ Hot water [HP EL]

■ Losses    Consumption of the reference

Savings compared to the Reference



Resource

Summary of results

consumption: 171 MWh/a

efficiency: 17,3%



CO<sub>2</sub>e

emissions (GWP100): 8 t/a



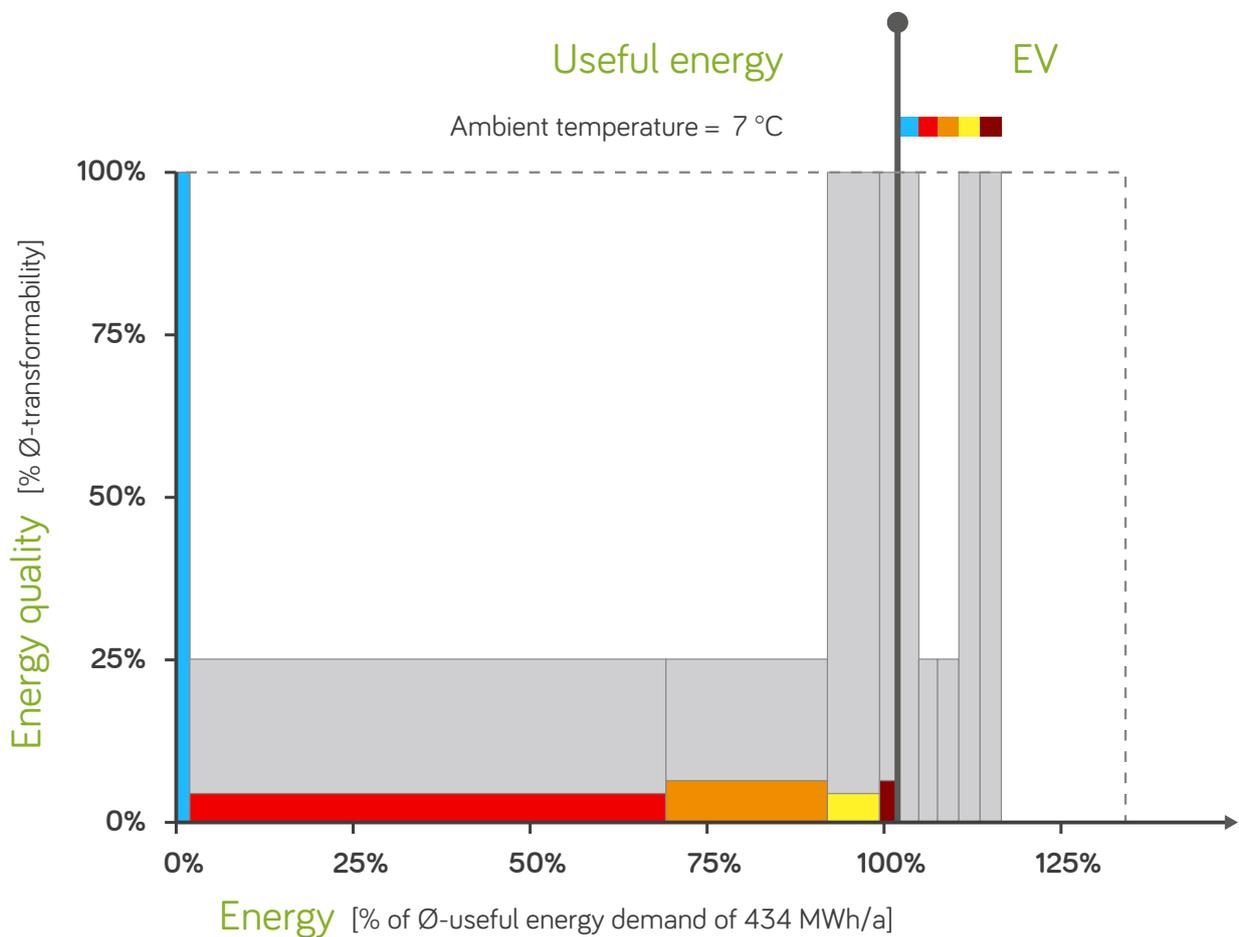
Costs\*\*

over life cycle: not specified

\*\*entered manually

Demand: Standard

Supply: Large HP DH



Demand [covered by]    Aux. power [PV power]    Space heat [DH LHP PV]    Hot water [DH LHP PV]    Space heat [EB PV]    Hot water [EB PV]

Losses    Consumption of the reference

Savings compared to the Reference



Resource

Summary of results

consumption: 153 MWh/a

efficiency: 21,3%



CO2e

emissions (GWP100): 7 t/a



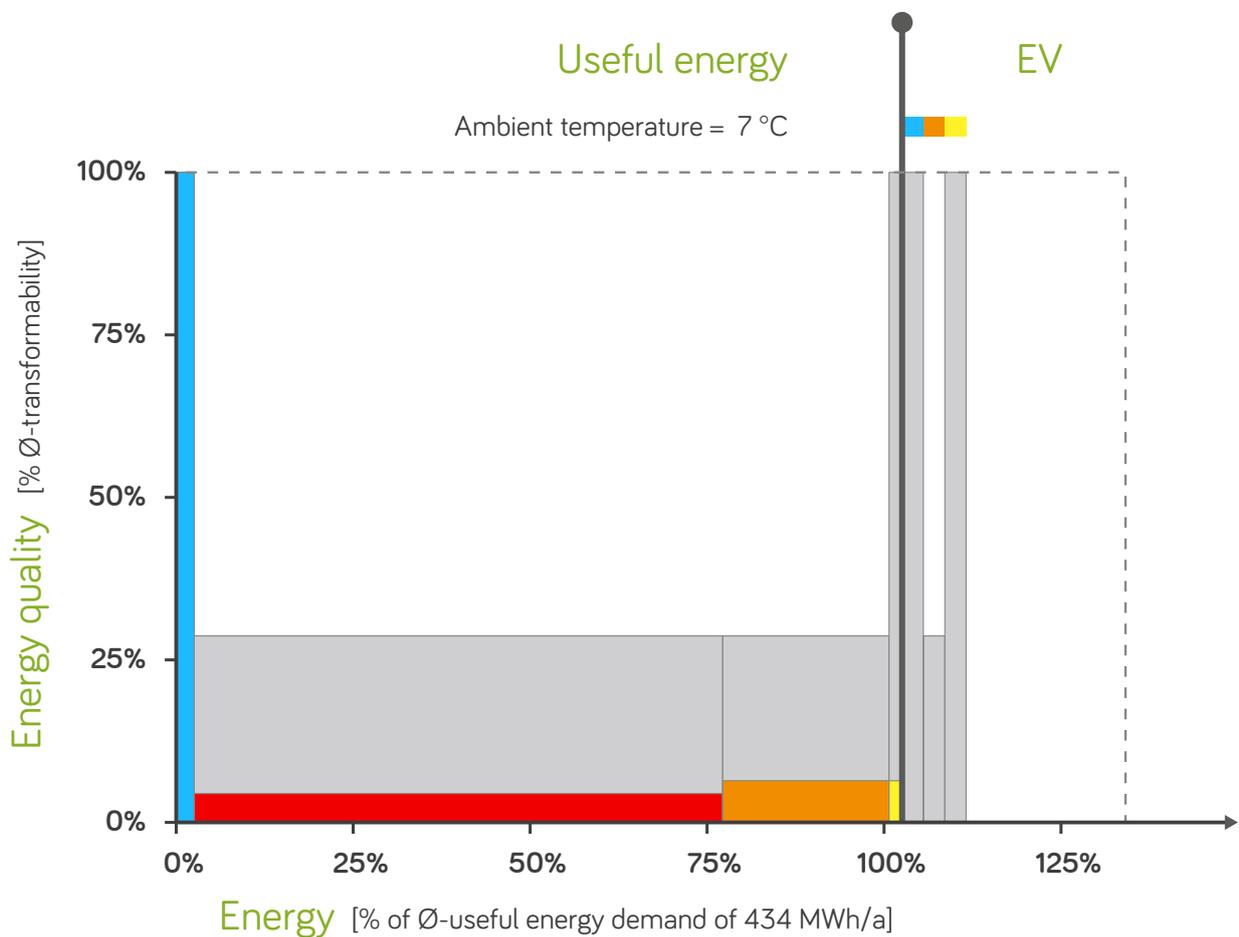
Costs\*\*

over life cycle: not specified

\*\*entered manually

Demand: Standard

Supply: Cold DH (PV)



Demand [covered by] ■ Aux. power [PV power] ■ Space heat [CDH PV] ■ Hot water [CDH PV] ■ Hot water [EB PV]

■ Losses    Consumption of the reference

Savings compared to the Reference



81%

Resource

Summary of results

consumption: 110 MWh/a

efficiency: 26,7%



94%

CO<sub>2</sub>e

emissions (GWP100): 7 t/a



n.s.

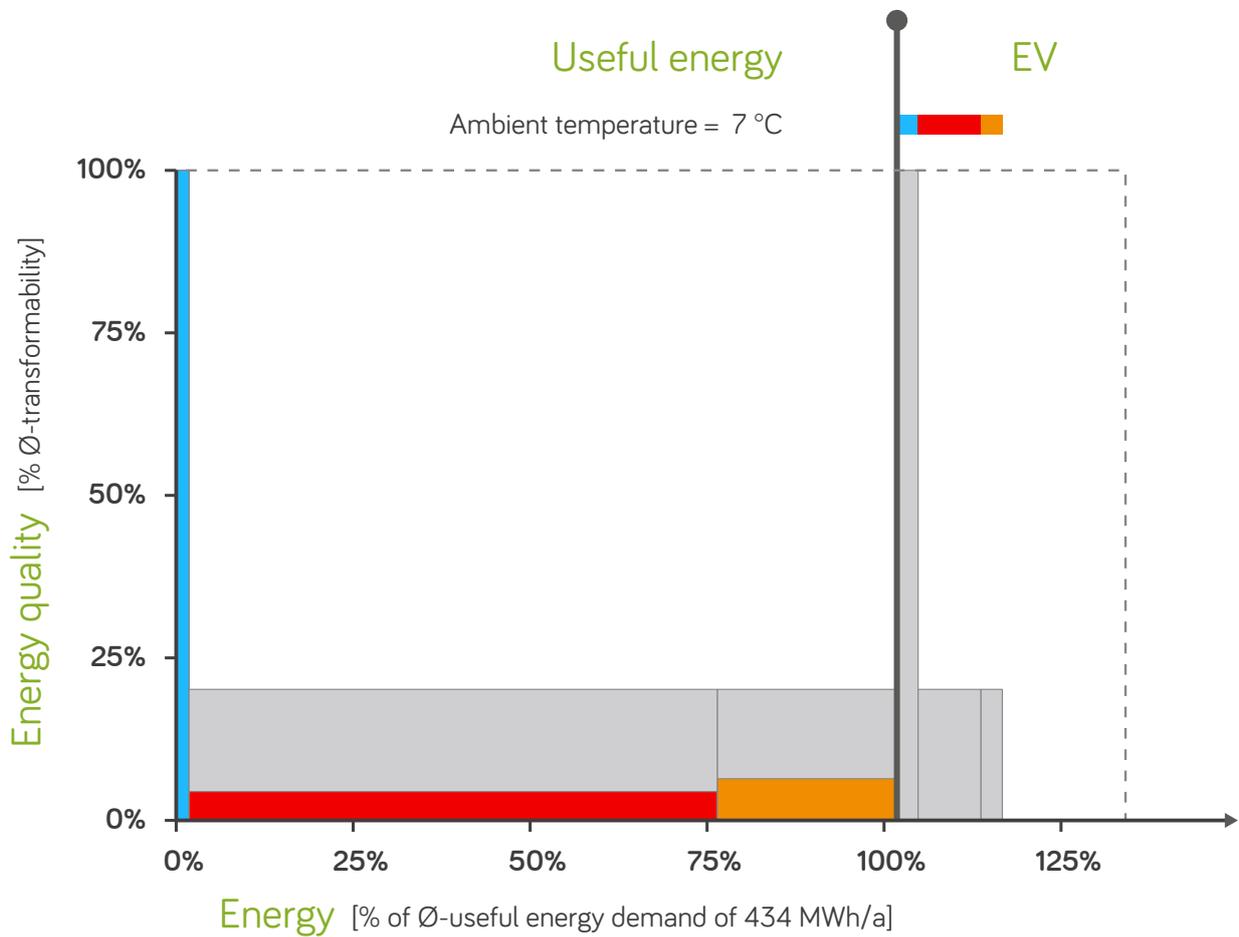
Costs\*\*

over life cycle: not specified

\*\*entered manually

Demand: Standard

Supply: Deep geothermal DH



Demand [covered by] ■ Aux. power [PV power] ■ Space heat [DH IDGT] ■ Hot water [DH IDGT]

■ Losses  Consumption of the reference



## Summary of results

As a basis for decision-making, resource consumption, CO<sub>2e</sub> emissions, and the cost summarized for the selected variants.

	Resource	CO <sub>2e</sub>	Costs**
<b>Sc1: NG cond. boiler</b>	This is the Reference scenario.		
Summary of results	consumption: <b>582 MWh/a</b>  efficiency: <b>3,7%</b>	emissions (GWP100): <b>112 t/a</b>	over life cycle: <b>0 k€/a</b>
<b>Sc2: DH NG CHP &amp; B</b>			
Savings compared to the Reference	<b>22%</b>	<b>23%</b>	<b>n.s.</b>
Summary of results	consumption: <b>455 MWh/a</b>  efficiency: <b>6,2%</b>	emissions (GWP100): <b>86 t/a</b>	over life cycle: <b>0 k€/a</b>
<b>Sc3: Air-source HP</b>			
Savings compared to the Reference	<b>70%</b>	<b>92%</b>	<b>n.s.</b>
Summary of results	consumption: <b>175 MWh/a</b>  efficiency: <b>12,2%</b>	emissions (GWP100): <b>9 t/a</b>	over life cycle: <b>0 k€/a</b>
<b>Sc4: DH LHP &amp; PV</b>			
Savings compared to the Reference	<b>71%</b>	<b>93%</b>	<b>n.s.</b>
Summary of results	consumption: <b>171 MWh/a</b>  efficiency: <b>17,3%</b>	emissions (GWP100): <b>8 t/a</b>	over life cycle: <b>0 k€/a</b>

\*\*entered manually



Resource

CO2e

Costs\*\*

Sc1: NG cond. boiler

This is the Reference scenario.

Summary of results

consumption:  
582 MWh/a

emissions (GWP100):  
112 t/a

over life cycle:  
0 k€/a

efficiency: 3,7%

Sc5: DH cold & HP

Savings compared to the Reference



Summary of results

consumption:  
153 MWh/a

emissions (GWP100):  
7 t/a

over life cycle:  
0 k€/a

efficiency: 21,3%

Sc6: DH deep GT

Savings compared to the Reference



Summary of results

consumption:  
110 MWh/a

emissions (GWP100):  
7 t/a

over life cycle:  
0 k€/a

efficiency: 26,7%

\*\*entered manually

## Making the right decision for your transformation project

Good decisions require sound and comprehensive information.

The exergy passes for the scenarios studied contain precise information on resource consumption, resource utilization, CO<sub>2</sub> emissions and energy costs. Resource utilization and resource consumption include energy consumption and energy efficiency.

The graphical part of the exergy pass makes consumption and efficiency comprehensible.

The traffic lights for savings facilitate comparison.

Based on the traffic lights, you can, for example, preselect the three variants that are most interesting for you. You can then take a closer look at these with the help of the exergy passes to arrive at a decision for one optimum scenario.

If the three evaluation parameters resource consumption, CO<sub>2</sub> emissions and energy costs are equally important to you, then select variants for which as many traffic lights as possible are yellow or even green. In this selection process, you benefit from the highest possible amount of savings.

If one criterion is particularly important to you, it is advisable to choose variants with especially high savings in this area. Then you decide to what extent you are willing to accept the values in the other traffic lights.

The values in the traffic lights say nothing about the absolute savings. To assess these, you can compare the information in the text under the traffic lights.

Costs for energy purchases can only ever give a first indication of cost-effective options. However, a cost-effectiveness decision should include all cost aspects. It is therefore advisable to determine the life cycle costs for the most interesting variants after completion of the preliminary planning. This data can then be used to make a final assessment.

Ultimately, the decision is yours. With this comparative study of planning alternatives, you can better justify your decisions in favor of a particular planning scenario. The comprehensive nature of the evaluation increases the certainty that you will be satisfied with your decision in the future.