REA: resource exergy analysis

Calculation guide
for energy systems,
including
district heating and cooling

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Introduction

The central goal of the energy transition is achieving climate neutrality as fast as possible. A realistic and target-oriented assessment of energy systems is an important basis for this.

With the increasing use of non-fossil sources, problems with existing evaluation systems for energy products and energy consumers become more relevant. In particular, the following are worth mentioning:

1. Non-renewable primary energy factors do not adequately consider the climate impact. For example, natural gas and hard coal are valued the same. Furthermore, they do not allow for differentiation of renewable energy supply systems.

2. Total primary energy factors are usually not suitable for assessing overall efficiency. Energy from solar thermal, waste heat, photovoltaics and natural gas are rated approximately the same.

3. Greenhouse gas emission factors cannot contribute to the effective implementation of the "efficiency-first" principle for energy systems that emit low amounts of greenhouse gases. Thus, despite much greater inefficiency, the combustion of green hydrogen in boilers would be considered almost equal to the use of green electricity in heat pumps using this indicator.

4. The indicator "share of renewable energies" is misleading in some cases. Even systems with high shares of renewable energies can contribute significantly to ecological damage, e.g. when using palm oil from former rainforest areas.

A sound solution to these problems is the combination of two, independent, reality-based indicators.

The frequently used non-renewable primary energy factors can be replaced by realistic greenhouse gas emission factors. However, these only allow an estimate of direct emissions.

The comprehensive implementation of the "efficiency first" principle is only possible through an additional assessment of the resource exergy consumption. The physical quantity exergy with suitable balance boundaries provides an optimal basis for this.

Furthermore, reduced resource exergy consumption helps to minimize indirect greenhouse gas emissions. This effect is caused by the demand-oriented supply usually expected from energy systems. If demand always needs to be covered, and all greenhouse gas neutral energy sources are used as intensively as possible, then any wastefulness leads to an increased use of fossil resources somewhere in the supply chain. This in turn causes indirect emissions due to resource wastefulness.

This calculation guide is the documentation and extension of the resource exergy analysis (REA) method, which has already been successfully applied in various research and consulting projects since 2010.

The REA allows resource energy consumption to be determined in a simple and physically sound way, thus minimising resource waste and indirect greenhouse gas emissions.

Furthermore, the REA offers the possibility to characterize heating, cooling and electricity with the help of resource exergy factors.

Together with greenhouse gas emissions analysis, the REA represents a progressive alternative to the established primary energy assessment.

This calculation guide is based on the nomenclature and conventions of the AGFW FW 309 worksheet series “Energy-based Assessment of District Heating and District Cooling”.

The calculation guide goes beyond the scope of AGFW FW 309 in that it also lays the foundations for the assessment of non-district heating systems. This allows a consistent comparison of all technology combinations competing with district heating, district cooling and cogeneration in terms of efficiency and resource conservation.

1 Scope of application

This calculation guide applies to processes whose function is to meet one or more energy demands.

Systems that provide material flows as primary products do not fall within the scope of this calculation guideline.

This calculation guide applies to the determination of resource exergy factors (REFs), resource exergy consumption (REC) and resource exergy efficiencies (REEs) of electricity, heating and cooling energy systems.

2 Normative references

The following documents are referred to in the text in such a way that some parts of them or their entire contents constitute demands of this document. For dated references, only the referenced edition shall apply. For undated references, the latest edition of the referenced document (including any amendments) shall apply.

AGFW FW 309-6 “Energy evaluation of district heating and district cooling – emission factors according to the working value and Carnot method”

3 Terms

For the purposes of this document, the following terms shall apply.

3.1 Allocation factor

α

Indicator between 0 and 1 that describes the shares of the inlet or output that are allocated to cogeneration products.

3.2 Weighting factor

f_{we}

Resource exergy factor, primary energy factor or emission factor

Note 1 on the term: In DIN EN ISO 52000-1:2018, weighting factor is a generic term for primary energy factor, emission factor, cost factor and other additional factors for weighting energy quantities. [1]

Note 2 on the term: In this calculation guide, it is primarily used for the resource exergy factor.

3.3 Utilization ratio or energy efficiency

η

Factor describing the usable portion of an energy input.

Note 1 on the term: The basis of the consideration is energy quantities, whereby the utilization ratio itself is unitless (benefit related to expenditure). Processes are the transfer/control, distribution, storage and generation of energy quantities. [2]

3.4 Waste heat

Heat generated in a process whose main objective is the production of a product or the provision of a service (including waste disposal).

Examples: Refineries, steel production and processing, chemical industry, data centres, electrolysers, laundries, cold stores, disposal systems (e.g. thermal waste treatment, waste water). [1]

3.5 Upstream chain

Expenses for extraction, processing, conversion and transport from the place of directly storable primary energy extraction to the boundary of the system under consideration.

4 Symbols and abbreviated terms

Table 1 – Symbols

Symbol	Property	Unit
α	Allocation factor	-
γ	Energy coefficient of performance	-
Δ	Difference	-
W	Electrical energy	J, Wh
E	Energy in general	J, Wh
X	Exergy in general	J, Wh
f	Factor	-
ϕ	Share (energy)	
η	Utilization ratio, energy efficiency	-
ξ	Utilization ratio, exergy efficiency	-
Σ	Total, sum	-
Q	Thermal energy	J, Wh
T	Thermodynamic temperature	K
ω	Share (electricity)	

Table 2 – Indices

Index	Label
0	Reference state for exergy calculations
a	Air
aux	Auxiliary
avg	Average
C	Carnot
cd	Cooling delivery
CED	Cumulated energy demand
CExD	Cumulated exergy demand
ch	Chiller
CO2eq	Carbon dioxide equivalent
com	Complex
d	Demand
dc	Deep cooling
dr	Driving
ds	Directly storable
e	External
el	Electric
f	Fuel-related
fin	Related to final energy
hd	Heat delivery
HHV	Higher heating value
in	Inlet
l	Losses
LHV	Lower heating value
max	Maximum
min	Minimum
mn	Mean
nren	Non-renewable
ns	Non-storable
nt	Non-thermal
out	Submitted

Index	**Label**
P	Primary energy
pc	Phase change
pm	Power mix
pr	Produced
R	Resource
ref	Reference
rf	Return flow
s	Storage
sf	Supply flow
syf	Synthetic fuel
t	Transport
T0	At reference temperature for exergy calculations
tg	Target
th	Thermal
ts	Thermal sources
wi	Wind
y	Index, counting variable without fixed relation to the counted unit
z	Index, counting variable without fixed relation to the counted unit

Table 3 – Abbreviated terms

Abbreviated terms	Meaning
CEENE	Cumulated exergy extraction from the natural environment
CExC	Cumulated exergy consumption
CExD	Cumulated exergy demand
DH	District heating
HHV	Higher heating value
CED	Cumulative energy demand
CEC	Cumulative energy consumption
CHC	Combined heating and cooling
CHP	Combined heat and power generation
LCA	Life cycle analysis
LHV	Lower heating value
REA	Resource exergy analysis
UED	Useful exergy demand
RE	Resource exergy
REE	Resource exergy efficiency
REF	Resource exergy factor
REC	Resource exergy consumption
GHG	Greenhouse gas

5 System boundaries and calculation steps

The balance boundary is defined by metering devices. A visual representation of the system boundaries can be found in Figure 1 in chapter 7.

Adjacent energy supply systems for thermal energy may only be evaluated as a single energy supply system if there is a thermal connection between all system components, e.g. through the heat transfer medium itself or components such as heat exchangers.

Thermally connected energy supply systems may only be divided into independent subsystems and assessed individually if the energy at the balance boundary is fully recorded with a measuring device.

All assessment methods presented in the following are applicable regardless of the selected calculation time step and require as input data the energy flows that transit the balance boundary and their weighting factors. It is assumed that the input data do not change in the time step under consideration. That means the presented equations are valid for steady-state flows.

To calculate annual weighting factors, the input data must cover a continuous period of at least one full year.

New and existing energy supply systems that have been refurbished or are to be refurbished and are t not yet operated in accordance with future conditions, may also be assessed using planning data.

6 Definitions

6.1 Energy demand / energy supply target

The energy demand refers to the amount of energy used to cover an existing demand without further energy losses. The object that determines the energy demand is the energy supply target, e.g. a house, a neighbourhood or a community.

6.2 Energy supply system

An energy supply system provides useful energy based on one or more input flows through transport and, if necessary, conversion, which covers one or more energy demands. An energy supply system can be a single technical system or a combination of technical systems.

6.3 Upstream chain

All process steps that enable the provision of the first directly storable energy flows used in the energy supply system are summarized as the upstream chain.

For fuels, it includes the expenses for extraction, storage and transport. Expenses for the construction of power plants do not have to be considered for fuel and electricity-using energy converters. The expected changes due to the consideration of infrastructure for fuel-using systems are maximally in the range of the variation of the weighting factors for the fuels and thus can generally be regarded as negligible [3].

For electricity generation from volatile sources and for the use of geothermal and solar thermal energy, the expenses for the construction of the energy conversion plants are considered in the weighting factors of the upstream chain, since these conversion plants transform energy that is not directly storable into energy that is directly storable.

Only in the case of the use of unavoidable waste and waste heat, no share of the upstream chain is considered in the weighting factors of the energy flows.

6.4 Energy system

An energy system is a process chain consisting of an energy supply target, an energy supply system and the upstream chains which are connected to them.

6.5 Exergy of energy flows

The exergy associated with an energy flow is the maximum work that can be achieved by applying an ideal thermodynamic process to bring the flow into equilibrium with a well-defined reference environment [4].

The thermodynamic properties of the reference environment such as temperature, pressure and chemical composition reflect properties of the environment that do not change measurably when energy or mass is exchanged with the energy or substance flow under consideration.

For a better understanding, the physical state variable exergy can be described as a product of energy and “energy quality” [5].

All non-thermal energy sources such as fuels or electricity have an energy quality of 100 %[1], which means that they can theoretically be completely converted into electricity or work.

Thermal energy flows have an energy quality that is below 100 %. For heat flows above the ambient temperature (reference temperature), a higher temperature means a higher energy quality. For heat flows below the reference temperature, a lower temperature means a higher energy quality [5].

Exergy is a property of the system of reference environment and the energy flow under consideration. Thus, it is not a property that depends exclusively on the energy flow considered, but it is associated with them. [5].

To avoid cumbersome expressions, this calculation guideline uses the simplified terminology “exergy of an energy flow”.

The exergy of closed systems is not considered for energy system analysis. It differs from the exergy of material and energy flows, like internal energy differs from enthalpy.

In most cases, it is not necessary to consider the exergy of mass flows for the energy system analysis. Fuel flows can be considered as energy flows, since their chemical or nuclear exergy approximately equals the energy that can be extracted from them.

6.6 Waste heat and cogeneration

Definitions of waste heat can vary. In the context of the REA waste heat is heat, that a technical system that was not optimized for heat utilization rejects to the environment. Generally, waste heat

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[1] For fuels, the ratio of exergy and higher heating value is often not exactly 100 %. Strictly speaking, the actually usable energy of a material flow must be determined via the transformation energy [2]. However, this is not done in the practical REA for reasons of simplification and due to the relatively large uncertainty in the weighting factors.

must be generated in a way that does not diminish the output of the main product. If using waste heat, no upstream losses are considered.

Technical systems that are optimized to provide heat among other products are considered cogeneration systems in the context of the REA. Heat from cogeneration systems is considered differently from waste heat, since appropriate shares of the upstream losses are allocated to the cogenerated heat.

6.7 Resource exergy

Commonly, a resource is understood to be a naturally existing stock of something that is [constantly] needed for a specific purpose, especially for human nutrition and economic production [6]. Resource exergy is the exergy associated with this stock.

As input flows of resource exergy (RE), only energy flows are considered that can be stored directly in their present form without further conversion or transmission. Resources can form a stock in the present form.

Energy flows that are lost to the global technical energy system if they are not used directly, such as solar energy, kinetic energy of wind and water currents, and geothermal and waste heat, do not constitute stocks and are therefore not considered resources.

In these cases, where the primary energy cannot be stored without conversion or transmission to a technical system, the first secondary energy that can be stored directly, without conversion or transmission, is considered a resource.

This means that when generating electricity from solar radiation or the kinetic energy of wind or river water, the electricity generated is considered a resource.

In the case of solar thermal systems, the hot water produced with it at a certain temperature level is considered a resource.

The resource potentially provided by waste heat and geothermal energy is the heat after transfer to a technical system (e.g. a water circuit). Waste heat is considered in the same way as geothermal energy, with the difference that the effort required to transfer it to a technical system is usually much lower. The necessity of releasing waste heat to the surroundings of the waste heat generator allows considering it as if it is extracted from the environment, thus making it a quasi-natural energy source.

Water in reservoirs represents an artificially generated resource, as the storage of water preserves part of its original potential energy, e.g. water in mountains. Accordingly, when considering water from reservoirs, losses in the conversion of potential energy into electricity must be properly considered for the determination of RE.

Thus, natural fuels represent the only naturally occurring resources for the energy system, as they are already stored as they are, without transfer to a technical system. This includes fossil, biogenic and nuclear fuels.

In the context of energy system analysis, RE refers to the exergy of energy flows that are taken from the natural environment and can be stored directly without conversion or transmission, as well as energy flows generated by conversion or transmission that can be stored directly.

6.8 Resource exergy consumption

Resource exergy consumption (REC) is a measure of the RE used in an energy system (e.g. a building with its supply chains). Its unit of measurement is joules (J) or watt-hours (Wh).

In addition to the exergy of the resource, the REC also includes shares of the REC caused by the construction and, if applicable, also the recycling of the required extraction plants, transformer and energy conversion plants. The consideration of energy conversion plants is only necessary for the generation of directly storable exergy flows from exergy flows that are not directly storable.

Due to the large differences in the REC due to origin of fuels, the comparably small REC of fuel-using energy conversion units can usually be neglected [3].

The REC is calculated based on system properties, such as energy efficiencies, temperatures and energy demands, as well as on data for the characterization of the upstream energy flows used (e.g. from Appendix A).

This document shows how the REC is calculated for energy supply systems.

A comparison of different combinations of energy supply systems and supply targets based on their REC enables the informed selection of resource-saving overall systems.

6.9 Resource exergy factor

The resource exergy factor (REF) is a measure of the resource exergy used to provide an energy flow under consideration. As a ratio of exergy to energy, it is unitless. The REF can be calculated as a function of the REC.

For energy flows, the REFs consider not only energy quantities, but also their energy quality.

While the REC helps to compare energy systems, the REF is a measure for comparing supply flows. In Appendix B to Appendix D differences are illustrated with examples.

REFs can be determined based on various exergy-based upstream chain factors. The latter are continuously being developed so that, in principle, various factors can be considered as a basis for calculating REFs, e.g. cumulative exergy demand (CExD) [7] or cumulative exergy extraction from natural environments (CEENE). [8]. However, it should be noted that many exergy-based characterization factors such as the CExDs or the CEENEs do not only consider directly storable exergy and thus must be converted at least partially into the respective REFs.

Appendix A provides an overview of REFs already calculated based on CExDs, which can be used as a basis for the REA. Strictly speaking, the values presented there are valid for Germany. However, except for the REFs for mains electricity, they can also be used in other countries due to similarity of the supply chains and the large variations of fuel and other REFs based on their origin.

Country-specific CExDs, that are the basis for calculating REFs, can be obtained from service providers [9] of life cycle databases, e.g. ecoinvent. For grid electricity, however, the REFs can also be estimated from the cumulative energy consumption for the national electricity mix, as it roughly corresponds to the respective REF.

For simplified calculation methods, it is possible in principle to estimate the REFs of energy flows entering an energy supply system thanks to upstream energy chain factors, such as the cumulative energy demand (CED). By using the factors described in Appendix A, this simplification can be avoided in the context of the energy system analysis.

In principle, REFs can also be used to assess non-energy material flows in addition to the assessment of energy flows. However, this requires detailed evaluations and, if necessary, adjustments of life cycle analysis data.

6.10 Useful exergy demand

For the calculation of the useful exergy demand (UED), the minimum required exergy quantity with which the task could theoretically be accomplished is considered as the demand. This can also be referred to as the target exergy quantity.

For non-thermal demands, the UED corresponds to the useful energy demand. For thermal demands, the UED results from the useful energy demand multiplied by the Carnot factor (see formula (3)) of the target temperature (e.g. for space heating: 20 °C).

For cooling demands, the UED results from the useful exergy demand multiplied by the absolute value of the Carnot factor of the target temperature (e.g. for deep-freezing: -18 °C).

For heating demands below the reference temperature and cooling demands above the reference temperature, no minimum NEB can be determined, since these demands could in principle be covered by heat transfer from the environment without any technical measures. In these cases, technical measures are taken to accelerate the heat exchange.

The definition of UED based on the target temperature ensures that exergy destruction in the supply chain is considered comprehensively and no potential for improvement is overlooked.

It should be noted that all UED can mostly be reduced, since, for example, in the case of space heating, the actual “demand” is only the thermal comfort of the inhabitants of the built space, which could also be met in other ways than by heating the entire living space. However, for a realistic thermodynamic modelling of buildings, the demand is approximated by the exergy that is minimally required to keep the considered buildings at 20 °C, and to heat water from a cold water temperature of about 10 °C to sufficiently hot water of 43 °C [10].

The electricity demand in the REA, is modelled based on the electricity demand by the user for his / her needs (lighting, washing, entertainment, etc.). However, the needs as well as the means to cover those needs can be different, e.g. dishwasher or washbasin. This also allows the REA to take sufficiency into account, i.e. savings through reduced needs.

6.11 Resource exergy efficiency

The resource exergy efficiency (REE) can be used to assess the degree of thermodynamic perfection of an energy supply system. It expresses how close the energy supply system under consideration, including the upstream chain, is to an ideal, loss-free process. Since loss-free systems are not possible, the REE is always below 100 %.

REE is Null for cases where a system is intended to accelerate a process that is occurring naturally anyway, such as the cooling of hot water above the reference temperature. REE cannot become negative. Thus, REE can theoretically only assume values between 0 % and 100 %.

The REE is influenced by the target temperatures of the UED but is not a function of the system size. It is an additional piece of information that can complement, but not replace, the REC and the REF.

7 Balance boundaries

Each energy system consists of the three parts upstream (B), energy supply system (C) and supply target (D) (see Figure 1). The flows (1 – 7) represent exergy flows. The resource exergy analysis (REA) method described in this document aims to calculate the REC of input flow 1 and derived quantities from the knowledge of the demand-supplying output flow 4)and various data on the system parts (B-D).

Input flow 6 only occurs when heat pumps are used and represents a heat flow from the environment or from waste heat. Output flow 7 only occurs in the case of cogeneration. In case the output flow 4 is a heat flow, the output flow 7 is usually an electrical flow.

In the case of non-thermal energy demands such as electricity or synthetic fuel, the supply target of the REA is the end of the supply line or pipe connected to the consumer.

In the case of thermal energy demands, the supply target is a room or object that is to be maintained at or brought to a specific target temperature.

Exergy losses from the balance boundary (A) are not represented.

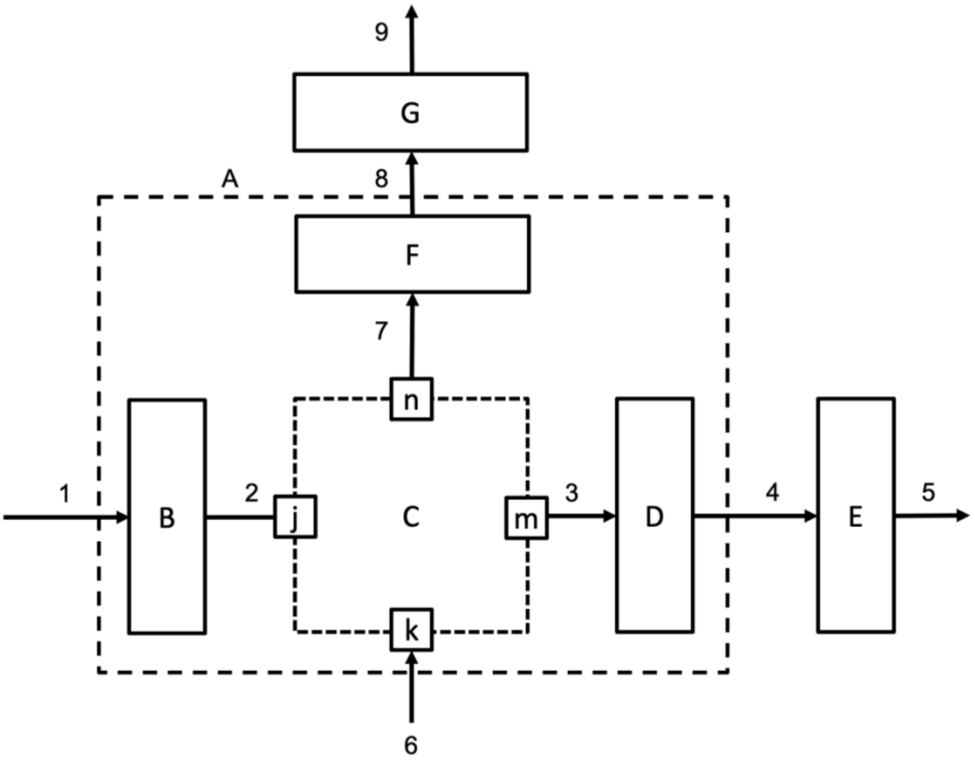

Figure 1 – Balance boundary of the resource exergy analysis

Legend

A	Balance boundary	1	Resource exergy consumption
B	Upstream chain (extraction, transport, losses)	2	Exergy supply to C
C	Energy supply system (e.g. boiler)	3	Exergy supply to D
D	Supply target (e.g. building volume)	4	Useful exergy demand (for heat flows: at target temperature)
E	Boundary to the environment (e.g. wall)	5	Exergy losses to the environment from the supply target
F	Supply target for a co-product (e.g. cold room)	6	Thermal exergy supply from the environment (only for some heat pumps and chillers)
G	Boundary to the environment (e.g. wall)	7	Exergy output through a co-product
j, k	Measuring devices for input into C	8	Useful energy demand covered by the co-product
m, n	Measuring devices for the output from C	9	Exergy loss to the environment

The energy supply system (element C in Figure 1) is considered as a black box, which is characterized by the interfaces, i.e. flows 2, 3, 6 and 7. For heat supply, it can consist of a single individual heating system or a combination of various energy conversion systems, such as heat pumps, cogeneration plants and waste heat utilization as well as a district heating network. Detailed examples of energy supply systems can be found in Appendix B and Appendix C.

The calculation of RECs only requires as input data the exergy flows that enter the supply system and their weighting factors for the characterization of the upstream chain (component B in figure 1). If corresponding process data, such as efficiencies etc. are known, the measurement at a single measuring point (element m or j in figure 1) can be sufficient to determine the REC (flow 1 in figure 1).

8 Calculation basis for energy systems

8.1 Basic equations

Many of the following equations have already been proposed and described in other publications [5], [11]. They are summarized here for use in resource exergy analysis and presented in consistent nomenclature.

The basis for the assessment of exergy of thermal flows is the Carnot cycle. The Carnot cycle is a thermodynamically ideal process for generating work from heat. It operates between two heat reservoirs at a constant temperature.

For heat transfer at varying temperature, the Carnot cycle remains applicable if the average thermodynamic temperature of the heat transfer is considered. This makes it possible to consider the heat transfer at changing temperature like heat transfer at a constant temperature. In the following, a formula is given which is valid for incompressible media without phase change[2].

$$T_{mn} = \frac{T_{sf} - T_{rf}}{\ln\left(\frac{T_{sf}}{T_{rf}}\right)} \tag{1}$$

where

T_{mn}	mean temperature of the heat transfer in kelvin [K]
T_{sf}	supply temperature from the heat exchanger on the side of the heating or cooling distribution system in kelvin [K]
T_{rf}	return temperature in the heat exchanger on the side of the heating or cooling distribution system in kelvin [K]

The reference temperature for determining the exergy of heat flows corresponds to the average outside air temperature in kelvin [K] for most energy systems on land.

$$\mathrm{T}_0 = T_{a,e,avg} \tag{2}$$

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[2] More general formulas for the thermodynamic mean temperature can be found in [11].

where

T_0	reference temperature for exergy calculation
$T_{a,e,avg}$	average outside air temperature in kelvin [K]

The mean temperature of the heat transfer and the reference temperature are the basis for calculating the Carnot factor, a key element for exergy-based evaluation of heat flows.

$$f_C = 1 - \frac{T_0}{T_{mn}} \tag{3}$$

where

f_C	Carnot factor
T_0	reference temperature for exergy calculation in kelvin [K]
T_{mn}	mean temperature of the heat transfer in kelvin [K]

Based on the Carnot factor, the exergy flow associated with a heat flow – simplified as: Exergy of the heat flow – is calculated.

$$X_{th} = Q \cdot f_C \tag{4}$$

where

X_{th}	exergy of the heat flow
Q	heat flow energy
f_C	Carnot factor

When the heat flow is below the outside air temperature, work can be generated by using heat from the environment. The Carnot factor for these heat flows is negative. This means that the exergy flow has the opposite direction of the heat flow under consideration [2]. The negative sign must be considered accordingly in exergy balances. I.e. if heat is extracted from the supply target below the outdoor temperature in a cooling process, exergy is added to the supply target of the cooling process.

The amount of exergy of a heat flow below ambient temperature corresponds to the absolute value of the corresponding exergy.

The exergy of electric power corresponds to its energy.

$$X_{el} = E_{el} \tag{5}$$

where

X_{el} exergy of electrical power

E_{el} energy of electrical power

The exergy associated with a fuel flow – simplified as exergy of a fuel flow – is calculated based on the thermodynamic material properties of the fuel flow. If no specific exergy is known, it can be approximated via equation (24).

8.2 Resource exergy consumption

The resource exergy consumption (REC) of an energy flow is the sum of all directly storable exergy flows used to provide it, which were either taken directly from the environment or from waste heat sources, or which were generated from exergy flows that cannot be directly stored. E.g. the REC of a heat flow is the sum of the exergy of directly storable energy flows that were used for its generation.

$$X_R = \sum_{1}^{y} X_{ds,in,y} \tag{6}$$

where

X_R resource exergy consumption of an energy flow

$X_{ds,in,y}$ directly storable exergy flow of the energy transfer y

The REC can also be calculated based on REF of the corresponding energy flow.

$$X_R = f_R \cdot E \tag{7}$$

where

X_R resource exergy consumption of an energy flow

f_R energy-related resource exergy factor of the energy flow under consideration

E energy flow

The total REC of an energy system can be determined by the sum of all resource exergy flows used to meet the total UED. E.g. the REC of a building's energy supply is the sum of the RECs of the heating, cooling and electrical flows used for its supply. If appropriate data is available, the REC for building construction and recycling can be considered to obtain the total REC of a building.

$$X_{R,sys} = \sum_{1}^{y} X_{R,in,y} \tag{8}$$

where

$X_{R,sys}$	resource exergy consumption of an energy system
$X_{R,in,y}$	resource exergy consumption of an incoming energy flow y

8.3 Resource exergy factor

The resource exergy factor (REF) is a weighting factor for characterizing an energy flow. It results from the ratio of the REC and the amount of the energy flow under consideration.

A dimensionless REF can be determined for each energy flow.

$$f_R = \frac{X_R}{E} \tag{9}$$

where

f_R	resource exergy factor of the energy flow under consideration
X_R	resource exergy consumption of the energy flow under consideration
E	energy flow considered

When multiple systems are used to provide an energy flow, based on equation (8) average REFs $f_{R,avg}$ in which the sum of the RECs of an energy supply system or an upstream chain is related to the energy flow under consideration.

$$f_{R,avg} = \frac{\sum_{1}^{y} X_{R,in,y}}{E} \tag{10}$$

where

$f_{R,avg}$	average resource exergy factor of the energy flow under consideration
$X_{R,in,y}$	resource exergy consumption of the incoming energy flow y
E	energy flow considered

8.4 Useful exergy demand

For all non-thermal energy demands, the UED is equal to the useful energy demand. This can be, for example, the electricity consumption of the current appliances.

$$X_{u,d,el} = P_d \tag{11}$$

where

$X_{u,d,el}$	useful exergy demand of the power supply
P_d	useful electrical energy demand

In the rare case that fuels are considered useful energy, they can be represented by their higher heating value according to equation (21). Ideally, however, the ratios of specific exergy to higher heating value from Appendix A are also considered.

The useful exergy demand (UED) of heat flows is calculated based on the minimum required exergy flows. For heat flows above the reference temperature, the target temperature for the desired heating must be known. In the case of space heating, this temperature corresponds to the desired room temperature.

$$X_{u,d,hd} = f_{C,hd,tg} \cdot Q_{d,hd} \tag{12}$$

where

$X_{u,d,hd}$	useful exergy demand of the heat supply
$f_{C,hd,tg}$	Carnot factor of heat with target temperature
$Q_{d,hd}$	heat demand

For heat flows below the reference temperature, the theoretical maximum possible temperature for the desired cooling must be known. In the case of space cooling, this temperature corresponds to the target temperature of the room.

For cooling to temperatures below the reference temperature, the Carnot factor becomes negative. The negative sign of the Carnot factor must be considered in exergy balances but is not considered for the determination of the UED [3].

$$X_{u,d,cd} = \left|f_{C,cd,tg}\right| \cdot Q_{d,cd} \tag{13}$$

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[3] For very low temperatures below $\frac{T_0}{2}$ (e.g. - 137 °C) the Carnot factor assumes values below -1. However, this is mostly only relevant for industrial systems (e.g. air liquefaction). The energy quality nevertheless remains below 100 %, as already mentioned. The exact relationships between exergy, energy and energy quality are shown in [5].

where

$X_{u,d,cd}$	useful exergy demand of the cooling supply
$f_{C,cd,\mathrm{tg}}$	Carnot factor of cooling at target temperature
$Q_{d,cd}$	cooling demand

8.5 Resource exergy efficiency

Exergy efficiency is the ratio of exergy delivered to exergy used. It is calculated based on the absolute amounts of the corresponding exergy flows.

$$\xi = \frac{|X_{out}|}{|X_{in}|} \tag{14}$$

where

ξ	exergy efficiency
X_{out}	exergy of the delivered energy flows
X_{in}	exergy of the energy flows used

The REE is the ratio of the sum of the considered useful exergy demand to the sum of the REC caused by it.

$$\xi_R = \frac{\sum_1^y \left|X_{u,d,out}\right|_y}{\sum_1^z \left|X_{R,in}\right|_z} \tag{15}$$

where

ξ_R	resource exergy efficiency
$X_{u,d,out}$	useful exergy demand
$X_{R,in}$	resource exergy consumption

If an outgoing but unused exergy flow was generated by a technical energy supply system from other exergy flows through conversion, it represents a loss and does not have to be considered in the REE. If, for example, waste heat is generated and released into the environment via cooling systems, this waste heat is not a product flow.

If several products are produced in a coupled manner in an energy system, the resource exergy used must be calculated and allocated to the different products in accordance with the criteria set out in Section 0 before assessing the REE.

If the REF is known, the REE of thermal demands can be calculated as follows:

$$\xi_{R_{th}} = \frac{\left|f_{C,d}\right|}{f_{R,avg}} \tag{16}$$

where

$\xi_{R,th}$	resource exergy efficiency (thermal)
$f_{C,d}$	Carnot factor of demand
$f_{R,avg}$	average resource exergy factor of the energy flows used

For electrical demands, the REE can be calculated as:

$$\xi_{R,el} = \frac{1}{f_{R,avg}} \tag{17}$$

where

$\xi_{R,el}$	resource exergy efficiency (electrical)
$f_{R,avg}$	average resource exergy factor of the energy flows used

Formula (17) also applies analogously to the REE of the production of synthetic fuels.

9 Explanation of calculation assumptions

9.1 Weighting factors of the upstream chain

Weighting factors of the upstream chain summarize the expenditures or emissions that are incurred in the upstream chain to generate the energy flows entering an energy supply system.

The main difference between the REFs and other exergy-based weighting factors is that the REFs only consider directly storable exergy flows. If no REFs are known, they can be estimated based on other weighting factors.

In this context, exergy-based weighting factors of the upstream chain are more suitable than energy-based weighting factors, as they consider the energy quality on the one hand and the exergy of material inputs on the other. If possible, exergy-based weighting factors should therefore be used as the basis for determining the REFs.

The REFs of different energy flows are shown in Appendix A. The REFs for electricity are valid for Germany 2022.

Ideally, REFs are based on cumulative exergy demand (CExD) [7]. This corresponds to the cumulative exergy consumption (CExC) [12]. It can be defined as the sum of all exergy flows that were used to generate an exergy flow under consideration. The CExD includes the thermal, chemical, mechanical and useable nuclear exergy of all mass flows used, as well as the kinetic, potential, electromagnetic and thermal of all energy flows used. However, no distinction is made between directly storable and non-directly storable exergy.

Likewise, transit exergy is often considered as exergy expenditure, which requires a correction, since REFs do not consider transit exergy. In this context, transit exergy refers to the exergy flows that flow unchanged through the energy system, e.g. the chemical exergy of water[4]. Accordingly, some adjustments must be made to make the CExD useable for the REA.

If no detailed information on exergy types of the CExD is available, the REF should better be approximated via the CED (cumulative energy demand), since transit exergy is not considered here by definition and thus only a correction for storability and possibly ratios of specific exergy to higher heating value is required.

9.2 Electricity (grid mix)

If it is unknown from which source consumed electricity comes, the REFs of the upstream chain for the current grid electricity mix are to be used for the assessment. The value for the grid electricity mix is averaged over the observation period of the assessment, i.e. annual average values for yearly analyses, monthly average values for monthly analyses and so forth. The average value for the grid electricity mix is calculated based on the current grid electricity mix.

Losses in the electricity grid are already considered in the weighting factors for grid electricity, unless this is explicitly excluded in the description of the weighting factors.

9.3 Green electricity

Green electricity is generally referred to as electricity from renewable energy sources. However, it is usually not ensured that the mostly low resource-exergy consumption of green electricity is not simultaneously considered in the general grid mix or does not lead to a neglected increase in resource-exergy factors for consumers of non-green electricity.

Power Purchase Agreements (PPAs) of green electricity have not been sufficiently explored to ensure additional generation of low resource-exergy electricity in line with consumption [13]. Therefore, to

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[4] Detailed, comprehensible conversions from CExC to the REA can be found in the Excel table on LCA data accompanying this document. [3].

exclude double counting of resource exergy savings and to ensure full additionality of resource exergy savings from supply systems with low REC, green electricity and electricity from PPAs are considered as grid electricity for the REA.

Green electricity can thus only be assumed, if the renewable energy converters are directly connected to the consumer and do not provide their power via the public electricity grid.

9.4 Direct-use electricity

Electricity that is used in the energy system under consideration without being fed into the general grid beforehand is designated as direct-use electricity. For the REA only direct-use electricity may be characterized with weighting factors that differ from grid electricity. Losses in the direct-use electricity grid due to storage and transport may have to be considered.

Some electricity generators provide direct-use electricity and electricity that is fed into the public electricity grid, e.g. private PV panels. In this case, only the share of direct-use electricity is evaluated using weighting factors that differ from those of the electricity grid mix.

9.5 Nuclear power

Electricity and heat from nuclear power can be assessed with the REA. Concerning the calculation of REC, REE and REV nuclear fuels are treated analogously to chemical fuels. Some REFs for nuclear fuels can be found in Appendix A.

9.6 Waste heat and co-production

In the context of the REA, waste heat is regarded as heat at a given temperature that must be released into the environment by technical systems so that they can function. It is not possible to operate the process without waste heat rejection. Examples of waste heat sources are industrial processes, computer centres, but also sewers.

Waste heat must be clearly distinguished from cogeneration. Cogeneration, in the context of the REA, refers to the production of at least two desired products through a common process. Adjustments are made to make all products as usable as possible. For example, a combined heat and power plant is designed for a higher heat output temperature than a condensing power plant.

Cogeneration can also be recognized by the fact that the corresponding process releases heat at a lower temperature if only one product is used. For example, the temperature of the heat transfer to the environment is usually lowered in the condensing mode of power plants, which can also be operated in cogeneration mode.

9.7 Utilization ratios and efficiencies

In principle, the average efficiency over the considered time step is used as a calculation parameter in the context of the REA. This means that monthly average values are used in a monthly analysis and annual average values in an annual analysis.

The average energy efficiency over the period under consideration is referred to as the utilization ratio or efficiency.

Energy efficiency values for fuels used in the REA generally refer to the higher heating value. If tabulated utilization ratios of energy published elsewhere are to be used for the calculation, it is to be assumed that these refer to the lower heating value, unless explicitly stated otherwise. If such lower heating value-related utilization ratios are used in the context of the REA, the utilization ratios must be converted accordingly.

$$\eta = \eta_{HHV} = \eta_{LHV} \cdot \frac{LHV}{HHV} \tag{18}$$

where

η_{HHV}	utilization factor (higher heating value-related)
η_{LHV}	utilization factor (lower heating value-related)
LHV	lower heating value
HHV	higher value

9.8 Temperatures for the calculation of exergy

For several energy systems, the application of the REA requires choosing temperatures for exergy calculation.

It is occasionally argued that internal process temperatures must be used. However, this is implausible because the exergy associated with heat can exclusively be used by the heat supply system after it has been released to it. Internal process temperatures, on the other hand, can be used well by the heat-generating process, e.g. to increase efficiencies.

This relationship can be well illustrated using the example of a block-CHP plant with waste heat utilization. If the high temperature of the waste gas were used directly in an ORC system for additional electricity generation, the electrical efficiency of the CHP system would increase. If, on the other hand, there is no additional electrical generation and the heat is transferred to a heat transport system with exergy losses due to temperature differences, only the temperature after the heat transfer is available to the heat transport system and thus only the exergy associated with this temperature.

Therefore, the REA uses the definition that the temperatures after the transfer to the heat supply system (e.g. the heating circuit or district heating) should always be used to determine the exergy of heat. This follows the logic that a system can only be made “responsible” for the losses that occur within. This creates an improved incentive to use waste heat as exergy-efficiently as possible.

Furthermore, the calculation of the resource exergy based on known temperatures of the heat supply system becomes possible[5].

Because of this definition, exergy losses of heat transfer in cogeneration processes are attributed to the non-thermal product, which in almost all cases is also the reason for the construction of the process.

9.9 Comparability

For the REA, all energy systems that fulfil a similar function for the user are basically comparable. The needs of the users can be extremely diverse without limiting comparability. For example, the REA allows the REC of a user in a hut without electricity in the forest to be compared with that of a user in a castle heated to 24 °C. In this way, all possible influences on the REC, such as sufficiency, efficiency and reduction, can be consistently considered in the REA.

Comparability in this case means that a calculation of resource exergy savings is useful.

Systems that fulfil different functions should not be compared in the REA to calculate savings. Nevertheless, in principle, these RECs can also be compared, e.g. to develop a more profound understanding of interrelationships, to prioritize savings efforts or to decide on the more sensible use of limited resources. For example, the REC for the provision of food can be compared with the REC for heating buildings to gain insights into the area in which savings are more effective in reducing the personal REC.

10 Simplifications

10.1 Background

A helpful simplification in communicating resource exergy analysis to lay people is to omit the word exergy. Therefore, it may be useful to speak of resource analysis instead of resource exergy analysis and of the resource consumption instead of the REC. However, the term exergy should be sufficiently well understood by the users of the REA, otherwise errors in application become more likely to occur.

Appendix A lists various REFs. In addition, further REFs for some infrastructures are available via the Excel spreadsheet that accompanies this guide [3]. Beyond that, it is usually difficult to obtain accurate exergy data, such as cumulative exergy consumption values for supply chains of materials and energy. This means that accurate data for exergy consumption in the construction of a system and its recycling is often not known.

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[5] This is the case because internal process temperatures in a dome process are often not known, while flow and return temperatures of the heat supply are usually measured.

Thus, most of the basic assumptions of the REA are subject to considerable uncertainties because accurate data is not sufficiently available. The use of well-founded approximations and simplifications for a simplified REA is necessary to enable the application of the REA even in cases where reliable exergy data is missing.

A simplified REA based on non-exergy data underestimates the REC, as the material exergy consumed cannot be considered in this way. Therefore, in case of uncertainties, all simplifications should be made in such a way that the REC is overestimated rather than underestimated.

Nevertheless, a simplified REA can offer many advantages of an exergy factor-based REA, as it is already much more comprehensive than a primary energy analysis by taking the energy quality into account in a physically correct way.

10.2 General

The following two simplifications for the average temperature should exclusively be used for preliminary estimates. They are not thermodynamic but arithmetic approximations. Equation (1) should be used for any final calculation.

$$T_{mn} \approx \frac{T_{sf} + T_{rf}}{2} \qquad (19)$$

where

T_{mn}	mean temperature of heat transfer without phase change in kelvin [K]
T_{sf}	supply temperature from the heat exchanger on the side of the heating or cooling distribution system in kelvin [K]
T_{rf}	return temperature in the heat exchanger on the side of the heating or cooling distribution system in kelvin [K]

If heat is primarily transferred in connection with phase changes of the medium, i.e. evaporation, condensation, melting, freezing, the mean temperature can be approximated via the corresponding phase change temperature.

$$T_{mn} \approx T_{pc} \qquad (20)$$

where

T_{mn}	mean temperature of heat transfer during phase change in kelvin [K]
T_{pc}	temperature of the phase change in kelvin [K]

If Appendix A provides no information on specific exergy, the exergy of fuels can be approximated by their higher heating value [11].

$$X_f \approx E_{HHV} \tag{21}$$

where

X_f	exergy of the fuel
E_{HHV}	higher heating value energy of the fuel

The energy of fuels in equations for determining energy efficiency is mostly determined by the lower heating value of the fuels. When specifying energy quantities of fuels, it can therefore be assumed that the values are based on the lower heating value, unless an explicit higher heating value references are made.

$$E_f = E_{LHV} \tag{22}$$

where

E_f	fuel energy
E_{LHV}	lower heating value energy of the fuel

10.3 Energy quality

Exergy can be understood as a product of energy and energy quality. The energy quality for all types of energy and mass flows has been derived in [5].

For energy flows, it can be simplified as the ratio between exergy and energy of an energy flow. Energy quality can never be higher than 100 %.

For non-thermal energy flows, energy quality equals 100%.

For heat flows, energy quality is lower than 100%.

The energy quality of heating equals the Carnot factor (see equation (3)).

The energy quality of cooling, with a maximum temperature difference of $\frac{T_0}{2}$ to the reference temperature T_0, can be approximated with the absolute value of the Carnot factor.

As an alternative to equation (3) the absolute value of the Carnot factor can also be determined from the ratio of exergy to energy:

$$|f_C| = \frac{|X_{th}|}{E_{th}} \tag{23}$$

where

f_C	Carnot factor (simplified energy quality) of the heat flow
X_{th}	exergy of the heat flow under consideration
E_{th}	energy of the heat flow under consideration

10.4 Use of the CED and the CEC in the REA

REFs for energy carriers are available in Appendix A and can be determined based on LCA data (CExD). If this does not provide the required data, the REC of energy flows and flows of fuels, can be approximated by using cumulative energy demand (CED) or cumulative energy consumption (CEC)[7]. These are often more easily accessible (e.g. in free national databases [14]) than CExD-values for the calculation of REF, which usually have to be purchased. Approximations within an analysis may then only use either the CEC or the CED.

In principle, the more comprehensive CED should be given preference over the CEC to minimize the difference to REF. In the following approximations, it is assumed that the CED is used. The simplifications for fuels and electricity are to be considered differently from simplifications for thermal energy flows.

10.4.1 Fuels and electricity

For electric energy, exergy corresponds to energy.

For fuels, the non-chemical exergy can typically be neglected, so that based on equations (21) and (22) the following simplification can be determined for the determination of the fuel exergy.

$$X_f \approx E_f \cdot \frac{E_{HHV}}{E_{LHV}} \tag{24}$$

where

X_f	exergy of the fuel
E_f	fuel energy
E_{HHV}	higher heating value of the fuel
E_{LHV}	lower heating value of the fuel

The REC for fuels and electricity can be simplified using the CED as follows:

$$X_{R,nt} \approx E_{ds,nt} \cdot f_{CED} \tag{25}$$

where

$X_{R,nt}$ resource exergy consumption of the non-thermal energy flow

$E_{ds,nt}$ energy of the directly storable, non-thermal energy flow

f_{CED} specific cumulative energy demand

10.4.2 Thermal energy

For directly storable thermal energy flows, such as heat from deep geothermal energy, solar thermal energy, and waste heat, it should be noted that the exergy of the heat flow differs significantly from its energy.

For unavoidable waste heat, consideration of the upstream chains is not necessary, as these expenditures are all allocated to the main process. The resource exergy of the waste heat corresponds to the exergy of the directly storable heat flow generated from the waste heat according to formula (4).

For other thermal sources, a consideration of the upstream chains (e.g. boreholes, collectors) is necessary. Here, in the case that no REFs (e.g. in Appendix A) are available, the REC can be estimated based on the respective CEDs. It is assumed that in the CED, all upstream expenditures have an energy quality of 100%. For the considered heat itself, however, the specific energy must be replaced by the exergy.

$$X_{R,th} \approx E_{ds,th} \cdot (f_{CED} - 1 + |f_C|) \tag{26}$$

where

$X_{R,th}$ resource exergy consumption of the thermal energy flow

$E_{ds,th}$ energy of the directly storable, thermal energy flow

f_{CED} specific cumulative energy demand

f_C Carnot factor of the thermal energy flow

10.5 Exergy efficiency

To calculate the REE, several input flows often must be considered. A simplified calculation based on individual known energy efficiencies is usually not possible. Instead, the useful exergy demand must be compared to the sum of all the RECs, according to equation (15).

Occasionally, it is helpful to be able to determine the exergy efficiency of system parts in addition to the REE of an overall system. This can be determined in a simplified way thanks to the corresponding energy efficiency.

The exergy efficiency of electricity generation from fuels without co-generation can be estimated as follows:

$$\xi_{el,f} \approx \eta_{el,f} \tag{27}$$

where

$\xi_{el,f}$	exergy efficiency of uncoupled power generation from fuels
$\eta_{el,f}$	(higher heating value-related) energy efficiency of uncoupled electricity generation from fuels

The exergy efficiency of boilers operated with fuels can also be shown in a simplified way.

$$\xi_{th,f} \approx \eta_{th,f} \cdot f_{C,d} \tag{28}$$

where

$\xi_{th,f}$	exergy efficiency of heat generation with fuel boilers
$\eta_{th,f}$	higher heating value-related energy efficiency of heat generation with boilers from fuels
$f_{C,th}$	Carnot factor of the heat demand at target temperature

If thermal sources are used for uncoupled electricity generation, the exergy efficiency depends on the Carnot factor of the heat source.

$$\xi_{el,ts} \approx \frac{\eta_{el,ts}}{f_{C,ts}} \tag{29}$$

where

$\xi_{el,ts}$	exergy efficiency of uncoupled electricity generation from thermal sources
$\eta_{el,ts}$	energy efficiency of uncoupled electricity generation from thermal sources
$f_{C,ts}$	Carnot factor of the heat from the thermal source

If heat is generated uncoupled from thermal sources thanks to a heat exchanger, the exergy efficiency of the heat transfer is simplified as:

$$\xi_{th,ts} \approx \eta_{th,ts} \cdot \frac{f_{C,d}}{f_{C,ts}} \tag{30}$$

where

$\xi_{th,ts}$	exergy efficiency of uncoupled heat generation from thermal sources
$\eta_{th,ts}$	energy efficiency of uncoupled heat generation from thermal sources
$f_{C,d}$	Carnot factor of the heat demand at target temperature
$f_{C,ts}$	Carnot factor of the heat from the thermal source

Exergy efficiency is zero for the generation of cooling above reference temperature and the production of heating below reference temperature. These processes do not provide a useful exergy flow, but instead accelerate naturally occurring thermal exchange.

11 Resource exergy analysis of energy systems

11.1 General

In the following, formulas for the calculation of the REC for the products of different energy supply systems are listed.

Some REFs can be obtained from Appendix A. Further REFs can be calculated from REC using the equations presented in section 8.3.

For the sections 11.2 to 0 it is assumed that only one product of each type of final energy flow is generated.

A universal formula for the calculation of REC can be found in section 11.7.

11.2 Power generation

11.2.1 General

This section provides an overview of the REC of electrical energy flows produced by electricity generators.

Power from the electric grid is assessed in accordance with the explanations in section 9.2. Examples for the calculation of the REC due to grid electricity consumption can be found in appendices B.7 and C.10.

11.2.2 Fuels

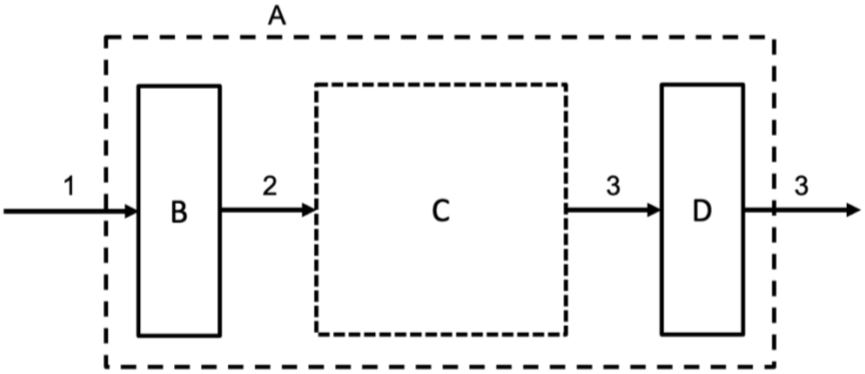

Figure 2 – Balance boundary of the resource exergy analysis for covering electricity demand from fuels

Legend

A Balance boundary

B Upstream chain (production, transport, losses)

C Energy supply system (e.g. power plant)

D Supply target

1 Resource exergy consumption

2 Exergy supply of C

3 Useful exergy demand of the supply target

$$X_{R,el,f} = \left(W_d + W_{l,s} + W_{l,t}\right) \cdot \frac{f_{R,f,in}}{\eta_{el}} \tag{31}$$

where

$X_{R,el,f}$	resource exergy consumption of electricity generation from fuels
W_d	covered electricity demand
$W_{l,s}$	electricity losses due to storage
$W_{l,t}$	electricity losses due to transport
$f_{R,f,in}$	resource exergy factor of the fuel used
η_{el}	electrical energy efficiency of the power generator (related to higher heating value)

Lacking tabulated exergy-based data, the electrical exergy efficiency of the generator can be estimated based on formula (27). As described in section 6.3, for fuel-using plants power generators the grey energy for the construction of the energy converter can be neglected [11], [15].

11.2.3 Solar radiation, water currents and wind power

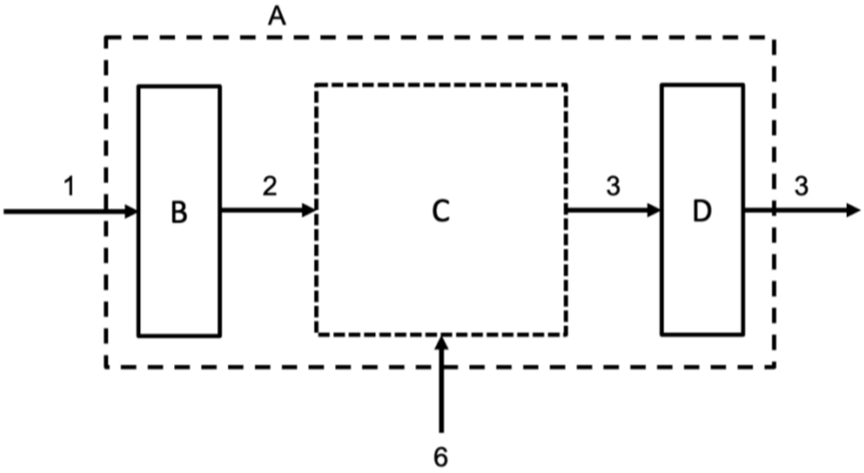

Figure 3 – Balance boundary of the resource exergy analysis for meeting electricity demand from energy flows that cannot be directly stored (solar, wind, current)

Legend

A	Balance boundary	1	Resource exergy consumption to produce the energy converters (e.g. wind turbines or photovoltaics).
B	Upstream chain (to produce the energy converters)	2	Exergy input to C
C	Energy supply system (e.g. photovoltaics, wind power)	3	Useful exergy demand
D	Supply target	6	Resource exergy consumption from sources that cannot be stored directly (e.g. solar radiation, wind), which is released again in the form of exergy that can be stored directly (e.g. electricity).

Solar radiation and kinetic energy of currents cannot be stored without conversion or transfer. Therefore, the first directly storable energy that is generated thanks to solar radiation or kinetic energy – e.g. electricity – is considered a resource.

The utilization ratio of the conversion of solar, wind or water currents into electricity is only relevant for the evaluation and comparison of the corresponding conversion technologies, such as photovoltaic panels, and does not have to be considered for the determination of the REC. The losses in the conversion of non-directly storable to directly storable forms of energy are thus not considered in the REA. However, the expenses for the construction of the conversion plants are included in the REA, as it is assumed that these are to be considered as resources (e.g. ores, fuels).

For electricity from solar radiation, wind power and water currents, the REC considers the amount of electricity generated as well as the REC allocated to the production and transport of the energy converters, i.e. photovoltaic panels, wind turbines and river water turbines.

$$X_{R,el,ns} = \left(W_d + W_{l,s} + W_{l,t}\right) \cdot f_{R,el,ns} \tag{32}$$

where

$X_{R,el,ns}$	resource exergy consumption of electricity supply from non-storable sources
W_d	covered electricity demand
$W_{l,s}$	power losses due to storage
$W_{l,t}$	electricity losses due to transport
$f_{R,el,ns}$	resource exergy factor of electricity from volatile renewable generation

11.3 Heat generation

11.3.1 General

This section gives an overview of formulas for the REC of heat flows provided by heat generators.

11.3.2 Boilers

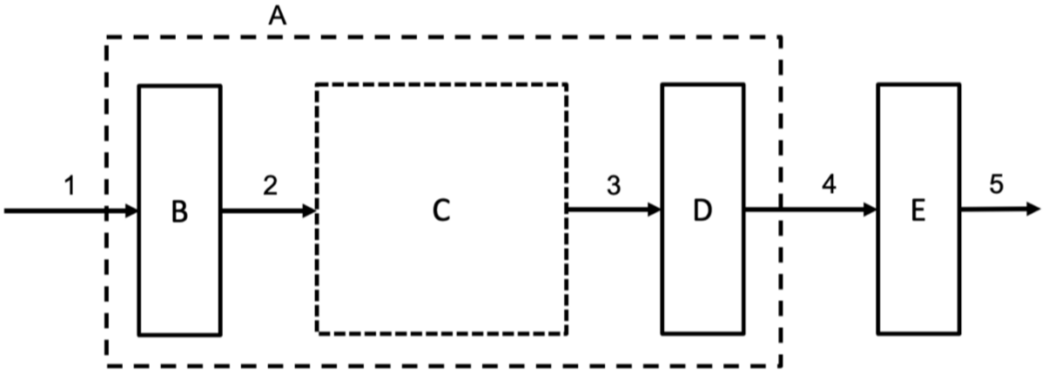

Figure 4 – Balance boundary of the resource exergy analysis for the coverage of a heat demand by a boiler

Legend

A	Balance boundary	1	Resource exergy consumption
B	Upstream chain (production, transport, losses)	2	Exergy input to C
C	Energy supply system (e.g. boiler)	3	Exergy input to D

D	Supply target (e.g. building volume)	4	Useful exergy demand (for heat flows: at target temperature)
E	Boundary to the environment (e.g. wall)	5	Exergy losses from the supply target to the environment

Boilers are understood here as energy supply systems that generate heat by conversion from other forms of energy, e.g. electricity or fuels. As described in section 6.3 the grey energy for the construction of the energy converter can be neglected in the case of fuel or electricity-using systems.

$$X_{R,th} = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot \frac{f_{R,in}}{\eta_{th}} \tag{33}$$

where

$X_{R,th}$	resource exergy consumption of heat supply with boilers
Q_d	covered heat demand
$Q_{l,s}$	heat losses due to storage
$Q_{l,t}$	heat losses through transport
f_R	resource exergy factor of the final energy source used
η_{th}	(higher heating value-related) thermal energy efficiency of the heat generator

11.3.3 Heat exchanger with waste heat, solar thermal energy or geothermal energy

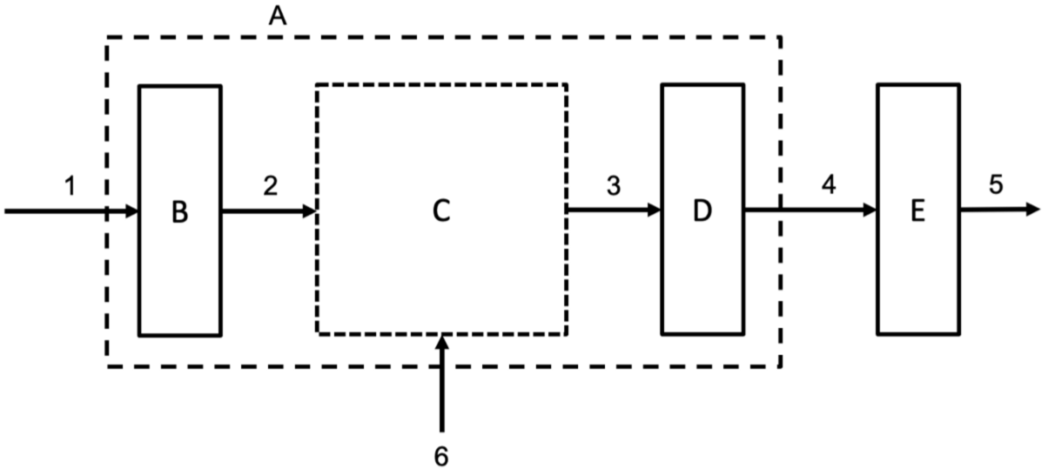

Figure 5 – Balance boundary of the resource exergy analysis for the coverage of a heat demand by thermal sources

Legend

A	Balance boundary	1	Resource exergy consumption to produce the heat transfer systems (e.g. solar thermal systems, heat exchangers).
B	Upstream chain (production, transport, losses)	2	Exergy input to C
C	Energy supply system (e.g. heat exchanger, solar thermal system)	3	Exergy input to D
D	Supply target (e.g. building volume)	4	Useful exergy demand (for heat flows: at target temperature)
E	Boundary to the environment (e.g. wall)	5	Exergy losses from the supply target to the environment
		6	Resource exergy consumption from sources that cannot be stored without heat transfer (e.g. solar heat, waste heat), which is released again in the form of directly storable exergy (e.g. hot water in the district heating system)

Solar radiation and kinetic energy from wind and water cannot be stored without conversion. Similarly, heat from geothermal energy cannot be stored without transfer, but is ultimately released into space.

Therefore, heat generated thanks to solar radiation, geothermal energy and kinetic energy from wind and water is considered a resource.

For heat from solar radiation, geothermal energy and kinetic energy of wind and water, the REC considers the amount of energy of the heat produced, its energy quality and the REC allocated to the operation for the production and transport of the energy converters, e.g. solar thermal collectors and heat exchangers.

$$X_{R,ts} = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot f_{R,ts} \tag{34}$$

where

$X_{R,ts}$	resource exergy consumption of heat supply from thermal sources
Q_d	covered heat demand
$Q_{l,s}$	heat losses due to storage
$Q_{l,t}$	heat losses through transport

$f_{R,ts}$ resource exergy factor of the thermal source

Thanks to the formulas (9) and (26) the REC of heat can be estimated based on energy-based or usual exergy-based key figures.

11.3.4 Heat pumps

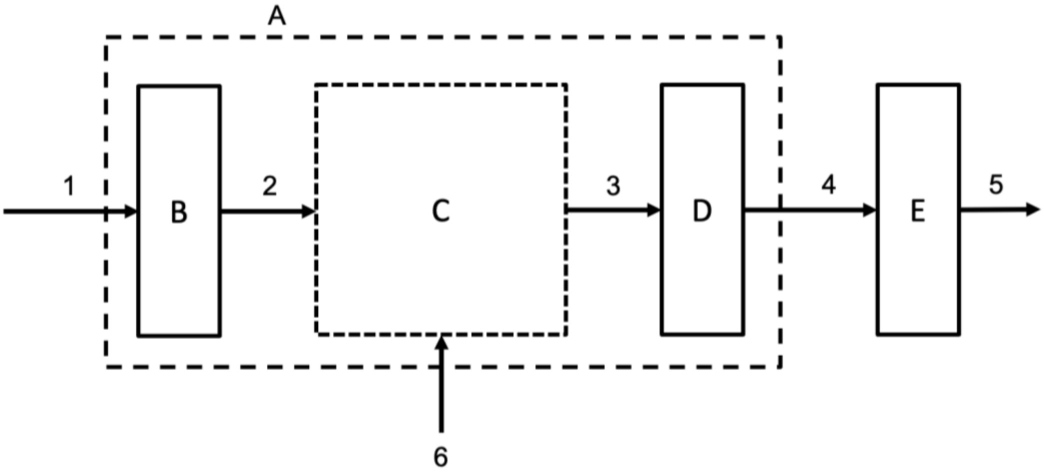

Figure 6 – Balance boundary of the resource exergy analysis for the coverage of a heat demand by heat pumps with a heat source temperature above the reference temperature

Legend

A	Balance boundary	1	Resource exergy consumption to produce the energy converters and the generation of the driving exergy.
B	Upstream chain (production, transport, losses)	2	Exergy input to C
C	Energy supply system (e.g. heat pump)	3	Exergy input to D
D	Supply target (e.g. building volume)	4	Useful exergy demand (for heat flows: at target temperature)
E	Boundary to the environment (e.g. wall)	5	Exergy losses from the supply target to the environment
		6	Resource exergy consumption of the heat absorbed by the heat pump, which is available in the heat pump system

The REC of heat supply from heat pumps is a sum of the RE used for construction and the RE used for operation. The RE required for operation is a sum of the RE used for the drive, e.g. for electricity, and the RE of the heat used.

The equation (35) applies only to heat pumps without a cooling function. If a heat pump is also used for cooling, the equations described in section 11.6.3 apply. If no heat is used but only cooling is provided, the heat pump is considered a chiller, which is described in section 11.4.

As explained in section 6.3, for systems that use electricity as a main input, the grey energy for the construction of the energy converter can be neglected.

The amount of heat absorbed by the heat pump is often not measured. To still be able to evaluate this heat, the amount of heat that is brought into the heat pump by the heat source can be determined thanks to an energy balance of the system. It is assumed that at least as much heat is absorbed from the heat source as is necessary to fulfil the energy balance. With this agreement, the REV for heat from a heat pump can be defined as follows based on the derivations in Appendix E:

$$X_{R,hp} = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot \left(\frac{f_{R,dr}}{\gamma_{hp}} + f_{C,ts} \cdot \left(1 - \frac{1}{\gamma_{hp}}\right)\right) \tag{35}$$

where

$X_{R,hp}$	resource exergy consumption of the heat supply with a heat pump
Q_d	covered heat demand
$Q_{l,s}$	heat losses due to storage
$Q_{l,t}$	heat losses through transport
$f_{R,dr}$	resource exergy factor of the driving energy
γ_{hp}	heat pump coefficient of performance in the time step under consideration
$f_{C,ts}$	Carnot factor of the thermal source

For heat pumps driven by solar thermal energy, heat from wind or river water, geothermal energy or waste heat, the factor $f_{R,in}$ can be determined using the formulae (9) and (26) based on energy-based or exergy-based weighting factors.

If the driving heat for a thermal heat pump is generated by a CHP plant, the REC of the CHP heat must be calculated according to section 0.

11.4 Refrigeration

In refrigeration, the Carnot factor of extracted heat below ambient temperature is negative. This means that an exergy flow is transferred to the cooled medium through heat extraction.

Refrigeration at or above the reference temperature is not an exergy-based demand, as it accelerates a process of cooling that occurs naturally when in contact with the reference environment. The REE of such processes is always zero. Nevertheless, a REC can be calculated for these tasks.

Losses of provided cooling result from unwanted heat input into the cooling medium. In the following, these unwanted heat inputs will be referred to as cooling losses $\left(Q_{cd,l}\right)$.

11.4.1 Direct cooling

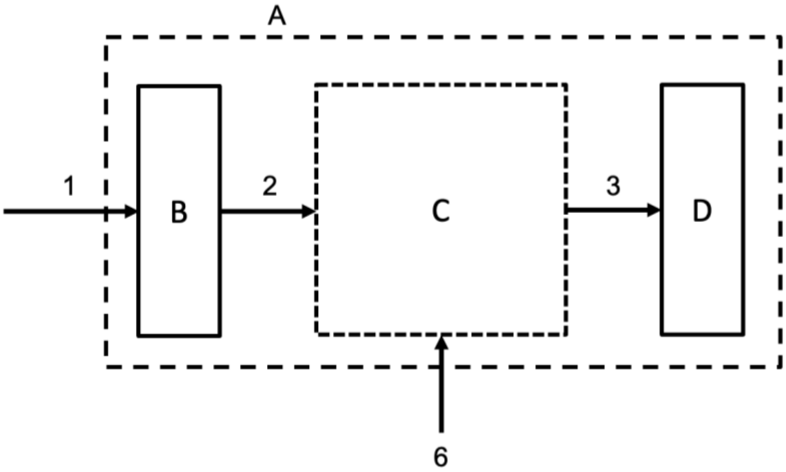

Figure 7 – Balance boundary of the resource exergy analysis for meeting a cooling demand above the reference temperature by direct cooling using a "cold source" with a temperature below the reference temperature

Legend

A	Balance boundary	1	Resource exergy consumption for auxiliary power generation
B	Upstream chain of auxiliary power generation (extraction, transport, losses)	2	Exergy supply by auxiliary flow to C
C	Energy supply system (e.g. pipes with heat exchanger and pump)	3	Exergy input to D by extracting a heat flow below the reference temperature from the supply target
D	Supply target (e.g. building volume)	6	Resource exergy consumption caused by rejecting a heat flow below the reference temperature to a "cooling source"

Direct cooling is cooling using thermal sources whose temperature is lower than the temperature of demand. This includes cooling with night air or with lake water, river water, seawater or natural ice.

Direct cooling is to be considered in the same way as waste heat, since here too, a resource is used that is available in a storable form near the demand. For this reason, the consideration of RECs to produce pipes and heat exchangers can also be dispensed with in this case.

$$X_{R,ts} = \left(Q_{cd,d} + Q_{cd,l,s} + Q_{cd,l,t}\right) \cdot \left|f_{R,ts}\right| \tag{36}$$

where

$X_{R,ts}$	resource exergy consumption of the cooling supply from direct cooling
$Q_{co,d}$	covered cooling demand
$Q_{co,l,s}$	cooling losses or heat input through storage
$Q_{co,l,t}$	cold losses or heat input due to transport
$f_{R,ts}$	resource exergy factor of the thermal source

Thanks to equations (9) and (26) the REC of cooling can be calculated based on energy-based or exergy-based weighting factors for heat.

Direct cooling is often accompanied by significant consumption of auxiliary power. The REV for its production must be considered accordingly, but this can be done separately.

11.4.2 Chillers

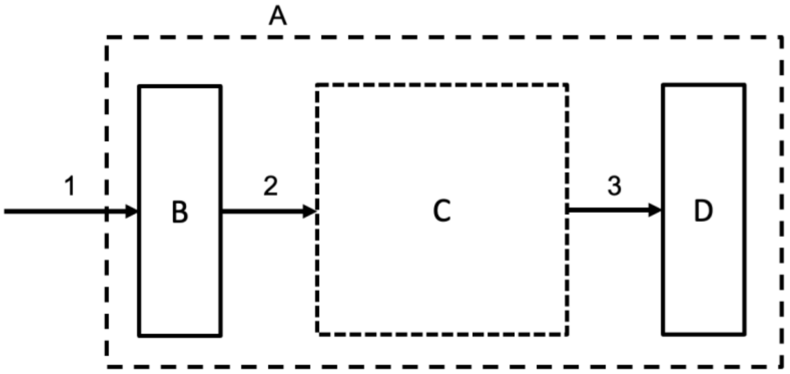

Figure 8 – Balance boundary of the resource exergy analysis for the coverage of a cooling demand above the reference temperature by a refrigerating machine with a heat flow below the reference temperature.

Legend

A	Balance boundary	1	Resource exergy consumption for the generation of driving exergy and the manufacture of the refrigerating machine
B	Upstream chain of driving exergy and production (extraction, transport, losses)	2	Exergy supply through driving exergy to C

C	Energy supply system (e.g. chiller)	3	Exergy input to D through withdrawal of a heat flow below the reference temperature
D	Supply target (e.g. building volume)		

In the REA chillers are cooling systems that absorb heat from a supply target and reject heat at or above reference temperature using some form of driving exergy.

The REC of the cooling with chillers is the sum of the RECs for construction and operation. The REC required for operation only considers the REC for the drive, e.g. for electricity. The heat absorbed by the refrigerating machine is not considered, as this represents a demand and is therefore not included in a consumption figure. The following formula applies to all cases in which the warm side of the refrigerating machine is not used. If it is used, the system becomes a system with heat-cooling cogeneration and must be evaluated according to chapter 11.6.3.

$$X_{R,ch} = \left(Q_{cd,d} + Q_{cd,l,s} + Q_{cd,l,t}\right) \cdot \frac{f_{R,dr}}{\gamma_{ch}} \tag{37}$$

where

$X_{R,ch}$	resource exergy consumption of the refrigeration supply with a refrigeration machine
$Q_{cd,d}$	covered cooling demand
$Q_{cd,l,s}$	cooling losses or heat input due to storage
$Q_{cd,l,t}$	cold losses or heat input due to transport
$f_{R,dr}$	resource exergy factor of the driving energy
γ_{ch}	working coefficient of the refrigerating machine in the time step under consideration

11.4.3 Deep cooling machines

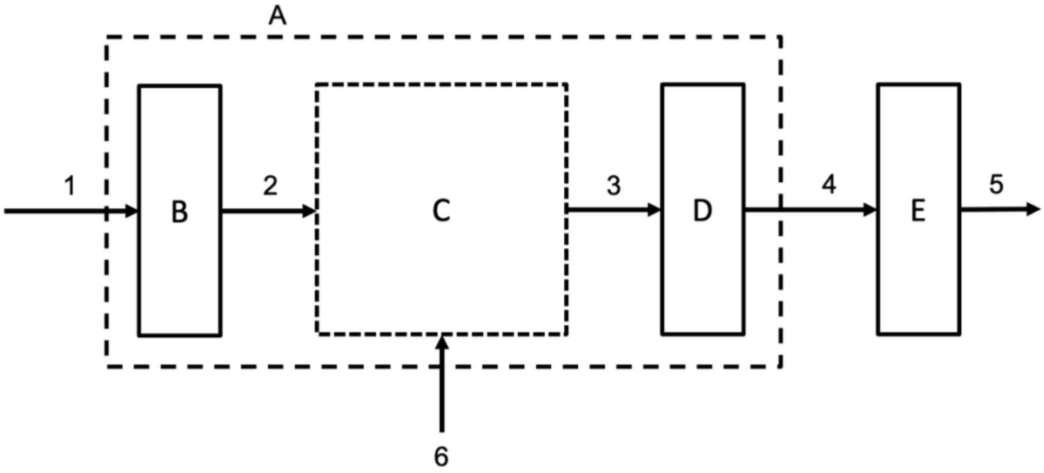

Figure 9 – Balance boundary of the resource exergy analysis for the coverage of a cooling demand by a deep cooling machine with a heat sink temperature and a target temperature below the reference temperature

Legend

A	Balance boundary	1	Resource exergy consumption to produce the driving exergy
B	Upstream chain of driving exergy and production (extraction, transport, losses)	2	exergy input to C
C	Energy supply system (e.g. deep cooling machine)	3	exergy input to D
D	Supply target (e.g. deep-freeze container)	4	Useful exergy consumption by extracting heat below reference temperature
E	Boundary to the environment (e.g. insulated wall)	6	Resource exergy consumption of the heat given off by the freezer below the reference temperature

In the REA, deep cooling machines are cooling systems that extract heat from a supply target and release heat below the reference temperature. Such systems can only be operated if other systems produce cold below the reference temperature or if a reservoir with such a temperature is naturally present, e.g. ice or snow during a day with temperatures above 0 °C.

The negative Carnot factor of heat below the reference temperature means that the heat flow released in deep cooling systems must be considered as an incoming exergy flow in the exergy system balance. Consequently, it also is an exergy input when the REC.

The REC of the cooling supply with deep cooling machines is made up of the REs for construction and operation. The RE required for operation considers the RE for the drive, e.g. for electricity, and the RE for the rejected heat below the reference temperature, which represents an exergy input flow. The heat absorbed by the deep cooling machine unit is not considered, as this represents a demand and is therefore not considered in a consumption variable.

The following equation (38) applies to all cases of a deep cooling machine. Below reference temperature, heating is just an acceleration of a naturally occurring process. Therefore, a combined heating and cooling system operating below reference temperature, is effectively considered a deep cooling machine.

Often the amount of heat given off by the deep cooling machine is not measured. To be able to evaluate this heat, the amount of heat that is transferred to the heat sink below the reference temperature can be determined thanks to an energy balance of the system. It is assumed that at least as much heat is absorbed by the heat sink as is necessary to fulfil the energy balance of the system. With this determination, the REV for cooling from a deep cooling machine can be defined as follows based on the derivations in Appendix E:

$$X_{R,dc} = \left(Q_{cd,d} + Q_{cd,l,s} + Q_{cd,l,t}\right) \cdot \left(\frac{f_{R,dr}}{\gamma_{dc}} + |f_{C,th}| \cdot \left(1 + \frac{1}{\gamma_{dc}}\right)\right) \tag{38}$$

where

$X_{R,dc}$	resource exergy consumption of the cooling supply with a deep cooling machine
$Q_{cd,d}$	covered cooling demand
$Q_{cd,l,s}$	cooling losses due to storage
$Q_{cd,l,t}$	cooling losses through transport
$f_{R,dr}$	resource exergy factor of the driving energy
γ_{dc}	Working coefficient of the deep cooling machine in the time step under consideration
$f_{C,th}$	Carnot factor of the rejected heat

11.5 Synthetic fuels

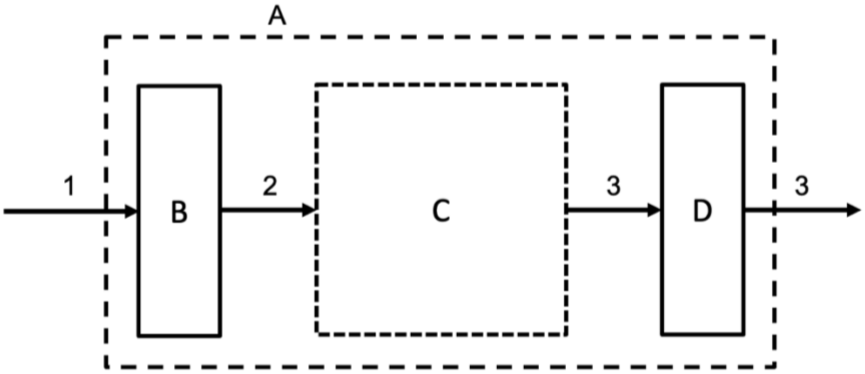

Figure 10 – Balance boundary of the resource exergy analysis to produce synthetic fuels

Legend

A	Balance boundary	1	Resource exergy consumption
B	Upstream chain (production, transport, losses)	2	Exergy input of C
C	Energy supply system (e.g. electrolyser)	3	Useful energy demand (e.g. hydrogen)
D	Supply destination (e.g. end of hydrogen pipeline)		

Like electrical energy, fuels are also energy carriers with an energy quality of 100 %. This means that they could theoretically be converted into electricity with an efficiency of 100 % [5]. The REC for their generation results from the REs of the necessary infrastructure and the REs for the operation of the corresponding generation plants.

$$X_{R,syf} = \left(E_d + E_{l,s} + E_{l,t}\right) \cdot \frac{f_{R,in}}{\eta_{syf}} \tag{39}$$

where

$X_{R,syf}$	resource exergy consumption of the synthetic fuel
E_d	energy demand
$E_{l,s}$	energy losses due to storage
$E_{l,t}$	energy losses due to transport
$f_{R,in}$	resource exergy factor of the directly storable resource used

η_{syf}	(higher heating value related) energy efficiency of the synthetic fuel generation plant.

If unavoidable waste heat from the production of synthetic fuels is used, the equations presented in section 0 apply to the evaluation of the waste heat. The determination of the REC of the synthetic fuel thereby remains unchanged compared to equation (39).

If the synthetic fuel production is adapted to extract heat at an increased temperature compared to unavoidable waste heat, REVs of the synthetic fuels as well as those of the heat must be calculated based on the universal equations for co-products in section 11.7.

11.6 Co-production

11.6.1 General

This section describes the rules for determining the RECs of special cases of co-production such as combined heat and power and combined heat and cooling. The corresponding equations are special forms of the universal equations presented in section 11.7. Variants of co-production not described in this section can be determined based on the corresponding universal equations.

11.6.2 Combined heat and power generation

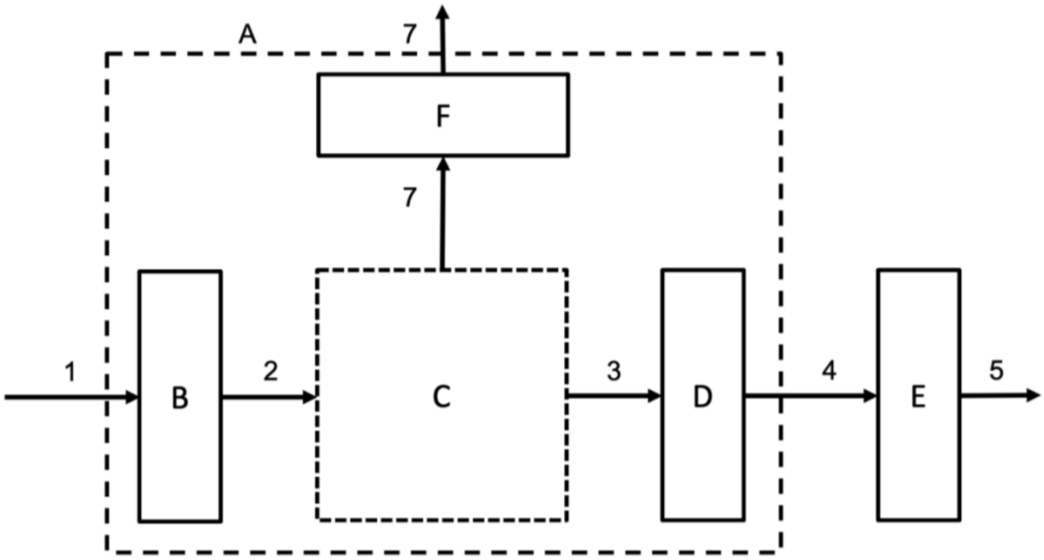

Figure 11 – Balance boundary of the resource exergy analysis for the coverage of a heat demand by cogeneration

Legend

A	Balance boundary	1	Resource exergy consumption to produce the energy converters and the provision of driving exergy (e.g. biogas or heat from deep geothermal energy).

B	Upstream chain (production, transport, losses)	2	Exergy input to C
C	Energy supply system (e.g. cogeneration plant)	3	Exergy input to D
D	Supply target (e.g. building volume)	4	Useful exergy demand (for heat flows: at target temperature)
E	Boundary to the environment (e.g. wall)	5	Exergy losses from the supply target to the environment
F	Supply target of the co-product (e.g. end of power line)	7	Co-product (e.g. electricity), the quantity of which depends on the supply system and the useful exergy demand supplied (e.g. heating)

The following formulas are only valid for CHP plants that are operated in CHP mode and produce only one heat flow and one electricity flow each.

A key element in the calculation of RECs for CHP plants is the allocation factor. The allocation factor for electricity allocates a part of the resources used in the cogeneration plant to electricity. The allocation factor for heat allocates a part of the resources used in the cogeneration plant to the generated heat. It is also used for allocation of emissions of the CHP plant.

The allocation of fuels or heat flows to electricity and heat from combined heat and power plants is carried out according to the Carnot method as described in AGFW FW 309-6 [16]. The allocation factor for electricity resulting from the Carnot method can be represented as follows:

$$\alpha_{el} = \frac{\eta_{el}}{\eta_{el} + \eta_{th} \cdot f_C} \tag{40}$$

where

α_{el}	allocation factor of the CHP electricity
η_{el}	electrical energy efficiency of the CHP plant
η_{th}	thermal energy efficiency of the CHP plant
f_C	Carnot factor of the heat transferred to the heat grid

The following applies to heat:

$$\alpha_{th} = \frac{\eta_{th} \cdot f_C}{\eta_{el} + \eta_{th} \cdot f_C} \tag{41}$$

where

α_{th}	allocation factor of the generated heat
η_{el}	electrical energy efficiency of the CHP plant
η_{th}	thermal energy efficiency of the CHP plant
f_C	Carnot factor of heat transferred to the heat grid

The following applies in general:

$$\alpha_{th} + \alpha_{el} = 1 \tag{42}$$

where

α_{th}	allocation factor of the generated heat
α_{el}	allocation factor of the generated electricity

The following applies to the REC of CHP electricity:

$$X_{R,el} = \left(W_d + W_{l,s} + W_{l,t}\right) \cdot \alpha_{el} \cdot \frac{f_{R,in}}{\eta_{el}} \tag{43}$$

where

$X_{R,el}$	resource exergy consumption of electricity supply from cogeneration
W_d	electricity demand covered by the CHP plant in CHP mode[6]
$W_{l,s}$	power losses due to storage
$W_{l,t}$	electricity losses due to transport
α_{el}	allocation factor of the electric current
$f_{R,in}$	resource exergy factor of the fuel or heat flow used
η_{el}	(higher heating value-related) electrical energy efficiency of the CHP plant

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[6] Only in rare, exceptional cases is a CHP plant used exclusively to supply heat and electricity demands. In most cases, peak load generators are also used. The formulas therefore only refer to the share of heat or electricity in the demand that is covered by the CHP plant.

The following applies to the heat flow generated by the CHP plant:

$$X_{R,th} = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot \alpha_{th} \cdot \frac{f_{R,in}}{\eta_{th}} \tag{44}$$

where

$X_{R,th}$	resource exergy consumption of the heat supply from cogeneration
Q_d	heat demand covered by the CHP plant in CHP operation
$Q_{l,s}$	heat losses due to storage
$Q_{l,t}$	heat losses through transport
α_{th}	allocation factor of CHP heat
$f_{R,in}$	resource exergy factor of the fuel or heat flow used
η_{th}	(higher heating value-related) thermal energy efficiency of the CHP plant

11.6.3 Combined heating and cooling

If both the hot and the cold sides of a heat pump cover a demand, this is called combined heating and cooling (CHC). Three cases are distinguished for the evaluation thanks to the REA.

1. If cooling in a CHC plant provides a cooling temperature above the reference temperature, e.g. in server rooms, no product energy flow can be assigned to the cooling flow.

   In this case, the entire REC of the CHC plant is assigned to heat. However, the absorbed heat flow (cooling) must be considered as resource input in the form of waste heat, otherwise the exergy balance is incomplete. In this case, the CHC plant is evaluated like a heat pump with waste heat utilization (see section 11.3.4).

2. If heating with a CHC plant takes place below the reference temperature, e.g. expansion valves, no product energy flow can be assigned to the heat flow.

   In this case, the entire REC is allocated to cooling. The “heating” heat flow below the reference temperature must be considered as free cooling for the energy balance and exergy balance following the rules laid out for deep cooling machines (see section 0).

3. If the heat demand is above and the cooling demand below the reference temperature, allocation of the REC to heating and cooling is necessary.

   There are several ways to determine the total RECs of the CHC plant. The simplest is to calculate the total REC first without allocation. It can then be allocated to both products.

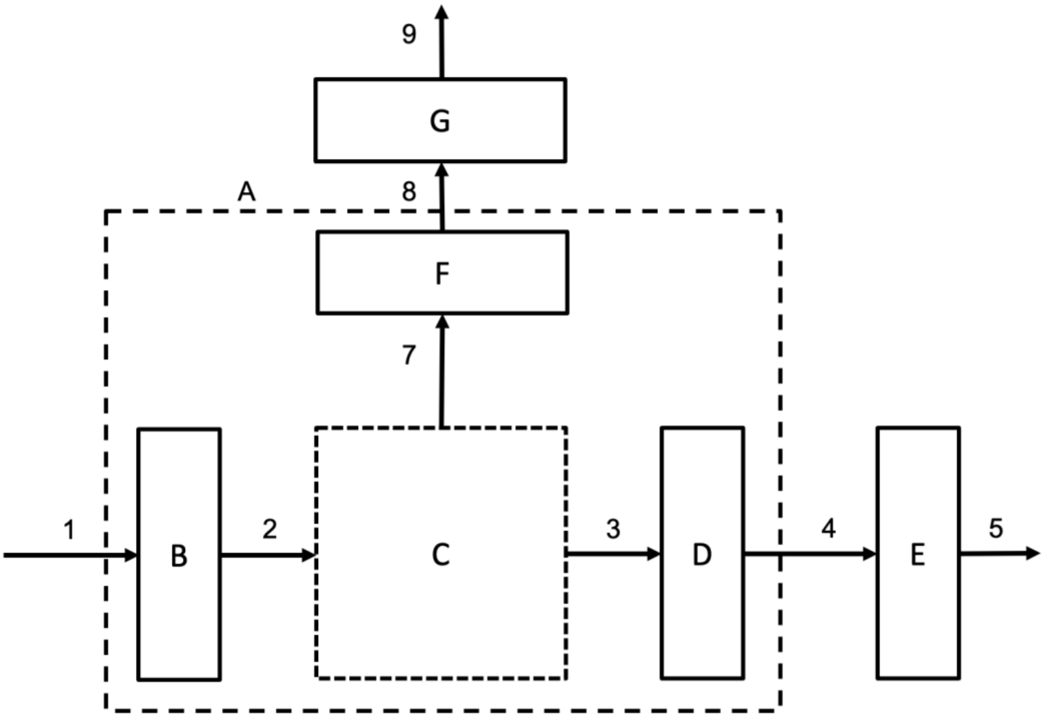

Figure 12 – Balance boundary of the resource exergy analysis for the coverage of a heating and cooling demand by a CHP plant with a heating target temperature above and a cooling target temperature below the reference temperature

Legend

A	Balance boundary	1	Resource exergy consumption to produce the energy converters and the generation of the drive energy (e.g. electricity).
B	Upstream chain (production, transport, losses)	2	Exergy input to C
C	Energy supply system (e.g. CHP plant)	3	Exergy input to D
D	Supply target: heat (e.g. space heating)	4	Useful exergy demand: Heat (for heat flows: at target temperature)
E	Boundary to the environment (e.g. insulated wall)	5	Exergy losses from the supply target to the environment
F	Supply target: cold	7	Exergy input to F
G	(e.g. cold room)	8	Useful energy demand: cooling (for heat flows: at target temperature)
		9	Exergy losses from the supply target to the surroundings

The resource exergy consumption of the overall CHC system for heat production above and cold production below the reference temperature is calculated as:

$$X_{R,sys} = \left(Q_{d,hd} + Q_{l,s,hd} + Q_{l,t,hd}\right) \cdot \frac{f_{R,in}}{\gamma_{hd}} \tag{45}$$

where

$X_{R,sys}$	resource exergy consumption of the overall heating-cooling cogeneration system
$Q_{d,hd}$	covered heat demand
$Q_{l,s,hd}$	heat losses due to storage
$Q_{l,t,hd}$	heat losses through transport
$f_{R,in}$	resource exergy factor of the driving energy
γ_{hd}	heat-related coefficient of performance

The REC of the entire system for heat production above and cold production below the reference temperature can also be calculated analogously based on the cold side values[7] :

$$X_{R,sys} = \left(Q_{d,cd} + Q_{l,s,cd} + Q_{l,t,cd}\right) \cdot \frac{f_{R,in}}{\gamma_{cd}} \tag{46}$$

where

$X_{R,sys}$	resource exergy consumption of the overall heating-cooling cogeneration system
$Q_{d,cd}$	covered cooling demand
$Q_{l,s,cd}$	cooling losses due to storage
$Q_{l,t,cd}$	cold losses due to transport
$f_{R,in}$	resource exergy factor of the driving energy
γ_{cd}	cooling-related coefficient of performance

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[7] Theoretically, the REC of the entire system could also be calculated based on cooling and heating. However, energy flows of different energy quality would then be added, which makes a basic understanding of the calculation and the process more difficult.

In the case that the temperature of the heat flow is above, and the temperature of the cold flow is below the reference temperature, the Carnot method is being used to allocate the driving energy to heating and cooling. The allocation factors for heat from such a CHC plant result as:

$$\alpha_{hd} = \frac{\gamma_{hd} \cdot f_{C,hd}}{\gamma_{hd} \cdot f_{C,hd} + \gamma_{cd} \cdot f_{C,cd}} \tag{47}$$

where

α_{hd}	allocation factor of the heat
γ_{hd}	heat-related coefficient of performance of the CHC plant
$f_{C,hd}$	Carnot factor of the heat transferred to the heating network
γ_{cd}	cooling-related coefficient of performance of the CHC plant
$f_{C,cd}$	Carnot factor of the cooling supplied to the cooling network

Analogously, the allocation factor for CHC cooling from such a CHC plant is defined as:

$$\alpha_{cd} = \frac{\gamma_{cd} \cdot f_{C,cd}}{\gamma_{hd} \cdot f_{C,hd} + \gamma_{cd} \cdot f_{C,cd}} \tag{48}$$

where

α_{cd}	allocation factor of cooling
γ_{hd}	heat-related coefficient of performance of the CHC plant
$f_{C,hd}$	Carnot factor of the heat transferred to the heating network
γ_{cd}	cooling-related coefficient of performance of the CHC plant
$f_{C,cd}$	Carnot factor of the cooling supplied to the cooling network

In general

$$\alpha_{hd} + \alpha_{cd} = 1 \tag{49}$$

where

α_{hd}	allocation factor of the generated heat
α_{cd}	allocation factor of the generated cooling

The REC of the heat from a CHC plant for heat supply above and cooling supply below reference temperature thus results in:

$$X_{R,hd} = \alpha_{hd} \cdot X_{R,sys} \tag{50}$$

where

$X_{R,hd}$	resource exergy consumption of the heat supply from combined heating and cooling
$X_{R,sys}$	resource exergy consumption of the overall combined heating and cooling system
α_{hd}	allocation factor of heating supply

The REC of the cold side for heat production above and cold production below the reference temperature is thus given as:

$$X_{R,cd} = \alpha_{cd} \cdot X_{R,sys} \tag{51}$$

where

$X_{R,cd}$	resource exergy consumption of the cooling supply from heat-cooling coupling
$X_{R,sys}$	resource exergy consumption of the combined heating and cooling system
α_{cd}	allocation factor of the cooling supply

The REFs can be used after determination of the REC according to Section 8.3.

11.7 Universal equations

The total REC of an energy system is the sum of the RECs for the supply of individual energy products (see formula 8).

The REC caused by an energy system for a product can generally be calculated using the following equation.

$$X_{R,y} = \left(E_{d,y} + E_{l,s,y} + E_{l,t,y}\right) \cdot \sum_{1}^{z} \left(\phi_z \cdot \alpha_{y,z} \cdot \frac{f_{R,in,z}}{\eta_{y,z}}\right) \tag{52}$$

where

$X_{R,y}$	resource exergy consumption of the product y
$E_{d,y}$	energy demand of product y by the supply target

$E_{l,s,y}$	energy losses of product y due to storage
$E_{l,t,y}$	energy losses of product y due to transport
ϕ_z	final energy share of the energy flow z that enters the supply system
$\alpha_{y,z}$	allocation factor of the product y when generated from the input stream z
$f_{R,in,z}$	resource exergy factor of the incoming energy flow z
$\eta_{y,z}$	energy efficiency (related to higher heating value) of the generation of the product y from the input stream z

The corresponding allocation factor of a product is calculated according to the generalized Carnot method:

$$\alpha_y = \frac{X_{pr,y}}{\sum_1^z X_{pr,z}} \tag{53}$$

where

α_y	allocation factor of the product y
$X_{pr,y}$	exergy of the product flow y
$X_{pr,z}$	exergy of the product stream z

The sum of all allocation factors is equal to one. Accordingly, for energy conversion plants without cogeneration, the allocation factor is also equal to one.

The final energy share of a final energy entering the supply system is calculated as:

$$\phi_z = \frac{E_{fin,z}}{\sum_1^x E_{fin,x}} \tag{54}$$

where

ϕ_z	final energy share of the energy flow z that enters the supply system
$E_{fin,z}$	final energy of the supply current z
$E_{fin,x}$	final energy of the supply current x

The exergy of thermal product flows is always determined based on the temperatures on the heat network side of the heat exchangers of the generation plants.

For generators that use only one final energy flow, the final energy shares are equal to one.

If a product is produced from several final energy flows without co-production, the corresponding RECs add up according to formula (52). The allocation factor is equal to one.

For heat pumps, chillers, deep cooling machines and CHC plants, formula (52) must be adapted. Instead of energy efficiency, the coefficient of performance is used to consider the share of the REC resulting from electricity or driving heat consumption. However, the heat absorbed from heat sources above the reference temperature also contributes to its REC. Similarly, heat generated below the reference temperature contributes to REC.

For the valuation of products from co-production, the REC consumed by the overall system is basically calculated according to a general form of the Carnot method – see formula (53).

Allocating the input flows to coupled product flows enables the comparison of such product flows with similar product flows from uncoupled production. The most common types of co-production (CHP and CHC) have already been presented in section 11.6.

In principle, the REA should be carried out in such a way that each plant is assessed individually, i.e. that products are only considered coming from co-production if they are produced in one process or plant.

Occasionally, however, too little data is available to evaluate individual plants or processes within an energy system. Thus, if several individual plants are connected to produce several products in a coupled manner within a black box, these individual plants can be evaluated as if they were one plant with co-production.

In this case, the RECs of the input flows would have to be added up and allocated to the products according to the product exergy (see formula (52) and (53)). Such a procedure is only permissible if it is not possible to consider individual plants. In this case, the results represent a well-founded approximation, but may deviate from the results for the REVs, which could be determined based on the consideration of the individual plants or processes.

Tables

Figures

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Appendix A
Weighting factors

A.1 General

The weighting factors presented in this section have been determined for Germany in 2022. They represent mean values from which measured factors can deviate greatly [17]. Due to this uncertainty for specific energy flows, all factors except the one for the German electricity mix can also be used in other countries without generating large systematic errors[8], as they only differ in the expenses and emissions for transport. In this context, the factors are the more accurate the closer the place of application is to the German-speaking region. In principle, however, a worldwide application of the factors listed here also appears permissible for analyses, since it can be assumed that the expenses for transport play a subordinate role for energy products.

Except for the quoted values of the primary energy factors, all standard weighting factors are shown in Table 4, Table 5, Table 6, Table 7 and Table 8 are determined in relation to higher heating value and therefore apply to the assessment of a higher heating value-related quantity of energy. They include all expenses for extraction, processing, conversion and transport from the place of primary energy extraction to the boundary of the system under consideration. These expenses are colloquially referred to as the upstream chain.

The central weighting factors for this calculation guide are the REFs.

Emission factors are given to allow a REA to be carried out in parallel with a GHG emissions analysis using data from the same database. In addition to CO_2, the data on greenhouse gas emissions also include emissions of other greenhouse gases such as methane and nitrous oxide, converted into CO_2 equivalents. For each energy flow, the greenhouse gas emissions over an observation period of 100 years (GWP100) and over an observation period of 20 years (GWP20) are given. The GWP20 values are generally higher, as short-lived greenhouse gases such as methane have a greater influence.

In addition to REF and CO_2 equivalents, cumulative energy demand (CED) and primary energy factors (PEF) are listed to allow a quantification of the difference to the respective REFs. The primary

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[8] Instead of the German electricity mix, the corresponding national electricity mixes in other countries must be considered. Since CExD-data is often not available for this, the REFs for electricity can be approximated with the respective CEDs. Emissions for the national electricity mix can usually be obtained from national databases. When procuring data, care should be taken to use data that is as well-founded as possible, that includes all upstream chains and that takes energy trade into account.

energy factors (non-renewable) are shown in relation to the lower heating value, as is customary in the most literature [9].

As additional information for fuels, the specific exergy and the higher heating value are also given. Both differ from each other in part because the specific exergy takes entropic effects into account.

A.2 Adjustments of weighting factors to REA

Some weighting factors were adjusted to the REA, as some REA balance boundaries do not match the specifications for the listed factors in the LCA database used [9].

Detailed information on all values and the performed adjustments can be found in the accompanying Excel table to this guide [3].

The following adjustments were made.

Adjustments for the REF compared to CExD from the LCA database:

1. The chemical exergy of water was not considered, as it represents a transit exergy for energy systems. Instead, corresponding CED values for the energy generated from hydropower were considered in the REFs.
2. For PV and wind power, the exergy-based contribution of “renewable solar” and “renewable kinetic” was set to one, i.e. conversion losses from solar and kinetic exergy to electrical are not considered.
3. For solar thermal, the solar exergy was replaced with the Carnot factor of the heat extraction from the solar collector.
4. For deep geothermal energy, the Carnot factor of heat extraction from the geothermal heat exchanger after transfer to the district heating system was added.

Adjustments in the tabulated CEDs presented in Appendix A compared to the CEDs from the LCA database:

1. In the case of electricity from hydropower in reservoirs, the potential energy was considered instead of the energy generated from hydropower, since the potential energy can already be stored directly.
2. For PV, wind power, solar thermal energy and deep geothermal energy, the energy-based contribution of “Renewable wind, solar, geoth” was set to one, i.e. conversion losses of solar and kinetic exergy into electrical or thermal energy are not considered.

3. For heat pumps, the contribution from “renewable, wind, solar, geoth.” was replaced with a contribution resulting from $\left(1-\frac{1}{\gamma_{hp}}\right)$. I.e. the heat exchangers used to extract heat from the heat source operate loss-free for the REA.

A.3 LCA-based standard weighting factors

The following weighting factors are mean values of the data from an LCA database [9].

Table 8 shows the original values adjusted to the REA balance boundaries. The calculations of the mean values can be traced in the accompanying Excel file to this calculation guide [3].

If the origin of oil, coal and gas is known, it is preferable to use the weighting factors given in

Table 8.

Following the ISO house style [18] the decimal sign is the comma, while numbers are grouped in groups of three to facilitate reading.

Table 4 – Weighting factors for fuels (arithmetic mean values)

	Energy source		$f_{P,nrene}$ in kWh/ kWh$_{LHV}$	Specific exergy in kWh/kg	Higher heating value in kWh/kg	REF (f_R)	CED	f_{CO2eq} (GWP100) in kg/kWh	f_{CO2eq} (GWP20) in kg/kWh
1	Fossil fuels	Heating oil	1,1	12,9	12,7	1,22	1,22	0,329	0,361
2		Heavy oil	1,1	12,9	12,7	1,16	1,16	0,351	0,396
3		Natural gas (mix)	1,1	14,0	14,9	1,26	1,25	0,272	0,314
4		Natural gas (pipeline)	1,1	14,0	14,9	1,13	1,12	0,248	0,290
5		Liquefied natural gas without fracking (LNG)	1,1	14,0	14,9	1,40	1,37	0,296	0,338
6		Hard coal	1,1	6,6	6,4	1,16	1,16	0,388	0,420
7		Lignite	1,2	2,9	2,8	1,15	1,15	0,435	0,444
8	Biogenic fuels	Biogas, directly from biogas plants	0,3	7,4	7,4	1,39	1,35	0,096	0,165
9		Biomethane	0,5	11,6	11,6	1,52	1,47	0,136	0,255
10		Bio-oil	1,1	11,3	11,3	1,82	1,74	0,188	0,201
11		Wood	0,2	5,6	5,7	1,16	1,13	0,012	0,014
12	Nuclear fuels	Uranium fuel rods (4% UO2 & MOX)		1 212 145	1 212 145	1,05	1,05	0,002	0,003

In the case of thermal sources, not all REFs can be specified with a fixed value, since the exergy of the heat flows depends on their temperature and on the reference temperature. To determine the Carnot factors, the temperatures on the heat network side of the generators are used as a basis. This means that the transmission losses from thermal sources are not considered.

Table 5 – Weighting factors for heating

	Energy source		**$f_{P,nrene}$ in kWh/kWh_{LHV}**	**REF (f_R)**	**CED**	**f_{CO2eq} (GWP100) in kg/kWh**	**f_{CO2eq} (GWP20) in kg/kWh**
1	Environmental heat	Ambient heat (air)	0,0a	0,00	1,00	0	0
2	Thermal energy sources	Shallow geothermal energy, heat from bodies of water	0,0	f_C	1,00	0	0
3		Deep geothermal energy	0,0	0,05+ f_C	1,04	0,011	0,012
4		Solar thermal	0,0	0,15+ f_C	1,13	0,020	0,023
5	Waste heat	unavoidable	0,0	f_C	1,00	0	0

Table 6 – Weighting factors for electricity

	Energy source		**$f_{P,nrene}$ in kWh/kWh_{LHV}**	**REF (f_R)**	**CED**	**f_{CO2eq} (GWP100) in kg/kWh**	**f_{CO2eq} (GWP20) in kg/kWh**
1	Power	network-related (DE)	1,8	2,63	2,55	0,476	0,533
2		directly from photovoltaics,	0,0	1,21	1,17	0,041	0,049
3		Directly from wind power	0,0	1,06	1,05	0,011	0,013
4		Directly from hydropower	0,0	1,07	1,07	0,011	0,013
5		Electricity from deep geothermal energy9	0,0	1,30	8,14	0,068	0,077

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[9] This value should only be used if a separate calculation of geothermal electricity generation based on electrical efficiencies is not possible. The first directly storable form of energy is hot water extracted from the surface, so this should be considered as a resource.

	Energy source		$f_{P,nrene}$ in kWh/kWh_{LHV}	REF (f_R)	CED	f_{CO2eq} (GWP100) in kg/kWh	f_{CO2eq} (GWP20) in kg/kWh
6	Power	Electricity from materials that must be thermally treated or disposed of (waste, sewage sludge, sewage gas, landfill gas, mine gas, etc.).	0,0	1,00	1,00	0	0

Table 7 - Weighting factors for cooling

	Energy source	$f_{P,nrene}$ in kWh/kWh_{LHV}	REF (f_R)	CED	f_{CO2eq} (GWP100) in kg/kWh	f_{CO2eq} (GWP20) in kg/kWh
1	Direct cooling with air or water from the environment	0,7	f_C	1,00	0	0

Table 8 – Weighting factors from the LCA database

Where required, the weighting factors for REF and CED have been adapted to the REA following the rules laid out in section A.2.

Record name	Unit	Specific exergy in kWh/kg	Higher heating value in kWh/kg	REF (f_R)	CED	f_{CO2eq} (GWP100) in kg/kWh	f_{CO2eq} (GWP20) in kg/kWh
	kg	46,50	45,80	1,25	1,25	0,335	0,366
Fuel oil (Saudi Arabia)	kg	46,50	45,80	1,19	1,19	0,317	0,340
Fuel oil (Russia)	kg	46,50	45,80	1,23	1,23	0,340	0,394
Heating oil (Canada)	kg	46,50	45,80	1,23	1,23	0,324	0,344
Heavy oil	kg	46,50	45,80	1,16	1,16	0,351	0,396
Natural gas (pipeline from Norway)	m^3	36,00	38,30	1,05	1,04	0,211	0,213

Record name	**Unit**	**Specific exergy in kWh/kg**	**Higher heating value in kWh/kg**	**REF (f_R)**	**CED**	**f_{CO2eq} (GWP100) in kg/kWh**	**f_{CO2eq} (GWP20) in kg/kWh**
Natural gas (pipeline from Russia)	m^3	36,00	38,30	1,21	1,20	0,285	0,366
Natural gas (liquefied gas from the USA, conventional production)	m^3	36,00	38,30	1,41	1,39	0,304	0,355
Natural gas (liquefied gas from Qatar)	m^3	36,00	38,30	1,38	1,35	0,287	0,322
Hard coal (Russia)	kg	24,23	23,49	1,20	1,20	0,410	0,488
Hard coal (USA)	kg	26,00	25,21	1,11	1,11	0,370	0,395
Hard coal (Australia)	kg	27,19	26,36	1,12	1,12	0,374	0,397
Hard coal (Colombia)	kg	24,63	23,88	1,08	1,08	0,356	0,360
Hard coal (Indonesia)	kg	16,21	15,72	1,32	1,32	0,429	0,459
Lignite (Germany)	kg	10,30	9,90	1,04	1,04	0,409	0,415
Lignite (Poland)	kg	10,30	9,90	1,07	1,07	0,417	0,423
Lignite (USA)	kg	10,30	9,90	1,16	1,16	0,438	0,448
Lignite (China)	kg	10,30	9,90	1,24	1,25	0,463	0,478
Lignite (Russia)	kg	10,30	9,90	1,26	1,26	0,447	0,458
Biogas (manure and residues, directly from biogas plants)	m^3	26,60	26,60	1,13	1,13	0,056	0,101
Biogas (maize and cultivated biomass, directly from biogas plants)	m^3	26,60	26,60	1,64	1,57	0,135	0,230

Record name	**Unit**	**Specific exergy in kWh/kg**	**Higher heating value in kWh/kg**	**REF (f_R)**	**CED**	**f_{CO2eq} (GWP100) in kg/kWh**	**f_{CO2eq} (GWP20) in kg/kWh**
Biomethane (liquid manure and residues)	m^3	41,60	41,60	1,28	1,28	0,098	0,192
Biomethane (maize and cultivated biomass)	m^3	41,60	41,60	1,76	1,67	0,175	0,318
Organic oil (rapeseed oil)	kg	40,50	40,50	1,65	1,58	0,213	0,226
Organic oil (palm oil)	kg	40,50	40,50	2,00	1,91	0,162	0,176
Wood – wood chips (cultivated biomass)	kg	20,10	20,10	1,08	1,03	0,007	0,008
Wood – wood chips (residual wood)	m^3	3842,91	3842,91	1,02	1,02	0,004	0,005
Wood – wood chips (Canada, cultivated biomass)	kg	20,10	21,10	1,34	1,31	0,010	0,010
Wood – pellets (waste wood)	kg	19,44	19,44	1,12	1,11	0,018	0,021
Wood – pellets (cultivated biomass)	kg	19,44	19,44	1,23	1,18	0,022	0,025
Electricity from PV (production mix, flat)	kWh	3,60	3,60	1,19	1,16	0,040	0,049
Electricity from PV (production mix, oblique)	kWh	3,60	3,60	1,22	1,18	0,042	0,050
Electricity from wind power	kWh	3,60	3,60	1,06	1,05	0,011	0,013
Electricity from run-of-river power	kWh	3,60	3,60	1,07	1,06	0,004	0,005
Electricity from hydroelectric power*	kWh	3,60	3,60	1,07	1,07	0,017	0,020

Record name	**Unit**	**Specific exergy in kWh/kg**	**Higher heating value in kWh/kg**	**REF (f_R)**	**CED**	**f_{CO2eq} (GWP100) in kg/kWh**	**f_{CO2eq} (GWP20) in kg/kWh**
Electricity from thermal waste treatment	kWh	3,60	3,60	1,00	1,00	0,000	0,000
Electricity mix (Germany)	kWh	3,60	3,60	2,63	2,55	0,476	0,533
Electricity mix (EU)	kWh	3,60	3,60	3,40	3,21	0,534	0,600
Heat from solar thermal (flat-plate collectors, production mix, flat)	MJ	1,00	1,00	0,12+f_C	1,10	0,016	0,019
Heat from solar thermal (flat-plate collectors, production mix, oblique)	MJ	1,00	1,00	0,11+f_C	1,10	0,015	0,017
Heat from solar thermal (vacuum tube collectors, production mix)	MJ	1,00	1,00	0,21+f_C	1,19	0,028	0,033
Heat from ground source heat pumps (10kW / COP 3.19)*	MJ	1,00	1,00	1,38	1,27	0,144	0,189
Heat from air source heat pumps (10 kW / COP 2,29)*	MJ	1,00	1,00	1,52	1,35	0,201	0,268
Heat from groundwater heat pumps (10 kW / COP 2.78)*	MJ	1,00	1,00	1,44	1,30	0,162	0,209

Record name	**Unit**	**Specific exergy in kWh/kg**	**Higher heating value in kWh/kg**	**REF (f_R)**	**CED**	**f_{CO2eq} (GWP100) in kg/kWh**	**f_{CO2eq} (GWP20) in kg/kWh**
Heat from river heat pumps (large heat pump 13 MW / COP 2.45)*.	MJ	1,00	1,00	1,47	1,32	0,174	0,217
Electricity from deep geothermal energy (open loop / hydrothermal – classic deep geothermal / electrical utilization ratio: 14 %*)	kWh	3,60	3,60	1,30	7,45	0,068	0,077
Heat from thermal waste treatment	kWh	3,60	3,60	1,00	1,00	0,000	0,000
Heat from deep geothermal energy	MJ	1,00	0,00	0,05+f_C	0,04	0,011	0,012
Fuel elements BWR, UO2 4.0% & MOX, at nuclear fuel fabrication plant	kg	4 415 553	4 415 553	1,07	1,07	0,002	0,003
Fuel elements PWR, UO2 4.0% & MOX, at nuclear fuel fabrication plant	kg	4 311 894	4 311 894	1,03	1,03	0,002	0,003
Green hydrogen from PV & Wind power*	kg	141,80	141,80	1,75	1,65	0,049	0,055

* These figures are intended as comparative values, as they only apply to certain COP / efficiency levels. They can be used for quick rough calculations. For accurate comparisons, weighting factors for heat pumps, green hydrogen and electrical generation from geothermal systems or hydropower from reservoirs must be calculated using the corresponding formulae in this calculation guide and the weighting factors for the energy flows used (electricity and heat).

Appendix B
Example analysis of a simple energy system with the REA (reference example)

Note: The calculated values for REC have been rounded to one decimal place.

B.1 Calculation assumptions and formula symbols for the reference example

In the following, a simple energy system will be examined using the REA as an example (reference example), which will be used for a comparison in Appendix D as a reference. The energy system contains a decentralized gas condensing boiler and a decentralized chiller. The public grid covers the electricity demand.

The focus of this system is on reducing energy demand, e.g. through insulation and the use of particularly efficient electrical appliances.

Since the energy system is used as a reference for the comparison in Appendix D, the total system properties are given the suffix “ref”.

The reference example can be represented by flow charts (Figure 13). In the following picture, only input flows and product flows that exceed the balance boundaries E or X are shown. Both flow diagrams are almost identical, with the difference that the cold flow 42 represents an energy input into the system, while at the same time it does not cover an exergy demand, as the “cooling demand” is above the reference temperature and thus only represents an acceleration of natural processes.

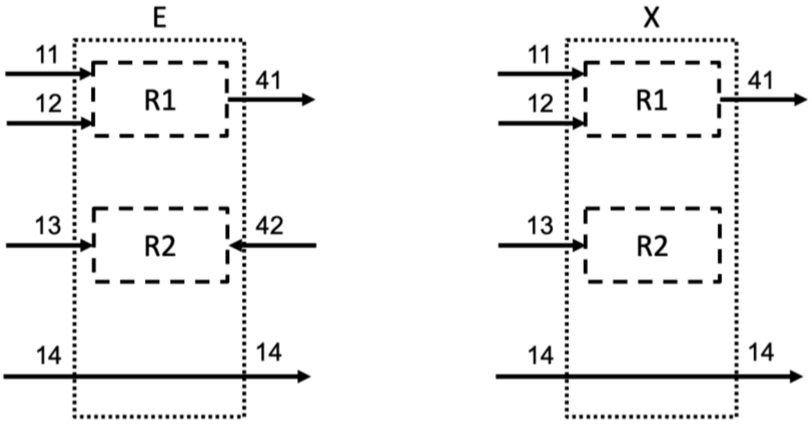

Figure 13 – Flow charts of the energy system: “reference example” for energy (E) and exergy (X)

Legend

E	Balance boundary of the reference example (energy-based)	11	Natural gas
X	Balance boundary of the reference example (exergy-based)	12	Auxiliary power from the mains
R1	Individual natural gas condensing boiler	13	Electricity from the grid
R2	Individual refrigerating machine	14	Electricity from the grid
		41	Heat
		42	“Cold”

The supply temperatures are the temperatures at the output of the generators. The temperature of cooling is below reference temperature. However, this temperature is irrelevant for the REA of a chiller that covers a demand above reference temperature.

B.2 Calculation assumptions and formula symbols for the reference example

Table 9 – Energy demand assumptions for the reference example

Energy system	Designation	Formula symbol	Value	Unit	Comment
R1	Heat demand	$Q_{d,hd,ref}$	80	MWh	
R2	Cooling demand	$Q_{d,cd,ref}$	25	MWh	The cooling demand is for cooling in some areas of the supply target.
R1, 14	Electricity demand	$W_{d,ref}$	20	MWh	

Table 10 – Assumptions for the performance indicators in the reference example

Energy system	Designation	Formula symbol	Value
R1	Energy efficiency of the natural gas boiler (based on higher heating value)	$\eta_{R1,1}$	95 %
R2	Annual performance factor chiller	$\gamma_{R2,cd}$	2,0

Table 11 – Assumptions for the temperatures in the reference example

Energy system	Designation	Formula symbol	Value in K (for calculation)	Value in °C (for information)
All	Reference temperature	T_0	283,15	10
All	Target temperature (heating and cooling)	$T_{d,tg}$	295,15	22

Table 12 – Assumptions for the auxiliary power demand in the reference example

Energy system	Designation	Formula symbol	Value
R1	Boiler	$\omega_{aux,R1}$	0,25 % | 0,0025*

* in relation to the generated heat flow

All REFs are taken from Appendix A.

Reductions in emerging equations are not made to ensure easier traceability.

B.3 Carnot factor of the heat demand

To simplify the analysis of the energy system, Carnot factors are to be calculated at this point, which are necessary for calculating the exergy flows. They are calculated according to the equations (1), (2) and (3) are determined. The Carnot factors are rounded to two decimal places, as the temperatures used for the calculation represent mean values over a period and are thus to be regarded as simplified assumptions.

Since only the target temperature plays a role in the reference example, only the Carnot factor of the heat demand is to be calculated here.

$$f_{C,tg} \tag{55}$$

$$= \left(1 - \frac{T_0}{T_{d,tg}}\right)$$

$$= \left(1 - \frac{283{,}15K}{295{,}15K}\right)$$

$$= 0{,}04$$

A Carnot factor of the cooling demand does not have to be calculated, as the temperature of the cooling demand is above the reference temperature and thus there is no exergy demand due to cooling. Instead there is only a demand for accelerated cooling, which would otherwise take place anyway. However, no exergy requirement can be formulated for this.

B.4 Useful exergy demand of the supply target

The useful exergy demand (UED) to be covered by the entire energy supply system is calculated according to the formula (12). This results in the following for the heat supply:

$$X_{d,hd} = f_{C,tg} \cdot Q_{d,hd} = 0{,}04 \cdot 80\ MWh = 3{,}2\ MWh \tag{56}$$

The value is rounded to one decimal place because it is a monthly analysis in which the fluctuations of the outdoor temperature would influence further decimal places. In some cases, the fluctuations of the outdoor temperature are so high that a range would have to be given in which the UED moves. However, since the UED is only an orientation value and not a central comparative value for a REA evaluation, the average value of the UED can be used for further calculations.

The electrical UED corresponds to the electricity demand.

The UED of cold is zero because the target temperature is higher than the reference temperature.

Thus, the REE for the cooling supply of the reference example is zero independent of the supply system. This in turn illustrates the lack of suitability of exergy efficiency as a universal comparative parameter for energy systems.

B.5 Heat from an individual natural gas boiler (R1)

The formula to be applied is formula (33). It is not necessary to take the lower heating value to higher heating value ratio into account, as the used REF and the energy efficiency assumed are already related to the higher heating value.

$$\begin{aligned} &X_{R,th,R1} \\ &= \frac{Q_{d,hd,ref}}{\eta_{th,R1}} \cdot \left(f_{R,f} + \omega_{aux,R1} \cdot f_{R,el,pm}\right) \end{aligned} \tag{57}$$

$$= \frac{80\ MWh}{0{,}95} \cdot (1{,}26 + 0{,}0025 \cdot 2{,}63)$$

$$= 111{,}6\ MWh$$

The REF of the heat from R1 is calculated according to formula (9) as:

$$f_{R,R1} = \frac{X_R}{E} = \frac{X_{R,R1}}{E_{d,hd}} = \frac{111{,}6\ MWh}{80\ MWh} = 1{,}40 \tag{58}$$

The REE of the supply of heat from R1 is given by the formula (16) as:

$$\xi_{R,R1} = \frac{\sum_1^y \left|X_{d,out}\right|_y}{\sum_1^z \left|X_{R,in}\right|_z} = \frac{X_{d,hd}}{X_{R,R1}} = \frac{3{,}2\ MWh}{111{,}6\ MWh} = 2{,}9\ \% \tag{59}$$

B.6 Cooling from an individual chiller (R2)

For the calculation of the REC from an individual chiller, formula (37) is applied.

$$\begin{aligned} &X_{R,R2} \\ &= \left(Q_{cd,d} + Q_{cd,l,s} + Q_{cd,l,t}\right) \cdot \frac{f_{R,in}}{\gamma_{ch}} \\ &= Q_{d,cd,ref} \cdot \frac{f_{R,el,pm}}{\gamma_{ch,R2}} \\ &= 25\ MWh \cdot \frac{2{,}63}{2{,}0} \\ &= 32{,}9\ MWh \end{aligned} \tag{60}$$

The REF of the cooling from R2 is obtained according to formula (9) as:

$$f_{R,R2} = \frac{X_R}{E} = \frac{X_{R,R2}}{Q_{d,cd}} = \frac{32{,}9\ MWh}{25\ MWh} = 1{,}32 \tag{61}$$

The REE of supplying the cooling from R2 is zero because the temperature at which the room is to be kept is above the reference temperature. I.e. cooling is only necessary due to a limited heat transfer rate but would basically happen by itself in the natural heat exchange with the environment.

B.7 Power consumption from the grid

The REC of the electricity consumption from the grid is calculated according to the explanations in section 9.2.

$$\begin{aligned} & X_{R,14} \\ & = W_d \cdot f_{R,el,pm} \\ & = 20\ MWh \cdot 2{,}63 \\ & = 52{,}6\ MWh \end{aligned} \tag{62}$$

The REF corresponds to the REF of the electrical power from the grid (2,63).

The REE is calculated according to formula (17).

$$\xi_{el,pm} = \frac{1}{f_{R,el,pm}} = \frac{1}{2{,}63} = 38{,}0\ \% \tag{63}$$

B.8 Overall system

Since only one supply system covers a demand at a time, the REC, the REF and the REE for heating, cooling and electricity each correspond to the values determined for the corresponding supply systems (R1, R2, 14).

The values for the reference example are given the additional index “ref”, as it is used as a reference system for comparisons. Appendix D comparisons.

The total REC of the reference example is:

$$\begin{aligned} & X_{R,ref} = \sum_{R1}^{y} X_{R,in,y} = X_{R,hd} + X_{R,cd} + X_{R,el} \\ & = (111{,}6 + 32{,}9 + 52{,}6)\ MWh = 197{,}1\ MWh \end{aligned} \tag{64}$$

The REC of the overall system is an informative assessment variable that allows the reference example to be compared with alternative systems, e.g. the more complex example of Appendix C and to determine the savings potentials of a complex system compared to a standard technology combination.

The average REF of the energy supply from the reference example is given by formula (10) as:

$$f_{R,avg,ref} = \frac{X_{R,ref}}{E_{d,hd,ref} + E_{d,cd,ref} + E_{d,el,ref}}$$

$$= \frac{197{,}1\ MWh}{80\ MWh + 25\ MWh + 20\ MWh} = 1{,}58 \tag{65}$$

The average REF of the energy system is to be regarded as a quantity, with severely limited informative value due to the consideration of energy flows of different energy quality (here electricity, heating and cooling).

No REE should be given for the present example, as a REE for cooling was not calculated.

The determined REFs für are primarily helpful in the selection and comparison of supply systems for heating, cooling and electricity, as described in Appendix D.

Appendix C
Example analysis of a complex energy system with the REA (complex example)

In the following, as an example a complex energy system with a renewable generation park (complex example) will be examined using the REA. The energy supply system consists of various almost greenhouse gas-neutral energy systems. The generator park contains: Boilers, thermal heat sources, a CHP plant powered by thermal energy, a CHC plant powered by PV-generated electricity and direct cooling.

The complex example (A1 – A6) is represented by the flow charts in Figure 14. In the following figure, only input flows and product flows that exceed the balance boundaries E or X are shown. Both flow diagrams are almost identical, with the difference that the cooling flows 45 and 64 represent an energy input of the system, while at the same no exergy demand is covered, since the target temperature of the cooling demand is above reference temperature.

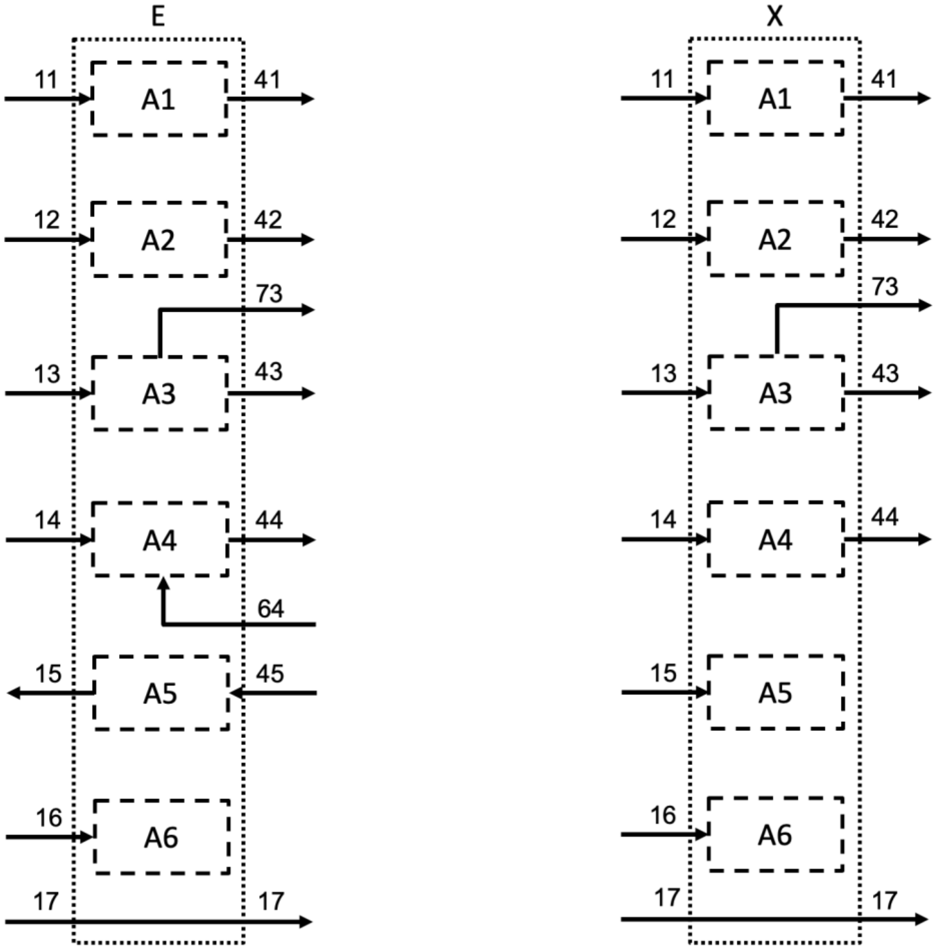

Figure 14 – Flow charts of the complex example for energy (E) and exergy (X)

Legend

E	Balance boundary of the complex example (energy-based)	11	Electricity from wind power
X	Balance boundary of the complex example (exergy-based)	12	Industrial waste heat
A1	Boiler with green hydrogen from wind power	13	Heat from deep geothermal energy
A2	Industrial waste heat	14	Electricity from photovolatics
A3	Deep geothermal CHP plant	15	Heat dissipation to a river
A4	Large CHC plant, operated with electricity from photovoltaics	16	Electricity from the grid
A5	Direct cooling with river water	41	Heat from boiler A1
A6	Auxiliary power supply of the energy park	42	Heat from waste heat A2
17	Electricity from the grid	43	Heat from CHP A3
73	Electricity from CHP plant A3	44	Heat from combined heating and cooling
64	“Cold” from combined heating and cooling (CHC)	45	“Cold” from direct cooling

C.1 Calculation assumptions and formula symbols for the complex example

Table 13 – Energy demand assumptions for the complex example

Energy system	Designation	Formula symbol	Value	Unit	Comment
All (sum)	Heat demand	$Q_{d,hd}$	100	MWh	
A4, A5	Cooling demand	$Q_{d,cd}$	40	MWh	The cooling demand is for cooling in some areas of the supply target.
A3, Mains	Electricity demand	W_d	30	MWh	

Table 14 – Assumptions for the performance indicators in the complex example

Energy system	**Designation**	**Formula symbol**	**Value**
A1	Energy efficiency of hydrogen boiler (higher heating value-related)	$\eta_{A1,1}$	90 %
A1	Energy efficiency of electrolyser (higher heating value-related)	$\eta_{A1,2}$	70 %
A3	Energy efficiency CHP plant (electrical)	$\eta_{A3,el}$	15 %
A3	Energy efficiency CHP plant (thermal)	$\eta_{A3,th}$	75 %
A4	Heat-related coefficient of performance of the CHC system	$\gamma_{A4,hd}$	3, 0
A1, A2, A3, A4	Energy efficiency of the district heating system (transport)	$\eta_{hd,t}$	88 %
A1, A2, A3, A4	Energy efficiency of the district heating system (storage)	$\eta_{hd,s}$	93 %
A3	Energy efficiency of the local power grid for own power supply (transport)	$\eta_{el,t}$	99 %
A4, A5	Energy efficiency of the district cooling system (transport)	$\eta_{cd,t}$	95 %
A4, A5	Energy efficiency of the district cooling system (storage)	$\eta_{cd,s}$	98 %

Waste heat utilisation and direct cooling do not require utilisation rates to calculate the resources consumed, as both energy sources are only evaluated after transfer to the energy supply system.

Table 15 – Assumptions for the temperatures in the complex example

Energy system	Designation	Formula symbol	Value in K (for calculation)	Value in °C (for information)
All	Reference temperature	$\boldsymbol{T_{0}}$	283,15	10
All	Target temperature (heat)	$\boldsymbol{T_{d,tg}}$	295,15	22
A1, A2, A3, A4	Supply temperature district heating	$\boldsymbol{T_{hd,sf,}}$	343,15	70
A1, A2, A3, A4	Return temperature district heating	$\boldsymbol{T_{hd,rf}}$	313,15	40
A3	Supply temperature from the deep geothermal borehole on the system side of the geothermal CHP system	$\boldsymbol{T_{ts,sf,A3}}$	453,15	180
A4, A5	District cooling supply temperature	$\boldsymbol{T_{cd,sf,}}$	277,15	4
A4, A5	Return temperature district cooling	$\boldsymbol{T_{cd,rf}}$	283,15	10

Table 16 – Assumptions for the auxiliary power consumption in the complex example

Energy system	Designation	Formula symbol	Value
A1	Boiler	$\omega_{aux,A1}$	0,2 % | 0,002
A2	Waste heat	$\omega_{aux,A2}$	0,5 % | 0,005
A1, A2, A3, A4	District heating	$\omega_{aux,hd,t}$	1,5 % | 0,015
A4, A5	District cooling	$\omega_{aux,cd,t}$	3,5 % | 0,035
A5	Cooling with river water	$\omega_{aux,A5}$	2,6 % | 0,026

Table 17 – Assumptions for the hares of thermal energy provided in the complex example

Energy system	Designation	Formula symbol	Value
A1	Boiler (heat)	$\boldsymbol{\phi_{A1,hd}}$	10 %
A2	Waste heat (heat)	$\boldsymbol{\phi_{A2,hd}}$	30 %
A3	CHP plant (heat)	$\boldsymbol{\phi_{A3,hd}}$	45 %
A4	CHC plant (heat)	$\boldsymbol{\phi_{A4,hd}}$	15 %

All REFs are taken from Appendix A.

Reductions in emerging equations are not made to ensure easier traceability.

C.2 Carnot factors for the energy system

To simplify the analysis of the energy system, Carnot factors are to be calculated at this point, which are necessary for calculating the exergy flows. They are calculated according to the equations (1), (2) and (3). The Carnot factors are rounded to two decimal places, as the temperatures used for the calculation represent mean values over a period and are thus to be regarded as simplified assumptions.

C.2.1 Carnot factor of demand

The Carnot factor of the demand corresponds to that in Section B.3.

$$f_{C,tg} = 0{,}04 \tag{66}$$

C.2.2 Carnot factor of district heating supply at heat generator

$$\begin{aligned} f_{C,hd} &= 1 - \frac{T_0}{T_{m,hd}} \\ &= 1 - \frac{T_0}{\left(\frac{T_{hd,sf} - T_{hd,rf}}{\ln\left(\frac{T_{hd,sf}}{T_{hd,rf}}\right)}\right)} \\ &= 1 - \frac{283{,}15K}{\left(\frac{343{,}15K - 313{,}15K}{\ln\left(\frac{343{,}15K}{313{,}15K}\right)}\right)} \end{aligned} \tag{67}$$

$$= 0{,}14$$

C.2.3 Carnot factor of heat from deep geothermal CHP (A3)

The heat of deep geothermal energy is used at the mean temperature of heat transfer. In doing so, according to section 9.8 only the temperatures on the supply system side are considered.

In concrete terms: The average temperature of the geothermal energy is calculated as an average temperature between supply and return temperature. The higher temperature corresponds to the supply temperature that is provided for the electricity generation plant. The lower temperature of the geothermal energy corresponds to the return temperature of the district heating network.

$$\begin{aligned} & f_{C,ts,A3} \\ & = 1 - \frac{T_0}{T_{m,ts}} \\ & = 1 - \frac{T_0}{\left(\frac{T_{ts,sf,A3} - T_{hd,rf}}{\ln \left(\frac{T_{ts,sf,A3}}{T_{hd,rf}} \right)} \right)} \\ & = 1 - \frac{283{,}15K}{\left(\frac{453{,}15K - 313{,}15K}{\ln \left(\frac{453{,}15K}{313{,}15K} \right)} \right)} \\ & = 0{,}25 \end{aligned} \tag{68}$$

C.2.4 Carnot factor of district cooling

For the cooling supply, particularly low temperatures were assumed to show an example how a REA for a CHC is performed. For Carnot factors of the cooling supply of zero and higher, all REC is allocated to heat in the case of combined heating and cooling. I.e. for these Carnot factors, an allocation is avoided, and the rules described in section 11.6.3 apply.

$$
\begin{aligned}
&f_{C,cd} \\
&= \left|1 - \frac{T_0}{T_{m,cd}}\right| \\
&= \left|1 - \frac{T_0}{\left(\frac{T_{cd,sf} - T_{cd,rf}}{\ln\left(\frac{T_{cd,sf}}{T_{cd,rf}}\right)}\right)}\right| \qquad (69) \\
&= \left|1 - \frac{283{,}15K}{\left(\frac{277{,}15K - 283{,}15K}{\ln\left(\frac{277{,}15K}{283{,}15K}\right)}\right)}\right| \\
&= |-0{,}01| \\
&= 0{,}01
\end{aligned}
$$

C.3 Useful exergy demand of the supply target

The useful exergy demand (UED) to be covered by the entire energy park is calculated according to the formula (12).

This results in the following for the heat supply:

$$X_{u,d,hd} = f_{C,tg} \cdot Q_{d,hd} = 0{,}04 \cdot 100\ MWh = 4\ MWh \qquad (70)$$

The value is rounded to one decimal place because it is a monthly analysis in which the fluctuations of the outdoor temperature would influence further decimal places. In some cases, the fluctuations of the outdoor temperature are so high that a range would have to be given for the UED. However, since the UED is only an informative value and not a central comparative value for a REA, this mean value of the UED can be used for further calculations.

The electrical UED corresponds to the electricity demand.

The UED of cold for the present example is zero, as the target temperature is higher than the reference temperature. Thus, it does not make sense to calculate exergy efficiencies for the cooling supply of the example. This in turn illustrates the lack of suitability of exergy efficiency as a universal comparative parameter for energy systems.

C.4 District heating from a boiler with green hydrogen from wind power (A1)

The formula to be applied is formula (33). It is not necessary to consider the heating value ratio because the resource used is not gas but renewable electricity.

$$\begin{aligned} & X_{R,th,A1} \\ & = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot \frac{f_{R,A1}}{\eta_{th}} \\ & = Q_{d,hd} \cdot \frac{\phi_{hd,A1}}{\eta_{hd,t} \cdot \eta_{hd,s}} \cdot \frac{f_{R,el,wi}}{\eta_{A1,1} \cdot \eta_{A1,2}} \\ & = 100\,MWh \cdot \frac{0{,}1}{0{,}88 \cdot 0{,}93} \cdot \frac{1{,}06}{0{,}9 \cdot 0{,}7} = \\ & = 20{,}6\,MWh \end{aligned} \tag{71}$$

The REF of the district heating from A1 is calculated according to the formula (9) as:

$$f_{R,A1} = \frac{X_R}{E} = \frac{X_{R,th,A1}}{Q_{d,hd} \cdot \phi_{hd,A1}} = \frac{20{,}6\,MWh}{100\,MWh \cdot 0{,}1} = 2{,}06 \tag{72}$$

The REE of the supply of district heating from A1 is calculated according to the formula (15) as:

$$\xi_{R,A1} = \frac{\sum_1^y \left|X_{d,out}\right|_y}{\sum_1^z \left|X_{R,in}\right|_z} = \frac{X_{d,hd} \cdot \phi_{hd,A1}}{X_{R,th,A1}} = \frac{4\,MWh \cdot 0{,}1}{20{,}6\,MWh} = 1{,}9\,\% \tag{73}$$

C.5 District heating from industrial waste heat (A2)

The formula to be applied is formula (34). The temperature of the waste heat is determined after transfer to the district heating and thus corresponds to the district heating mean temperature at the generator. This means the Carnot factor of district heating (0,14 from section C.2.2) can be used as the REF.

$$\begin{aligned} & X_{R,th,A2} \\ & = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot f_{R,ts,in} \end{aligned} \tag{74}$$

$$= Q_{d,hd} \cdot \frac{\phi_{hd,A2}}{\eta_{hd,t} \cdot \eta_{hd,s}} \cdot f_{R,ts,in}$$

$$= 100\,MWh \cdot \frac{0{,}3}{0{,}88 \cdot 0{,}93} \cdot 0{,}14 = 36{,}7\,MWh \cdot 0{,}14 = 5{,}1\,MWh$$

The REF of the district heating from A2 is calculated according to the formula (9) as:

$$f_{R,A2} = \frac{X_{R,th,A2}}{E_{A2}} = \frac{X_{R,th,A2}}{Q_{d,hd} \cdot \phi_{hd,A2}} = \frac{5{,}1\,MWh}{100\,MWh \cdot 0{,}3} = 0{,}17 \qquad (75)$$

The REE of the supply of district heating from A2 is calculated according to formula (15) as:

$$\xi_{R,A2} = \frac{\sum_1^y \left|X_{d,out}\right|_y}{\sum_1^z \left|X_{R,in}\right|_z} = \frac{X_{d,hd} \cdot \phi_{hd,A2}}{X_{R,th,A2}} = \frac{4\,MWh \cdot 0{,}3}{5{,}1\,MWh} = 23{,}5\,\% \qquad (76)$$

C.6 District heating from deep geothermal energy combined heat and power (A3)

C.6.1 Heat

To calculate the REC of heat from cogeneration, use formula (44) and formula (53) are used. The Carnot factor (0,25 from section C.2.3) for heat from deep geothermal energy was used for allocation.

$$\begin{aligned} & X_{R,th,A3} \\ & = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot \alpha_{th} \cdot \frac{f_{R,in}}{\eta_{th}} \\ & = Q_{d,hd} \cdot \frac{\phi_{hd,A3}}{\eta_{hd,t} \cdot \eta_{hd,s}} \cdot \frac{X_{pr,th}}{X_{pr,el} + X_{pr,th}} \cdot \frac{f_{R,in}}{\eta_{th,A3}} \\ & = Q_{d,hd} \cdot \frac{\phi_{hd,A3}}{\eta_{hd,t} \cdot \eta_{hd,s}} \cdot \frac{\eta_{th,A3} \cdot f_{C,hd}}{\eta_{el,A3} + \eta_{th,A3} \cdot f_{C,hd}} \cdot \frac{f_{R,in}}{\eta_{th,A3}} \\ & = 100\,MWh \cdot \frac{0{,}45}{0{,}88 \cdot 0{,}93} \cdot \frac{0{,}75 \cdot 0{,}14}{0{,}15 + 0{,}75 \cdot 0{,}14} \cdot \frac{0{,}05 + 0{,}25}{0{,}75} \\ & = 55{,}0\,MWh \cdot 0{,}41 \cdot \frac{0{,}3}{0{,}75} = 9{,}1\,MWh \end{aligned} \qquad (77)$$

The REF of the district heating from A3 is calculated according to formula (9) as:

$$f_{R,A3} = \frac{X_R}{E} = \frac{X_{R,th,A3}}{Q_{d,hd} \cdot \phi_{hd,A3}} = \frac{9{,}1\,MWh}{100\,MWh \cdot 0{,}45} = 0{,}20 \qquad (78)$$

The REE of heat from A3 is calculated as:

$$\xi_{R,th,A3} = \frac{\sum_1^y \left|X_{d,out}\right|_y}{\sum_1^z \left|X_{R,in}\right|_z} = \frac{X_{d,hd} \cdot \phi_{hd,A3}}{X_{R,th,A3}} = \frac{4\,MWh \cdot 0{,}45}{9\,MWh} = 19{,}8\,\% \tag{79}$$

C.6.2 Power

To calculate the REC of CHP electricity, formula (43) is used. It is assumed here that the temperature of the heat extracted from deep geothermal CHP corresponds to the temperature in the district heating network. The Carnot factor (0,25) for the heat from deep geothermal energy was taken from section C.2.3.

Since the CHP plant's electricity production is fixed to the heat production, the electricity produced by the geothermal CHP plant can be determined via the heat demand covered by it and the efficiencies via the following formula.

$$\begin{aligned} & W_{d,A3} + W_{l,s,A3} + W_{l,t,A3} \\ & = Q_{d,hd} \cdot \frac{\phi_{A3,hd}}{\eta_{hd,t} \cdot \eta_{hd,s}} \cdot \frac{\eta_{el,A3}}{\eta_{th,A3}} \\ & = 100\,MWh \cdot \frac{0{,}45}{0{,}88 \cdot 0{,}93} \cdot \frac{0{,}15}{0{,}75} = 55{,}0\,MWh \cdot \frac{0{,}15}{0{,}75} = 11{,}0\,MWh \end{aligned} \tag{80}$$

This results in the REC for the electricity from A3 being:

$$\begin{aligned} & X_{R,el,A3} \\ & = \left(W_d + W_{l,s} + W_{l,t}\right) \cdot \alpha_{el} \cdot \frac{f_{R,in}}{\eta_{el}} \\ & = \left(W_{d,A3} + W_{l,s,A3} + W_{l,t,A3}\right) \cdot \frac{X_{pr,el}}{X_{pr,el} + X_{pr,th}} \cdot \frac{f_{R,in,A3}}{\eta_{el,A3}} \\ & = \left(W_{d,A3} + W_{l,s,A3} + W_{l,t,A3}\right) \cdot \frac{\eta_{el,A3}}{\eta_{el,A3} + \eta_{th,A3} \cdot f_{C,hd}} \cdot \frac{f_{R,in,A3}}{\eta_{el,A3}} \\ & = 11{,}0\,MWh \cdot \frac{0{,}15}{0{,}15 + 0{,}75 \cdot 0{,}14} \cdot \frac{0{,}30}{0{,}15} \\ & = 11{,}0\,MWh \cdot 0{,}59 \cdot \frac{0{,}30}{0{,}15} = 12{,}9\,MWh \end{aligned} \tag{81}$$

The correct allocation can be checked by waiving an allocation and then comparing the REC of the power and heat production with the sum of the allocated RECs:

$$
\begin{aligned}
& X_{R,A3} \\
& = X_{R,el,A3} + X_{R,th,A3} \\
& = \left(Q_{d,hd} \cdot \frac{\phi_{A3,hd}}{\eta_{hd,t} \cdot \eta_{hd,s}}\right) \cdot \frac{f_{R,in,A3}}{\eta_{th,A3}} \\
& = \left(100\ MWh \cdot \frac{0{,}45}{0{,}88 \cdot 0{,}93}\right) \cdot \frac{0{,}05 + 0{,}25}{0{,}75} = 55{,}0\ MWh \cdot \frac{0{,}30}{0{,}75} \\
& = \ 22{,}0\ MWh = 12{,}9\ MWh + 9{,}1\ MWh
\end{aligned} \tag{82}
$$

The sum of all allocation factors is 1.

$$
\begin{aligned}
& \alpha_{el} + \alpha_{th} \\
& = \frac{\eta_{el,A3}}{\eta_{el,A3} + \eta_{th,A3} \cdot f_{C,hd}} + \frac{\eta_{th,A3} \cdot f_{C,hd}}{\eta_{el,A3} + \eta_{th,A3} \cdot f_{C,hd}} \\
& = \frac{\eta_{el,A3} + \eta_{th,A3} \cdot f_{C,hd}}{\eta_{el,A3} + \eta_{th,A3} \cdot f_{C,hd}} = 0{,}59 + 0{,}41 = 1
\end{aligned} \tag{83}
$$

Since CHP electricity can only be considered with its own weighting factors if it is not supplied to the grid but directly to the supply target, transport losses for direct-use electricity are also considered to calculate the REF of the electricity at the supply target. The REF of the electricity from A3 is calculated according to the formula (9) as:

$$
f_{R,el,A3} = \frac{X_R}{E} = \frac{X_{R,el,A3}}{W_{d,el,A3}} = \frac{12{,}9\ MWh}{11\ MWh \cdot 0{,}99} = 1{,}18 \tag{84}
$$

The REE of the supply of electricity from A3 is given by the formula (15) as:

$$
\xi_{R,elA3} = \frac{\sum_1^y \left|X_{d,out}\right|_y}{\sum_1^z \left|X_{R,in}\right|_z} = \frac{W_{d,el,A3}}{X_{R,el,A3}} = \frac{1}{f_{R,el,A3}} = \frac{1}{1{,}18} = 84{,}4\ \% \tag{85}
$$

The REE for electricity from geothermal CHP can be unusually high – i.e. above 60 % - because, unlike fuel-based CHP plants, there is no exergy destruction through combustion and no exergy destruction through heat transfer from the geothermal source to the supply system.

C.7 District heating and cooling from a large-scale heat pump with heat cooling cogeneration and electricity from photovoltaics (A4)

C.7.1 General

The complex example was constructed in such a way that a CHC allocation is necessary to demonstrate it. I.e. the CHC plant produces heat above and cold below the reference temperature.

It should be noted that the allocation to heat and cooling is based on the temperatures at the plant. However, despite the REC allocated to cooling, an exergy demand is not covered since the target temperature for cooling is above the reference temperature. This means, the exergy of the cooling is destroyed when the demand is met.

Nevertheless, the acceleration of the natural cooling process by the CHC system under consideration creates a REC for the cooling supply.

For CHC systems where the temperatures provided by the system for both heating and cooling demand are above the reference temperature, the entire REV would have to be allocated to heat according to section 11.6.3.

C.7.2 Cold extraction, as a basis for allocation

For CHC plants, the cooling produced is a function of the heat generated, and can be determined using the energy balance based on the derivations in Appendix E if no measured values are available:

$$\begin{aligned}
&Q_{cd,A4} \\
&= Q_{d,hd,A4} \cdot \frac{\phi_{hd,A4}}{\eta_{hd,t} \cdot \eta_{hd,s}} - W_{el,A4} \\
&= Q_{d,hd,A4} \cdot \frac{\phi_{hd,A4}}{\eta_{hd,t} \cdot \eta_{hd,s}} - \frac{Q_{d,hd,A4} \cdot \frac{\phi_{hd,A4}}{\eta_{hd,t} \cdot \eta_{hd,s}}}{\gamma_{hd,A4}} \\
&= Q_{d,hd} \cdot \frac{\phi_{hd,A4}}{\eta_{hd,t} \cdot \eta_{hd,s}} \cdot (1 - \frac{1}{\gamma_{hd,A4}}) \\
&= \left(100\ MWh \cdot \frac{0{,}15}{0{,}88 \cdot 0{,}93}\right) \cdot \left(1 - \frac{1}{3{,}0}\right) = 18{,}3\ MWh \cdot \frac{2}{3} \\
&= 12{,}2\ MWh
\end{aligned} \tag{86}$$

C.7.3 Heat

For the calculation of the REC of heat from CHC, formula (44) and formula (53) are applied.

$$
\begin{aligned}
&X_{R,hd,A4} \\
&= \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot \alpha_{hd} \cdot \frac{f_{R,dr}}{\gamma_{hd,A4}} \\
&= Q_{d,hd} \cdot \frac{\phi_{hd,A4}}{\eta_{hd,t} \cdot \eta_{hd,s}} \cdot \frac{X_{pr,hd,A4}}{X_{pr,cd,A4} + X_{pr,hd,A4}} \cdot \frac{f_{R,el,PV}}{\gamma_{hd,A4}} \\
&= Q_{d,hd} \cdot \frac{\phi_{hd,A4}}{\eta_{hd,t} \cdot \eta_{hd,s}} \cdot \frac{Q_{d,hd} \cdot \phi_{hd,A4} \cdot f_{C,hd}}{Q_{cd,A4} \cdot f_{C,cd} + Q_{d,hd} \cdot \phi_{hd,A4} \cdot f_{C,hd}} \cdot \frac{f_{R,el,PV}}{\gamma_{hd,A4}} \qquad (87) \\
&= \left(100\ MWh \cdot \frac{0{,}15}{0{,}88 \cdot 0{,}93}\right) \cdot \frac{100\ MWh \cdot 0{,}15 \cdot 0{,}14}{12{,}2\ MWh \cdot 0{,}01 + 100\ MWh \cdot 0{,}15 \cdot 0{,}14} \cdot \frac{1{,}21}{3{,}0} \\
&= 18{,}3\ MWh \cdot 0{,}9 \cdot \frac{1{,}21}{3{,}0} \\
&= 7{,}0\ MWh
\end{aligned}
$$

The REF of the district heating from A4 is calculated according to formula (9) as:

$$
f_{R,A4} = \frac{X_R}{E} = \frac{X_{R,th,A4}}{Q_{d,hd} \cdot \phi_{hd,A4}} = \frac{7\ MWh}{100\ MWh \cdot 0{,}15} = 0{,}47 \qquad (88)
$$

The REE of heat from A4 is calculated as:

$$
\xi_{R,th,A4} = \frac{\sum_1^y \left|X_{d,out}\right|_y}{\sum_1^z \left|X_{R,in}\right|_z} = \frac{X_{d,hd} \cdot \phi_{hd,A4}}{X_{R,th,A4}} = \frac{4\ MWh \cdot 0{,}15}{7\ MWh} = 8{,}6\ \% \qquad (89)
$$

C.7.4 Cold

The simplest way to calculate the REC of the last unknown product of a joint production is to subtract the allocated REC of the already known products from the total REC.

$$
\begin{aligned}
&X_{R,cd,A4} \\
&= X_{R,A4} - X_{R,hd,A4} \\
&= \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot \frac{f_{R,dr}}{\gamma_{hd,A4}} - \left(\left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot \alpha_{hd} \cdot \frac{f_{R,dr}}{\gamma_{hd,A4}}\right) \qquad (90) \\
&= \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot \frac{f_{R,el,PV}}{\gamma_{hd,A4}} \cdot \left(1 - \alpha_{hd,A4}\right)
\end{aligned}
$$

$$= \left(100\,MWh \cdot \frac{0{,}15}{0{,}88 \cdot 0{,}93}\right) \cdot \frac{1{,}21}{3{,}0}$$

$$\cdot \left(1 - \frac{100\,MWh \cdot 0{,}15 \cdot 0{,}14}{12{,}2\,MWh \cdot 0{,}01 + 100\,MWh \cdot 0{,}15 \cdot 0{,}14}\right)$$

$$= 18{,}3\,MWh \cdot \frac{1{,}21}{3{,}0} \cdot 0{,}1$$

$$= 0{,}4\,MWh$$

The REF of district cooling from A4 is calculated according to formula (9) as:

$$f_{R,A4} = \frac{X_R}{E} = \frac{X_{R,th,A4}}{Q_{d,cd}} = \frac{0{,}4\,MWh}{12{,}2\,MWh} = 0{,}03 \tag{91}$$

The REE of cooling from A4 is zero because the temperature of the supply target is above the reference temperature, and thus the exergy demand for cooling is zero. This does not contradict the fact that the heat flow used for cooling is linked to an exergy flow. The "cooling exergy" of the cooling medium is dissipated when the cooling task is fulfilled, since there is no thermodynamic cooling demand, but the cold is only used to accelerate natural processes.

C.8 District cooling from direct cooling with river water (A5)

The formula to be applied is equation (34). The temperature of the direct cooling is determined after transfer to the district cooling, and thus corresponds to the district cooling temperature at the generator.

Since the delivered cold quantity is given, but also the cold produced by the CHC plant A4 from formula (86) is known, the cooling produced by direct cooling results as:

$$Q_{cd,A5} = \left(Q_{d,cd,A5} + Q_{l,s,cd,A5} + Q_{l,t,cd,A5}\right)$$

$$= \left(Q_{d,cd} + Q_{l,s,cd} + Q_{l,t,cd} - Q_{cd,A4}\right)$$

$$= \left(\frac{Q_{d,cd}}{\eta_{cd,t} \cdot \eta_{cd,s}} - Q_{cd,A4}\right) \tag{92}$$

$$= \left(\frac{40\,MWh}{0{,}95 \cdot 0{,}98} - 12{,}2\,MWh\right)$$

$$= 30{,}8\,MWh$$

This results in the REC of district cooling taken directly from the river:

$$X_{R,cd,A5} = Q_{cd,A5} \cdot f_{R,ts,in} = 30{,}8\,MWh \cdot 0{,}01 = 0{,}03\,MWh \tag{93}$$

The REF of the district cooling delivered to the supply target from A5 is calculated according to the formula (9) to formula (94).

$$\begin{aligned} &f_{R,A5} \\ &= \frac{X_{R,cd,A5}}{Q_{cd,A5} \cdot \eta_{cd,t} \cdot \eta_{cd,s}} \\ &= \frac{0{,}3\,MWh}{30{,}8\,MWh \cdot 0{,}95 \cdot 0{,}98} = \frac{0{,}3\,MWh}{28{,}6\,MWh} = 0{,}01\,MWh \end{aligned} \tag{94}$$

The REE of the district cooling supply from A5 is zero because the temperature at which the room is to be maintained is above the reference temperature. This means that the cold supply is only used to accelerate a natural process.

C.9 Auxiliary power of the generator park (A6)

The REC for the provision of auxiliary power corresponds to the REC of the electricity purchased from the public grid. It must be considered that the auxiliary power required for the operation of the CHC plant is already considered in the coefficient of performance for the plant and is therefore not counted as auxiliary power for the generation park.

Since the REC of the auxiliary power is to be allocated separately to both products for the determination of the REFs, it must be calculated separately for the heat and for the cooling supply.

For the REC of the auxiliary power consumption of the heat, this results in:

$$\begin{aligned} &X_{R,A6,hd} \\ &= \left(\begin{array}{c} \left(\omega_{aux,hd,t} + \omega_{aux,A1} \cdot \phi_{A1} + \omega_{aux,A2} \cdot \phi_{A2}\right) \\ \cdot \left(Q_{d,hd} + Q_{l,s,hd} + Q_{l,t,hd}\right) \end{array} \right) \cdot f_{R,el,pm} \\ &= \left((0{,}015 + 0{,}002 \cdot 0{,}1 + 0{,}005 \cdot 0{,}003) \cdot \frac{100\,MWh}{0{,}88 \cdot 0{,}93} \right) \cdot 2{,}63 \\ &= 2{,}0\,MWh \cdot 2{,}63 = 5{,}4\,MWh \end{aligned} \tag{95}$$

The REC of the auxiliary power consumption of the refrigeration results as:

$$\begin{aligned} &X_{R,A6,cd} \\ &= \left(\omega_{aux,cd,t} \cdot \left(Q_{d,cd} + Q_{l,s,cd} + Q_{l,t,cd}\right) + \omega_{aux,A5} \cdot Q_{cd,A5}\right) \cdot f_{R,el,pm} \end{aligned} \tag{96}$$

$$= \omega_{aux,cd,t} \cdot (Q_{cd,A4} + Q_{cd,A5}) + \omega_{aux,A5} \cdot Q_{cd,A5}$$

$$= 0{,}035 \cdot (12{,}2\ MWh + 30{,}8\ MWh) + 0{,}026 \cdot 30{,}8\ MWh$$

$$= 6{,}1\ MWh$$

The calculation of the REF and the REE of the auxiliary power can be dispensed with, as these correspond to the REF and the REE (see formula (63) of the power used.

Thus the REC of the auxiliary power used in the complex example is:

$$X_{R,A6} = X_{R,aux,hd} + X_{R,aux,cd} = 5{,}4\ MWh + 6{,}1\ MWh = 11{,}5\ MWh \tag{97}$$

C.10 Power consumption from the grid (17)

The REC of the electricity consumption from the grid is calculated according to section 9.2 as the product of the electricity demand and the REF of the grid electricity. Since part of the electricity demand is covered by the geothermal CHP, the electricity demand from the grid is reduced accordingly.

$$\begin{aligned} & X_{R,17} \\ & = \left(W_d - (W_{d,A3} + W_{l,s,A3} + W_{l,t,A3})\right) \cdot f_{R,el,pm} \\ & = \left(W_d - \left(Q_{d,hd} \cdot \frac{\phi_{A3,hd}}{\eta_{hd,t} \cdot \eta_{hd,s}} \cdot \frac{\eta_{el,A3}}{\eta_{th,A3}}\right)\right) \cdot f_{R,el,pm} \\ & = \left(30\ MWh - \left(100\ MWh \cdot \frac{0{,}45}{0{,}88 \cdot 0{,}93} \cdot \frac{0{,}15}{0{,}75}\right)\right) \cdot 2{,}63 \\ & = 50\ MWh \end{aligned} \tag{98}$$

The REF corresponds to the REF of the electric current from the grid.

The REE is calculated according to formula (63).

C.11 Overall system of the complex example

C.11.1 Heat

The REC of the heat is:

$$X_{R,hd} \tag{99}$$

$$= \sum_{1}^{y} X_{R,in,y,hd}$$

$$= X_{R,A1} + X_{R,A2} + X_{R,th,A3} + X_{R,hd,A4} + X_{R,A6,hd}$$

$$= (20{,}6 + 5{,}1 + 9{,}1 + 7 + 5{,}4)\ MWh = 47{,}2\ MWh$$

The average REF of the district heating from the complex example is given by formula (10) as:

$$f_{R,avg,hd} = \frac{X_{R,hd}}{E_{d,hd}} = \frac{47{,}2\ MWh}{100\ MWh} = 0{,}47 \tag{100}$$

The average REE of the heat supply in relation to the supply target is thus as follows:

$$\xi_{R,avg,hd} = \frac{f_{C,hd}}{f_{R,avg,hd}} = \frac{0{,}04}{0{,}47} = 8{,}5\ \% \tag{101}$$

C.11.2 Cold

The REC of the cold is:

$$X_{R,cd}$$

$$= \sum_{1}^{y} X_{R,in,y,cd} \tag{102}$$

$$= X_{R,A4,cd} + X_{R,A5} + X_{R,A6,cd}$$

$$= (0{,}4 + 0{,}3 + 6{,}2)\ MWh = 6{,}9\ MWh$$

In the case of district cooling supply, it becomes clear that especially in the case of supply with low energy quality, the REC of the auxiliary flow can be the primary cause of REC and must therefore be considered even in the case of relatively small demands.

The average REF of district cooling from the energy park is given by formula (10) as:

$$f_{R,avg,cd} = \frac{X_{R,cd}}{E_{d,cd}} = \frac{6{,}9\ MWh}{40\ MWh} = 0{,}17 \tag{103}$$

The average REE of the cooling supply in relation to the supply target is zero since the room target temperature is above the reference temperature.

C.11.3 Power

The REC of the power consumption is:

$$X_{R,el} = \sum_{A1}^{y} X_{R,in,y} = X_{R,el,A3} + X_{17} = 12{,}9\,MWh + 50\,MWh = 62{,}9\,MWh \tag{104}$$

The average REF of the power supply from the energy park is given by formula (10) as:

$$f_{R,avg,el} = \frac{X_{R,el}}{E_{d,el}} = \frac{62{,}9\,MWh}{30\,MWh} = 2{,}1 \tag{105}$$

The average REE of the electricity supply in relation to the supply target is thus calculated as follows:

$$\xi_{R,avg,el} = \frac{1}{f_{R,avg,el}} = 47{,}7\,\% \tag{106}$$

C.11.4 Total

The total REC of the complex example is:

$$X_{R,com} = \sum_{A1}^{y} X_{R,in,y} = X_{R,hd} + X_{R,cd} + X_{R,el} + X_{R,A6}$$
$$= 47{,}2\,MWh + 6{,}9\,MWh + 62{,}9\,MWh + 11{,}5\,MWh = 128{,}5\,MWh \tag{107}$$

The REC of the entire system is an evaluation parameter that allows to compare the complex example with the reference example from Appendix B to determine the savings potentials. Such a comparison is described in Appendix D.

The average REF of the energy supply from the energy park is given by formula (10) as:

$$f_{R,avg,com} = \frac{X_R}{E_{d,hd} + E_{d,cd} + E_{d,el}} = \frac{128{,}5\,MWh}{100\,MWh + 40\,MWh + 30\,MWh} = 0{,}69 \tag{108}$$

When calculating the REF (total), auxiliary flows are not included in the denominator.

The REF total of the energy park is to be considered as an informative value, as its value is very limited due to the reference to energy flows of different energy quality. REFs are primarily helpful in selecting and comparing supply systems for heating, cooling and electricity and should generally always characterize a specific energy flow.

The average REE of the cooling supply related to the supply target is, by definition, zero for the case of cooling above the reference. This means that REE for cooling above the reference temperature is neither suitable for characterizing nor for comparing different systems, as cooling processes with target temperatures above the reference temperature are basically avoidable from a thermodynamic perspective and only accelerate a naturally occurring process. Against this background, the calculation of a REE (total) can generally be avoided.

Appendix D Comparison of supply and energy systems with the REA

D.1 General

In Appendix B and Appendix C two energy systems were analysed, which will be compared here. Since both energy systems provide the user with the environmental conditions required, they are comparable despite different energy demands.

Table 18 – Energy demands of the compared energy system examples in Appendix B and Appendix C

	Reference example (Appendix B)	**Complex example (Appendix C)**
Heat demand in MWh	80	100
Cooling demand in MWh	25	40
Electricity demand in MWh	20	30

D.2 Comparison of energy systems with the REA

The reduction of the REC by the complex example (com) compared to the reference example (ref) results as:

$$\Delta X_R = X_{R,ref} - X_{R,com} = 197{,}1\ MWh - 128{,}5\ MWh = 68{,}6\ MWh \qquad (109)$$

It is often useful to also calculate the relative savings, as this is a universal measure of how much better or worse a given energy system is compared to a reference energy system that meets the same demand (in this case: occupant comfort). Even if the demand (occupant comfort) is the same, the energy demand may differ if, for example, insulation measures have been implemented or the electricity demand has been reduced without loss of comfort, e.g. through efficient electrical appliances.

$$\frac{\Delta X_R}{X_{R,ref}} = \frac{68{,}6\ MWh}{197{,}1\ MWh} = 35\ \% \qquad (110)$$

To illustrate the limited suitability of the REFs for comparing energy systems, both total REFs are compared here.

$$\Delta f_R = f_{R,ref} - f_{R,com} = 1{,}58 - 0{,}76 = 0{,}83 \qquad (111)$$

The relative saving of resource exergy per unit of energy is calculated based on the respective REFs and results in:

$$\frac{\Delta f_R}{f_{R,ref}} = \frac{0,83}{1,58} = 52\ \% \tag{112}$$

In this comparison, it becomes clear that the change in the REF differs from the change in the REC, as energy consumption differences between the two variants are not considered in the REF.

Since not only supply systems, but overall systems consisting of supply system and supply target must be optimized, the REF can only be used as a consistent comparative parameter if the supply target has the same energy demand in all examined variants or if the question of differences in the supply systems should be answered.

D.3 Heat

The reduction of the REC for the heat supply by the complex example (com) compared to the reference example (ref) is:

$$\Delta X_{R,hd} = X_{R,hd,ref} - X_{R,hd,com} = 111,6\ MWh - 47,2\ MWh = 64,4\ MWh \tag{113}$$

The relative savings of REC for heating thus are:

$$\frac{\Delta X_{R,hd}}{X_{R,hd,ref}} = \frac{64,4\ MWh}{111,6\ MWh} = 58\ \% \tag{114}$$

For the comparison of the heat supply systems, the difference of the REF is calculated.

$$\Delta f_{R,hd} = f_{R,hd,ref} - f_{R,hd,com} = 1,4 - 0,47 = 0,93 \tag{115}$$

The relative savings in heat supply based on the REF are:

$$\frac{\Delta f_{R,hd}}{f_{R,hd,ref}} = \frac{0,93}{1,4} = 66\ \% \tag{116}$$

D.4 Cold

The reduction of the REC for the cooling supply by the complex example (com) compared to the reference energy system (ref) results as:

$$\Delta X_{R,cd} = X_{R,cd,ref} - X_{R,cd,com} = 32,9\ MWh - 6,9\ MWh = 26,0\ MWh \tag{117}$$

The relative savings of REC for cooling thus are:

$$\frac{\Delta X_{R,cd}}{X_{R,cd,ref}} = \frac{26\ MWh}{32,9\ MWh} = 79\ \% \tag{118}$$

For the comparison of the cooling supply systems, the difference of the REFs is calculated.

$$\Delta f_{R,cd} = f_{R,cd,ref} - f_{R,cd,com} = 1{,}32 - 0{,}17 = 1{,}15 \tag{119}$$

The relative savings in the cooling supply based on the REF are:

$$\frac{\Delta f_{R,cd}}{f_{R,cd,ref}} = \frac{1{,}15}{1{,}32} = 87\ \% \tag{120}$$

D.5 Power

The reduction in the REC for power supply by the complex example (com) compared to the reference example (ref) is:

$$\Delta X_{R,el} = X_{R,el,ref} - X_{R,el,com} = 52{,}6\ MWh - 62{,}9\ MWh = -10{,}3\ MWh \tag{121}$$

A negative value here means that more resource exergy was consumed compared to the reference system. The relative savings of resource exergy for power are thus as follows.

$$\frac{\Delta X_{R,el}}{X_{R,el,ref}} = \frac{-10{,}3\ MWh}{52{,}6\ MWh} = -20\ \% \tag{122}$$

For the comparison of the power supply systems, the difference of the REF is calculated.

$$\Delta f_{R,cd} = f_{R,el,ref} - f_{R,el,com} = 2{,}63 - 2{,}10 = 0{,}53 \tag{123}$$

The relative savings in electricity supply based on the REF are:

$$\frac{\Delta f_{R,el}}{f_{R,el,ref}} = \frac{0{,}53}{2{,}63} = 20\ \% \tag{124}$$

Here it becomes clear that even with more resource-efficient energy supply systems, a higher REC can be caused if an increased demand more than compensates for the savings in energy supply.

D.6 Evaluation

Table 19 – Assumptions and results of the REA of the considered examples in Appendix B (reference example) and Appendix C (complex example)

	Heat reference example	Heat complex example	Cold reference example	Cold complex example	Power reference example	Power complex example	Total reference example	Total complex example
Energy demand in MWh	80	100	25	40	20	30	125	170
REC in MWh	111,6	47,2	32,9	6,9	52,6	62,9	197,1	128,5
REF	1,4	0,47	1,32	0,17	2,63	2,10	1,58	0,76

Table 20 – Savings of the complex example from Appendix C compared to the reference example from Appendix B

	REC Heat	REF Heat	REC Cold	REF cold	REC Current	REF current	REC total	REF total
Savings	58 %	66 %	79 %	87 %	-20 %	20 %	35 %	52 %

The tables above show that the reference example from Appendix B consumes significantly more resources than the complex example from Appendix C. Only the REC of electricity of the complex example is greater than that of the reference, which is evident from negative savings values. The comparison of the REFs in this case clarifies that the supply system is nevertheless more resource saving. However, due to the 50 % increase in demand in the complex example compared to the reference, the REF reduction for electricity (20 %) is not sufficient for REC savings in the field of electricity.

It becomes obvious that the savings are unevenly distributed. For example, when comparing the REFs, it becomes obvious that the energy supply system of the complex example is much more resource saving than the reference energy supply system. The savings of the REFs are always greater than those of the REC.

Due to the lower demand of the reference energy system, which can be achieved, for example, through better insulation and more efficient household appliances, the savings in the field of REC are thus lower in comparison of the entire energy systems than if comparing REFs.

The comparison illustrates that different comparison variables should be used depending on the comparison task.

If only supply systems are to be selected, REFs would be compared. However, due to the consideration of demand, a comparison of REVs offers the greater certainty of making the right choice of energy systems. Thus, in general any application of REA should focus on comparing RECs.

Appendix E
Derivations

In the following, some formula expressions used in the REA are derived for better comprehensibility.

The transformations of the formulae are only marked with a collective number in each case.

Energy balance of a heat pump or chiller:

$$\begin{aligned} E_{dr} + Q_{cd} &= Q_{hd} \\ E_{dr} &= Q_{hd} - Q_{cd} \end{aligned} \tag{125}$$

where

E_{dr}	Drive energy
Q_{cd}	Heat absorbed or cold produced
Q_{hd}	Heat given off

Derivation of the heat given off if the amount of cooling and the driving energy are known.

$$\begin{aligned} \gamma_{cd} &= \frac{E_{cd}}{E_{dr}} = \frac{E_{cd}}{E_{hd} - E_{cd}} \\ \gamma_{cd} \cdot (E_{hd} - E_{cd}) &= E_{cd} \\ \gamma_{cd} \cdot E_{hd} - \gamma_{cd} \cdot E_{cd} &= E_{cd} \\ \gamma_{cd} \cdot E_{hd} &= \gamma_{cd} \cdot E_{cd} + E_{cd} \\ E_{hd} &= E_{cd} + \frac{E_{cd}}{\gamma_{cd}} = E_{cd} \cdot \left(1 + \frac{1}{\gamma_{cd}}\right) \end{aligned} \tag{126}$$

where

E_{dr}	Driving energy
Q_{cd}	Heat absorbed or cold produced
Q_{hd}	Heat given off
γ_{cd}	Coefficient of performance of the cold supply in the time step under consideration

Derivation of the heat absorbed or cold produced if the amount of heating and the driving energy are known:

$$\begin{aligned}
&\gamma_{hd} = \frac{E_{hd}}{E_{dr}} = \frac{E_{hd}}{E_{hd} - E_{cd}} \\
&\gamma_{hd} \cdot (E_{hd} - E_{cd}) = E_{hd} \\
&\gamma_{hd} \cdot E_{hd} - \gamma_{hd} \cdot E_{cd} = E_{hd} \\
&-\gamma_{hd} \cdot E_{cd} = -\gamma_{hd} \cdot E_{hd} + E_{hd} \\
&\gamma_{hd} \cdot E_{cd} = \gamma_{hd} \cdot E_{hd} - E_{hd} \\
&E_{cd} = E_{hd} - \frac{E_{hd}}{\gamma_{hd}} = E_{hd} \cdot \left(1 - \frac{1}{\gamma_{hd}}\right)
\end{aligned} \tag{127}$$

where

E_{dr}	Driving energy
Q_{cd}	Heat absorbed or cold produced
Q_{hd}	Heat released
γ_{hd}	Coefficient of performance of the heat supply in the time step under consideration