

REA: Resource Exergy Analysis - A basic guideline for application

Andrej Jentsch (✉ andrej.jentsch@richtvert.de)

Richtvert <https://orcid.org/0000-0003-2413-0507>

Method Article

Keywords: exergy, resources, decision making support, policy support, climate change

Posted Date: December 5th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-979554/v2>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

REA: Resource Exergy Analysis

A basic guideline for application

Andrej Jentsch

Date: 5 December 2021

DRAFT

Acknowledgements

The author thanks Étienne Saloux, Julien Ramousse and Robin Wiltshire who supported the preparation of this guideline in its current form with comments, revisions and suggestions.

DRAFT

Disclaimer

This publication is currently a draft and therefore a work in progress. Errors are more likely to occur than in final publications. If you find an error, please reach out to the author: Andrej.jentsch@richtvert.de. Thank you.

DRAFT

Table of Contents

Acknowledgements	2
Disclaimer	3
1 Background	5
1.1 REA in comparison to PEA	5
2 Methodology	7
2.1 Allocation method and evaluation of cogeneration	9
2.2 Exergy passes and REA	12
2.3 REA calculation instructions	12
2.3.1 Basic equations	15
2.3.2 Resource exergy efficiency (RE)	17
2.3.3 Approximations & Simplifications	18
2.3.4 General equations for cogeneration assessment	23
2.3.5 Overall resource consumption	25
2.3.6 Electricity generation from fuels without CHP	26
2.3.7 Electricity from CHP using fuels	27
2.3.8 Heat from electrical boilers	28
2.3.9 Heat from boilers	29
2.3.10 Heat from CHP using fuels	29
2.3.11 Heat from heat pumps	30
2.3.12 Heat from thermal sources (Excess heat, Solar thermal, Geothermal)	32
2.3.13 Heat from CHP using thermal sources	32
2.3.14 Cooling from refrigeration machines	33
2.3.15 Direct cooling from thermal sources (Sea, river and lake water)	34
2.3.16 Hydrogen and other synthetic fuels from primary fuels or electricity	35
References	36

1 Background

Resource Exergy Analysis (REA) is a more comprehensive and consistent analysis methodology than Primary Energy Analysis (PEA) and it is just as simple to use. It has been applied and improved for more than ten years (Hertle et al., 2016; Jentsch, 2010, 2016; Jentsch et al., 2009). This guidebook provides support for all who want to use it. Resource exergy analysis (REA) is a proven type of exergy analysis that can replace primary energy analysis with a more comprehensive and consistent methodology while still remaining similarly simple. This guidebook is meant to provide support for all who want to apply it and do not want to derive the approach from less instructive publications.

The aim of REA is to provide a comprehensive comparison of energy systems based on physics and sensible system boundaries. It should be complemented with an analysis of GHG emissions and life cycle cost.

While REA is complementary to GHG analysis it is similarly important to stop climate change.

Solutions that consume excess resources inevitably lead to an increased demand for supply systems. More systems require more time to be built. Thus excess resource consumption directly increases the time required to reach climate targets.

Therefore, a combination of GHG analysis and REA is essential to enable well-informed decisions and reach climate targets in time.

1.1 REA in comparison to PEA

PEA fails to include all the necessary elements required to ensure a complete picture of an energy system and the energy quality associated with it. Therefore, PEA often produces misleading results, especially if heating and cooling systems are considered. Consequently, decisions based on PEA carry the risk of favoring suboptimal technology choices, thereby increasing the likelihood of catastrophic climate change.

The key difference between PEA and REA lies in the consideration of energy quality. REA goes beyond the Law of Conservation¹ of Energy and also considers the

¹ The first law of thermodynamics

the Law of Irreversibility² thus ensuring transparent identification of resource-saving solutions.

DRAFT

² The second law of thermodynamics

2 Methodology

REA can be applied dynamically and statically. It can include all resources used in the life cycle of an energy system or only energy resources consumed. In its most simple form it follows the approach of primary energy analysis and considers only the consumption of energy resources for the operation of the considered energy systems (Jentsch, 2016).

The variable that is the central result of any REA is the Cumulated Exergy Consumption (CExC) associated with resource use. It is labeled as resource consumption in the following. This simplification appears justified by the fact, that exergy can provide a unified measurement for all fuels and materials extracted from the earth or the surroundings (Brockway et al., 2016).

REA aims to fairly compare all kinds of energy systems. Thus only material and energy flows that are usable on demand (UoD flows) are considered resources.

The reasoning behind this definition is, that UoD flows are lost if they are not used. Consequently, solar radiation and kinetic energy of wind, rivers or currents are not considered resources. Additionally, this definition is supported by the fact that historical exergy consumption of UoD flows, such as the solar radiation needed to create fossil fuels or biomass is not considered in energy system analysis.

While the actual flows of sun and kinetic as exergy can provide a unified measurement for all fuels and materials extracted from the earth or the surroundings (Brockway et al., 2016). In this report CExC of wind and water are not considered resources, the efficiency of their conversion to storable forms of exergy (resources) is still having an impact on REA evaluation results. The less efficient a conversion is UoD flows to resources is the higher the overhead for any provided exergy unit becomes. This means that the CExC per unit of energy delivered increases. E.g. the CExC of power from PV panels might be 1,1 for efficient PV systems and 1,2 for less efficient converters.

In order to reduce the CExC for conversion processes from UoD flows additional exergy analyses should be performed in order to minimize the use of land and materials.

Due to difficulty to obtain data on material exergy the analysis is often limited to the RC that is caused by harvesting, transporting and using energy. This means RC extends the view beyond primary energy by considering energy quality but neglects some material and grey exergy aspects, such as the resources required to build and recycle a heating system.

In order to assess the resource consumption and efficiency of the overall energy consumption the balance boundaries have been defined as shown in Figure in accordance with (Jentsch, 2010).

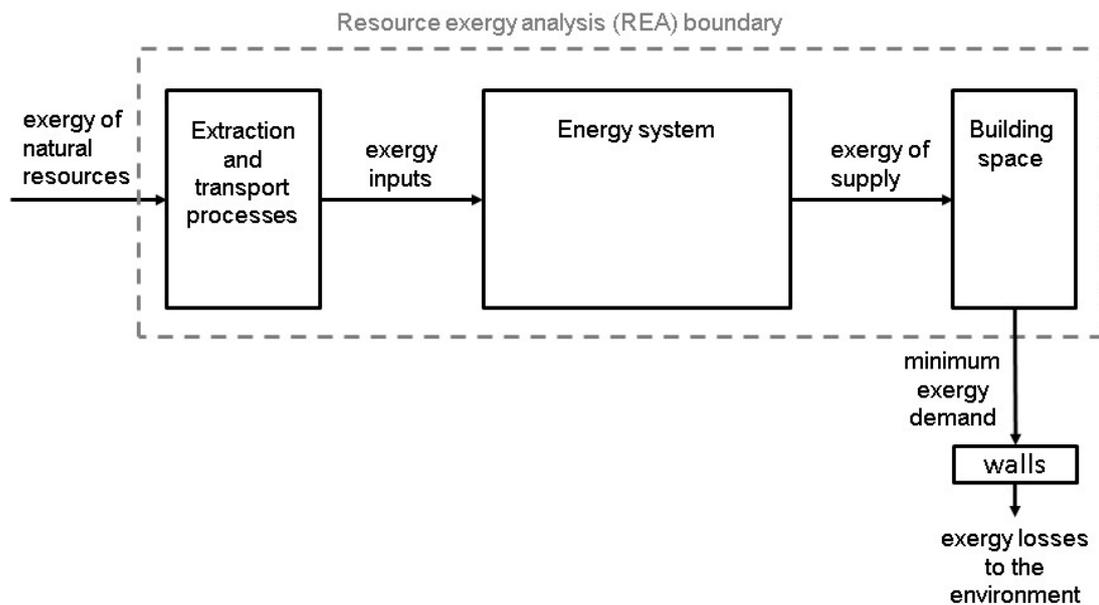


Figure 1: Balance boundaries to assess resource consumption and resource efficiency of thermal supply systems

In the following the assumptions underlying this boundary definition are explained.

1. Only flows of directly storable primary energy (UoD flows) are considered as input flows. In cases where the primary energy is not storable without transformation (solar radiation or kinetic energy of wind and water) the first storable secondary energy is considered to be the primary energy for the comparison.
 - 1.1. This means that for solar thermal plants it is not the solar radiation that is considered to be the resource but the hot water that has been generated by it at a given temperature level.
 - 1.2. For PV power production the electricity produced is considered as the storable primary energy.
 - 1.3. For most electrical inputs this means that the losses from the extraction of the fuels to the provision of electricity have to be considered. This also means

considering the energy required for producing the energy transformation technologies such as solar panels and energy extraction rigs such as those used for harvesting natural gas. Therefore all calculations that consider the use of electricity require the knowledge of the Cumulated Exergy Consumption of power.

- 1.3.1. Since power is often taken from the grid instead of a dedicated generator, it is key to make realistic assumptions about which power plant generates the power used. E.g. if a technology such as heat pumps increases the electrical demand on the grid, it is best to consider the power coming from the marginal / price-setting power plant. Only technologies that replace existing electrical users but use less or equal power than the technologies replaced can be assumed to use the current grid mix. Any excess electrical demand ideally should also be calculated with the marginal power mix.
2. For the calculation of resource efficiency the minimum required amount of exergy with which the task could theoretically be accomplished is considered the demand. This ensures that no improvement potentials have been overlooked. It has to be noted that all demands still have the possibility to be reduced since the actual “demand” is simply thermal comfort of the district’s inhabitants, which could also be covered in different ways than by heating the complete living space. In order to allow realistic thermodynamic modeling the demand has been approximated by the exergy minimally required to keep the considered buildings at 20 °C and heat water from cold water temperature of around 10°C to sufficiently hot water at 43°C (DIN, 2005).
3. The comparability of the considered alternatives is ensured by keeping the supply task, such as thermal comfort and needs for mechanical and electrical energy fixed. This makes it possible to pinpoint the causes for the identified improvements.

2.1 Allocation method and evaluation of cogeneration

In order to assess cogeneration processes an allocation method needs to be chosen. The only fully scientific method that can be universally applied and is currently available is the exergy method, also labeled Carnot method (Jentsch, 2015). Therefore this method has been chosen to calculate the resource and emission fractions that are allocated to the products from cogeneration.

The equations used for calculating resource exergy are derived from (Jentsch 2010)³ and fundamental calculation basics of energy system analysis such as energy balances.

In the following the general logic behind the used equations is explained.

In order to assess energy systems first a complete energy balance is prepared. That means for any flow of final energy the production chains are considered through the use of Cumulated Energy Consumption (CExC) factors that can be found in Eco-Databases, e.g. (*ecoinvent database*, 2021). The CExC is the ratio of exergy consumed per unit of energy or material supplied.

If access to respective databases is not available, the CExC of non-thermal energy resources can be approximated by using the Cumulated Energy Consumption (CEC) (Umweltbundesamt, 2021). The CEC is the ratio of the energy contained in the resource and the energy used for extraction, transformation and transport to the energy supplied. CEC values for resources are always above 1, due to the law of energy conservation. This means more energy is extracted and used than supplied. E.g. for natural gas a CEC value can be 1.16 (Bejan et al., 1996).

For thermal energy resources the CExC can be approximated by subtracting 1 from the CEC value and adding the Carnot Factor (see equation (34)). E.g. for solar thermal energy the CEC can be 1.04 (IWU, 2014). So with a Carnot Factor of 0.3 the CExC for solar thermal energy would be 0.24.

Additionally, it is assumed that all efficiencies and CEC factors only account for the Lower Heating Value of fuels (LHV). In order to approximate the exergy value of fuels the Higher Heating Value (HHV) of fuels (Bejan et al., 1996) is considered by using ratios of HHV to LHV from literature (DIN, 2010a).

For CHP units the fuel share allocated to heating is calculated based on the Carnot method (Jentsch 2015).

For heat pumps which extract heat at other temperatures other than that of the environment it is required to take the exergy of the extracted heat into account. Ideally data on the amount of heat extracted is available as well as data on its average temperature. However, in most cases the amount of heat extracted is not measured. In this case the difference between the heat produced and the electricity input is assumed to be the extracted heat since this is the minimum amount of heat

³ Jentsch, A. (2010) "A novel exergy-based concept of thermodynamic quality and its application to energy system evaluation and process analysis", Dissertation, Technical University of Berlin

required to fulfil the energy balance. The temperature at which the exergy of this heat is evaluated is the average temperature of the heat source, e.g. ground temperature of 10 °C.

As a second step the exergy associated with the considered energy flows is calculated. Since only for thermal energy flows energy quality is below 100%, the exergy of all non-thermal energy flows equals the energy required to transform the fuel exergy into power in an ideal fuel cell (Jentsch 2010). The amount of fuel exergy can be approximated by the higher heating value (HHV) (Bejan et al., 1996).

Exergy is a property of the considered flow and the reference environment. Ideally, the reference environment is an accurate representation of the thermodynamic and chemical properties of the natural environment of the considered energy system. That means its temperature, pressure and chemical composition are known exactly for any given time and place.

However, since the natural environment is not in a strict thermodynamic equilibrium and changes with natural cycles and locations it is usually sensible to make simplifying assumptions about it, such as a reference temperature, pressure and chemical composition being the same in the considered area.

Heat flows at reference temperature are not associated with an exergy flow. Only thermal energy flows that deviate from the reference temperature are associated with an exergy flow. The exergy associated with a heat flow is a product of the amount of energy of the heat flow and the Carnot factor (34).

It is important to calculate the Carnot factor with the thermodynamic average temperature of any heat flow (1), (2) (3) and the fixed reference temperature, since the Carnot cycle is defined for operation between constant temperature heat reservoirs and not for heat transfers from flows that change temperature.

With the use of average temperatures the exergy of heat flows that change in temperature such as the heat flow needed to heat domestic hot water can be approximated by a heat transfer at a constant thermodynamic average temperature.

If no data on CExC is available and only CEC can be used it is assumed that the difference between Primary energy and final energy is non-thermal and therefore has an energy quality of 100 %. E.g. for deep geothermal energy the CEC can be 1.07 (BMU, 2007). Since the geothermal energy itself is thermal only 0.07 units of energy are considered to be high quality energy. The resource exergy associated with geothermal energy would therefore be a sum of 0.07 plus the Carnot factor of the heat extracted from the geothermal source – e.g. 0.27 in total.

2.2 Exergy passes and REA

Exergy passes (Jentsch, 2010; Jentsch et al., 2009)(Jentsch, 2016) are a means to make REA more transparent and understandable. By separating exergy into a product of energy and energy quality the differences of REA from PEA become obvious. The fundamentals for splitting exergy into these two factors can be found in Jentsch, 2010.

In order to assess the energy quality easiest to calculate the energy and exergy associated with a considered flow. Once energy and exergy flows are known an average energy quality can be calculated by dividing the two values.

It is important to note that for this to apply the energy balance must be fulfilled for all considered technologies. E.g., for CHP it is assumed that heat at reference temperature fills the gap between the allocated fuel and the heat output. Using heat at reference temperature to fill energy balances that lack data does not impact exergy analysis results since this heat is associated with an exergy flow of zero.

The ratio of exergy to energy is calculated for the demand side but also for the primary energy / resource side, thus allowing to compare the average energy quality of demand with the one of the supply.

These are the fundamentals that allow to calculate the values needed for the exergy passes. Specific equations can be deduced from these principles.

In exergy passes the term resource is used as an abbreviation for resource exergy.

2.3 REA calculation instructions

In the following instructions are provided how the resource exergy consumption (RC) and resource exergy demand can be calculated.

Table 1: Table of abbreviations

C	Chemical exergy (reactive apart from fuels) and non-reactive. Includes compressed air.
CEC	Cumulated Energy Consumption
CExC	Specific Cumulated Exergy Consumption

	(approximated with the Specific Cumulated Energy Consumption))
CF	Carnot Factor
En	Energy
Ex	Exergy
F	Fuel
M	Mechanical work
N	Nuclear energy (fission)
P	Power
PE	Primary energy of power, heat and fuels
PF	Performance Factor
Q	Heat
R	Refrigeration / Cooling Heat extraction below ambient air temperature
RC	Resource exergy consumption
RD	Resource exergy demand
RE	Resource exergy efficiency
RS	Resource share attributed to a considered flow
	ε Exergy efficiency
	η Energy efficiency

Table 2: Table of subscripts

a	average
b	boiler
chp	combined heat and power
d	demand
dc	direct cooling
el	electrical
En	energy
F	fuel
f	flow
hp	heat pump
hs	heat storage
ht	heat transfer
i	input
l	losses
nt	non-thermal
md	minimum demand in an ideal case
o	output
P	Power
pc	phase change
Pm	Power mix
pr	primary
ps	power storage

pt	power transfer
Q	heat
rf	return flow
rm	refrigeration machine
s	storage
sf	supply flow
SF	synthetic fuel
sh	sensible heat
R	
t	transfer
tc	thermal cooling
tf	thermal flow
th	thermal
ts	thermal sources
x	final number of variables
Σ	sum

2.3.1 Basic equations

The Carnot cycle is a thermodynamically ideal process for generating work from heat. It is operating between two heat reservoirs of constant temperature.

For heat transfer at changing temperature an average thermodynamic temperature of heat transfer can be calculated. It allows considering heat transfer at changing temperature like heat transfers at constant temperature.

Many of the equations presented here can be found in (Bejan et al., 1996; Jentsch, 2010).

The thermodynamic average temperature of incompressible fluids ($T_{a,ht}$) without phase change is a function of supply (T_{sf}) and return temperature (T_{rf}).

Thermodynamic average temperature of heat transfer from incompressible fluids without phase change.

$$T_{a,ht} = \frac{T_{sf} - T_{rf}}{\ln\left(\frac{T_{sf}}{T_{rf}}\right)} \quad (1)$$

The thermodynamic average temperature of heat transfer ($T_{a,ht}$) for fluids that undergo a phase change equals the phase change temperature (T_{pc}).

Thermodynamic average temperature of heat transfer from fluids during phase change (Evaporation / condensation / freezing / thawing).

$$T_{a,ht} = T_{pc} \quad (2)$$

The Carnot factor of heat transfer (CF_{ht}) is a function of the reference temperature (T_0) and the thermodynamic average temperature of the heat transfer ($T_{a,ht}$).

Carnot Factor

$$CF_{ht} = 1 - \frac{T_0}{T_{a,ht}} \quad (3)$$

The Carnot Factor equals the energy quality of heat. If it is negative, it indicates that the exergy flow has the opposed direction to that of the energy flow. This happens for heat flows below reference temperature. It can be explained by the fact that if a heat flow below reference temperature is available, power could be generated from using heat from the reference environment to produce work. In the case of negative Carnot Factor values, its absolute value can approximate the energy quality of heat extraction for normal cooling and refrigeration. Details on how to calculate the energy quality of all types of energy flows are found in (Jentsch, 2010). The Carnot Factor equals the energy quality of heat. If it is negative its absolute value can approximate the energy quality of heat flows for normal cooling and refrigeration.

The exergy flow associated with heat is a function of the Carnot factor of the heat transfer (CF_{ht}) and the transferred heat (Q). The following equation is also valid for

cooling. In this case a negative exergy value indicates that the exergy flow is opposed to the heat flow. So, while heat is extracted exergy is added to the target of the cooling process.

Exergy flow

associated with heat

$$Ex_Q = CF_{ht} \cdot Q \quad (4)$$

The exergy flow associated with power (Ex_P) equals power (P).

Exergy flow

**associated with
power**

$$Ex_P = P \quad (5)$$

Exergy efficiency (ε) is a function of the considered exergy demand (Ex_o) and the exergy input (Ex_i).

Exergy efficiency

$$\varepsilon = \frac{Ex_d}{Ex_i} \quad (6)$$

Energy efficiency (η) is a function of the considered energy demand (En_d) and the energy input (En_i).

Energy efficiency

$$\eta = \frac{En_d}{En_i} \quad (7)$$

2.3.2 Resource exergy efficiency (RE)

Resource exergy efficiency (RE) can be used to evaluate the degree of thermodynamic perfection of an energy system. It expresses how close the considered system is to an ideal lossless process. RE is always below 100% due to irreversibilities. It is an additional information that should not replace Resource exergy consumption (RC) since it is not influenced by the total demand, therefore neglecting aspects of system size, demand and insulation.

The Resource exergy demand (RD) needs to be calculated based on an understanding of the minimally required exergy flows. For space heating this can be 20 °C space temperature and the heat required to compensate for heat losses through the building envelope. For power it can be the power consumption of the current appliances. It is important that for a comparison RD that the temperature demand is equal for all considered heat flows. Only if RD allows the supply of the same quality of end use, values are meaningful for comparison. Otherwise, RD provides valuable additional information to understand Resource exergy Efficiency

(RE better). E.g., power supply is usually much more efficient than heat supply, since the RD for heat is often so low that even small deviations from perfection have a large impact.

The Resource exergy efficiency (RE or ε_R) of a whole system is function of all Resource exergy demands (RD) that the considered system covers and the Resource exergy Consumption (RC) of all system parts.

Resource exergy efficiency

$$\varepsilon_R = RE = \frac{\sum_1^x RD}{\sum_1^x RC} \quad (8)$$

Resource exergy demand of thermal supply tasks (RD_{th}) should be defined based on the energy demand (En_d) and the minimum energy quality ($|CF_{md,ht}|$) that allows to fulfill the task.

Resource exergy demand of thermal supply tasks

$$RD_{th} = En_d \cdot |CF_{md,ht}| \quad (9)$$

Resource exergy demand (RD) of non-thermal exergy demand equals the minimum exergy demand (Ex_{md}).

Resource exergy demand of non-thermal supply tasks

$$RD = Ex_{md} \quad (10)$$

While resource exergy demand can be specified using only two equations for thermal and non-thermal flows, the definition of resource exergy consumption (RC) is dependent on the systems used to cover the demand. Equations on calculating RC are provided in chapter 2.3.5 and following.

2.3.3 Approximations & Simplifications

A key simplification in communication is to drop the word exergy. It is often misinterpreted and insufficiently well understood. Therefore, it can be sensible to talk of resource analysis instead of resource exergy analysis and of resource consumption instead of resources exergy consumption. The term exergy however should be sufficiently well understood by people applying REA since otherwise errors in application become more likely.

Usually, it is challenging to obtain accurate exergy data, such as the Cumulated Exergy Consumption (CEXC) values for supply chains of material. This means accurate data for the exergy consumption of building and recycling required to deliver a given energy or material flow is not known. A simplified REA that is based on non-exergy data tends therefore to underestimate resource consumption. All simplifications should therefore be done in a way to rather overestimate resource consumption than underestimate it to get more realistic values.

Additionally, there are usually significant uncertainties associated with most basic assumptions. Therefore, it seems acceptable to allow the use of well justified approximations and simplifications for static, simplified REA to enable the application of exergy resource analysis even in cases, where reliable exergy data is lacking.

The following two simplifications for the average temperature should only be used for draft estimations. They are not thermodynamic but arithmetic approximations. For the final calculation equation (1) and (2) should be used.

While also requiring the temperature of the supply flow (T_{sf}) and the temperature of the return flow (T_{rf}) with the following simplifications it becomes easy to estimate the average temperatures ($T_{a,ht}$)

Simplified average temperature of heat transfer at changing temperatures

$$T_{a,ht} \approx \frac{T_{sf} + T_{rf}}{2} \quad (11)$$

If heat transfer occurs from an incompressible fluid undergoing phase change the phase change temperature (T_{pc}) can be used for approximation.

Simplified average temperature of heat transfer that includes phase change and only low heat transfer at changing temperatures

$$T_{a,ht} \approx T_{pc} \quad (12)$$

The exergy associated with fuels (E_{χ_F}) can be approximated with the higher heating value of the fuel (HHV_F) (Bejan et al., 1996).

**Estimate for fuel
exergy**

$$Ex_F \approx HHV_F \quad (13)$$

In the heating sector many energy efficiencies are defined as the ratios of the output energy to the lower heating value (LHV_F). This is where values of efficiencies over 100% come from, which seem to contradict the law of energy conservation⁴ as they imply that more energy is generated than is put in. To be able to use these efficiencies without creating inconsistencies in REA it is assumed that fuel energy values used in efficiency equations ($En_{F,\eta}$) equal the lower heating value of the fuel.

**Fuel energy as
considered in
common efficiency
values.**

$$En_{F,\eta} \approx LHV_F \quad (14)$$

The energy quality for all types of flows has been derived in (Jentsch, 2010). However, for energy flows it can be simplified as the ratio of the exergy associated with a flow (Ex_f) and its energy flow (En_f). Energy quality can never be higher than 100% since the law of energy conservation postulates that the amount of power generated from an energy flow in context with its environment can never exceed the amount of energy put into the conversion process. Any ratio of exergy and energy that exceeds 100% has likely been calculated by not considering all energy flows that are relevant. A full discussion of details of the energy quality concept can be found in (Jentsch, 2010).

**Energy quality
associated with a
flow**

$$EQ \approx \frac{Ex_f}{En_f} \quad (15)$$

For the purpose of performing a simplified REA without raising inconsistencies the Energy of non-thermal flows (En_{nt}) is therefore set to equal the exergy associated with the non-thermal flows (Ex_{nt}).

**Energy associated
with non-thermal
energy and mass
flows**

$$En_{nt} \approx Ex_{nt} \quad (16)$$

⁴ The first law of thermodynamics.

In the case of fuels this equation means that the energy of the fuel (En_F) and the exergy of the fuel (Ex_F) can be approximated by the higher heating value (HHV_F) of the fuel.

**Energy and exergy
of fuels**

$$En_F \approx Ex_F \approx HHV_F \quad (17)$$

The underlying assumption for the following simplification of Cumulated Exergy Consumption of non-thermal flows is that all losses are of the same type as the considered fuel. This means that non-thermal energy losses equal exergy losses and that the energy quality (see equation (15)) of these losses is 100%. Consequently, the Cumulated Exergy Consumption associated with non-thermal energy flows ($CExC_{nt}$) can be approximated with the Cumulated Energy Consumption of non-thermal energy flows (CEC_{nt}).

**Estimate for
Cumulated Exergy
Consumption of
non-heat flows**

$$CExC_{nt} \approx CEC_{nt} \quad (18)$$

This equation means that for natural fuels Cumulated Exergy Consumption ($CExC_F$) approximated by the Cumulated Energy Consumption of the fuel (CEC_F).

**Estimate for
Cumulated Exergy
Consumption of fuel
flows**

$$CExC_F \approx CEC_F \quad (19)$$

For synthetic fuels such as hydrogen a Cumulated Energy Consumption of the synthetic fuel (CEC_{SF}) might not be available as it is very dependent on the processes used to produce the synthetic fuel. If the production chain of synthetic fuels however is known the Cumulated Exergy Consumption of the synthetic fuel ($CExC_{SF}$) can be approximated by the resource consumption (RC_{SF}) of the synthetic fuel production chain.

**Estimate for
Cumulated Exergy
Consumption of
synthetic fuels if
their production
chain is known**

$$CEXC_{SF} \approx RC_{SF} \quad (20)$$

In order to approximate Cumulated Exergy Consumption of thermal flows ($CEXC_{tf}$), it can be assumed that the losses that are caused in the upstream chain are non-thermal flows of an energy quality of 100%. However, the Cumulated Energy Consumption (CEC_{tf}) of any resource heat flow, such as solar thermal heat, always includes the energy of the heat itself. Consequently, for every unit of heat delivered a unit of heat energy needs to be subtracted from CEC_Q in order to obtain the non-thermal losses that occur apart from the heat delivered itself. The specific exergy of the thermal flow, which equals the absolute value of the Carnot Factor ($|CF_{tf}|$), can then be added to provide an overall estimate of the Cumulated Exergy Consumption of thermal sources ($CEXC_{tf}$).

**Estimate for the
Cumulated Exergy
Consumption of
thermal flows**

$$CEXC_{tf} \approx (CEC_Q - 1 + |CF_{tf}|) \quad (21)$$

Thermal sources include heat from solar thermal energy, geothermal energy, unavoidable waste heat and free cooling using sea, river and lake water.

The underlying assumption for the following approximations of exergy efficiency is that most energy efficiency values for fuel using technologies are relating the energy output to the Lower Heating Value (LHV_F) while exergy associated with fuels can be approximated with the higher heating value (HHV_F).

**Estimate for the
exergy efficiency of
power generation**

$$\varepsilon_{el} \approx \eta_{el} \cdot \frac{LHV_F}{HHV_F} \quad (22)$$

**Estimate for the
exergy efficiency of
using fuel boilers**

$$\varepsilon_{th} \approx \eta_{th} \cdot \frac{LHV_F}{HHV_F} \cdot CF_{ht} \quad (23)$$

The ratio $\frac{LHV_F}{HHV_F}$ is usually between 0.96 and 0.9 for combustible fuels (DIN, 2010b). For non-fuels this ratio does not apply.

If an average Cumulated Exergy Consumption for power mix ($CEXC_{pm}$) where the exact composition of the contributing fuels is unknown, an average ratio of lower and higher heating value ($\frac{LHV_{F,a}}{HHV_{F,a}}$) can be used and should be set to the estimate of 0.93 at least for the power share from fuels in the power mix.

For simplification's sake it can also be acceptable to set the value to 0.93 for the totality of power since the value for the most common fossil fuel of the future – natural gas / methane - is 0.9 and it is better to assume a resource consumption that is somewhat too high than in reality than too low. A deviation that can overestimate exergy input appears acceptable since usually resource consumption for building and recycling is neglected.

2.3.4 General equations for cogeneration assessment

A cogeneration unit is a system that uses one or a set of exergy inputs to produce a set of valuable exergy outputs that are used to cover demands. Exergy Analysis allows consistent allocation of input exergy to all valuable products produced by a cogeneration unit.

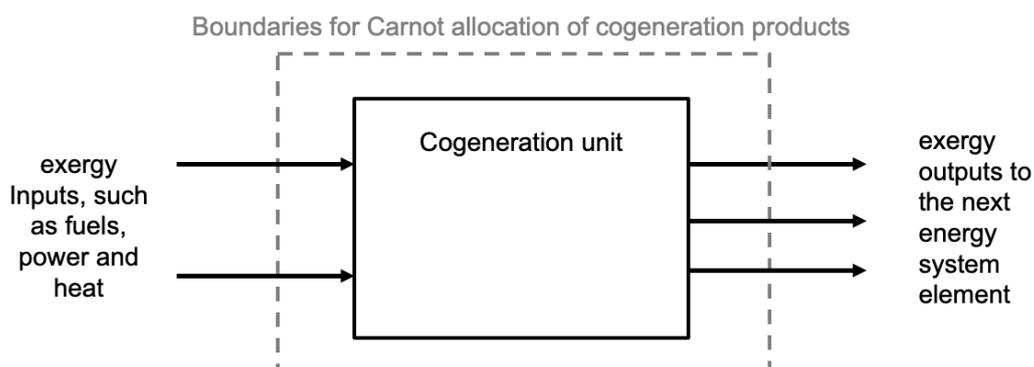


Figure 2: Balance boundaries to allocate resource shares to cogeneration products with the Carnot method

Generally, allocation to an exergy flow in a CHP unit producing different product streams can be calculated as follows.

Cogeneration share attributed to a product flow from cogeneration

$$CS_{f, chp} = \frac{Ex_f}{\sum_{z=1}^z Ex_z} \quad (24)$$

This equation is applicable to all types of cogenerations. This means if a cogeneration system produces any combination of heating, cooling, chemicals and power it can be used.

Due to the temperature dependency of exergy all heat flows that cross the cogeneration unit's balance boundary should be considered at their respective temperature levels and as separate products if they are used separately. If different heat exchangers at different temperatures heat up a single output flow, only the temperature of the fluid flow that crosses the balance boundary of the cogeneration unit is considered.

Equation (2421) allows the allocation of resources to a coproduction of non-energy products (such as chemicals and refined metals etc.) and energy products (such as heat, power and cooling). However, in order to assess the exergy flow associated with non-energy products it is usually necessary to assess mechanical, concentration and chemical exergy which requires a deeper level of analysis (Jentsch, 2016) than usually used for energy systems comparison.

Please note that the $CExC$ of the fuel is not relevant to calculating the cogeneration share as it is only dependent on the cogeneration product exergy flows and therefore universally applicable to all types of resource consumption by the CHP process. The equations of the cogeneration share can also be applied to allocate any other products of a cogeneration system such as greenhouse gas emissions.

The following two equations are valid for the type of CHP that produces a single heat flow and power.

Cogeneration share of heat from cogeneration of one power and one heat flow

$$CS_{Q, chp} = \frac{Ex_Q}{Ex_Q + Ex_P} \approx \frac{CF_{ht} \cdot \eta_{th, chp}}{CF_{ht} \cdot \eta_{th, chp} + \eta_{el, chp}} \quad (25)$$

**Cogeneration share
of power from
cogeneration of one
power and one heat
flow**

$$CS_{P,chp} = 1 - RS_{Q,chp} \approx \frac{\eta_{el,chp}}{CF_{ht} \cdot \eta_{th,chp} + \eta_{el,chp}} \quad (26)$$

2.3.5 Overall resource consumption

The total resource consumption (RC_{Σ}) for a supply scenario is calculated by adding the resource consumption of all individual demands based on the share of energy demand associated with the considered flow (En_d).

**Total resource
consumption of an
energy system**

$$RC_{\Sigma} = \sum_1^x \frac{En_{d,x}}{\Sigma En_d} \cdot RC_x \quad (27)$$

In cases where non-energy flows such as materials are considered the non-energy exergy demand can be used to calculate the minimum energy demand associated with such flows. The addition must be based on the energy demand share ($\frac{En_{d,x}}{\Sigma En_d}$) and not on the exergy demand share as only energy is conserved and therefore adds up to 100% after summation.

If only power from various sources is considered in a power mix the total resource consumption ($RC_{\Sigma,p}$) can be calculated as a function of the power share of a given source x ($\frac{P_x}{\Sigma P}$) and the resource consumption of that supply chain ($RC_{P,x}$).

**Resource
consumption of the
power mix**

$$RC_{\Sigma P} = \sum_1^x \frac{P_x}{\Sigma P} \cdot RC_{P,x} \quad (28)$$

Solar exergy and the kinetic exergy of the wind are not usable on demand. They fluctuate. Therefore, they are not considered resources. The first storable form of exergy is considered the resource in the case of sun and wind. This is usually electrical energy but can also be thermal energy.

Usually, the conversion losses in converting sun and wind to power are also neglected in the CEC values, which can easily be checked by looking at the respective values. The CEC indicates how much energy is used in order to produce a considered unit of energy. A CEC in the order of magnitude of 1.2 for PV means that 1.2 kWh of energy were used for every kWh generated. One unit of energy is the

electricity that is delivered from PV. The 0.2 addition stem from upstream energy consumption for construction of the PV cells written off over the calculated lifetime of the PV units. It is obvious that this value cannot relate the PV output to the input of solar radiation, since the efficiency of conversion is in the order of magnitude of 20%. If considering the conversion loss from solar energy to power in PV, the resulting CEC would be in the order of magnitude of 5. instead of 1, since about 5 units of solar energy were used to produce one unit of electricity.

In general, it is recommendable to only consider exergy flows as input that are changed in the process. E.g., nuclear exergy should only be considered if it is actively converted to a useful energy form. Normally it transits most energy conversion chains unchanged and therefore can be ignored as it is not consumed. All losses of harvesting and transportation are consequently allocated to exergy that is used in the following process chain.

The same is valid for non-fuel chemical exergy if the chemical composition and concentration of a medium remains the same. In this case chemical exergy should be ignored for the calculation of resource consumption.

Please note that in order to assess the total exergy transfer to a system by interaction with a material flow such as hot, pressurized natural gas, it is necessary to assess first the thermal exergy and only then the other types of exergies. All types of exergy need to be added separately based on their absolute values (Jentsch, 2010).

Total exergy associated with exergy transfer from a material flow.

$$Ex = |Ex_{th,o} - Ex_{th,i}| + |Ex_{C,T0,o} - Ex_{C,T0,i}| + |Ex_{M,T0,o} - Ex_{M,T0,i}| + |Ex_{N,T0,o} - Ex_{N,T0,i}| \quad (29)$$

2.3.6 Electricity generation from fuels without CHP

The resource consumption for power generation is a function of the power demand (P_d), the power losses through storage ($P_{l,s}$), the power losses due to transfer ($P_{l,t}$), the Cumulated Exergy Consumption of the power supply chain ($CEXC_p$) and the electrical exergy efficiency (ε_{el}).

Resource consumption of non-CHP power

$$RC_p = (P_d + P_{l,s} + P_{l,t}) \cdot \frac{CEXC_p}{\varepsilon_{el}} \quad (30)$$

generation from fuels

For natural fuels the equation can be simplified using equation (19) to a function of the Cumulated Energy Consumption of the fuel (CEC_F), the electrical energy efficiency (η_{el}) and the ratio of lower to higher heating value of the fuel ($\frac{LHV_F}{HHV_F}$).

Simplified resource consumption of non-CHP power generation from fuels

$$RC_P \approx (P_d + P_{l,s} + P_{l,t}) \cdot \frac{CEC_F}{\eta_{el} \cdot \frac{LHV_F}{HHV_F}} \quad (31)$$

For synthetic fuels where no Cumulated Energy Consumption (CEC_F) values are available, such as hydrogen, the equation can be simplified using equation (20) to a function of the resource consumption of the synthetic fuel (RC_{SF}), the electrical energy efficiency (η_{el}) and the ratio of lower to higher heating value of the synthetic fuel ($\frac{LHV_{SF}}{HHV_{SF}}$).

Simplified resource consumption of non-CHP power generation from synthetic fuels

$$RC_P \approx (P_d + P_{l,s} + P_{l,t}) \cdot \frac{RC_{SF}}{\eta_{el} \cdot \frac{LHV_{SF}}{HHV_{SF}}} \quad (32)$$

2.3.7 Electricity from CHP using fuels

The resource consumption for power generation from CHP is a function of the power demand (P_d), the power losses through storage ($P_{l,s}$), the power losses due to transfer ($P_{l,t}$), the Cumulated Exergy Consumption input of the fuel or heat source ($CExC_i$) and the cogeneration share of power ($CS_{P,chp}$) from equation (2623).

Resource consumption of electricity from heat and power CHP

$$RC_{P,chp} = (P_d + P_{l,s} + P_{l,t}) \cdot CS_{P,chp} \cdot CExC_i \quad (33)$$

For CHP from fuels this equation can be simplified to a function of the Cumulated Energy Consumption of the fuel (CEC_F).

**Resource
consumption of
electricity from heat
and power CHP using
fuels**

$$RC_{P,chp} = (P_d + P_{l,s} + P_{l,t}) \cdot CS_{P,chp} \cdot CEC_F \quad (34)$$

For thermal sources this equation can be simplified using equation (2117) to a function of Cumulated Energy Consumption associated with the thermal source (CEC_{ts}) and the Carnot factor of the thermal source (CF_{ts}).

**Resource
consumption of
electricity from heat
and power CHP
using thermal
sources⁵**

$$\begin{aligned} RC_{P,chp,ts} \\ \approx (P_d + P_{l,s} + P_{l,t}) \cdot CS_{P,chp} \\ \cdot CS_{P,chp} \cdot (CEC_{ts} - 1 + CF_{ts}) \end{aligned} \quad (35)$$

2.3.8 Heat from electrical boilers

The resource consumption for heat generation from electrical boilers is a function of the heat demand (Q_d), the heat losses due to storage ($Q_{l,s}$), the heat losses due to transfer ($Q_{l,t}$), the Cumulated Exergy Consumption for power ($CEXC_p$) and the exergy efficiency of the electrical boiler ($\varepsilon_{b,el}$).

**Resource
consumption of heat
from electric boilers**

$$RC_{b,el} = (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CEXC_p}{\varepsilon_{b,el}} \quad (36)$$

In a simplified analysis this equation can be transformed into using the Cumulated Energy Consumption for power generation (CEC_p), the energy efficiency of the boiler ($\eta_{b,el}$) and the ratio of the average lower to the higher heating value of the fuels used for electricity generation ($\frac{LHV_{F,el,a}}{HHV_{F,el,a}}$).

**Simplified resource
consumption of heat
from electric boilers**

$$RC_{b,el} \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CEC_p}{\eta_{b,el} \cdot \frac{LHV_{F,el,a}}{HHV_{F,el,a}}} \quad (37)$$

⁵ CHP from thermal sources refers to CHP using geothermal, solar thermal or waste heat sources. It is a sensible solution if the temperature obtained from the source is significantly higher than the temperature required by the demand side system, e.

If an average $CExC_p$ for power mix is used $\frac{LHV_{F,el,a}}{HHV_{F,el,a}}$ should be set to the estimate of 0.93 - at least for the power share from fuels in the power mix (see chapter 2.3.3).

2.3.9 Heat from boilers

The resource consumption for heat generation from boilers is a function of the heat demand (Q_d), the heat losses due to storage ($Q_{l,s}$), the heat losses due to transfer ($Q_{l,t}$), the Cumulated Exergy Consumption of the input ($CExC_i$) and the exergy efficiency of the boiler (ε_b).

Resource

**consumption of heat
from boilers**

$$RC_b = (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CExC_i}{\varepsilon_b} \quad (38)$$

In a simplified analysis this equation can be transformed into using the Cumulated Energy Consumption of the fuel (CEC_F), the energy efficiency of the boiler (η_b) and the ratio of the average lower to the higher heating value of the fuel ($\frac{LHV_F}{HHV_F}$).

**Simplified resource
consumption of heat
from boilers using
primary fuels**

$$RC_b \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CEC_F}{\eta_b \cdot \frac{LHV_F}{HHV_F}} \quad (39)$$

For synthetic fuels, for which a Cumulated Energy Consumption of the fuel is not known this universal equation can be transformed into using the resource consumption of the fuel (RC_{SF}), the energy efficiency of the boiler (η_b) and the ratio of the average lower to the higher heating value of the synthetic fuel ($\frac{LHV_{SF}}{HHV_{SF}}$).

**Simplified resource
consumption of heat
from boilers using
synthetic fuels**

$$RC_b \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{RC_{SF}}{\eta_b \cdot \frac{LHV_{SF}}{HHV_{SF}}} \quad (40)$$

2.3.10 Heat from CHP using fuels

The resource consumption for heat generation from CHP using fuels is a function of the heat demand (Q_d), the heat losses due to storage ($Q_{l,s}$), the heat losses due to transfer ($Q_{l,t}$), the Cumulated Exergy Consumption input of the fuel or heat source ($CExC_i$) and the cogeneration share of heat ($CS_{Q,chp}$) from equation (2522).

Resource

**consumption of heat
from heat and power
CHP**

$$RC_{Q,chp} = (Q_d + Q_{l,s} + Q_{l,t}) \cdot CS_{Q,chp} \cdot CExC_i \quad (41)$$

For CHP from fuels this equation can be simplified to a function of the Cumulated Energy Consumption of the fuel (CEC_F).

Resource

**consumption of heat
from heat and power
CHP using fuels**

$$RC_{Q,chp} = (Q_d + Q_{l,s} + Q_{l,t}) \cdot CS_{Q,chp} \cdot CEC_F \quad (42)$$

For thermal sources this equation can be simplified using equation (2117) to a function of Cumulated Energy Consumption associated with the thermal source (CEC_{ts}) and the Carnot factor of the thermal source (CF_{ts}).

Resource

**consumption of heat
from heat and power
CHP using thermal
sources⁶**

$$\begin{aligned} RC_{Q,chp,ts} \\ &\approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot CS_{Q,chp} \\ &\cdot CS_{Q,chp} \cdot (CEC_{ts} - 1 + CF_{ts}) \end{aligned} \quad (43)$$

2.3.11 Heat from heat pumps

The resource consumption for heat generation for heat pumps is a function of the heat demand (Q_d), the heat losses due to storage ($Q_{l,s}$), the heat losses due to transfer ($Q_{l,t}$), the Cumulated Exergy Consumption input of the fuel or heat source ($CExC_i$) and the Carnot factor of the heat transfer ($CF_{ht,hp}$) and the performance factor of the heat pump (PF_{hp}).

The equation uses the assumption that the exergy influx from heat is not exactly known from measurements. Therefore, the minimum amount of energy from heat needed to fulfill the energy balance ($1 - \frac{1}{APF_{hp}}$) is multiplied with the Carnot factor of the heat extracted from the source ($CF_{ht,hp}$) to estimate it.

⁶ CHP from thermal sources refers to CHP using geothermal, solar thermal or waste heat sources. It is a sensible solution if the temperature obtained from the source is significantly higher than the temperature required by the demand side system, e.

The performance factor is used in the following equation instead of the Coefficient of Performance as it is more comprehensive and considers consumption for auxiliary demands. This means not only the consumption of the heat pump itself but also of supporting systems needed to operate the heat pump is considered.

The PF_{hp} ideally matches the time steps of the analysis. E.g., if an analysis considers annual average values the annual performance factor should be used. For a monthly analysis the monthly performance factor should be used etc.

The $CF_{ht, hp}$ is zero for heat from air since this heat is freely available and virtually unlimited.

$$RC_{hp} = (Q_d + Q_{l,s} + Q_{l,t}) \cdot \left(\frac{CExC_i}{PF_{hp}} + CF_{ht, hp} \cdot \left(1 - \frac{1}{PF_{hp}} \right) \right) \quad (44)$$

Several simplifications can be applied if values for the Cumulated Exergy consumption are not known.

Simplification for power as a function of the Cumulated Energy Consumption of power (CEC_p):

$$CExC_i \approx CEC_p$$

Simplification for primary fuels as a function of the Cumulated Energy Consumption of fuels (CEC_F):

$$CExC_i \approx CEC_F$$

Simplification for synthetic fuels as a function of the Cumulated Energy Consumption of synthetic fuels (CEC_{SF}) or their Resource Consumption (RC_{SF}):

$$CExC_i \approx CEC_{SF} \approx RC_{SF}$$

Simplification for CHP as a function of the Cumulated Energy Consumption of fuels (CEC_F) and the Cogeneration Share of the driving energy flow for the refrigeration machine (CS_{rm}):

$$CExC_i \approx CS_{rm} \cdot CEC_F$$

Simplification for thermal flows as a function of the Cumulated Energy Consumption of heat (CEC_Q) or their Carnot Factor (CF_{tf}) based on equation (2117):

$$CEXC_i \approx RC_{ts} \approx (CEC_Q - 1 + |CF_{tf}|)$$

2.3.12 Heat from thermal sources (Excess heat, Solar thermal, Geothermal)

The resource consumption for heat generation from thermal sources is a function of the heat demand (Q_d), the heat losses due to storage ($Q_{l,s}$), the heat losses due to transfer ($Q_{l,t}$), the Cumulated Exergy Consumption input of the heat source ($CEXC_i$) and the Carnot factor of the heat transfer ($CF_{ht,hp}$).

Resource

consumption for heat from thermal sources

$$RC_{ts} = (Q_d + Q_{l,s} + Q_{l,t}) \cdot CEXC_{ts} \quad (45)$$

Using equation (2117) for heat flows this can be transformed to a function that considers the Cumulated Energy Consumption for thermal sources CEC_{ts} if values for Cumulated Exergy Consumption are not available.

Simplified resource consumption for heat from thermal sources

$$RC_{ts} \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot (CEC_{ts} - 1 + CF_{ts}) \quad (46)$$

Auxiliary power or fuel consumption needs to be considered separately like an electrical demand. The resource consumption of the auxiliary demand needs to be added to the resource consumption of the thermal source system to obtain the total resource consumption.

2.3.13 Heat from CHP using thermal sources

The resource consumption for heat generation by CHP from thermal sources is a function of the heat demand (Q_d), the heat losses due to storage ($Q_{l,s}$), the heat losses due to transfer ($Q_{l,t}$), the Cumulated Exergy Consumption input of the fuel or heat source ($CEXC_i$) and the Cogeneration share of heat ($CS_{Q,chp}$).

Resource consumption allocated to heat from thermal CHP.

Resource

consumption of heat from CHP from thermal sources

$$RS_{Q,chp,ts} = (Q_d + Q_{l,s} + Q_{l,t}) \cdot CS_{Q,chp} \cdot CEXC_{ts} \quad (47)$$

Using equation (2117) for heat flows this can be transformed to a function that considers the Cumulated Energy Consumption for thermal sources (CEC_{ts}) and the

Carnot factor of the thermal source (CF_{ts}) if values for Cumulated Exergy Consumption are not available.

Simplified resource consumption of heat from thermal sources

$$RC_{ts} \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot CS_{Q,chp} \cdot (CEC_{ts} - 1 + CF_{ts}) \quad (48)$$

Auxiliary power or fuel consumption needs to be considered separately like an electrical demand. The resource consumption of the auxiliary demand needs to be added to the resource consumption of the thermal source system to obtain the total resource consumption.

2.3.14 Cooling from refrigeration machines

The resource consumption for cooling generation from power or fuels is a function of the cooling demand (R_d), the cooling losses due to storage ($R_{l,s}$), the cooling losses due to transfer ($R_{l,t}$), the Cumulated Exergy Consumption input of the fuel or power source ($CExC_i$) and the performance factor of the refrigeration machine (PF_{rm}).

Resource consumption of cooling from chillers

$$RC_{rm} = (R_d + R_{l,s} + R_{l,t}) \cdot \frac{CExC_i}{PF_{rm}} \quad (49)$$

For chillers that produce only cooling, no consideration of the rejected heat is required, since it is considered a loss to the surroundings.

Simplification for power as a function of the Cumulated Energy Consumption of power (CEC_p):

$$CExC_i \approx CEC_p$$

Simplification for primary fuels as a function of the Cumulated Energy Consumption of fuels (CEC_F):

$$CExC_i \approx CEC_F$$

Simplification for synthetic fuels as a function of the Cumulated Energy Consumption of synthetic fuels (CEC_{SF}) or their Resource Consumption (RC_{SF}):

$$CExC_i \approx CEC_{SF} \approx RC_{SF}$$

Simplification for CHP as a function of the Cumulated Energy Consumption of fuels (CEC_F) and the Cogeneration Share of the driving energy flow for the refrigeration machine (CS_{rm}):

$$CExC_i \approx CS_{rm} \cdot CEC_F$$

Simplification for thermal flows as a function of the Cumulated Energy Consumption of heat (CEC_Q) or their Carnot Factor (CF_{tf}) based on equation (2117):

$$CExC_i \approx RC_{ts} \approx (CEC_Q - 1 + |CF_{tf}|)$$

2.3.15 Direct cooling from thermal sources (Sea, river and lake water)

The resource consumption for cooling generation from power or fuels is a function of the cooling demand (R_d), the cooling losses due to storage ($R_{l,s}$), the cooling losses due to transfer ($R_{l,t}$), the Cumulated Exergy Consumption input of the thermal source ($CExC_{ts}$).

Resource consumption of direct cooling from thermal sources

$$RC_{dc} = (R_d + R_{l,s} + R_{l,t}) \cdot CExC_{ts} \quad (50)$$

Using equation (2117) for heat flows this can be transformed to a function that considers the Cumulated Energy Consumption for direct cooling (CEC_{dc}) and the Carnot factor of the direct cooling heat flow (CF_{dc}) if values for Cumulated Exergy Consumption are not available.

Simplified resource consumption of direct cooling from thermal sources

$$RC_{dc} \approx (R_d + R_{l,s} + R_{l,t}) \cdot (CEC_{dc} - 1 + |CF_{dc}|) \quad (51)$$

For heat flows below reference temperature the Carnot Factor is below zero. This indicates that the exergy flow has an opposite direction in relation to the energy flow. So, while heat is extracted from the target of cooling, exergy is provided to that target.

Auxiliary power or fuel consumption needs to be considered separately like an electrical demand. The resource consumption of the auxiliary demand needs to be added to the resource consumption of the thermal source system to obtain the total resource consumption.

2.3.16 Hydrogen and other synthetic fuels from primary fuels or electricity

The resource consumption for synthetic fuels from power is a function of the fuel demand (R_d), the fuel losses due to storage ($R_{l,s}$), the fuel losses due to transfer ($R_{l,t}$), the Cumulated Exergy Consumption input of the input ($CExC_i$) and the exergy efficiency of the synthetic fuel production (ε_{SF}).

Resource consumption of synthetic fuel from primary fuels or power

$$RC_{SF} = (F_d + F_{l,s} + F_{l,t}) \cdot \frac{CExC_i}{\varepsilon_{SF}} \quad (52)$$

If the resource used for synthetic fuel production is fuel or power, it can be simplified to be a function of the Cumulated Energy Consumption of the input (CEC_i) and the energy efficiency if it is based on the Higher Heating Values ($\eta_{SF,HHV}$).

Simplified resource consumption of synthetic fuel from primary fuels or power if efficiency is based on HHV values

$$RC_{SF} \approx (F_d + F_{l,s} + F_{l,t}) \cdot \frac{CEC_i}{\eta_{SF,HHV}} \quad (53)$$

The underlying assumption for the simplification in equation (5346) is that for fuel-to-fuel conversion the HHV of fuels are considered only. If this is not clearly the case it might be necessary to include the $\frac{LHV}{HHV}$ ratios in the equation as follows:

Simplified resource consumption of synthetic fuel from primary fuels or power if efficiency is based on LHV values

$$RC_{SF} \approx (F_d + F_{l,s} + F_{l,t}) \cdot \frac{CEC_i}{\eta_{SF,LHV} \cdot \frac{LHV_i}{HHV_i} \cdot \frac{HHV_{SF}}{LHV_{SF}}} \quad (54)$$

References

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

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

Brockway, P., Kjelstrup, S., Dewulf, J., Siebentritt, S., Valero, A., & Whelan, C. (2016). *In a resource-constrained world: Think exergy not energy*.
<https://doi.org/10.13140/RG.2.1.4507.0326>

DIN. (2005). *DIN EN 806 „Technische Regeln für Trinkwasserinstallationen“*. Beuth.
<https://www.haustechnikdialog.de/SHKwissen/311/DIN-EN-806-Technische-Regeln-fuer-Trinkwasserinstallationen>

DIN. (2010a). *DIN 18599 2010: Beiblatt 1*.

DIN (Hrsg.). (2010b). *Energy efficiency of buildings—Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting—Part 1: General balancing procedures, terms and definitions, zoning and evaluation of energy sources*. Beuth.

Ecoinvent database. (2021). <https://ecoinvent.org/>

Hertle, H., Jentsch, A., Eisenmann, L., Brasche, J., Brückner, S., Schmitt, C., Sager, C., & Schurig, M. (2016). *Die Nutzung von Exergieströmen in kommunalen Strom-Wärme-Systemen zur Erreichung der CO₂-Neutralität von Kommunen bis zum Jahr 2050* (Nr. 35/2016; Climate Change).
<https://www.umweltbundesamt.de/publikationen/die-nutzung-von-exergiestromen-in-kommunalen-strom>

IWU. (2014). *Kumulierter Energieaufwand und CO₂-Emissionsfaktoren verschiedener Energieträger und –versorgungen*.
http://www.iwu.de/fileadmin/user_upload/dateien/energie/werkzeuge/kea.pdf

Jentsch, A. (2010). *A novel exergy-based concept of thermodynamic quality Development of a novel thermodynamic concept and its application to energy system evaluation and process analysis*. Suedwestdeutscher Verlag fuer Hochschulschriften.
<http://nbn-resolving.de/urn:nbn:de:101:1-20110220616> OR
<http://dx.doi.org/10.14279/depositonce-2399>

Jentsch, A. (2015). Obtaining unbiased results in CHP assessment—The Carnot-Method for Allocation of Fuel and Emissions. *EuroHeat&Power International Edition*, 12(11/2015), 26–28.

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

Jentsch, A., Dötsch, C., Beier, C., & Bargel, S. (2009). Neues Bewertungswerkzeug für Energieversorgungsszenarien. *EuroHeat & Power*, 2009(4), 38–45.

Umweltbundesamt. (2021). *Prozessorientierte Basisdaten für Umweltmanagement-Instrumente (ProBas)*. <https://www.probas.umweltbundesamt.de/php/index.php>