REA: resource exergy analysis - Guidelines for evaluating and comparing energy systems

Andrej Jentsch (andrej.jentsch@richtvert.de)
Richtvert https://orcid.org/0000-0003-2413-0507

Method Article

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REA: resource exergy analysis

Guidelines for evaluating and comparing energy systems

Andrej Jentsch

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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.

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1 Background

Resource exergy analysis (REA) has been applied and improved for more than a decade (Hertle et al., 2016; Jentsch, 2010, 2016; Jentsch et al., 2009). 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.

REA is a proven type of exergy analysis that can replace Primary energy analysis with a more comprehensive and consistent methodology while remaining similarly simple.

REA is also a key element required to achieving climate targets as fast as possible.

1.1 Motivation

Climate change mitigation is one of the great challenges of our time. An unprecedented transformation is required to decarbonize energy systems. A key question at the beginning of each transition effort is to find out: What are the optimal solutions to mitigate climate change?

It is obvious that to stop climate change it is necessary to minimize short- and long-lived greenhouse gas emissions (GHGE) as much as possible. However, energy systems that are free of direct GHGE can still cause an overall increase GHGE if the energy economy is still using GHG-emitting sources.

The reason for this effect is wastefulness. Wastefulness in otherwise GHG-free energy systems increases the amount of GHGE-free energy supply required to cover a considered demand. That means that less GHGE-free energy converters are available for the rest of the energy system and overall fossil fuel use is increased.

A good example for this effect is the use of hydrogen from GHGE-free power (green hydrogen) boilers for heating. While by themselves using green hydrogen in boilers can be considered GHGE-free, the production chain generates significant losses at the conversion from green electricity to green hydrogen and at the conversion of a valuable chemical fuel to heat for space heating. Alternatively, green electricity can be used in air-source heat pumps that use dedicated GHGE-free electricity to upgrade ambient heat to a useful temperature level.

If comparing both options it becomes obvious that the green hydrogen boiler uses more than four times the resources than an air-source heat pump operated with the same source of power (North & Jentsch, 2021). This means that if one windmill were required to cover the demand using air-source heat pumps three more windmills would be required to cover the same demand using a green hydrogen boiler.

The three additional windmills required to cover the losses of the green hydrogen boiler system reduce the windmills available for other uses. Since all electricity from windmills is usually used, this means that the power used to cover avoidable losses of the hydrogen boiler needs to be generated by other, usually fossil sources. Consequently, GHGE of the overall energy system are likely to increase if green hydrogen boilers are used to cover space heating demand instead of air-source heat pumps.

This example is meant to illustrate the essential nature of minimizing consumption before decarbonizing the remaining supply. To effectively mitigate climate change minimizing resource exergy consumption is equally important as minimizing direct GHGE from a considered energy system.

This guidebook details resource exergy analysis (REA). A well-tested and comprehensive method suitable to replace primary energy analysis. REA aims to make the global effort to decarbonize the global energy system more efficient and effective and help reach climate targets in time.

1.2 A definition of exergy

Exergy associated with a flow of mass or energy is the maximum work obtainable by using an ideal thermodynamic process to bring the flow into equilibrium with a clearly defined reference environment (Rant, 1956).

The thermodynamic properties of the reference environment such as temperature, pressure and chemical composition should reflect properties of the ambient environment that do not change noticeably when exchanging energy or mass with the considered flow.

For better understanding, the physical property “exergy” can be described as a product of energy and “energy quality”. It thus increases the scope of energy system analysis from energy to include all thermodynamic effects including those on energy quality.

All non-thermal energy carriers such as fuels or electricity have an energy quality of 100%, which means that in theory they can be fully transformed into electricity or work.

Thermal energy flows have an energy quality that is usually much lower than 100%. For heat flows above the temperature of the surroundings (reference temperature), a higher temperature means higher energy quality.

For heat flows below reference temperature a lower temperature means higher energy quality (Jentsch, 2010).

Exergy optimization helps minimize losses in technical systems and entails matching the quality levels of energy supply and demand to optimize the utilization of high-value resources, such as combustible fuels.

1.3 REA in comparison to Primary Energy Analysis

A common standard for the analysis of system efficiency and valuable primary energy consumption is primary energy analysis (PEA) (DIN, 2010a). Its key indicator is the primary energy factor (PEF) that is meant to characterize the consumption of primary energy per unit of energy delivered. However, in a world that transitions to a fully carbon-neutral economy the PEF becomes increasingly problematic (Paulick et al., 2017).

The primary energy approach ignores the fact that heat is of lower physical value than power and fuels. This can make heat from solar thermal sources look equally valuable as power from photovoltaics, even though it is obvious that there is a much wider range of uses for power than for heat at low temperatures.

The conventional attempt to remedy some of the problems resulting from this ignorance is to only assess the primary energy consumption (PEC) of fossil fuels. Unfortunately, this quickly becomes problematic if GHGE-free technologies are compared since all fossil PEC of renewables is close to zero thus making impossible to assess and compare the wastefulness of GHGE-free energy systems.

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 due to wasteful resource utilization.

The key difference between PEA and REA lies in the consideration of energy quality. REA goes beyond the law of conservation[1] of energy and also considers the law of

[1] The first law of thermodynamics

entropy generation[2] thus ensuring transparent identification of resource-saving solutions.

REA is a more comprehensive and consistent analysis methodology than PEA and it is just as simple to use. It is fully based in physics without need for “man-made” assumptions and thus can provide a reflection of physical reality as accurately as the available data and analysis capacity allows.

1.4 The relevance of REA to mitigating climate change

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 GHGE and life cycle cost. While REA is complementary to GHGE analysis it is similarly important to stop climate change.

Solutions that consume excess resources, even if these resources are GHGE-free, inevitably lead to an increased demand for supply systems. More carbon neutral supply systems require more time to be built. Thus, excess resource exergy consumption directly increases the time required to reach climate targets.

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

[2] The second law of thermodynamics

2 Methodology

2.1 General methodology description

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 exergy 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 can be stored directly without need for transformation – storable exergy (SE) flows - are considered resources. Only SE flows can be used directly to supply a considered load profile.

The reasoning behind this definition is, that SE flows are lost if they are not used. Consequently, solar radiation and kinetic energy of wind, rivers or currents are not considered resources. Instead, the first storable product after transformation from these primary energy flows is considered a resource (such as power from wind, rivers and PV and solar thermal heat. Additionally, this definition is supported by the fact that historical exergy consumption to create existing SE flows, such as the solar radiation needed to create fossil fuels or biomass is not considered in energy system analysis.

While in this report the exergy of solar radiation, and the kinetic energy of river water and wind are not considered as 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 from a non-storable exergy flow to a SE flow is, the more converters need to be built to harvest these non-storable exergy flows. Since the grey energy to build converters such as windmills and PV panels is accounted for in the CExC of the SE flows (power and heat), this means that the CExC per unit of energy delivered increases. E.g., the CExC of power from photovoltaic (PV) panels might be 1,1 for efficient PV systems and 1,2 for less efficient converters.

To reduce the CExC for conversion processes from SE flows additional exergy analyses should be performed. This can help to significantly reduce the use of land and materials.

Due to difficulty to obtain data on material exergy a simplified form of REA can be performed using cumulated energy consumption (CEC) values that are more readily available in databases. Such simplified analysis assesses the only the resource exergy consumption (REC) that is caused using energy for building, harvest, transport, conversion and recycling. This type of simplified REA consequently neglects some material and grey exergy aspects, such as the materials required to build and recycle a heating system. However, this type of simplified REA is still significantly more consistent and comprehensive than conventional PEA since it uses CEC values instead of PEF, takes energy quality into account and utilizes consistent boundary definitions for all types of energy systems.

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

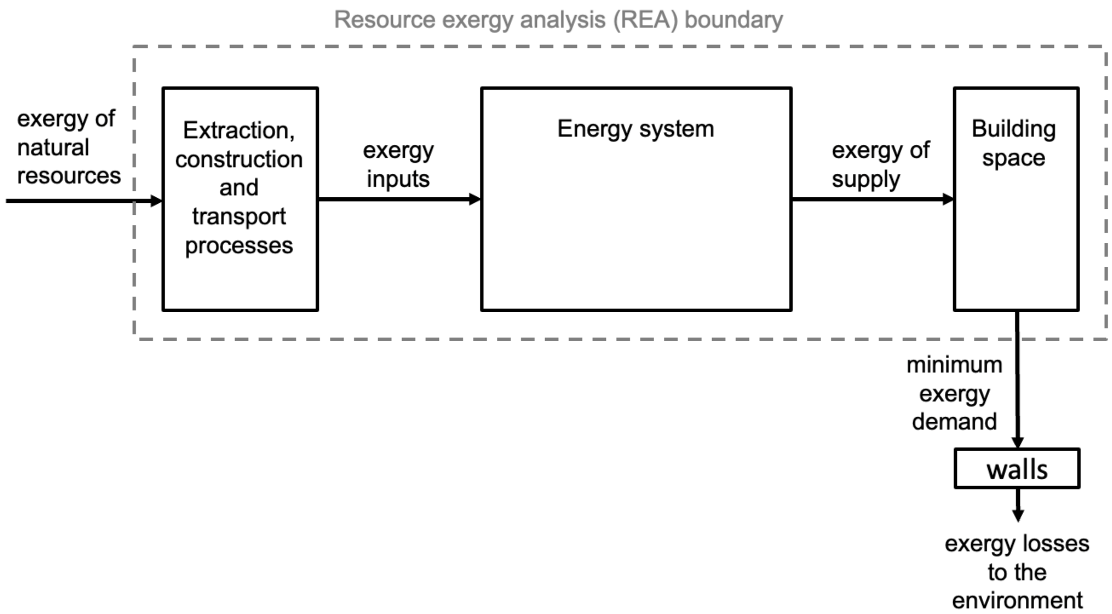

Figure 1: Balance boundaries to assess resource exergy consumption and resource efficiency of thermal supply systems

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

1. Only flows of directly storable primary energy (SE 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 the resource for the comparison.

1.1. This means that for solar thermal plants it is not the solar radiation that is 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 resource used.

1.3. For most electrical flows this means that the losses from the extraction of the fuels and the resources required to build the required energy converters must be considered such as solar panels and energy extraction rigs for harvesting natural gas.

2. For the calculation of resource efficiency, the minimum required amount of exergy with which the task could theoretically be accomplished is considered as the demand. This ensures that no improvement potentials have been overlooked. It must be noted that all demands still have the possibility to be reduced since in the case of space heating 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. However, 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 can be ensured by keeping the supply task, such as thermal comfort and needs for mechanical and electrical energy fixed. This makes it easier to distinguish improvements in overall system efficiency from improvements in the area of sufficiency.

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.

Figure 2: Sample exergy passes for an energy supply scenario.(Jentsch, 2021)

To calculate the energy quality associated with an energy flow it is easiest to divide the exergy associated with the flow by its energy.

It is important to note that to be able to calculate exergy passes for all technologies 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. For heat pumps it is assumed that the heat source provides an amount of heat that equals the heat output minus the electricity input. 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 derived from these principles.

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

3 Calculation fundamentals

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

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 (AGFW, 2014; 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. The respective equations can be found in chapter 3.

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 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 based on the cumulated energy consumption (CEC) (Umweltbundesamt, 2021).

The CEC is the ratio of the usable[4] energy of the resource and the energy used for extraction, transformation and transport to the energy supplied. CEC values for energy flows 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).

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).

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[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

[4] Usually this means nuclear energy is neglected and only one form of energy such as chemical energy is considered.

For CHP units the fuel share allocated to heating is calculated based on the Carnot method (AGFW, 2014; 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 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 know 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 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 (3).

It is important to calculate the Carnot factor with the thermodynamic average temperature of any heat flow (1), (2) 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 %. Thus, for thermal energy resources the CExC can be approximated by subtracting 1 from the CEC value and adding the Carnot Factor (see equations (3) & (36)).

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 (e.g. 0.2) of the heat extracted from the geothermal source – e.g. 0.27 in total.

E.g. for solar thermal energy the CEC can be 1.04 (IWU, 2014). So, with a Carnot Factor of 0.3 the approximated CExC for solar thermal energy would be 0.34.

3.1 Basic exergy 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.

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

The thermodynamic average temperature of heat transfer ($T_{a,ht}$) for fluids that undergo a phase change and do not change temperature equals the phase change temperature (T_{pc}).

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

$$T_{a,ht} = T_{pc} \tag{2}$$

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

$$CF_{ht} = 1 - \frac{T_0}{T_{a,ht}} \tag{3}$$

The Carnot factor equals the energy quality of heat above reference temperature. 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. The negative prefix however needs to be considered in exergy balances.

Details on how to calculate the energy quality of all types of energy flows are found in (Jentsch, 2010).

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 below reference temperature. 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

$$Ex_Q = CF_{ht} \cdot Q \tag{4}$$

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

Exergy flow associated with power

$$Ex_P = P \tag{5}$$

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

Exergy efficiency

$$\varepsilon = \frac{Ex_d}{Ex_i} \tag{6}$$

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

Energy efficiency

$$\eta = \frac{En_d}{En_i} \tag{7}$$

3.2 Resource Exergy

Resource exergy Consumption (REC) differs from the sum of CExC in so far that it only considers all directly storable mass and energy flows used to produce the considered energy or mass flow. Exergy flows that are not directly storable (such as exergy associated with solar radiation, running water or wind) are not considered resources (see chapter 2 for details).

Resource exergy is a universal measure for limited resources that can in principle be used on demand due to being directly storable. It can be defined based on the specific CExC[5] of directly storable exergy flows $(CExC_R)$. $CExC_R$ is a function of the exergy associated with all resources (ΣEx_R) used to produce a considered energy or mass flow (En_f) or (m_f). For thermal flows it can be lower than one but never zero.

Definition of cumulated exergy consumption for energy flows

$$CExC_R = \frac{\Sigma Ex_R}{En_f} \tag{8}$$

Definition of cumulated exergy

$$CExC_R = \frac{\Sigma Ex_R}{m_f} \tag{9}$$

In this document Cumulated Exergy Consumption is used synonymously with Cumulated Exergy Demand as defined in (Boesch et al., 2007).

consumption for mass flows

To obtain the total resource exergy consumption (REC) of a system the $CExC_R$ needs to be multiplied with the respective energy and/or mass flows used by the system (En_f or m_f) as follows:

Definition of total resource exergy consumption of a system

$$REC = \sum_{1}^{y} CExC_{R,m,y} \cdot m_{f,y} + \sum_{1}^{z} CExC_{R,En,z} \cdot En_{f,z} = \sum_{1}^{y} \frac{\Sigma Ex_R}{m_{f,y}} \cdot m_{f,y} + \sum_{1}^{z} \frac{\Sigma Ex_R}{En_{f,z}} \cdot En_{f,z} \tag{10}$$

3.3 Resource Exergy Efficiency (REE)

Resource exergy efficiency (REE) 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. REE is always below 100% due to irreversibilities. It is an additional information that should not replace REC since it is not influenced by the total demand, therefore neglecting aspects of system size, demand and insulation.

The resource exergy demand (RED) needs to be calculated based on an understanding of the minimally required exergy flows. For all non-thermal demands RED equals the useful energy demand. This can be the power consumption of the current appliances or in the rare case where fuels are considered useful energy it can be approximated by their higher heating value (HHV). For building supply however, the useful energy is usually rarely a fuel but rather heat or power. While fuels are final energy forms that are used to produce one or the other.

For space heating the minimum exergy demand can be calculated by assuming a minimum space temperature that needs to be kept constant, such as 20 °C. Together with the amount of heat consumed this defines the Resource Demand minimally required to compensate for heat losses through the building envelope.

If RED allows the supply of the same quality of end use (e.g. the same level of comfort), values are most meaningful for comparison. Otherwise, RED provides valuable additional information to understand REE better. E.g., power supply is usually much more efficient than heat supply, since the RED for heat is often so low that even small deviations from perfection have a large impact.

The resource exergy efficiency (REE or ε_R) of a whole system is a function of all resource exergy demands (RED) that the considered system covers and the resource exergy consumption (REC) of all system parts.

Resource exergy efficiency

$$\varepsilon_R = REE = \frac{\sum_1^x RD}{\sum_1^x RC} \tag{11}$$

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

Resource Exergy Demand of thermal supply tasks

$$RD_{th} = En_d \cdot |CF_{md,ht}| \tag{12}$$

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

Resource Exergy Demand of non – thermal supply tasks

$$RD = Ex_{md} \tag{13}$$

While RED can be specified using only two equations for thermal and non-thermal flows, the definition of RED is dependent on the systems used to cover the demand. Equations on calculating REC are provided in chapter 3.6 and following.

3.4 Approximations & Simplifications

A key simplification in communication is to drop the word exergy. It is often misinterpreted and often 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 materials and energy. This means that accurate data for the exergy consumption of building a system and recycling it are not known.

A simplified REA that is based on non-exergy data underestimates resource exergy consumption as material exergy consumed cannot be considered this way. However, it can still provide many benefits of a REA based on CExC as it is already significantly more comprehensive than PEA.

It is important though that in the case of uncertainties all simplifications should be done in a way to rather overestimate REC 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 simplified REA to enable the application of resource exergy analysis even in cases, where reliable exergy data is lacking.

3.4.1 General simplifications

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 equations (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 simplications it becomes easy to estimate the average temperatures ($T_{a,ht}$).

Simplified average temperature of heat transfer at changing temperatures	$T_{a,ht} \approx \frac{T_{sf} + T_{rf}}{2}$	*(14)*

If heat transfer occurs from an incompressible fluid undergoing phase change and temperature 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	$T_{a,ht} \approx T_{pc}$	*(15)*

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

Estimate for specific fuel exergy	$Ex_F \approx HHV_F$	*(16)*

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 conservation[6] 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 $\left(En_{F,\eta}\right)$ equal the lower heating value of the fuel.

Specific fuel energy as considered in common efficiency values.	$En_{F,\eta} \approx LHV_F$	*(17)*

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 $\left(En_f\right)$. 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 and how to calculate exergy and energy of various types of flows can be found in (Jentsch, 2010). A more general introduction to calculating exergy flows can be found in (Bejan et al., 1996).

Since for heat flows below the reference temperature, the energy that can be converted into work comes from the environment, these exergy values have a negative prefix. These currents can be simplified as cold flows.

The ratio of exergy to the energy of a cold flow falls below -100% at mean temperatures lower than half the reference temperature without representing a physical contradiction. In a very simplified way, the following equation can be used for communication purposes for "cold flows" with a mean temperature higher than half the reference temperature without raising questions.

[6] The first law of thermodynamics.

Energy quality associated with a flow

$$EQ \approx \frac{|Ex_f|}{En_f} \tag{18}$$

To 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 and non-fuel energy and mass flows

$$En_{nt} \approx Ex_{nt} \tag{19}$$

In the case of fuels this equation needs to be adapted to account for the common practice to evaluate fuel energy (En_F) with the lower heating value (LHV_F). This means that 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

$$Ex_F \approx HHV_F \approx En_F \cdot \frac{HHV_F}{LHV_F} \tag{20}$$

3.4.2 Estimating cumulated exergy consumption using energy-based metrics

For energy flows specific cumulated exergy consumption can be approximated using specific cumulated energy consumption as most of the exergy consumed on average is associated with the energy of a flow (Boesch et al., 2007) associated with the resources used (CEC_R). However, a distinction must be made between thermal and non-thermal energy flows. While non-thermal energy flows are associated with an exergy approximated by the amount of energy they carry, thermal energy flows are associated with a significantly lower exergy flow. The following equations show approximations usable to calculate estimates for CExC based on CEC values.

Specific cumulated energy consumption associated with used resources (CEC_R) is a function of the total primary energy (ΣEn) used to produce a considered energy flow (En_f).

Definition of Cumulated Energy Consumption for energy flows

$$CEC_R = \frac{\Sigma En}{En_f} \tag{21}$$

That means that CEC equals the primary energy used for extraction, transformation & transport and the energy contained in considered flow divided by the energy contained in the considered flow.

It is possible to also use the cumulated energy demand (CED) (VDI, 2012) instead of the CEC. CED includes non-energetic use of primary energy such as oil for plastics or wood for construction. To assess which of the two metrics is closer to the CExC a dedicated comparison would be useful, that so far is missing.

The underlying assumption for the following simplification of CExC 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 (18)) of these losses is 100%. Consequently, the CExC associated with resource exergy consumption of non-thermal, non-fuel energy flows $\left(CExC_{R,nt}\right)$ can be approximated with the CEC of non-thermal energy flows $(CEC_{R,nt})$.

Estimate for cumulated exergy consumption of non-thermal flows

$$CExC_{R,nt} \approx CEC_{R,nt} \tag{22}$$

For the cumulated energy consumption of fuels (CEC_F) in the it can be assumed that the ratio of the lower to the higher heating value of the fuels used $(\frac{HHV_{F,a}}{LHV_{F,a}})$ is already considered in the CEC value. Thus, for fuels the CExC $(CExC_F)$ can be approximated by approximated by the CEC of the fuel (CEC_F).

Estimate for cumulated exergy consumption of fuel flows

$$CExC_F \approx CEC_F \tag{23}$$

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 CExC of the synthetic fuel $(CExC_{SF})$ can be approximated by the resource exergy consumption (REC_{SF}) of the synthetic fuel production chain.

Estimate for cumulated exergy consumption of synthetic fuels if their production chain is known

$$CExC_{SF} \approx REC_{SF} \tag{24}$$

Several further simplifications can be applied if values for the CEC input associated with power are not known.

To In the following the CEC associated with resources used for power generation is assumed to follow this rule.

Simplification for power as a function of the CEC of the average power mix ($CEC_{P,a}$):

Simplification for the resource exergy consumption of power from the grid

$$CExC_{P,a} \approx CEC_{P,a} \tag{25}$$

This means that the cumulated energy consumption of the average power mix can be used to estimate the resource exergy consumption of electrified demands associated with power use unless dedicated power is available.

If instead of power fuels are used to operate the heat pump, the equations remain essentially the same except that the cumulated exergy consumption associated with resource use $(CExC_{R,i})$ is replaced by the cumulated exergy consumption associated with the fuel used $(CExC_F)$ or with the cumulated exergy consumption of the synthetic fuel production chain $(CExC_{SF})$. Both can be estimated based on the respective cumulated energy consumption (CEC_F, CEC_{SF}):

Simplification for the cumulated exergy consumption of fuels

$$CExC_{R,i} \approx CEC_F \tag{26}$$

Simplification for the cumulated

$$CExC_{R,i} \approx CEC_{SF} \tag{27}$$

exergy consumption of synthetic fuels

If the driving energy for a heat pump originates from a CHP process the cogeneration share of the heat (CS_Q) needs to be considered along with the cumulated exergy consumption of the fuel or heat driving the CHP machine.

Cumulated exergy consumption of if driving flows are produced by CHP plants

$$CExC_i \approx CS_Q \cdot \frac{CExC_{i,chp}}{\varepsilon_{chp}} \tag{28}$$

The cumulated exergy consumption of the driving input from thermal sources $(CExC_{R,i})$ according to equation (36) can be simplified as a function of the cumulated energy consumption of the thermal source (CEC_{ts}) and the absolute value of the Carnot factor of this heat (CF_{ts}). An derivation of this equation is presented in the following subchapter.

Simplification for the cumulated exergy consumption of thermal driving flows

$$CExC_{R,i} \approx (CEC_{ts} - 1 + |CF_{ts}|) \tag{29}$$

3.4.3 Derivation of resource exergy consumption of thermal supply flows

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

Figure 4 shows how a thermal supply flow (3) is generated by using thermal flows (2) and non-thermal auxiliary flows (1) such as power to operate pumps.

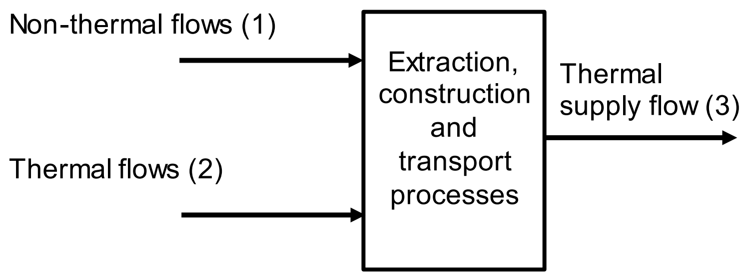

Figure 3: Flow chart to illustrate the exergy use of thermal systems

CEC does not consider the energy quality of thermal flows. Therefore, to use CEC as a basis for calculating REC, the different energy quality of thermal and non-thermal flows needs to be considered.

Furthermore, in many cases the heat provided by the thermal source (ground, solar panels, waste heat) (2) is not measured directly. Therefore, a further assumption has to be made how it relates to the thermal supply flow (3).

To rather overestimate than underestimate the REC associated with the supply flow 3, it can be assumed that the energy losses that are caused in the upstream chain of the thermal flow 3 are non-thermal flows of an energy quality of 100% (1). This means that flow 2 and flow 3 are equal.

Therefore the cumulated energy consumption (CEC_{tf}) can be assumed to be function of flow (3) and flow (1).

Estimate for the cumulated energy consumption of thermal supply flows

$$CEC_{tf} = \frac{(En_1 + En_2)}{En_3} \approx \frac{En_1}{En_3} + 1 \tag{30}$$

Flow (2) can still differ from flow (3) in terms of exergy if the average temperature of flow (2) is known to be different than the average temperature of flow (3).

If the temperatures of flows 2 are not known, an assumption needs to be made based on the temperatures of flow 3. Depending on the considered system the temperatures of flow 2 can be assumed to be equal to the temperatures of flow 3 plus a temperature difference assumed based on the supply system. The more losses due to pipe length, pipe insulation and heat exchangers can be expected the higher this temperature difference should be.

To rather over- than underestimate the resource consumption a temperature difference of 10 K can be assumed to be an acceptable value. This temperature difference leads to higher temperatures for flow 2 than for flow 3 for heating and for lower temperatures of flow 2 than flow 3 for heat flows below reference temperature.

For flows below reference temperature the exergy associated with the flow becomes negative while the energy flow is still positive. Thus, the Carnot factor for these flows needs to be considered as an absolute value if using CEC to estimate CExC.

Estimate for the cumulated energy consumption of thermal supply flows

$$CExC_{R,tf} \approx \frac{En_1}{En_2} + |CF|_{3+10K} \approx \frac{En_1}{En_2} + |CF|_2 \tag{31}$$

Therefore, the specific cumulated exergy consumption ($CExC_{R,tf}$) of the thermal supply flow 3, can be approximated by a sum of the absolute value of specific exergy of the thermal flow represented by the Carnot factor ($|CF_{tf}|$), and the specific cumulated energy consumption (CEC_{tf}) minus 1.

Estimate for the cumulated resource exergy consumption of thermal flows

$$CExC_{R,tf} \approx \left(CEC_{tf,2} - 1 + \left|CF_{tf}\right|_2\right) \tag{32}$$

In some cases CExC values for solar thermal heat ($CExC_{st}$) consider all input exergy and not only resource exergy. The latter is problematic as solar technology CExC is sometimes calculated based on the exergy of solar radiation instead of the exergy of the first storable resource (e.g. heat or power). To still be able to use these values for cases where $CExC_{st} > 1$, $CExC_{R,st}$ can be treated like CEC_{tf}.

Estimate for the cumulated resource exergy consumption of thermal flows from solar thermal sources

$$CExC_{R,st} \approx \left(CExC_{st} - 1 + |CF_{tf}|\right) \tag{33}$$

3.4.4 Estimating resource exergy consumption of thermal supply flows

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

Figure 4 shows how a thermal supply flow (3) is generated by using thermal flows (2) and non-thermal auxiliary flows (1) such as power to operate pumps.

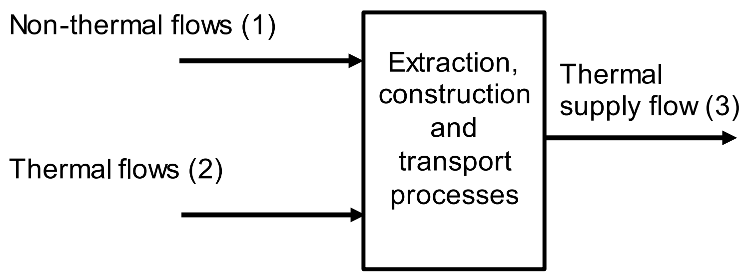

Figure 4: Flow chart to illustrate the exergy use of thermal systems

CEC does not consider the energy quality of thermal flows. Therefore, to use CEC as a basis for calculating REC, the different energy quality of thermal and non-thermal flows needs to be considered.

Furthermore, in many cases the heat provided by the thermal source (ground, solar panels, waste heat) (2) is not measured directly. Therefore, a further assumption has to be made how it relates to the thermal supply flow (3).

To rather overestimate than underestimate the REC associated with the supply flow 3, it can be assumed that the energy losses that are caused in the upstream chain of the thermal flow 3 are non-thermal flows of an energy quality of 100% (1). This means that flow 2 and flow 3 are equal.

Therefore the cumulated energy consumption $\left(CEC_{tf}\right)$ can be assumed to be function of flow (3) and flow (1).

Estimate for the cumulated energy consumption of thermal supply flows

$$CEC_{tf} = \frac{(En_1 + En_2)}{En_3} \approx \frac{En_1}{En_3} + 1 \quad (34)$$

Flow (2) can still differ from flow (3) in terms of exergy if the average temperature of flow (2) is known to be different than the average temperature of flow (3).

If the temperatures of flows 2 are not known, an assumption needs to be made based on the temperatures of flow 3. Depending on the considered system the temperatures of flow 2 can be assumed to be equal to the temperatures of flow 3 plus a temperature difference assumed based on the supply system. The more losses due to pipe length, pipe insulation and heat exchangers can be expected the higher this temperature difference should be.

To rather over- than underestimate the resource consumption a temperature difference of 10 K can be assumed to be an acceptable value. This temperature difference leads to higher temperatures for flow 2 than for flow 3 for heating and for lower temperatures of flow 2 than flow 3 for heat flows below reference temperature.

For flows below reference temperature the exergy associated with the flow becomes negative while the energy flow is still positive. Thus, the Carnot factor for these flows needs to be considered as an absolute value if using CEC to estimate CExC.

Estimate for the cumulated energy consumption of thermal supply flows

$$CExC_{R,tf} \approx \frac{En_1}{En_2} + |CF|_{3+10K} \approx \frac{En_1}{En_2} + |CF|_2 \tag{35}$$

Therefore, the specific cumulated exergy consumption ($CExC_{R,tf}$) of the thermal supply flow 3, can be approximated by a sum of the absolute value of specific exergy of the thermal flow represented by the Carnot factor ($|CF_{tf}|$), and the specific cumulated energy consumption (CEC_{tf}) minus 1.

Estimate for the cumulated resource exergy consumption of thermal flows

$$CExC_{R,tf} \approx \left(CEC_{tf,2} - 1 + \left|CF_{tf}\right|_2\right) \tag{36}$$

In some cases CExC values for solar thermal heat ($CExC_{st}$) consider all input exergy and not only resource exergy. The latter is problematic as solar technology CExC is sometimes calculated based on the exergy of solar radiation instead of the exergy of the first storable resource (e.g. heat or power). To still be able to use these values for cases where $CExC_{st} > 1$, $CExC_{R,st}$ can be treated like CEC_{tf}.

Estimate for the cumulated resource exergy consumption of thermal flows from solar thermal sources

$$CExC_{R,st} \approx \left(CExC_{st} - 1 + |CF_{tf}|\right) \tag{37}$$

3.4.5 Fuel related efficiency

It is common that energy efficiency of energy systems using fuels is defined using the lower heating value of a fuel. This can lead to energy efficiency values larger than one hundred percent, thereby creating the impression that more energy is generated than put in. To be consistent with the law of energy conservation therefore energy efficiency values from literature (η_{LHV}) for fuel based systems need to be corrected by considering the ration of lower to higher heating value $\left(\frac{LHV}{HHV}\right)$ in order to provide a more consistent measure of energy efficiency related to the higher heating value (η_{HHV}).

Fuel efficiency related to the higher heating value	$\eta_{F,HHV} = \eta_{F,LHV} \cdot \frac{LHV_F}{HHV_F}$	*(38)*

3.4.6 Estimations of exergy efficiency using energy efficiency values

The underlying assumption for the following approximations of exergy efficiency of fuel-based systems $\left(\varepsilon_{el,F}\right)$ is that most energy efficiency values for fuel using technologies $(\eta_{el,F})$ 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 from fuels	$\varepsilon_{el,F} \approx \eta_{el,F} \cdot \frac{LHV_F}{HHV_F}$	*(39)*
Estimate for the exergy efficiency of using fuel boilers	$\varepsilon_{th} \approx \eta_{th} \cdot \frac{LHV_F}{HHV_F} \cdot CF_{tf}$	*(40)*

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.

Estimate for the exergy efficiency of uncoupled power generation from thermal sources

$$\varepsilon_{el} \approx \frac{\eta_{el}}{CF_{ts}} \tag{41}$$

Estimate for the exergy efficiency of uncoupled heat generation using heat exchangers

$$\varepsilon_{th} \approx \eta_{th} \cdot \frac{CF_{tf}}{CF_{ts}} \tag{42}$$

3.5 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. A consideration of resource exergy is not required in this allocation as all the exergy inputs for extraction, construction and transport would cancel out in the respective equations.

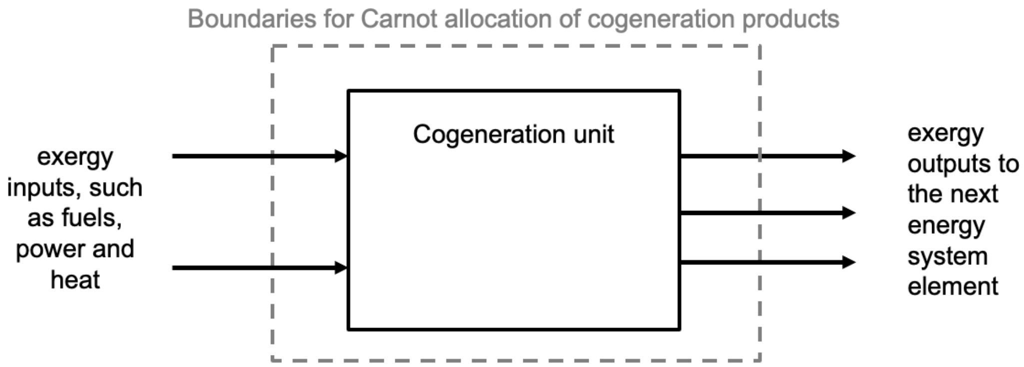

Figure 5: Balance boundaries to allocate resource shares to cogeneration products with the Carnot method

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 using the Carnot method

$$CS_{f,chp} = \frac{Ex_f}{\sum_{f=1}^{z} Ex_z} \quad (43)$$

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 these flows 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 (43) 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.

The equations of the cogeneration share can also be applied to allocate any other products of a cogeneration system such as greenhouse gas emissions (AGFW, 2014).

The following two equations are valid for the type of CHP that produces a single heat flow and power. A consideration of LHV to HHV ratios is not required in the following equations that are based one energy efficiency since they would cancel out.

Cogeneration share of heat from cogeneration of one power and one heat flow using the Carnot method

$$CS_{Q,chp} = \frac{Ex_Q}{Ex_Q + Ex_P} \approx \frac{CF_{ht} \cdot \eta_{th,chp}}{CF_{ht} \cdot \eta_{th,chp} + \eta_{el,chp}} \quad (44)$$

Cogeneration share of power from cogeneration of one power and one heat flow using the Carnot method

$$CS_{P,chp} = 1 - CS_{Q,chp} \approx \frac{\eta_{el,chp}}{CF_{ht} \cdot \eta_{th,chp} + \eta_{el,chp}} \quad (45)$$

3.6 Overall resource exergy consumption

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

Total resource exergy consumption of an energy system

$$REC_{\Sigma} = \sum_{1}^{x} \frac{En_{d,x}}{\Sigma En_d} \cdot REC_x \tag{46}$$

In cases where non-energy flows such as materials are considered the non-energy exergy demand equals the minimum energy demand associated with such flows since energy flows into a system can never be smaller than the exergy flows coming out of it. 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.

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 exergy consumption.

Please note that 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.

$$Ex = |Ex_{th}| + |Ex_{C,T0}| + |Ex_{M,T0,}| + |Ex_{N,T0}| \tag{47}$$

The assessment of resource exergy consumption from non-energy sources is treated in this document only briefly since it focusses on REA for energy systems. Therefore, in this document mainly thermal, mechanical and chemical exergy of fuels are considered, while concentration chemical exergy is not focused upon. Electrical exergy is not associated with a mass flow and therefore can be considered separately as a mass-free exergy flow.

3.7 Selecting appropriate assumptions for the use of electricity

With increasing electrification, the importance of realistically assessing the resource exergy consumption of using power increases. There are three types of power that could be considered: the average power mix, the marginal power mix and dedicated power.

The average power mix is based on all power that is generated to cover demands in the electrical grid thus representing the average values of emissions, cumulated energy consumption and cumulated exergy consumption. So, if 20% of all power is generated by PV, the share of PV power in the average power mix is 20%.

The marginal power plant is the one that produces more energy if the demand is increased by one unit. The marginal power mix is an average over all marginal power production in the timeframe used for the assessment of resource exergy consumption, e.g. one year. So, if power from PV is always used fully by the grid and all changing loads are covered by power from fuels, PV is never part of the marginal power mix. Instead, the marginal power mix is an average over the power generated by fuels to cover the last produced unit of energy. E.g., an annual marginal power mix could consist of 60% power from hard coal fired plants and 30% of power from gas fired condensing plants and 10% of power from gas CHP plants.

Dedicated power is power that comes from a source that is built additionally to cover a newly created demand. E.g., Additional PV panels or wind power converters that within the given time frame produce at least as much power as the new electrical demand.

Depending on the assumptions for the type of power used, the resource exergy consumption to cover a given demand can change radically. Thus, a heat pump operated by power from coal can lead to higher emissions and resource exergy consumption than a natural gas boiler. If the same heat pump is driven by dedicated PV power that was built in addition to existing PV capacity however, it would lead to significantly reduced resource exergy consumption and emissions in comparison to the natural gas boiler.

It is imperative to choose the assumed source of power as realistically as possible to avoid under- or overestimation of the resource exergy consumption of electrical systems.

While it can appear reasonable to assume that additional electrical loads are covered by the marginal power mix, this approach can lead to a significant overestimation of the resources consumed and GHG emitted by power consuming systems.

This aspect becomes obvious when performing a thought experiment. The underlying assumption is that all renewable power is always used and only one marginal power plant using fossil fuels is in operation. If power demand is doubled and renewable power generation is doubled the new load is almost completely covered by new GHG-free production. Were the marginal power plant assumed to be the source for the newly created demand, it would seem as if the whole new demand is covered by fossil fuels, while in practice this is not the case. This thought experiment shows that considering power from marginal power plants can easily lead to overestimation of emissions for the use of power.

Instead, it seems advisable to follow a different approach, when assuming power sources.

Two rules of thumb to decide what source of power to assume for REA could be the following:

1. Due to the simultaneous increase in electric loads and renewable power generation capacity it is uncertain, whether in the transition period to a fully GHG-free power supply the power mix will include a larger, lower or constant share of power from GHG-emitting fuels. Therefore, it appears recommendable to use a current value of the average power mix including imports and exports to cover all power demands. It is key to use current values to obtain realistic results. For a simplified life-time prognosis of technology impacts, it appears justified to assume the power mix properties as constant as they could increase or decrease in the future. If needed a scenario analysis with different assumptions concerning the development of the power mix should be performed to assess the possible impact of electrical systems.

2. All systems that use power generation capacity built specifically to cover a new demand (such as PV panels to cover the demand of heat pumps) are assumed to use this dedicated power. As a simplification to obtain a first estimate the grid can be assumed to provide the electrical storage to balance power generation and demand on an annual basis. So, if newly built PV panels deliver equal or more electricity within a year than the heat pumps they supply, the heat pumps can be assumed to be operated with PV power only.

   If details on the power mix over time are available a more accurate way to assess the impact of dedicated power would be to consider the difference of the on-site production of the dedicated electrical generators (PV panels) to the current power mix. So, e.g. in summer PV produces three times the energy needed to operate the heat pumps. The difference of resource consumption of power that is not fed to heat pumps and the power from the summer marginal power plant is a bonus. In winter the PV panels produce only half of the energy needed to operate the heat pumps, so half the power needs can be assumed to come from power mix in winter. The latter will lead to additional resource consumption in winter. However, the bonus from the summer months can be subtracted from the additional emissions generated in winter and still lead to a resource consumption that would result if PV panels were assumed to supply all power year round. On the other hand the bonus could also be lower than the additional emissions in winter thus yielding different results. This principle can be applied also on a dynamic basis considering hours or even minutes.

If power from various sources is considered in a power mix the total resource exergy consumption $\left(REC_{\Sigma,\mathrm{p}}\right)$ can be calculated as a function of the power share of a given source x $\left(\frac{P_x}{\Sigma \mathrm{P}}\right)$ in the considered time frame and the resource exergy consumption of that supply chain $(REC_{P,x})$. This equation is a specific form of equation (46).

Resource exergy consumption of the power mix

$$REC_{\Sigma \mathrm{P}} = \sum_{1}^{x} \frac{P_x}{\Sigma P} \cdot REC_{P,x} \qquad (48)$$

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 be proved by looking at the respective values. The CEC indicates how much energy is used to produce a considered unit of energy. A CEC of 1.2 for PV means that 1.2 kWh of energy were used for every kWh delivered. 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 plus the energy invested in construction, since the efficiency of conversion from solar radiation to power 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.

To ensure the CO2-balance of power from the grid works, so called Eco-power that is sold on the market should not be considered CO2-free. Otherwise there is the danger that CO2-emissions from the electrical grid are not accounted for. Instead all supply from the grid should be calculated with an average power mix. Only if dedicated, additional GHG-free power supply is installed to supply the newly build electrical demand, should it be considered GHG-free electricity.

4 Technology assessment

The general idea to assess technologies is to use data from databases for energy carriers and mass flows for input flows to evaluate output flows of energy systems.

This means that in general the resource exergy consumption can be calculated based on the Cumulated Exergy Consumption of directly storable energy $\left(CExC_{ds,i}\right)$ for the considered energy flow and the energy input into the energy system (En_i).

Resource exergy consumption as a function of cumulated exergy consumption

$$RC = CExC_{ds,i} \cdot En_i \tag{49}$$

In order to obtain an equation that relates the resource exergy consumption to the product of the energy system, the energy of the output (En_o) needs to be introduced into the equation. This in turn can be expressed as a function of the energy efficiency of the energy system (η).

Resource exergy consumption related to a generic output without cogeneration

$$\begin{aligned} RC = \frac{RC}{En_o} \cdot \mathrm{En_o} &= En_o \cdot CExC_{ds,i} \cdot \frac{En_i}{En_o} \\ &= En_o \cdot CExC_{ds,i} \cdot \frac{1}{\eta} \\ &= En_o \cdot \frac{CExC_{ds,i}}{\eta} \end{aligned} \tag{50}$$

To obtain an expression of this equation that considers the demand side of an energy system it can be expressed as a function of the energy demand (En_d), the energy losses due to transport from the energy system to the demand side $(En_{l,t})$ and the energy losses due to storage $(En_{l,s})$

Resource exergy consumption related to a generic output without cogeneration

$$RC = (En_d + En_{l,s} + En_{l,t}) \cdot \frac{CExC_{ds,i}}{\eta} \tag{51}$$

If the energy system is using fuel as an input flow and the cumulated exergy consumption of the fuel is assumed to be a ratio of exergy to the higher heating value of the fuel, the efficiency (η) is the (η_{HHV}) from equation (38).

4.1 Heat generation

4.1.1 Boilers

The resource exergy 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 CExC of the used input flow $(CExC)$ and the energy efficiency of the boiler (η_b).

Resource exergy consumption of heat from electric boilers

$$RC_{b,el} = (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CExC_i}{\eta_b} \tag{52}$$

For electrical boilers in a simplified analysis this equation can be transformed into a form that uses the CEC for power generation (CEC_P) and the energy efficiency of the electric boiler $(\eta_{b,el})$.

Simplified resource exergy consumption of heat from electric boilers

$$RC_{b,el} \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CEC_P}{\eta_{b,el}} \tag{53}$$

For boilers using natural fuels the equation can be transformed into using the CEC 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 exergy consumption of heat from boilers using natural fuels

$$REC_b \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CEC_F}{\eta_b \cdot \frac{LHV_F}{HHV_F}} \tag{54}$$

For synthetic fuels, for which a CEC of the fuel is not known equation (52) can be expressed as a function of the resource exergy consumption of the fuel (REC_{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 exergy consumption of heat from boilers

$$REC_b \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{REC_{SF}}{\eta_b \cdot \frac{LHV_{SF}}{HHV_{SF}}} \tag{55}$$

using synthetic fuels

4.1.2 Thermal sources (Excess heat, Solar thermal, Geothermal)

Since solar radiation is not directly storable the heat from the solar thermal collectors is considered a resource. Waste heat can be considered to be dumped into and harvested from the environment. The heat flows from the earth's core loose temperature on their way to the surface anyway, so that the heat from the earth is usually lost and only becomes a resource if harvested. Therefore, for heat generation from thermal sources a consideration of exergy efficiency is not required as they do not need to be transformed.

The resource exergy consumption for heat generation from thermal sources is a function of the heat demand (Q_d), the heat losses due to storage $\left(Q_{l,s}\right)$, the heat losses due to transfer $\left(Q_{l,t}\right)$, the cumulated exergy consumption input of the thermal sources $\left(CExC_{R,ts}\right)$.

Resource exergy consumption for heat from thermal sources

$$REC_{ts} = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot CExC_{R,ts} \tag{56}$$

Using equation (36) 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 and of the Carnot factor of the thermal flow at the temperature of extraction (CF_{ts}).

Simplified resource exergy consumption for heat from thermal sources

$$REC_{ts} \approx \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot (CEC_{ts} - 1 + CF_{ts}) \tag{57}$$

Auxiliary power or fuel consumption needs to be considered separately like an electrical or fuel demand. The resource exergy consumption of the auxiliary demand needs to be added to the resource exergy consumption of the thermal source system using equation (46) to obtain the total resource exergy consumption.

4.1.3 Heat pumps

If the exergy influx into the heat pump from the heat source (ground, water etc.) is not exactly known from measurements the heat input from the heat source into the condenser (Q_i) can be estimated from the energy balance of a heat pump that is a function of the power consumed (P_{hp}), the heat influx from the heat source (Q_i), the heat output (Q_o) and the heat losses (Q_l).

Energy balance of a heat pump	$$P_{hp} + Q_i = Q_o + Q_l$$	*(58)*

As a simplification the heat losses of the heat pump can be neglected if they are unknown, since all heat losses increase the power consumed and are thus largely considered in the amount of power used by the heat pump. Equation (59) introduce the performance factor or the heat pump (PF_{hp}).

The performance factor is used in the following equations instead of the coefficient of performance as it is more comprehensive and considers consumption for auxiliary demands. It is defined as the total amount of heat delivered divided by the total amount of power consumed by the heat pump system in the considered time frame, e.g. a year. This means not only the power 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.

Simplified Energy balance of a heat pump used to estimate heat extraction	$$P_{hp} + Q_i = \frac{Q_o}{PF_{hp}} + Q_i \approx Q_o$$	*(59)*
Simplified Energy balance of a heat pump used to estimate heat extraction	$$\left(1 - \frac{1}{PF_{hp}}\right) \cdot Q_o \approx Q_i$$	*(60)*

Therefore, the minimum specific amount of energy from the heat pump heat source needed to fulfill the energy balance of the heat pump $(1 - \frac{1}{PF_{hp}})$ is multiplied with the Carnot factor of the heat extracted from the source ($CF_{ht,hp}$) to estimate the thermal resource exergy consumption ($REC_{ht,hp}$) associated with it:

Resource exergy consumption associated with the minimum heat extracted by a heat pump

$$REC_{ht,hp} = Q_i \cdot CF_{ht,hp} \approx \left(1 - \frac{1}{PF_{hp}}\right) \cdot Q_o \cdot CF_{ht,hp} \tag{61}$$

Average heat transfer temperatures used to calculate the Carnot factor in the heat pump equations $\left(CF_{ht,hp}\right)$ should also be averaged over the time steps used for analysis, e.g. yearly, monthly, hourly.

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

The resource exergy consumption for heat generation for heat pumps is a function of the heat demand (Q_d), the heat losses due to storage $\left(Q_{l,s}\right)$, the heat losses due to transfer $\left(Q_{l,t}\right)$, the cumulated exergy consumption input associated with the fuel, power or heat resources used $\left(CExC_{R,i}\right)$ and the Carnot factor if the heat transfer $\left(CF_{ht,hp}\right)$ and the performance factor of the heat pump $\left(PF_{hp}\right)$.

Resource exergy consumption of a heat pump using a simplified approach

$$REC_{hp} \approx \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot \left(\frac{CExC_{R,i}}{PF_{hp}} + CF_{ht,hp} \cdot \left(1 - \frac{1}{PF_{hp}}\right)\right) \tag{62}$$

In the case of sorption heat pumps the driving exergy flow for the heat pump comes from a thermal source, a boiler or a CHP unit. This means that the cumulated exergy consumption of the driving input $\left(CExC_{R,i}\right)$ equals the resource exergy consumption of the respective flows and needs to be calculated according to equations (52), (56) and (73) respectively.

4.2 Power generation

For power-only generation the resource exergy consumption for power generation is a function of the power demand (P_d), the power losses through storage $\left(P_{l,s}\right)$, the power losses due to transfer $(P_{l,t})$, the cumulated exergy consumption of the fuel used to produce power $(CExC_F)$ and the electrical exergy efficiency (ε_{el}).

Resource exergy consumption of

$$REC_P = \left(P_d + P_{l,s} + P_{l,t}\right) \cdot \frac{CExC_F}{\varepsilon_{el}} \tag{63}$$

non-CHP power generation from fuels

For natural fuels the equation can be simplified using equation (23) 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 exergy consumption of non-CHP power generation from fuels

$$RC_P \approx (P_d + P_{l,s} + P_{l,t}) \cdot \frac{CEC_F}{\eta_{el} \cdot \frac{LHV_F}{HHV_F}} \tag{64}$$

For thermal sources this equation can be simplified using equation (36) 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 exergy consumption of electricity generated using thermal sources[7]

$$RC_{P,chp,ts} \approx (P_d + P_{l,s} + P_{l,t}) \cdot \frac{CEC_{ts} - 1 + CF_{ts}}{\eta_{el,ts}} \tag{65}$$

For synthetic fuels where no cumulated energy consumption (CEC_F) values are available, such as hydrogen, the equation can be simplified using equation (24) to a function of the resource exergy consumption of the synthetic fuel (REC_{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 exergy consumption of non-CHP power generation from synthetic fuels

$$REC_P \approx (P_d + P_{l,s} + P_{l,t}) \cdot \frac{REC_{SF}}{\eta_{el} \cdot \frac{LHV_{SF}}{HHV_{SF}}} \tag{66}$$

[7] 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.

4.3 Cooling generation

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

The resource exergy consumption for cooling generation from power or fuels is a function of the cooling demand (R_d), the cooling losses due to storage $\left(R_{l,s}\right)$, the cooling losses due to transfer $\left(R_{l,t}\right)$, the cumulated exergy consumption of the resource input of the thermal source $\left(CExC_{ts,R}\right)$. The latter variable is considered as an absolute value in order to account for the fact that heat flows below reference temperature have a negative prefix which is only relevant in exergy balances.

Resource exergy consumption of direct cooling from thermal sources

$$REC_{dc} = \left(R_d + R_{l,s} + R_{l,t}\right) \cdot |CExC_{R,ts}| \qquad (67)$$

Using equation (36) for heat flows this can be transformed to a function that considers the cumulated energy consumption for direct cooling (CEC_{dc}) and the absolute value of the Carnot factor of the direct cooling heat flow ($|CF_{dc}|$) if values for cumulated exergy consumption are not available.

Simplified resource exergy consumption of direct cooling from thermal sources

$$REC_{dc} \approx \left(R_d + R_{l,s} + R_{l,t}\right) \cdot \left(CEC_{dc} - 1 + |CF_{dc}|\right) \qquad (68)$$

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 or fuel demand. The resource exergy consumption of the auxiliary demand needs to be added to the resource exergy consumption of the thermal source system using equation (46) to obtain the total resource exergy consumption.

4.3.2 Refrigeration machines

The resource exergy consumption for cooling generation from power or fuels is a function of the cooling demand (R_d), the cooling losses due to storage $\left(R_{l,s}\right)$, the cooling losses due to transfer $(R_{l,t})$, the cumulated exergy consumption for resource input of the fuel or power source $(CExC_{R,i})$ and the performance factor of the refrigeration machine (PF_{rm}).

Resource exergy consumption of cooling from chillers	$$REC_{rm} = (R_d + R_{l,s} + R_{l,t}) \cdot \frac{CExC_{R,i}}{PF_{rm}}$$	*(69)*

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

4.4 Hydrogen and other synthetic fuels

The resource exergy consumption for synthetic fuels from power is a function of the fuel demand (F_d), the fuel losses due to storage $(F_{l,s})$, the fuel losses due to transfer $(F_{l,t})$, the cumulated exergy consumption of the input $(CExC_{R,i})$ and the energy efficiency of the synthetic fuel production (η_{SF}).

Resource exergy consumption of synthetic fuel from primary fuels or power	$$RC_{SF} = (F_d + F_{l,s} + F_{l,t}) \cdot \frac{CExC_{R,i}}{\eta_{SF}}$$	*(70)*

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 $(CEC_{R,i})$ and the energy efficiency if it is based on the higher heating values $(\eta_{SF,HHV})$.

Simplified resource exergy consumption of synthetic fuel from primary fuels or power if efficiency is based on HHV values	$$REC_{SF} \approx (F_d + F_{l,s} + F_{l,t}) \cdot \frac{CEC_i}{\eta_{SF,HHV}}$$	*(71)*

The underlying assumption for the simplification in equation (71) 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 exergy consumption of synthetic fuel from primary fuels or power if efficiency is based on LHV values

$$RC_{SF} \approx (F_d + F_{l,s} + F_{l,t}) \cdot \frac{CEC_i}{\eta_{SF,LHV} \cdot \frac{LHV_i}{HHV_i} \cdot \frac{HHV_{SF}}{LHV_{SF}}} \quad (72)$$

4.5 Cogeneration

The basic principle of allocating shares of an input flow to cogenerated products has been explained in Chapter 3.5 and equation (43).

4.5.1 Heat from combined heat and power

The resource exergy consumption for heat generation from CHP is a function of the heat demand (Q_d), the heat losses due to storage $\left(Q_{l,s}\right)$, the heat losses due to transfer $\left(Q_{l,t}\right)$, the CExC input of the fuel or heat source ($CExC_i$), the thermal energy efficiency (η_{th}) and the cogeneration share of heat ($CS_{Q,chp}$) from equation (44).

Resource exergy consumption of heat from heat and power CHP

$$REC_{\mathrm{Q},chp} = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot CS_{Q,chp} \cdot \frac{CExC_i}{\eta_{th}} \quad (73)$$

For CHP from natural fuels this equation can be simplified to a function of the CEC of the fuel (CEC_F) and the energy efficiency of the thermal part of the CHP unit ($\eta_{th,F}$) as well as the LHV and HHV ratio of the fuel ($\frac{LHV_F}{HHV_F}$)

Resource exergy consumption of heat from heat and power CHP using fuels

$$REC_{Q,chp,F} \approx \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot CS_{Q,chp} \cdot \frac{CEC_F}{\eta_{th,F} \cdot \frac{LHV_F}{HHV_F}} \quad (74)$$

For synthetic fuels, for which a CEC of the fuel is not known equation (73) can be simplified to a function of the resource exergy consumption of the fuel (REC_{SF}), the thermal energy efficiency of the CHP unit ($\eta_{th,SF}$) and the ratio of the average lower to the higher heating value of the synthetic fuel ($\frac{LHV_{SF}}{HHV_{SF}}$).

Simplified resource exergy consumption of heat from boilers using synthetic fuels

$$REC_b \approx \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot CS_{Q,chp} \cdot \frac{REC_{SF}}{\eta_{th,SF} \cdot \frac{LHV_{SF}}{HHV_{SF}}} \tag{75}$$

For thermal sources this equation can be simplified using equations (4) and (36) to a function of CEC associated with the thermal source (CEC_{ts}), the thermal efficiency of the CHP unit using thermal sources ($\eta_{th,ts}$) and the Carnot factors of the thermal source (CF_{ts}) and the generated heat from CHP (CF_{chp}).

Resource exergy consumption of heat from heat and power CHP using thermal sources[8]

$$REC_{Q,chp,ts} \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot CS_{Q,chp} \cdot \frac{CEC_{ts} - 1 + CF_{ts}}{\eta_{th,ts}} \tag{76}$$

4.5.2 Electricity from combined heat and power

The resource exergy consumption for power generation from CHP is a function of the power demand (P_d), the power losses through storage $\left(P_{l,s}\right)$, the power losses due to transfer $\left(P_{l,t}\right)$, the electrical exergy efficiency of power generation (ε_{el}) the cumulated exergy consumption input of the fuel or heat source ($CExC_i$) and the cogeneration share of power ($CS_{P,chp}$) from equation (45).

Resource exergy consumption of electricity from heat and power CHP

$$REC_{\mathrm{P},chp} = \left(P_d + P_{l,s} + P_{l,t}\right) \cdot CS_{P,chp} \cdot \frac{CExC_i}{\eta_{el}} \tag{77}$$

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

[8] 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.

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

$$REC_{\mathrm{P},chp} \approx \left(P_d + P_{l,s} + P_{l,t}\right) \cdot CS_{P,chp} \cdot \frac{CEC_F}{\eta_{el,F} \cdot \frac{LHV_F}{HHV_F}} \tag{78}$$

For thermal sources this equation can be simplified using equation (36) to a function of cumulated energy consumption associated with the thermal source (CEC_{ts}), the electrical efficiency of power generation from thermal sources ($\eta_{el,ts}$) and the Carnot factor of the thermal source at the temperature of extraction (CF_{ts}).

Resource exergy consumption of electricity from heat and power CHP using thermal sources[9]

$$RC_{P,chp,ts} \approx \left(P_d + P_{l,s} + P_{l,t}\right) \cdot CS_{P,chp} \cdot \frac{CEC_{ts} - 1 + CF_{ts}}{\eta_{el,ts}} \tag{79}$$

[9] 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.

Abbreviations

Table 1: Table of abbreviations

C	Chemical exergy (reactive apart from fuels) and non-reactive. Includes compressed air.
CEC	Specific cumulated energy consumption
CExC	Specific cumulated exergy 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
REC	Resource exergy consumption
RED	Resource exergy demand
REE	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
ds	directly storable
el	electrical
En	energy
F	fuel
f	flow
hp	heat pump
hs	heat storage
ht	heat transfer
i	input
l	losses
nt	non-thermal
m	mass
md	minimum demand in an ideal case
mm	marginal mix
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	Resource
t	transfer
tc	thermal cooling
tf	thermal flow
th	thermal
ts	thermal sources
x	final number of variables
Σ	sum

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