REA: Resource Exergy Analysis - A basic guideline for application

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Method Article

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REA: Resource Exergy Analysis

A basic guideline for application

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1 Background

Resource exergy analysis is a proven type of exergy analysis that can replace primary energy analysis with a more comprehensive and consistent system while still remaining similarly simple. It has been applied and improved for over ten years in practice e.g. (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 deduce the approach from less instructive publications.

The aim of REA is to provide a realistic comparison of different complex energy systems based on physics and sensible system boundaries. It should usually be complemented with an analysis of GHG emissions and Cost. This way Efficiency, Climate protection and Economic viability can be assessed transparently thus enabling truly well-informed decisions.

Primary energy analysis (PEA) often fails to paint the complete picture of energy and the energy quality associated with it. Therefore PEA often leads to misleading results especially if heating and cooling systems are considered. Consequently, decisions based on PEA always carry the risk of favoring suboptimal technology choices, thereby increasing the risk of catastrophic climate change.

The key difference between primary energy analysis (PEA) and REA is the consideration of energy quality. REA goes beyond the law of energy conservation[1] and also considers the law irreversibility[2] thus ensuring transparent identification of truly efficient solutions.

Upgrading to REA allows decision makers to avoid costly mistakes and reliably fulfill their responsibility to their families

[1] The first law of thermodynamics

[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 unit that is considered as the basic unit of assessment is the Cumulated Exergy Consumption (CExC). In this report this will be labeled as resource consumption, in order to allow an easier intuitive understanding of the property. 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). Since the word “resources” generally means “things that are used in order to achieve a desired outcome” the Cumulated Exergy Consumption as an indicator provides probably the property that is closest to the universal understanding of resource consumption.

However it has to be noted that in the case of solar radiation and kinetic energy of wind, rivers or currents CExC might exceed the Resource Exergy Consumption (REC). This is due to the fact that for REA aims at fairly comparing all systems and therefore only energy forms that are usable on demand are considered resources. CExC on the other hand does not distinguish between exergy that is lost if not used (sun and wind) and exergy that can be used on demand. At the same time it tends to ignore historical exergy consumption, such as the solar radiation needed to create fossil fuels.

Due to difficulty to obtain data on material exergy the analysis usually is limited to the REC that is caused by harvesting, transporting and using energy. This means it extends the view beyond primary energy but neglects material and grey exergy aspects.

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

- Only flows of directly storable primary energy are considered as input flows. In cases where the primary energy is not storable without transformation (solar radiation or kinetic energy of the wind) the first storable secondary energy is considered to be the primary energy for the comparison.

    - This means that for solar thermal plants it is not the solar radiation that is considered to be the primary energy but the hot water that has been generated by it at a certain temperature level.

    - For PV power production the electricity produced is considered the storable primary energy.

    - For most electrical inputs this means that the losses from the extraction of the fuels to the provision of electricity have to be taken into account. This also means taking into account 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 knowledge of the Cumulated Exergy Consumption of power.

- For the calculation of efficiencies 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 districts inhabitants, which could also be covered by very space suits. However, in order to allow thermodynamic modeling the demand has been approximated by the exergy minimally required to keep the considered buildings at 20 °C and supply sufficiently hot water at 43°C.

- The comparability of the considered alternatives is ensured by keeping the supply task fixed. This makes it possible to pinpoint the causes for the identified improvements.

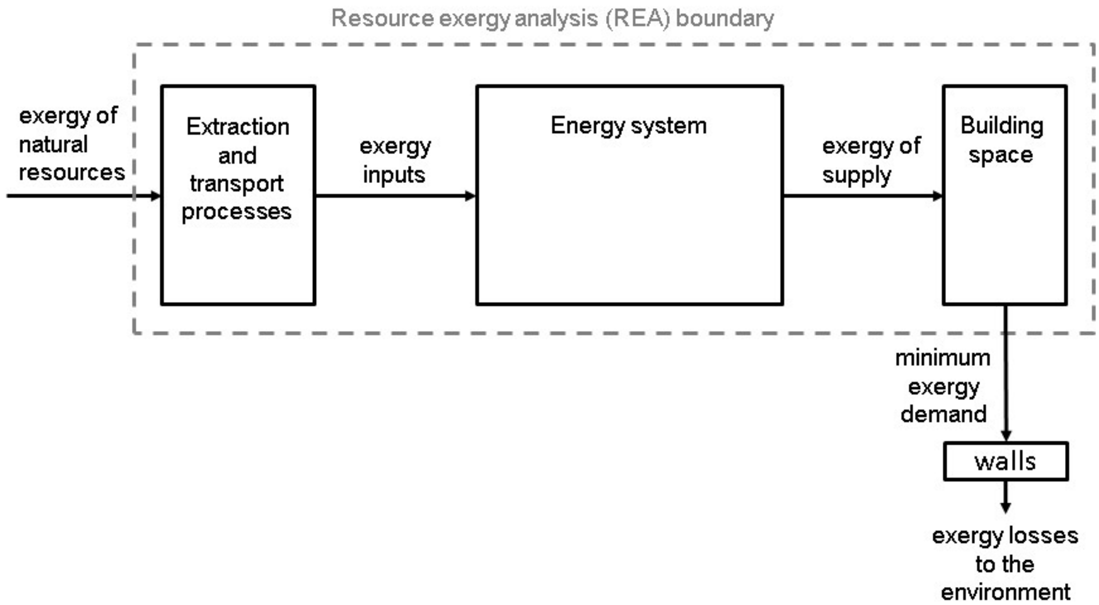

Figure 3: Balance boundaries to assess resource consumption and resource efficiency of thermal supply systems

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 which is also labeled Carnot method (Jentsch, 2015). Therefore this method has been chosen to calculate the resource and emission fraction that is allocated to heat and electricity from cogeneration respectively.

In this way external effects such as the replacement of power from the grid by power from CHP have been neglected. This allows an evaluation of resource savings independent of external effects.

2.2 Calculation logic

The equations used for calculating resource exergy be deduced from (Jentsch 2010)[3] and fundamental calculation basics of energy system analysis.

[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

In order to simplify understanding 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 (CEC) factors that can be found in Eco-Databases, e.g EcoInvent.

Additionally it is assumed that all efficiencies and CEC factors only account for the Lower Heating Value of fuels (LHV). In order to obtain the total amount of energy the Higher Heating Value (HHV) of fuels is considered by using ratios of HHV to LHV from literature.

For CHP units the fuel share allocated to heating is calculated based on the Carnot method (Jentsch 2015). In order to fulfill the energy balance it is assumed that the difference between the allocated fuel and the heat output is put in as heat at reference temperature. This type of heat has an energy quality of zero and is therefore not associated with an exergy flow. This assumption is based on the fact that all CHP processes need to reject heat at least at the temperature of the environment in order to function.

For heat pumps a similar assumption is made in order to fulfill the energy balance. The difference between the heat produced and the electricity input is assumed to be heat at the temperature of the heat source. While it would be better if data on actually extracted heat from the heat source were available this provides a sufficiently accurate way to fulfill the energy balance if this data is not available.

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 (Jentsch 2010).

For thermal energy flows above reference temperature the Carnot factor is calculated. It is important to calculate the Carnot factor with the average temperature of any heat flow 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 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 %.

2.3 Exergy passes and REA

Exergy passes (Jentsch, 2010; Jentsch et al., 2009) 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.

However, in general it is sufficient to know the energy and exergy of a considered flow. Once energy and exergy flows are known an average energy quality can be calculated by dividing the two values. 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.

The fundamentals for calculating resource exergy demand and consumption of the considered scenarios is shown in the following.

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

2.4 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

APF	Annual Performance Factor
C	Chemical exergy (reactive apart from fuels) and non-reactive. Includes compressed air.
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
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 subscipts

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

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

2.4.1 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).

Average temperature of heat transfer from fluids without phase change.

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

Average temperature of heat transfer from fluids during phase change (Evaporation / condensation / freezing / thawing).	$$T_{a,ht} = T_{pc}$$	(2)
Average temperature of heat transfer from fluids during temperature and phase change (Evaporation / condensation / freezing / thawing).	$$T_{a,ht} = \frac{1}{Q_{pc} + Q_{sh}} \cdot \left(Q_{pc} \cdot T_{pc} + Q_{sh} \cdot \frac{T_{ff} - T_{rf}}{\ln\left(\frac{T_{ff}}{T_{rf}}\right)} \right)$$	(3)
Carnot Factor	$$CF_{ht} = 1 - \frac{T_0}{T_{a,ht}}$$	(4)

The Carnot Factor equals the energy quality of heat. If it is negative its absolute value can approximate the energy quality of heat extraction for normal cooling and refrigeration.

Exergy flow associated with heat	$$Ex_Q = CF_{ht} \cdot Q$$	(5)

This 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 power	$$Ex_P = P$$	(6)

Exergy efficiency
$$\varepsilon = \frac{Ex_o}{Ex_i} \quad (7)$$

Energy efficiency
$$\eta = \frac{En_o}{En_i} \quad (8)$$

2.4.2 Resource exergy efficiency (RE)

Resource exergy efficiency (RE) can be used to evaluate the physical sophistication of an energy system. It is always below 100% due to irreversibilities. It is an additional information that should not replace RC since it is not influenced by the total demand, therefore neglecting aspects of system size, demand and insulation.

In order to calculate it the exergy demand needs to be calculated based on an understanding of the minimally required exergy flows. For heat this can be 20 °C space temperature and for power the power consumption of the current appliances. While the RD can be defined differently it is important that for a comparison it is defined according to the same principles for all considered energy systems. Only if RD allows the supply of the same quality of end use, values are meaningful for comparison. Otherwise RD provides valuable information on the sophistication of various supply chains. 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.

Resource exergy efficiency
$$\varepsilon_R = RE = \frac{\sum_1^x RD}{\sum_1^x RC} \quad (9)$$

Resource exergy demand should be defined based on the energy demand and the minimum energy quality that allows to fulfill the task.

Resource demand of thermal supply tasks
$$RD_{th} = En_d \cdot |CF_{md,ht}| \quad (10)$$

Resource demand of non – thermal supply tasks	$RD = Ex_{md}$	(11)

2.4.3 Approximations & Simplifications

A key simplification in communication is to drop the word exergy. It is often misinterpreted are 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. At the same time 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 REA to enable the application of exergy resource analysis even in cases, where exergy data is lacking.

Simplified average temperature of heat transfer at changing temperatures	$T_{a,ht} \approx \frac{T_{ff} + T_{rf}}{2}$	(12)

Simplified average temperature of heat transfer that includes phase change and only low heat transfer at changing temperatures	$T_{a,ht} \approx T_{pc}$	(13)

Both simplifications for the average temperature should only be used for draft estimations. For the final calculation equation (3) should be used.

Estimate for fuel exergy (Bejan et al., 1996)	$Ex_F \approx HHV_F$	(14)
Usual assumption for fuel energy	$En_F \approx LHV_F$	(15)

The underlying assumption for the following simplification of CExC is that all losses are of the same type as the considered fuel.

Estimate for Cumulated Exergy Consumption of non-heat flows	$CExC_F \approx CEC_F$	(16)
Estimate for the Cumulated Exergy Consumption of thermal sources	$CExC_{ts} \approx \left(CEC_Q - 1 + CF_{ts}\right)$	(17)

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.

Estimate for the exergy efficiency of power generation	$\varepsilon_{el} \approx \eta_{el} \cdot \frac{LHV_F}{HHV_F}$	(18)

Estimate for the exergy efficiency of using fuel boilers	$\varepsilon_{th} \approx \eta_{th} \cdot \frac{LHV_F}{HHV_F} \cdot CF_{ht}$	(19)

The ratio $\frac{LHV_p}{HHV_p}$ is 1 for all non-fuel sources. It is usually between 0.96 and 0.9 for combustible fuels (DIN, 2010).

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

For simplification 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.

If power from various sources contributes to the considered mix the effective $CExC_{\Sigma,\mathrm{p}}$ can be calculated as follows:

Resource consumption of the power mix	$RC_{\Sigma\mathrm{P}} = \frac{P_1}{\Sigma\mathrm{P}} \cdot RC_{P,1} \cdot \frac{P_2}{\Sigma\mathrm{P}} \cdot RC_{P,2} \cdot \ldots \cdot \frac{P_x}{\Sigma\mathrm{P}} \cdot \mathrm{R}C_{P,x}$	(20)

2.4.4 General equations for cogeneration assessment

Exergy Analysis allows consistent allocation of driving exergy to all valuable products in a cogeneration process. Generally, allocation to an exergy flow in a CHP unit producing different product streams can be calculated as follows.

Resource share attributed to a product flow from CHP	$RS_{f,chp} = \frac{Ex_f}{\sum_{f=1}^{z} Ex_z}$	(21)

This equation is applicable to all types of cogeneration. This means if a machine produces any combination of heating, cooling and power. Due to the temperature dependency of exergy all heat flows that cross its balance boundary should be considered at their respective temperature levels and as separate products if they are use separately. If different heat exchangers at different temperatures heat up a single fluid flow, only the temperature of the fluid flow that crosses the balance boundary is considered.

Equation (21) allows the allocation of resources to a coproduction of non-energy products and energy products. However, in order to assess the exergy flow associated with non-energy products it is usually necessary to asses 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 resource share as it is only dependent on the CHP product exergy flows and therefore universally applicable to all types of resource consumption by the CHP process.

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

Resource share of heat from CHP

$$RS_{Q,chp} = \frac{Ex_Q}{Ex_Q + Ex_P} \approx \frac{CF_{ht} \cdot \eta_{th,chp}}{CF_{ht} \cdot \eta_{th,chp} + \eta_{el,chp}} \quad (22)$$

Resource share of power CHP plant

$$RS_{P,chp} = 1 - RS_{Q,chp} \approx \frac{\eta_{el,chp}}{CF_{ht} \cdot \eta_{th,chp} + \eta_{el,chp}} \quad (23)$$

2.4.5 Overall resource consumption

The total resource consumption for a supply scenario is calculated by adding the Resource consumption of all individual demands within an energy system. If the demand is covered by more than one source, the total consumption can be calculated as

Total resource consumption of an energy system

$$\begin{aligned} RC_\Sigma = & \sum_1^p \frac{P_p}{\Sigma \mathrm{P}} \cdot RC_{P,p} + \sum_1^q \frac{Q_q}{\Sigma \mathrm{Q}} \cdot RC_{Q,q} \\ & + \sum_1^v \frac{R_v}{\Sigma \mathrm{R}} \cdot RC_{R,v} + \sum_1^w \frac{F_w}{\Sigma \mathrm{F}} \cdot RC_{F,w} \\ & + \sum_1^x \frac{C_x}{\Sigma \mathrm{C}} \cdot RC_{C,x} + \sum_1^y \frac{M_y}{\Sigma \mathrm{M}} \cdot RC_{M,y} \\ & + \sum_1^z \frac{N_z}{\Sigma \mathrm{N}} \cdot RC_{N,z} \end{aligned} \quad (24)$$

Solar exergy and the kinetic exergy of the wind are not usable on demand. They fluctuate. Therefore they are not considered exergy resources. The first storable form of exergy after conversion to a storable form 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 from sun and wind to power is also neglected in the CEC values, which can easily be checked by looking at the respective values. E.g. a CEC in the order of magnitude of 1.2 for PV would be very unlikely if considering the fact that only 20% of the high exergy solar energy are converted to power. If considered this conversion loss alone would lead to CEC of 5 and higher.

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.

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 exergy. 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.

$$\begin{aligned} Ex = &\left|Ex_{th,o} - Ex_{th,i}\right| + \left|Ex_{C,T0,o} - Ex_{C,T0,i}\right| \\ &+ \left|Ex_{M,T0,o} - Ex_{M,T0,i}\right| \\ &+ \left|Ex_{N,T0,o} - Ex_{N,T0,i}\right| \end{aligned} \tag{25}$$

2.4.6 Electricity generation from fuels without CHP

Resource consumption of non-CHP power generation from fuels

$$RC_P = (P_d + P_{l,s} + P_{l,t}) \cdot \frac{CExC_i}{\varepsilon_{el}} \tag{26}$$

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

$$RC_P \approx (P_d + P_{l,s} + P_{l,t}) \cdot \frac{CEC_F}{\eta_{el} \cdot \frac{LHV_F}{HHV_F}} \quad (27)$$

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

$$RC_P \approx (P_d + P_{l,s} + P_{l,t}) \cdot \frac{CEC_{SF}}{\eta_{el} \cdot \frac{LHV_{SF}}{HHV_{SF}}} \quad (28)$$

2.4.7 Electricity from CHP using fuels

Resource consumption of heat from heat and power CHP

$$RC_{\mathrm{P},chp} = (P_d + P_{l,s} + P_{l,t}) \cdot RS_{P,chp} \cdot CExC_i \quad (29)$$

Simplification for primary fuels: $CExC_i \approx CEC_F$

Simplification using synthetic fuels: $CExC_i \approx RC_{SF}$

Resource consumption of heat from CHP from thermal sources

$$RS_{P,chp,ts} \approx \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot RS_{P,chp} \cdot (CEC_{ts} - 1 + CF_{ts}) \quad (30)$$

2.4.8 Heat from electrical boilers

Resource consumption of heat from electric boilers

$$RC_{b,el} = (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CExC_P}{\varepsilon_{b,el}} \quad (31)$$

Simplified resource consumption of heat from electric boilers

$$RC_{b,el} \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CEC_P}{\eta_{b,el} \cdot \frac{LHV_{F,el,a}}{HHV_{F,el,a}}} \quad (32)$$

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.

2.4.9 Heat from boilers

Resource consumption of heat from boilers

$$RC_b = (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CExC_i}{\varepsilon_b} \quad (33)$$

Simplified resource consumption of heat from boilers using primary fuels

$$RC_b \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{CEC_F}{\eta_b \cdot \frac{LHV_F}{HHV_F}} \quad (34)$$

Simplified resource consumption of heat from boilers using synthetic fuels

$$RC_b \approx (Q_d + Q_{l,s} + Q_{l,t}) \cdot \frac{RC_{SF}}{\eta_b \cdot \frac{LHV_{SF}}{HHV_{SF}}} \quad (35)$$

2.4.10Heat from CHP using fuels

Resource consumption of heat from heat and power CHP

$$RC_{Q,chp} = (Q_d + Q_{l,s} + Q_{l,t}) \cdot RS_{Q,chp} \cdot CExC_i \quad (36)$$

Simplification: $CExC_i \approx CEC_F$

Simplification using synthetic fuels: $CExC_i \approx RC_{SF}$

2.4.11 Heat from electrical and fuel-driven heat pumps

$$RC_{hp} = (Q_d + Q_{l,s} + Q_{l,t}) \cdot \left(\frac{CExC_i}{APF_{hp}} + CF_{ht,hp} \cdot \left(1 - \frac{1}{APF_{hp}}\right)\right) \quad (37)$$

The $CF_{ht,hp}$ is 0 for heat from air since this heat is freely available and virtually unlimited.

Simplification for power: $CExC_i \approx CEC_P$

Simplification for primary fuels: $CExC_i \approx CEC_F$

Simplification for synthetic fuels: $CExC_i \approx CEC_{SF}$

2.4.12 Heat from thermal sources (Excess heat, Solar thermal, Geo thermal)

Resource consumption for heat from thermal sources

$$RC_{ts} = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot CExC_{ts} \quad (38)$$

Simplified resource consumption for heat from thermal sources

$$RC_{ts} \approx \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot (CEC_{ts} - 1 + CF_{ts}) \quad (39)$$

2.4.13 Heat from CHP using thermal sources

Primary exergy (=resource) consumption allocated to heat from thermal CHP.

Resource consumption of heat from CHP from thermal sources

$$RS_{Q,chp,ts} = \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot RS_{Q,chp} \cdot CExC_{ts} \quad (40)$$

Simplified resource consumption of heat from CHP from thermal sources

$$RS_{Q,chp,ts} \approx \left(Q_d + Q_{l,s} + Q_{l,t}\right) \cdot RS_{Q,chp} \cdot (CEC_{ts} - 1 + CF_{ts}) \quad (41)$$

2.4.14 Cooling from chillers driven by power or fuels

Resource consumption of cooling from chillers

$$RC_{rm} = (R_d + R_{l,s} + R_{l,t}) \cdot \frac{CExC_i}{APF_{rm}} \quad (42)$$

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: $CExC_i \approx CEC_P$

Simplification for primary fuels: $CExC_i \approx CEC_F$

Simplification for synthetic fuels: $CExC_i \approx CEC_{SF}$

2.4.15 Cooling from chillers driven by heat (absorption, adsorption, CHP)

Resource consumption of cooling from chillers

$$RC_{tc} = (R_d + R_{l,s} + R_{l,t}) \cdot \frac{CExC_{ts}}{APF_{rm}} \quad (43)$$

Resource consumption of cooling from thermal chillers

$$RC_{tc} \approx (R_d + R_{l,s} + R_{l,t}) \cdot \frac{(CEC_{ts} - 1 + |CF_{ts}|)}{APF_{rm}} \quad (44)$$

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

2.4.16 Cooling from thermal sources (Sea, river and lake water)

Resource consumption of direct cooling from thermal sources

$$RC_{dc} = \left(R_d + R_{l,s} + R_{l,t}\right) \cdot CExC_{ts} \tag{45}$$

Simplified resource consumption of direct cooling from thermal sources

$$RC_{dc} \approx \left(R_d + R_{l,s} + R_{l,t}\right) \cdot \left(CEC_{dc} - 1 + |CF_{ts}|\right) \tag{46}$$

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.

2.4.17 Hydrogen and other synthetic fuels from primary fuels or electricity

Resource consumption of synthetic fuel from primary fuels or power

$$RC_{SF} = \left(F_d + F_{l,s} + F_{l,t}\right) \cdot \frac{CExC_i}{\varepsilon_{SF,i}} \tag{47}$$

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

$$RC_{SF} \approx \left(F_d + F_{l,s} + F_{l,t}\right) \cdot \frac{CEC_i}{\eta_{SF,i}} \tag{48}$$

The underlying assumption for the simplification in equation (46) 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	$$RC_b \approx (F_d + F_{l,s} + F_{l,t}) \cdot \frac{CEC_i}{\eta_{SF,i} \cdot \frac{LHV_i}{HHV_i} \cdot \frac{HHV_{SF}}{LHV_{SF}}}$$	(49)

2.5 References

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

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 (Hrsg.). (2010). *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.

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

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.

3 Conflict of interest

The author is free from conflict of interest concerning the topic of this publication.