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Allocation of CO_2-Emissions to Power and Heat from CHP-Plants

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1 Introduction

The separated allocation of CO_2-emissions to the cogeneration products electricity and heat is necessary and receives an increasing significance in energy policy, because the two products have to face up to the ecological "competitors" at different markets. In the case of electricity this is a global market, which complicates an ecological evaluation because its "origin" is hardly documented and therefore difficult to assess. In the case of heat this is slightly more easy, because heat supplies a regional and relatively limited market. The possible competitors are boilers.

With an allocation of the primary energy and accordingly the CO_2-emissions specific emissions of the cogeneration products can be calculated and with that the ecological quality compared to other generation alternatives can be shown and used e.g. as a marketing instrument.

This evaluation assumes that the CO_2-emissions of energy supply alternatives can be determined respectably and reliably. In case of heat the best alternative is simply the condensing boiler. The comparison with more complex technologies like a heat pump is more critically since the origin of the electricity as the operating power can mostly be identified only by presumptions, which of course can be impeached by potential opponents of the district heating with cogeneration.

The same applies to the ecological evaluation of the cogeneration product electricity. Therefore it is recommended to calculate and disclose the specific CO_2-emissions. Additionally the reduction of emissions, which is achieved only by cogeneration units, should be emphasized. For the comparison the use of such "alternative units" is advisable whose obviousness has to be accepted by law and ordinances.

The following discussions are carried out in two stages regarding the comparative assessment and the allocation of primary energy and respectively CO_2-emissions.

2 Assessment of the „Origin"

2.1 Harmonized efficiency reference values according to EU guideline

Harmonized reference values of efficiency have already been established based on the EU guideline 2004/8/EG [1] at 2006/12/21. They are the basis for the comparison of cogeneration units with the separated generation of heat and electricity and serve the designation of the energy conversion quality.

For the further analysed cogeneration units, which mainly apply natural gas as fuel, the harmonized reference value of efficiency of the heating station is

$$\text{Ref } H\eta = 90\ \%.$$

The value for the alternative electricity generation in a power plant is determined by

- The applied fuel (in this case natural gas)
- A base value of efficiency dependent on the year of start of operation
- Correction values dependent on the voltage level of feeding and on the average annual ambient temperature ($t_{a,m} = 9\,^{\circ}C$)

As examples the following cogeneration units have been analysed and will be compared:

- CU 1: Combined cycle heat and power plant,
- CU 2: Gas turbine with waste heat boiler,
- CU 3: Combustion engine heat and power plant,
- CU 4: Low power back pressure turbine.

The harmonized reference values of efficiency of the alternative power plants are limited by

- Minimum: Ref $E\eta$,min =0,478 (CU 4) and
- Maximum: Ref $E\eta$,max =0,500 (CU 2),

which thus represent reference units of high quality.

With the values of the cogeneration net electricity feeding $E_{CHP,net}$ and the cogeneration heat feeding to the heating system H_{CHP} the fuel consumption of the separated generation is calculated with

$$H_{Fuel,Ref} = \frac{E_{CHP,net}}{Ref\,E\eta} + \frac{H_{CHP}}{Ref\,H\eta} \tag{1}$$

A high efficient cogeneration unit according to [1] and [2] should realize a reduction of the primary energy consumption

$$PES = \left(1 - \frac{H_{Fuel,CHP}}{H_{Fuel,Ref}}\right) \cdot 100\% \tag{2}$$

of more than 10 %.

Because the values often include also shares of separated generation, the cogeneration share of the fuel energy is determined by the annual fuel efficiency

$$\eta_{a,Fuel} = \frac{E_{net} + H}{H_{Fuel}} \tag{3}$$

to $H_{Fuel,CHP} = (E_{CHP,net} + H_{CHP}) / \eta_{a,Fuel}$. (4)

The results show that all cogeneration units except CU 4 achieve the high efficiency criterion.

If it should be useful to limit oneself to the application of the EU guideline, then two approaches are possible.

At first a primary energy or emission allocation can be carried out by partitioning according to the primary energy consumption of the separated generation of electricity and heat. The partitioning factor α of the cogeneration electricity results from

$$\alpha_E = \frac{E_{CHP,net} / Ref E\eta}{H_{Fuel,Ref}} \quad (5)$$

and that of cogeneration heat is $\alpha_H = 1 - \alpha_{E.}$

With the cogeneration emission values $Em_{CO2,CHP}$ the emission shares of the products

- Cogeneration electricity $Em_{CO2,CHP,E} = Em_{CO2,CHP} * \alpha_E$ (6)
- Cogeneration heat $Em_{CO2,CHP,H} = Em_{CO2,CHP} * \alpha_H$ (7)

and hence, if necessary, the specific product-related CO_2-emissions Em can be calculated from the specific fuel-related emissions em_{CO2}. In this paper natural gas is applied with $em_{CO2} = em_{CO2,NG} = 198$ kg/MWh.

To compare the emissions of the separated generation based on the harmonized reference values of efficiency

$$Em_{CO_2,RefE} = \frac{E_{CHP,net}}{Ref\ E\eta} \cdot em_{CO_2} \quad (8)$$

and

$$Em_{CO_2,RefH} = \frac{H_{CHP}}{Ref\ H\eta} \cdot em_{CO_2} \quad (9)$$

are used respectively.

A „bonus method“ according to the calculation of primary energy factors by DIN 4701-10, where the primary energetic advantages are credited to only one product, is also possible for a comparison.

Following this procedure the whole cogeneration emissions $E_{CO2,KWK}$ reduced by the emissions of the separated generation of heat (with harmonized reference value of efficiency)

$$Em_{CO_2,RefH} = \frac{H_{CHP}}{Ref H\eta} \cdot em_{CO_{2,NG}} \quad (10)$$

are assigned to the cogeneration electricity, so that the specific emissions are

$$em_{CO_2,CHP,E} = \frac{Em_{CO_2,CHP} - Em_{CO_2,RefH}}{E_{CHP,net}} \tag{11}$$

Evaluating the emissions of the heat, exactly like in the case of the determination of primary energy reduction the emissions of a “displaced” reference power plant

$$Em_{CO_2,RefE} = \frac{E_{CHP,net}}{RefE\eta} \cdot em_{CO_2} \tag{11a}$$

would be credited. Thus the specific emissions are

$$em_{CO_2,CHP} = \frac{Em_{CO_2,CHP} - Em_{CO_2,RefE}}{H_{CHP}} . \tag{12}$$

Although the last presented assessment is carried out according to a valid rule it has to be valuated critically, due to the allocation of the particular advantages to only one product.

2.2 Assessment by means of the Primary Energy Factor

The explanations are based upon the German rule DIN 4701-10, which applies for the calculation of the primary energy factor of a heating network $f_{PE,HN}$ [3].

Limiting oneself to the evaluation of the cogeneration products, the equation to calculate the primary energy factor of the heating network is

$$f_{PE,HN,CHP} = \frac{H_{Fuel,CHP} \cdot f_{PE,Fuel} + \left(E_{aux} - E_{CHP,net}\right) \cdot f_{PE,E}}{H_{CHP,net}} \tag{13}$$

with E_{aux} – auxiliary electricity consumption for pumps et al.
$f_{PE,Fuel}$ – primary energy factor of the fuel (natural gas:1.1)
$f_{PE,E}$ – mean primary energy factor of the electricity generation in Germany
$H_{CHP,net}$ – generated heat reduced by heat losses of the network (heat delivered to the consumer).

The primary energy factor of the heating network is the primary energy consumption for the heat production $PE_{H,CHP}$ in relation to the net cogeneration heat. Thus the whole primary energy conversion chain is considered. The advantage of the “displacement” of electricity in the German generation system is completely credited to the heat. For the emission allocation of course only the numerator of (13), further called $PE_{H,CHP}$, is used. If such a criterion should also be applied on the cogeneration electricity, then the net heat, which is not produced in cogeneration and is displaced by cogeneration, has to be “credited” to the primary energy consumption.

Analogously following the rule DIN 4701-10 the primary energy consumption of the cogeneration electricity $PE_{CHP,E}$ results from

$$PE_{CHP,E} = f_{PE,Fuel} \left(H_{Fuel,CHP} - H_{CHP} \; / \; \eta_{a,HS}\right) \tag{14}$$

with $\eta_{a,HS} = 0{,}90$ for the annual fuel efficiency of an alternative gas heating station.

Herefrom it is already clear that the electricity bonus for the primary energy factor of heat goes on the account of the primary energy factor of cogeneration electricity, even more at increasing power and heat ratio.

If the determined values are used to allocate the primary energy to the cogeneration products, i. e. to the cogeneration electricity

$$\alpha_E = \frac{PE_{CHP,E}}{PE_{CHP,H} + PE_{CHP,E}} \tag{15}$$

and accordingly to the cogeneration heat

$$\alpha_H = 1 - \alpha_E$$

then the impact will become still more apparent.

Like presented in the previous chapter, the assigned absolute and specific CO_2-emissions can be calculated from this.

The assessment by primary energy factors shows exorbitant high specific CO_2-emissions for the cogeneration electricity compared to the assessment by harmonized reference values of efficiency according to the EU guideline. Nevertheless ecologic advantages are visible compared to the evaluation of the German electricity mix (analysis of the year 2005 [4], see table 3). Although the nuclear energy as well as the renewable energy are rated to zero in the mix, the resulting specific CO_2-emissions are

$$em_{CO2,mix} = 199{,}6 \text{ kg/MWh}_{Fuel} \,.$$

This gives specific electricity related CO_2-emissions using a primary energy factor of the electricity of $f_{PE,E} = 2{,}7$ of

$$em_{CO2,E} = f_{PE,E} \cdot em_{CO2,mix} = 539 \text{ kg/MWh}_{E} \,.$$

However, from the preceding reasons an evaluation based on modified primary energy factors cannot be recommended.

2.3 Physically based allocation methods

2.3.1 Introduction

Relating to the previous explanations at the current state a thermodynamically based allocation criterion for the identification of the specific emissions combined with a comparison based on the EU guideline can be recommended. For it several methods are considerable, like discussed since PAUER [5].

2.3.2 Caloric allocation

The most feasible method for non-specialists, the so called caloric allocation (CA), is carried out based on the first law of thermodynamics. The energy flows delivered to the electric grid and to the heating system are "treated equally" and it is obtained

$$\alpha_{E,CA} = \frac{E_{CHP,net}}{E_{CHP,net} + H_{CHP}} = \frac{C_{CHP}}{1 + C_{CHP}} \tag{16}$$

and $\alpha_{H,CA} = 1 - \alpha_{E,CA}$.

C is the power to heat ratio..

Despite the plausibility this method has to be criticized from the thermodynamic view because it only evaluates the quantity but not the quality of energy. But the already repeatedly mentioned advantages of the cogeneration result from the generation of work combined with the heat supply. The second law of thermodynamics gives the benchmark for the convertibility of thermal energies. Therefore physically founded methods are based on the assessment of the ability to work of the energies – exergetic assessment – and on the calculation of the reduced electricity generation (electricity loss) caused by the heat delivery respectively.

2.3.3 Exergetic allocation

For the exergetic assessment the calculation of the exergy Ex of the heat is particularly simple using the thermodynamic mean temperature of the heating network

$$T_{m,HN} = \frac{T_{V,m} - T_{R,m}}{\ln \frac{T_{V,m}}{T_{R,m}}} \tag{17}$$

with the mean annual temperatures of flow line $T_{V,m}$ and return line $T_{R,m}$. It follows

$$Ex_{CHP,HN} = \left(1 - \frac{T_{a,m}}{T_{m,HN}}\right) \cdot H_{CHP} \tag{18}$$

with the mean annual ambient temperature of the heating period $T_{a,m}$.

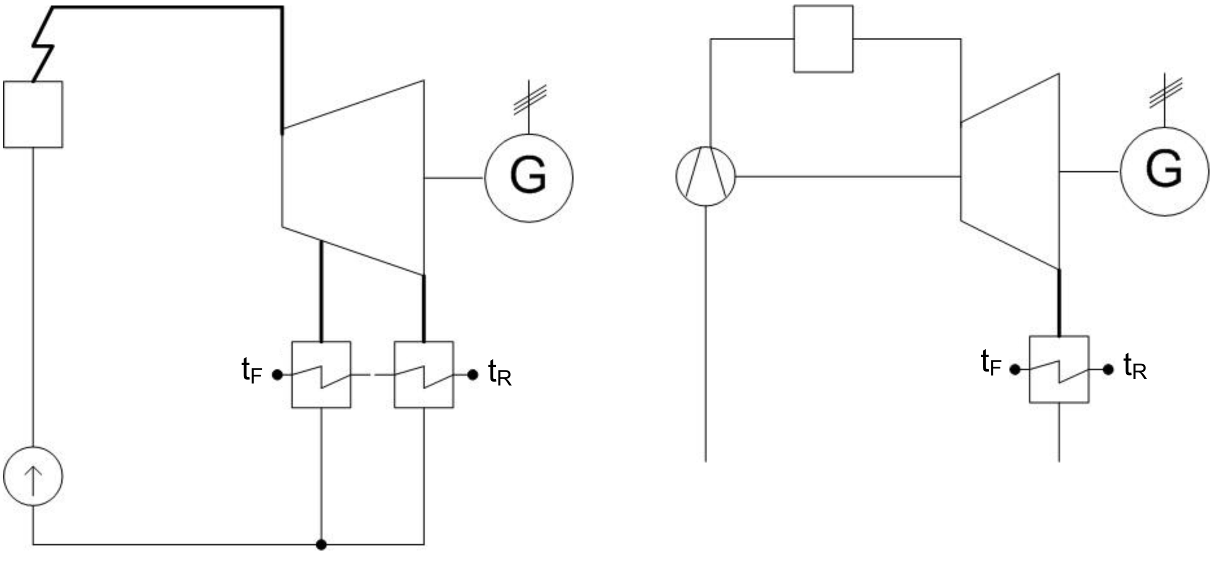
According to [6] $T_{a,m}$ = 276,45 K respectively $t_{a,m}$ = 3,3 °C was used.

With it the allocation factors are

$$\alpha_{E,ex} = \frac{E_{CHP,net}}{Ex_{CHP,HN} + E_{CHP,net}} \tag{19}$$

and $\alpha_{H,ex} = 1 - \alpha_{E,ex}$.

This method can be carried out relatively simple because the needed data are detectable by measures. But thermodynamically they are not really "clean" because the losses of exergy caused by the heat exchange from the cogeneration process to the heating system are not allocated to the heat. The following example illustrates this problem. For the same parameters of the heat network (e. g. $t_{F,m}$ = 110 °C, $t_{R,m}$ = 60 °C) the heat exchange of a extraction back-pressure turbine is shown on the left side of the picture and the heat exchange of a gas turbine with waste heat boiler is shown on the right side of the picture.



Picture 1 Extraction back-pressure turbine and gas turbine with waste heat boiler

Assuming minimal temperature differences of 10 K, the internal thermodynamic mean temperature of the process for the described steam turbine with equal distribution of the heat network temperature is

$$T_{m,i} = 2/(1/T_E + 1/T_B) \tag{20}$$

and respectively $T_{m,i}$ = 380 K with the temperatures of extraction steam T_E and back-pressure steam T_B.

For the thermodynamic mean temperature of the gas turbine unit equation (18) can be used

$$T_{m,i} = (T'_{GT} - T''_{GT}) / \ln \frac{T'_{GT}}{T''_{GT}} .$$

From the assumptions $T_{m,i}$ = 549 K is calculated. Cogeneration units with gas motors will be situated between these values, because they get the heat from the motor waste heat and the enthalpy of the flue gas.

The thermodynamic mean temperature of the heat network is $T_{m,HN}$ = 357 K according to the assumptions.

Because it will not be possible in the practical operation of a cogeneration unit to provide data of the internal process an average annual inner thermodynamic mean temperature with passable expense, a constant value of the heat exchanger "exchange efficiency" based on the frequency should be applied for all cases

$$\eta_{HE} = T_{m,HN} / T_{m,i} . \tag{21}$$

That is fully acceptably since neither the harmonized reference values of efficiency of the EU guideline nor the primary energy factor of DIN 4701-10 represent the practical comparable case of a special cogeneration unit.

For the further procedure the value of $\eta_{HE} = 0{,}85$ calculated in [7] is recommended.

However a major transparency could be reached if confident internal process data could be used for all units.

Using the above mentioned value of η_{HE} an exergetic allocation has been carried out by means of the internal thermodynamic mean temperature of the process for all units.

2.3.4 Electricity based allocation – Dresden Method

The method was proposed by Zschernig and Sander [8] and is based on the exergetic assessment. Compared to the exergetic model it incorporates the real exchange process.

Units with an electricity loss caused by heat extraction (water steam condensation) can be evaluated simply by the electricity loss due to the heat extraction. Mainly in smaller heat and power stations where the determination of the heat losses is complicated the exergy of the heat rated by a real degree of process quality ν_P can be used as an equivalent electricity loss.

But all considered units except CU 1 are units without an electricity loss since the generation of electricity is not reduced by the heat extraction:

- In back-pressure steam processes the generation of electricity increases with the extraction of heat.
- At gas motors and gas turbines no additional fuel is necessary due to the heat extraction. There is no change in the fuel consumption for the electricity generation.

In the extreme case it can be derived that the heat can be supplied free of charge. This seems to be unjustifiable since the heat also represents fuel energy. Therefore the transformation of the delivered heat into an equivalent electricity loss is recommended. Thus it has to be calculated which amount of electricity could be generated from the extracted heat.

For this real assumptions of the degree of process quality and the condensing temperature are made. It is suggested to use values of $\nu_P = 0{,}85$ and $T_{m,out} = T_{m,cond} = 30\ °C$.

The electricity loss ΔE as an electric work results to

$$\Delta E = H_{CHP} \cdot \eta_C \cdot \nu_P \qquad \text{with} \quad \eta_C = 1 - \frac{T_{m,cond}}{T_{m,out}} \qquad \text{and} \qquad \nu_P = \frac{\eta_P}{\eta_C}. \tag{22}$$

For all types of cogeneration units the fuel consumption and thus the emissions can be allocated to electricity and heat after the determination of the electricity loss in the simple form

$$H_{Fuel,E} = \frac{E_{max} - \Delta E}{E_{max}} \cdot H_{Fuel} \tag{23}$$

and

$$H_{Fuel,H} = \frac{\Delta E}{E_{max}} \cdot H_{Fuel} \tag{24}$$

with $E_{max} = E + \Delta E$ as the maximum possible electricity generation without heat supply.

By using realistic assumptions for the electricity generation potential from the extracted heat a slightly lower fuel part is allocated to the heat as in the exergetic assessment.

The precision can be increased if the process data are known. Instead of the heat for instance the extracted steam can be used for the potential of electricity generation (see also 2.3.2). The results are then comparable to the exergetic assessment with evaluation of the delivered heat because a heat exchange efficiency is applied there which has the same value like the degree of process quality in the electricity based method. A difference exists in the choice of the lower temperature level (ambient respective condensing temperature).

3 Summary

The allocation of the fuel consumption of cogeneration units to the products electricity and heat can be carried out by different methods which are based more or less on the laws of thermodynamics. Subsequently the CO_2 emissions can be allocated.

From the thermodynamic point of view the exergetic allocation with process internal temperatures and the electricity based method (Dresden method) respectively should be preferred.

Literature

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[2] Commission Decision of 21 December 2006 establishing harmonised efficiency reference values for separate production of electricity and heat in application of Directive 2004/8/EC of the European Parliament and of the Council
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[3] DIN 4701-10

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[8] Zschernig, J.; Sander, T.: „KWK-Strom“ - Was ist das?
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Appendix: Calculation results

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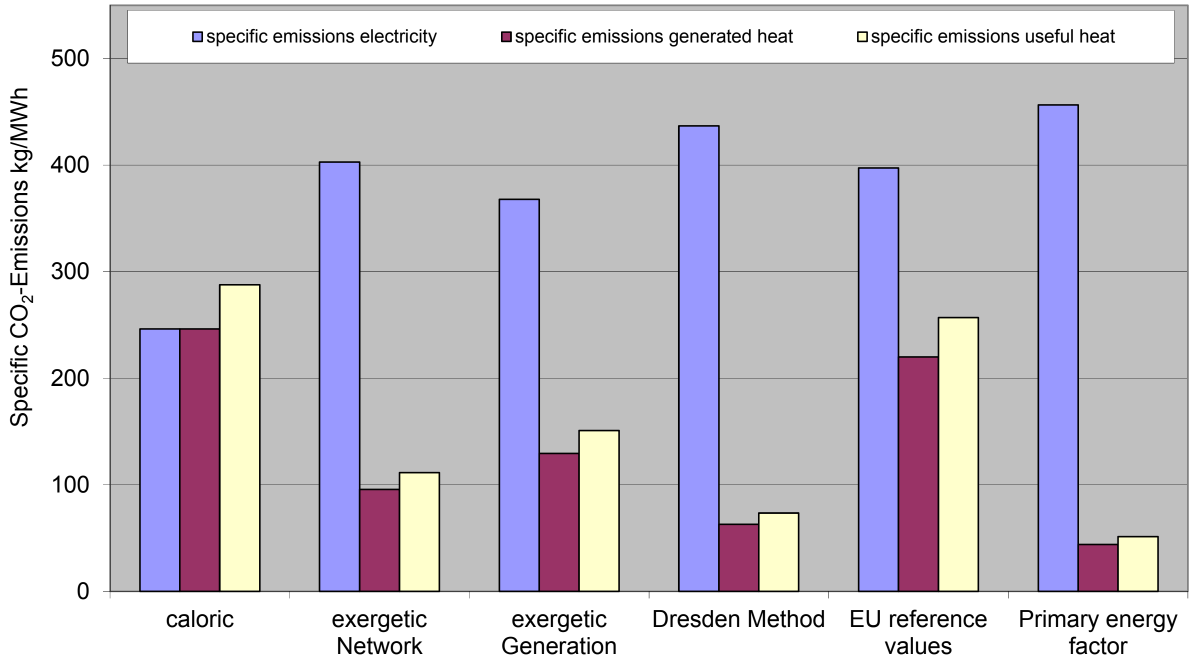
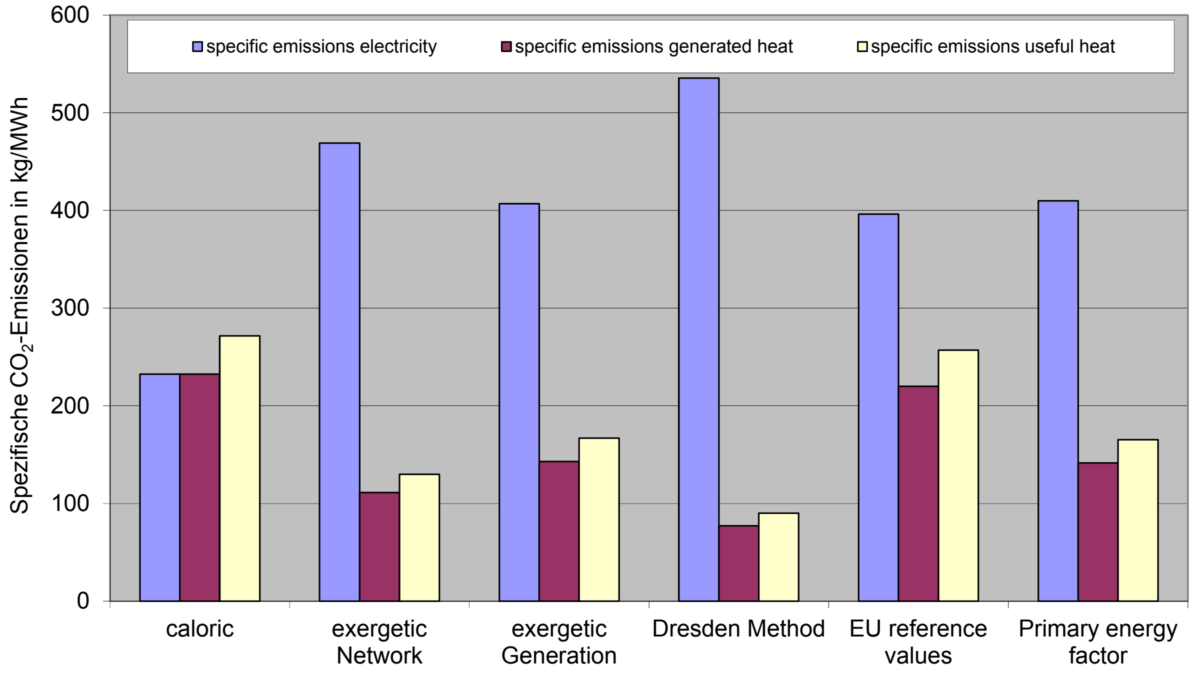


Picture 2 **CU 1: Combined cycle heat and power plant**



Picture 3 **CU 2: Gas turbine with waste heat boiler**

Appendix: Calculation results

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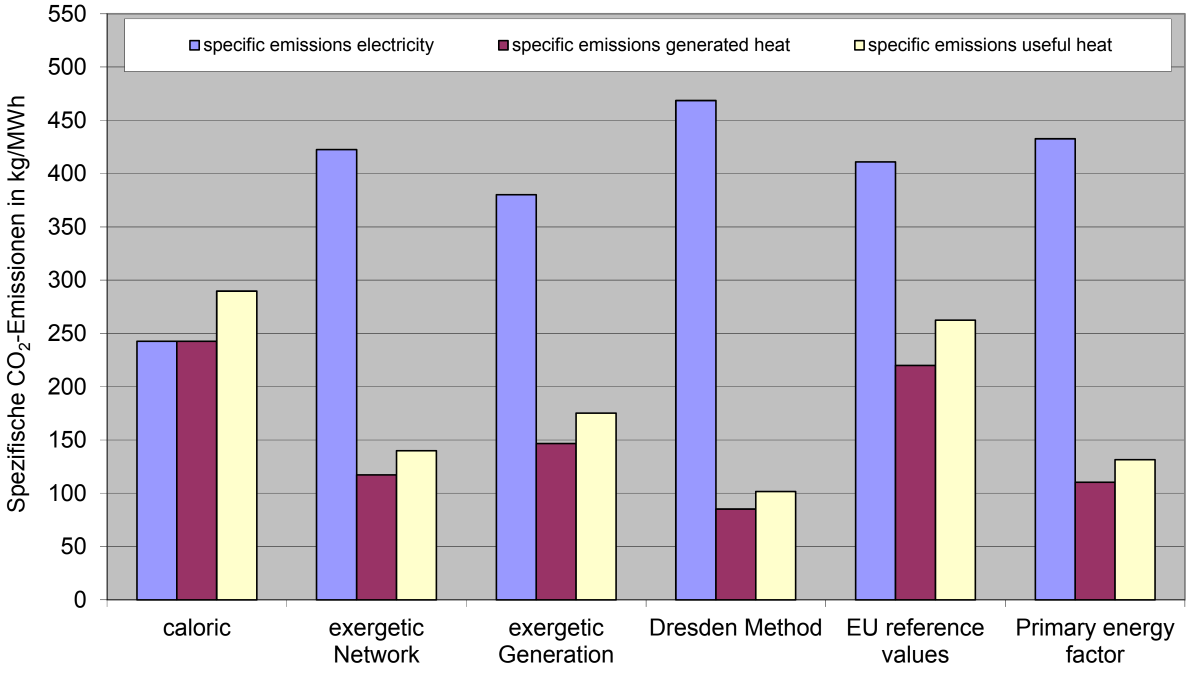
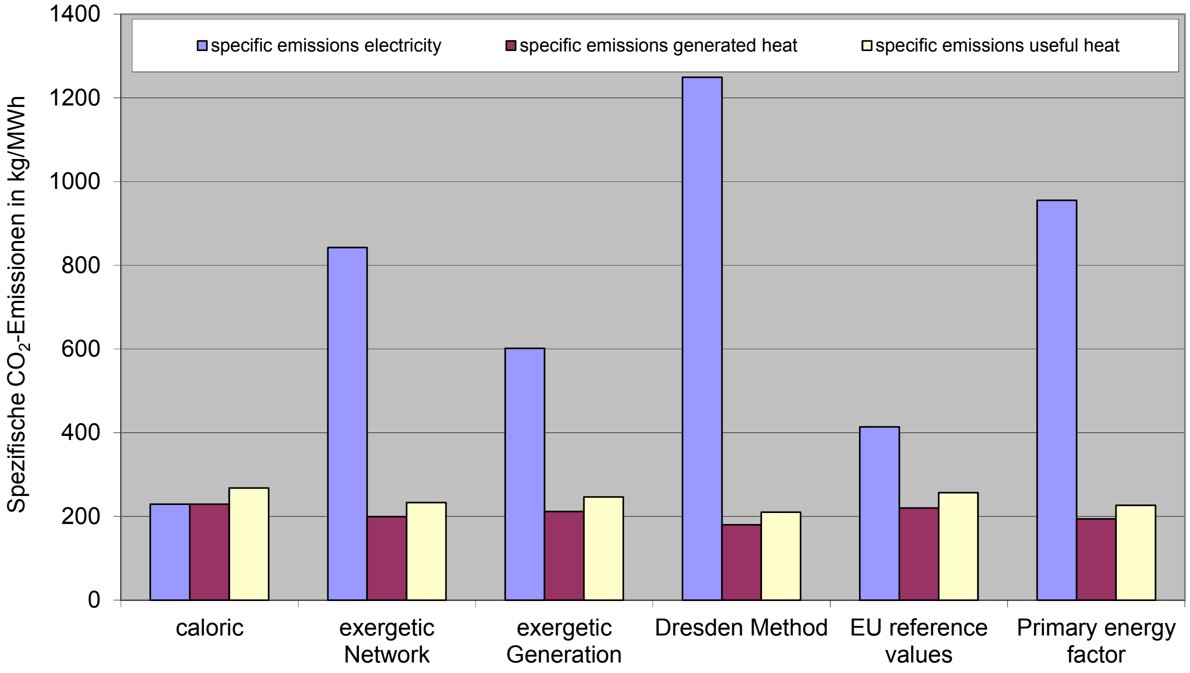


Picture 4 **CU 3: Combustion engine heat and power plant**



Picture 5 **CU 4: Low power back pressure turbine**