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On the thermodynamics of cogeneration

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Abstract — Cogeneration of various energy forms in a single piece of equipment has the potential of saving primary energy in comparison to separate generation. The amount of energy saving depends on the thermodynamic parameters of the systems to be compared and can be presented in a closed formula. For the particular case of cogeneration in a steam turbine a thorough thermodynamic analysis on the basis of exergy losses reveals the reasons for the higher efficiency. It is due to the facts that on producing the useful heat $\dot{Q}$ a transfer of this heat over the temperature difference between the heat intake of the cycle and the temperature of the heat demand is replaced by a power cycle and that separate power production is avoided altogether. This leads to a rational allocation of primary energy and in turn of emissions to the coupled energy forms. © 2000 Éditions scientifiques et médicales Elsevier SAS

cogeneration / exergy loss / power cycle / thermodynamic analysis / waste heat

Nomenclature

E	exergy
P	power
PE	primary energy
Q	heat

Greek symbols

η	efficiency
σ	power to heat ratio
ω	overall efficiency
ζ	exergetic efficiency

Subscripts

B	boiler
C	cogeneration
el	electrical
P	power
PP	power plant
Q	heat
0	environment

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1. INTRODUCTION

In community as well as industrial energy systems a considerable amount of primary energy could be saved via a more extensive use of cogeneration. Although this fact is generally accepted, there is considerable controversy about the overall potential of this technology. This relates to the situation that primary energy saving through cogeneration is determined by a variety of parameters, which must be properly taken into account. Even more uncertainty is associated with the allocation of primary energy contributions to the generation of electricity and heat, respectively. This problem is relevant for an ecological comparison of different technologies of power and heat generation. A position frequently taken is that this allocation cannot be performed unambiguously. In practice, this problem is solved by some sort of residual approach. Typically, the primary energy demand in cogeneration district heating systems is obtained by substracting the fuel demand of a standard reference power station form that of the cogeneration system. Clearly, this attributes all the advantages of cogeneration to heat generation. Alternatively, the primary energy demand for power production in cogeneration is frequently calculated by substracting the fuel demand of a standard heating system from that of the cogeneration system, thus attributing all advantages of cogeneration to power production.

Obviously, both methods are mutually exclusive. Further, they are both physically wrong. In this contribution we demonstrate that a simple thermodynamic analysis of cogeneration reveals the conditions under which a substantial reduction of primary energy demand can be achieved and leads to a rational allocation of primary energy distribution over the produced energy forms.

2. THERMODYNAMIC PARAMETERS

In evaluating the primary energy demand PE of a cogeneration system and comparing it to the primary energy demand PE^* for the separate generation of the same energy streams power P_{el} and heat $\dot{Q}$, we first introduce the relevant thermodynamic parameters for both technologies (*figure 1*). These are the boiler efficiency

$$\eta_{\mathrm{B}} = \frac{\dot{Q}}{PE_Q} \tag{1}$$

and the power plant efficiency

$$\eta_{\mathrm{el}} = \frac{P_{\mathrm{el}}}{PE_P} \tag{2}$$

for the separate generation in a standard boiler and standard power plant, with PE_Q and PE_P as the primary energy demand of the boiler and the power plant, respectively. The relation of the power production to the heat production is referred to as

$$\sigma = \frac{P_{\mathrm{el}}}{\dot{Q}} \tag{3}$$

In a cogeneration system both energy forms are produced simultaneously and may not necessarily have the same relation to each other as in separate generation, i.e.

$$\sigma_{\mathrm{C}} = \frac{P_{\mathrm{el,C}}}{\dot{Q}_{\mathrm{C}}} \neq \sigma \tag{4}$$

Further, the electrical efficiency of the cogeneration plant is defined as

$$\eta_{\mathrm{el,C}} = \frac{P_{\mathrm{el,C}}}{PE_{\mathrm{C}}} \tag{5}$$

with PE_{C} as the primary energy demand of the cogeneration plant. It should be noted that equation (5) does not reflect the electrical efficiency in the usual sense since it is based on the total primary energy instead of only that part which is exclusively used for power production.

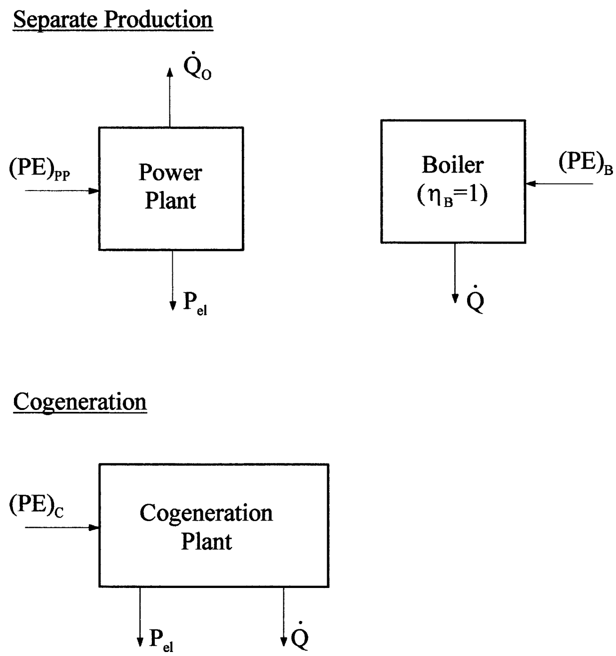

Figure 1. Energy balances for separate production and cogeneration.

Still, its denomination as electrical efficiency has generally come into use. Finally, the overall efficiency of the cogeneration plant is designated as

$$\omega_{\mathrm{C}} = \frac{P_{\mathrm{el,C}} + \dot{Q}_{\mathrm{C}}}{PE_{\mathrm{C}}} \tag{6}$$

Equations (4)–(6) are not independent of each other. They are related by

$$\omega_{\mathrm{C}} = \eta_{\mathrm{el,C}}\left(1 + \frac{1}{\sigma_{\mathrm{C}}}\right) \tag{7}$$

In a steam turbine process which represents by far the most important technology of cogeneration the electrical efficiency of the same equipment decreases on changing from power plant operation to cogeneration. *Figure 2* shows the parameter

$$\gamma = \frac{P_{\mathrm{el}} - P_{\mathrm{el,C}}}{\dot{Q}_C} \tag{8}$$

which reflects the loss of power production in cogeneration with respect to power plant operation in relation to the heat generated, as a function of the heating system temperature for some typical technologies. The severest reduction of power generation is found for a reversible process. A sophisticated cogeneration plant with steam

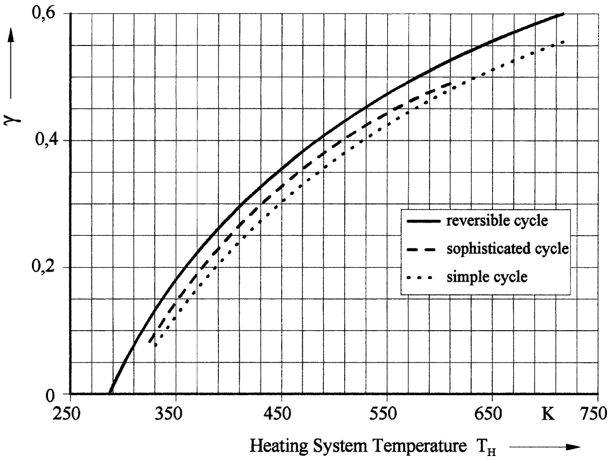

Figure 2. Loss of power production for various cogeneration steam cycles as a function of the heating system temperature.

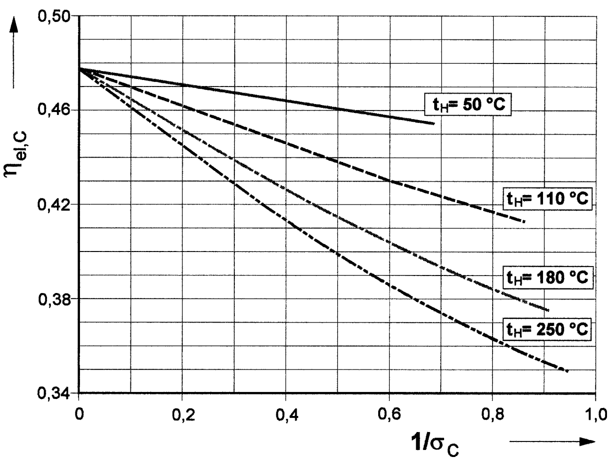

Figure 3. Decrease of the electrical efficiency with increasing heat generation.

parameters of 550 °C and 20 MPa, 6-fold preheating, one intermediate heating at 7.5 MPa and isotropic turbine efficiencies of 0.9 has a slightly smaller value of γ. Finally, a simple cogeneration cycle is shown with the same steam parameters yet no preheating and intermediate heating and a lower turbine efficiency of 0.82. This rather simple technology is associated with a still smaller reduction of power generation. Heat generation in several temperature steps further reduces the value of γ. In *figure 3*, we investigate the decrease of the electrical efficiency on changing from pure power plant operation to cogeneration, as measured by an increasing value of $1/\sigma_C$. The decrease becomes more prominent with increasing temperature demand of the heating system. Thus a bottoming cycle with a steam turbine contribution as in the simple cycle above but including a gas turbine with an inlet temperature of 1 200 °C, an isotropic efficiency of 0.9 and a pressure ratio of 7.67, which has an electrical efficiency of 0.478 in power plant operation, will assume a value of $\eta_C = 0.417$ in cogeneration operation with $\sigma_C = 1.25$ and with a heating system temperature of $t_H = 110$ °C. The corresponding total efficiency is $\omega = 0.7506$. The curves in *figure 3* end at full counter pressure operation, where the maximum value of ω is achieved and the remaining losses are due the efficiencies of the burning chamber and the steam generator. For lower values of $1/\sigma_C$ part of the steam is not used for useful heat production but instead produces heat which has to be transfered to the cooling tower. The values of the total efficiency will then decrease.

3. PRIMARY ENERGY DEMAND

When $PE^* = PE_Q + PE_P$ represents the total primary energy demand for the production of the heat $\dot{Q}$ and the power P_{el} in separate pieces of equipment and ΔP_{el} is the additional power required from a power plant in order to satisfy to the total power demand P_{el}, i.e.

$$P_{el} = P_{el,C} + \Delta P_{el} \tag{9}$$

then the ratio of the primary energy demand PE with cogeneration to the primary energy demand PE^* for separate production can be shown to be

$$\frac{PE}{PE^*} = \left\{1 + \frac{\sigma\eta_B}{\eta_{el,C}}\left[1 - \frac{\eta_{el,C}}{\eta_B\sigma_C} + \frac{\eta_{el,C}}{\eta_{el}}\frac{\Delta P_{el}}{P_{el}} \cdot \left(1 - \frac{\eta_{el}}{\eta_{el,C}} + \frac{\eta_{el}}{\eta_B\sigma_C}\right)\right]\right\}\left(1 + \frac{\sigma\eta_B}{\eta_{el}}\right)^{-1} \tag{10}$$

This relation which can easily be extended to include refrigeration from absorption chillers [1] is displayed graphically in *figures 4–6*. In *figure 4* the cogeneration unit is a typical motor equipment and the power plant represents the standard average efficiency in Germany. In *figure 5* the same cogeneration unit is compared to a modern gas-driven combined gas and steam power plant. The conditions under which a substantial reduction of the primary energy demand is obtained by cogeneration become rather clear. The most favourite situation is that in which the power/heat ratio σ is reproduced exactly by the cogeneration equipment, i.e. $\sigma = \sigma_C$. In this rare case the amount of primary energy reduction depends on the thermodynamic parameters σ_C, η_B, $\eta_{el,C}$ and η_{el}. The reduction becomes greater with decreasing differences between $\eta_{el,C}$ and η_{el}. Clearly, comparing a modern

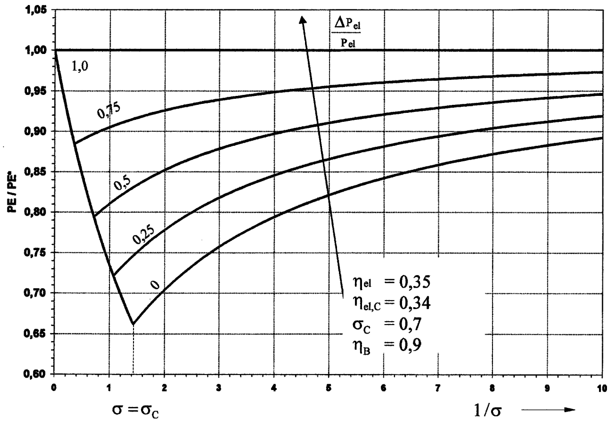

Figure 4. Primary energy saving for a motor unit in comparison with a standard power plant.

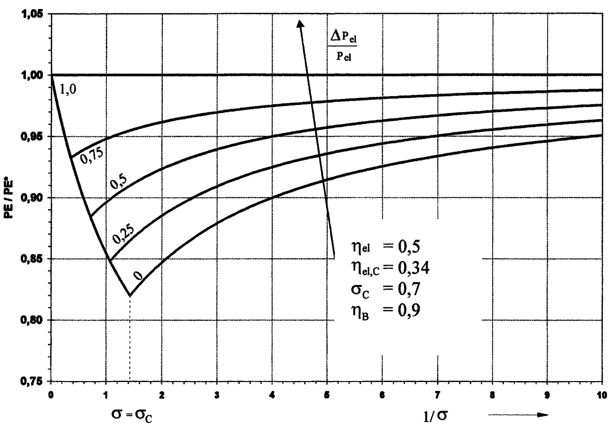

Figure 5. Primary energy saving for a motor unit in comparison with a modern gas/steam power plant.

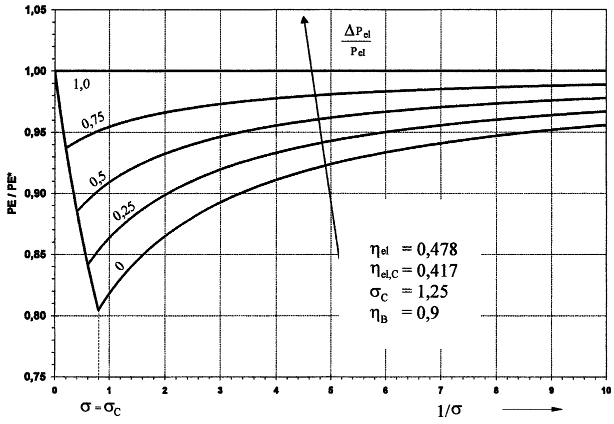

Figure 6. Primary energy saving for a modern gas/steam power plant when switching to cogeneration operation.

cogeneration equipment with an old power plant will give rise to a very high reduction of primary energy but is just as unfair as comparing a modern power plant with an old cogeneration equipment. In *figure 6*, a power plant which can be transformed into a cogeneration plant by taking out steam at some higher pressure is represented, thus eliminating any ambiguousness in the choice of parameter values. The general appearance of the diagram remains unchanged.

While the level of reduction is determined by the special case $\sigma = \sigma_C$ it is modulated significantly when $\sigma \neq \sigma_C$. For $\sigma < \sigma_C$, as typically encountered during the winter period, no additional power is required from the power station, although the boiler will have to contribute heat, i.e. $\dot{Q}_B > 0$. This situation is represented by the lower limiting curve for $1/\sigma > 1/\sigma_C$. On the other hand, for $\sigma > \sigma_C$, additional power is required from a power plant, but no heat from a boiler. This situation is represented by the lower limiting curve for $1/\sigma < 1/\sigma_C$. In practice, both additional heat from a boiler as well as additional power from a power plant may be needed over some time period to account for the typical energy profile requirement. Clearly, an optimum fit of the cogeneration plant into the energy system is crucial to exploit the potential of this technology, since otherwise only meager energy savings can be achieved.

4. ENERGETIC AND EXERGETIC ALLOCATION OF PRIMARY ENERGY DEMAND

In addition to the formal residual method for allocation of primary energy to the coupled energy forms power and heat two more fundamental approaches have been discussed in the literature. A simple method is an allocation according to the amounts of energy forms, i.e.

$$\frac{PE_{C,P}}{PE_{C,Q}} = \frac{P_{el,C}}{\dot{Q}_C} = \sigma_C \qquad (11)$$

This assumption leads to unphysical consequences in the sense that the following relations hold:

$$\omega_C = \frac{P_{el,C} + \dot{Q}_C}{PE_{C,P} + PE_{C,Q}} = \frac{P_{el,C}}{PE_{C,P}} = \frac{\dot{Q}_C}{PE_{C,Q}}$$

This would mean that the energetic efficiencies of power production and of heat production are mutually equal and the same as the total efficiency of the cogeneration plant irrespective of the technology considered. This is obviously unacceptable and would attribute an efficiency of close to unity to electricity generation. An alternative approach performs the allocation according to the exergy of the energy forms, i.e.

$$\frac{PE_{C,P}}{PE_{C,Q}} = \frac{P_{el,C}}{E_{Q,C}} = \frac{\sigma_C}{\eta_{Carnot}} \qquad (12)$$

where $\eta_{Carnot} = 1 - T_0/T$ is the Carnot factor associated with the heat. This assumption, too, leads to unphysical results. The exergetic efficiencies of power production and heat production become with this assumption respectively

$$\zeta_P = \frac{P_{el,C}}{PE_{C,P}} = \frac{P_{el,C}(1+\eta_{Carnot}/\sigma_C)}{PE_{C,P}(1+\eta_{Carnot}/\sigma_C)} = \frac{P_{el,C} + \dot{Q}_C\eta_{Carnot}}{PE_C}$$

and

$$\zeta_Q = \frac{\dot{Q}_C\eta_{Carnot}}{PE_{C,Q}} = \frac{\dot{Q}_C\eta_{Carnot}(1+\sigma_C/\eta_{Carnot})}{PE_{C,Q}(1+\sigma_C/\eta_{Carnot})} = \frac{P_{el,C} + \dot{Q}_C\eta_{Carnot}}{PE_C}$$

They are again equal, irrespective of the technology considered. Again, this must be physically wrong and would attribute just as little exergy loss to heat generation as to power generation. The efficiencies of power and heat production in a cogeneration plant depend sensitively on the details of the equipment and of the processes. Any allocations of primary energy to the coupled energy forms not taking into account such elementary facts must, therefore, be rejected on physical grounds and have righteously be criticized [2].

5. ALLOCATION OF PRIMARY ENERGY DEMAND ACCORDING TO EXERGY LOSSES

A rational allocation of the primary energy demand of cogeneration to the coupled energy forms must account for the details of the thermodynamic processes. It can be obtained by an analysis of the entropy production or, equivalently, of the exergy losses associated with the production of heat and power. The method adopted relates the primary energy saving of cogeneration with respect to separate heat and power production to the exergy losses associated with these technologies and then analyses the saved exergy losses in terms of their origin in power or heat production. The energy balances of the systems to be compared are shown in *figure 1*. Generally, the primary energy saving of a cogeneration plant as compared to a power plant and a boiler for separate power and heat production [3] can be expressed as

$$\Delta PE = (PE)_{PP} + (PE)_B - (PE)_C$$

The indices PP, B and C denote power plant, boiler and cogeneration, respectively. Performing exergy balances for all types of equipment and setting primary energy equal the exergy, without loss of generality this becomes

$$\Delta PE = (\Delta E)_{PP} + (\Delta E)_B - (\Delta E)_C$$

when ΔE is the exergy loss.

The exergy losses of the processes depend on the details of the equipment. We denote with T' the average temperature of the hot gas produced in the combustion processes, with T^* the average temperature of the heat intake of the cycles and with T the average temperature of the useful heat. T_0 is the temperature of the environment. Then, if we assume $\eta_B = 1$, reversible cycles and zero temperature differences for heat transfer in a first approximation, the exergy loss of the power plant can be expressed as

$$(\Delta\dot{E})_{PP} = \dot{Q}_{PP} - \dot{Q}_{PP}\left(1 - \frac{T_0}{T'}\right) + T_0\dot{Q}_{PP}\frac{T' - T^*}{T'T^*}$$

This exergy loss arises to one part from the irreversible combustion and to the other part from the irreversible heat transfer of the power plant heat intake $\dot{Q}_{PP}$ over the temperature difference between the hot combustion gas and the upper level of the cycle. Symilarly, the exergy loss associated with heat generation in a boiler reads

$$(\Delta\dot{E})_B = \dot{Q} - \dot{Q}\left(1 - \frac{T_0}{T'}\right) + T_0\dot{Q}\frac{T' - T^*}{T^*T'} + T_0\dot{Q}\frac{T^* - T}{T^*T}$$

Here, an additional contribution of the exergy loss is due to the transfer of the heat $\dot{Q}$ from T^* to the final useful temperature T, where T^*, of course, does not physically exist in a boiler and has been introduced here for formal reasons. Finally, a cogeneration plant will have an exergy loss of

$$(\Delta\dot{E})_C = \dot{Q}_C - \dot{Q}_C\left(1 - \frac{T_0}{T'}\right) + T_0\dot{Q}_C\frac{T' - T^*}{T^*T'}$$

where $\dot{Q}_C$ is the heat intake of the cogeneration plant. Using the energy balances for the power plant

$$\dot{Q}_{PP} = P_{el} + \dot{Q}_0$$

and the cogeneration plant

$$\dot{Q}_C = P_{el} + \dot{Q}$$

finally leads to

$$\Delta PE = \dot{Q} T_0 \frac{T^* - T}{T^* T} + \dot{Q}_0 \left[1 - \left(1 - \frac{T_0}{T^*}\right)\right]$$
$$= \Delta PE_Q + \Delta PE_P \tag{13}$$

Thus, the primary energy saving due to cogeneration originates from two parts, which can be allocated unambiguously to the energy forms produced. The first part represents the exergy loss that originates from the transfer of the heat $\dot{Q}$ over a temperature difference between the heat intake temperature of the cycle and the temperature of the useful heat. This exergy loss, which arises during heat production in a boiler, is avoided in a cogeneration plant since this transfer of heat is replaced there by a (reversible) cycle. It must, therefore, be allocated to the produced heat. The second part relates to the heat $\dot{Q}_0$ which is transmitted as waste heat to the environment in a power plant. Associated with the production of this waste heat is the exergy loss of combustion and that of heat transfer to the intake temperature of the cycle. Since the waste heat $\dot{Q}_0$ arises during power production in a power plant and is avoided in a cogeneration plant this contribution to the primary energy saving must be allocated to the produced power.

The simplifications leading to equation (4) can be easily relaxed. A boiler efficiency $\eta_B < 1$ and a finite temperature difference ΔT for heat transfer will modify equation (4) to

$$\Delta PE = \dot{Q} T_0 \frac{T^* - (T + \Delta T)}{T^*(T + \Delta T)}$$
$$+ \dot{Q}_0 \left[\frac{1}{\eta_B} - \left(1 - \frac{T_0}{T^*}\right) + \frac{\Delta T}{T_u + \Delta T}\right]$$
$$= \Delta PE_Q + \Delta PE_P \tag{14}$$

Further, there is a contribution to the total energy saving that originates form entropy production in the turbines of the power plant and the cogeneration plant, respectively. It is due to the fact that entropy production in the turbine of a cogeneration plant will enhance the heat production and is, thus, not entirely useless, contrary to that in the power plant. This contribution is small in modern equipment and will not be considered here.

Finally, the allocation of primary energy to the coupled energy forms produced reads [3]

$$PE_{C,Q} = PE_B - \Delta PE_Q \tag{15}$$

and

$$PE_{C,P} = PE_{PP} - \Delta PE_P \tag{16}$$

Clearly, in order to evaluate equations (6) and (7) the thermodynamic cycles must be defined. Thus, contrary to the simple approaches discussed above, and in accord with physical reality, the allocation based on an detailed analysis of exergy losses will depend on the technology used. Further, when specific emission factors such as ε_{CO_2} in $t_{CO_2} \cdot MWh^{-1}$ are introduced for a particular fuel, the emissions of a cogeneration plant can easily be allocated to the coupled energy forms.

6. A NUMERICAL EXAMPLE

To illustrate the results of the present approach to other methods of allocation we study a numerical example included in a recent publication of the German Engineering Association (VDI) [4]. There a cogeneration equipment was considered with $P_{el,C} = 100$ MW, $\dot{Q}_C = 300$ MW, $\eta_{el,C} = 0.2$, leading to an overall efficiency of $\omega_C = 0.8$.

We first present the results obtained from the residual approach as also documented in [4]. One possible approach on this basis substracts the primary energy needed to produce the electrical power $P_{el,C}$ in a standard power plant from the primary energy of the cogeneration plant to obtain an allocation of primary energy to the heat produced as

$$PE_{C,Q} = PE_C - \frac{P_{el,C}}{\eta_{el}} = 500 - \frac{100}{0.4} = 250 \text{ MW}$$

where quite arbitrarily an electrical efficiency of 0.4 has been assumed for the power plant as was suggested in [4]. The primary energy used for power production must then be

$$PE_{C,P} = PE_C - PE_{C,Q} = 250 \text{ MW}$$

Using a specific emission factor of $0.333 t_{CO_2} \cdot MWh^{-1}$ for coal the CO_2 emission to be attributed to electrical production in cogeneration is

$$\varepsilon_{C,P} = \frac{PE_{C,P}}{P_{el,C}} \cdot 0.333 = 0.833 t_{CO_2} \cdot MWh^{-1}$$

while that to be attributed to heat production is

$$\varepsilon_{C,Q} = \frac{PE_{C,Q}}{\dot{Q}_C} \cdot 0.333 = 0.2784 t_{CO_2} \cdot MWh^{-1}$$

If, on the other side, the primary energy needed in a standard boiler to produce the heat $\dot{Q}_C$ is subtracted from the total primary energy demand of the cogeneration plant, one gets an alternative result for the primary energy demand of the power production in a cogeneration system, i.e.

$$PE_{C,P} = PE_C - \frac{\dot{Q}_C}{\eta_B} = 500 - \frac{300}{0.9} = 166.7\ \text{MW}$$

and, in turn,

$$PE_{C,Q} = PE_C - PE_{C,P} = 333.3\ \text{MW}$$

Here the boiler efficiency η_B was assigned a value of 0.9 in accordance with [4]. For this rather different allocation of primary energy the associated CO_2 emissions are $\varepsilon_{C,P} = 0.555$ and $\varepsilon_{C,Q} = 0.370$. Both allocations lack physical significance, but may well serve as standards on the basis of consensus.

The energetic allocation of primary energy demand according to (11) leads to

$$PE_{C,P} = \sigma_C PE_{C,Q} = \frac{P_{el,C}}{\omega_C} = \frac{100}{0.8} = 125\ \text{MW}$$

and

$$PE_{C,Q} = \frac{\dot{Q}_C}{\omega_C} = \frac{300}{0.8} = 375\ \text{MW}$$

with associated emissions of $\varepsilon_{C,P} = \varepsilon_{C,Q} = 0.416\ t_{CO_2}{\cdot}\text{MWh}^{-1}$. The exergetic method according to (12), i.e.

$$PE_{C,P} = PE_{C,Q} \frac{\sigma_C}{\eta_{Carnot}} = (500 - PE_{C,P}) \frac{0.3333}{0.2261}$$

gives $PE_{C,P} = 297.9$ MW, $PE_{C,Q} = 202.1$ MW along with $\varepsilon_{C,P} = 1.000 t_{CO_2}{\cdot}\text{MWh}^{-1}$ and $\varepsilon_{C,Q} = 0.2251\ t_{CO_2}{\cdot}\text{MWh}^{-1}$, where a temperature of $T = 372.34$ K has been associated to the heat demand according to [4] and the temperature of the environment is $T_0 = 288.15$ K. Thus, the energetic method lets the cogeneration power production appear even more favourable than the residual method based on a standard boiler. The exergetic method, on the other side, attributes to the cogeneration heat production even less primary energy and emissions than the residual method based on a standard power station. Such results obviously do not make sense.

The allocation based on an analysis of exergy losses is more difficult to evaluate. We have to make a decision about the cogeneration process to be considered, since many different ones will reproduce the data used in [4]. For simplicity we here choose a reversible cycle with $\omega_C = \eta_B = 0.8$ and a heating system temperature of $T = 372.34$ K in accordance with [4]:

$$\eta_{el,C} = 0.2 = \frac{P_{el,C}}{PE_C} = \frac{T_C^* - T}{T_C^*} \eta_B$$

The appropriate temperature of the heat intake of the cogeneration process is $T_C^* = 496.45$ K. Going through standard cycle calculations reveals that a water/steam mass-flow rate of $\dot{m}_C = 133\ \text{kg}{\cdot}\text{s}^{-1}$ is required for cogeneration operation, while for power operation a mass-flow rate of $\dot{m}_{PP} = 79\ \text{kg}{\cdot}\text{s}^{-1}$ is needed. This finally leads to the results

$$\begin{aligned} PE_{C,Q} &= PE_B - \Delta PE_Q \\ &= \frac{300}{0.8} - 288.15 \cdot 300 \frac{496.45 - 372.34}{496.45 \cdot 372.34} \\ &= 317\ \text{MW} \end{aligned}$$

and

$$\begin{aligned} PE_{C,P} &= PE_{PP} - \Delta PE_P \\ &= \frac{79 \cdot 3\,012}{0.8} - 79 \cdot 1\,748 \left[\frac{1}{0.8} - \left(1 - \frac{288.15}{496.45} \right) \right] \\ &= 183\ \text{MW} \end{aligned}$$

where the numbers $q_C = 3\,012\ \text{kJ}{\cdot}\text{kg}^{-1}$ and $q_0 = 1\,748\ \text{kJ}{\cdot}\text{kg}^{-1}$ are the specific heat intake and the specific heat rejection of the power plant operation as obtained from the standard cycle calculations. Clearly, these results are rather different from those of the other approaches. The associated CO_2 emissions are

$$\varepsilon_{C,P} = \frac{PE_{C,P}}{P_{el,C}} \cdot 0.333 = 0.6094 t_{CO_2}{\cdot}\text{MWh}^{-1}$$

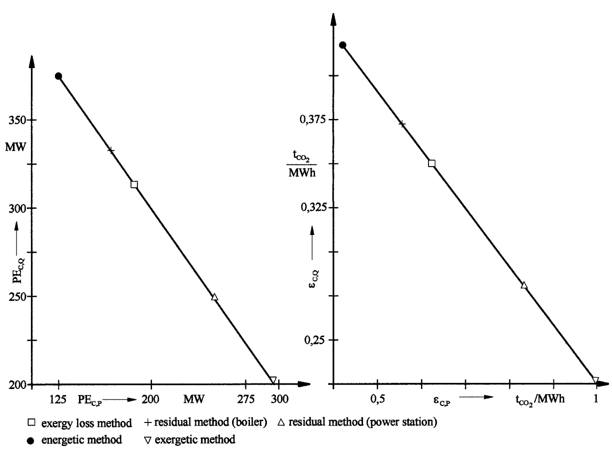

Figure 7. Graphical representations of the options for primary energy and emission allocation.

and

$$\varepsilon_{C,Q} = \frac{PE_{C,Q}}{\dot{Q}_C} \cdot 0.333 = 0.3519 t_{CO_2} \cdot \mathrm{MWh}^{-1}$$

All these figures are subject to slight alternations when a different cycle is chosen. The basic results, however, will be the same, i.e. the exergy loss analysis leads to results in between the two reasonable extremes represented by the two residual approaches. It may finally be worthwile to note that any primary energy or emission allocation must lie on straight lines as shown in *figure 7* for the numerical example considered.

7. CONCLUSIONS

The energy conversion in a cogeneration system has been analysed on the basis of thermodynamic laws. It has been shown that the saving of primary energy depends sensitively on the parameters of the technology and, in particular, on the match between the power/heat ratio of the cogeneration equipment and the demand. It has further been demonstrated that a rational allocation of primary energy and in turn of emissions to the coupled energy forms produced can be derived by a consideration of the exergy losses in the various types of equipment.

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