EXERGETIC COMPARISON OF ENERGY-BASED EFFICIENCY INDICATORS FOR COMBINED HEAT AND POWER (CHP)

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ABSTRACT

In many countries, legislative regulations in favor of combined heat and power production (CHP) have been implemented. Although these regulations put different emphasis on power production vs. process heat production, they are based on energy quantities and not on exergy. In order to analyze and compare the exergetic consequences of the various legislations, a relative avoided irreversibility (RAI) is defined. This can be regarded as the irreversibility that is avoided when a reference plant with separate production is replaced by an actual CHP plant. A series of natural-gas fired industrial and district heating CHP plants, under varying operational conditions, are used as test cases, and the consequences of the various legislations are shown. It is seen that some, but not all, CHP cases are exergetically beneficial to separate generation. The exergetic improvements were only to a limited degree captured by the various energy-based efficiency indicators. Some legislatively defined indicators appeared to discourage thermodynamic improvements.
Keywords: Exergy, CHP, cogeneration, efficiencies, legislation, comparison, evaluation

1 INTRODUCTION

Cogeneration or CHP is sometimes regarded as the materialization of the 2nd law of thermodynamics. First, electricity is produced from the high-exergy heat, and next, thermal energy is produced from heat at lower temperatures. On a 1st-law basis, CHPs provide a substantially higher output than plants for separate electricity generation.

Several countries have implemented legislations promoting CHP. The new EU CHP directive [1] contributes to this and describes the process for developing a future standard for CHP efficiencies. However, to define the “useful output” and “input”, raises a number of methodological considerations that can be measured and expressed in a number of different ways, with also the potential for misleading or faulty comparisons. An increasing number of national definitions shows considerable differences in how to evaluate CHP efficiency. A common feature, though, is that they are not based on the 2nd law. A 2nd-law efficiency can be used to measure the performance of a plant and to compare with other plants. This can give a qualitative comparison and assessment of the various concepts of CHP evaluation mentioned above. The present study is an attempt to do a quantitative investigation of these concepts of evaluation. Then, the exergetic concequences of the various legislations can be discussed.

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2 COMPARISON OF SYSTEMS FOR ENERGY CONVERSION

2.1 Relative Avoided Irreversibility

The exergy loss (irreversibility) of a certain case can be expressed $(1-\psi)E_{\text{in}}$, where ψ is the exergy efficiency, that is, the ratio of usable exergy output to exergy input, and E_{in} is the exergy input (usually the fuel exergy).

A case or process can be compared to a specified reference case. The irreversibility that is avoided by replacing the reference case by the new case will be

$$(1-\psi_{\text{ref}})E_{\text{in,ref}} - (1-\psi)E_{\text{in}} \quad (1)$$

where the subscript "ref" denotes a reference case. The term avoided irreversibility presumes that the case is an improvement from the reference case. However, the quantity will be negative if the utilization is worsened.
The term can be made dimensionless by the input to the reference case, and the Relative Avoided Irreversibility is expressed

$$\text{RAI} = (1-\psi_{\text{ref}}) - (1-\psi)E_{\text{in}} / E_{\text{in,ref}} \quad (2)$$

In a general notion, this quantity can be regarded as the irreversibility of the specific case or system, subtracted from the irreversibility that would have been there if the case or system was not applied.

2.2 Comparison with energy-based efficiencies or improvement indicators.

Quite a few efficiencies and efficiency-improvement indicators are defined on a technical or legislative basis. In most instances, these are based on energy considerations. Thus, all forms of usable energy, *e.g.* fuel, electricity, and heat, are accounted for by their energy value (*i.e.* heating value).

Similar to the outline above, a Relative Avoided Loss can be expressed

$$\text{RAL} = (1-\eta_{\text{ref}}) - (1-\eta)H_{\text{in}} / H_{\text{in,ref}} \ . \quad (3)$$

Here, η is some defined efficiency, H_{in} is the energy input (usually the fuel LHV), and subscript "ref" again denotes a reference case. This formulation can be used for the variety of efficiencies shown below. RAL is the loss of energy, according to the chosen definition of efficiency, that is avoided when the reference case is replaced by the actual case.

If the efficiency η in Eq. (3) is the total energy efficiency (e.g. electric energy plus heat divided by the fuel LHV), the RAL is the loss of energy that is avoided because the actual case has replaced the reference case. This is known as the Relative Primary Energy Savings (RPES). In most cases, the energy efficiency is different from the exergy efficiency. Other definitions of efficiency, based on technology or policy reasoning, give different evaluations of energy, and accordingly, of the utilized and lost energy.

For a thermodynamic comparison of the different indicators, the ratio of RAI to RAL can be used as metric. Thus, if

- RAI>RAL, the improvement is underestimated by the indicator,
- RAI=RAL, the improvement is evaluated in accordance with thermodynamics,
- RAI<RAL, the improvement is overestimated by the indicator,
- RAI/RAL<0, the emphasis of the indicator is in the wrong direction.

2.3 Efficiency indicators for combined heat and power (CHP)

The ratio of delivered useable energy to the energy input can be termed the total energy efficiency or CHP efficiency. For a system producing heat and power this can be expressed

$$\eta_{\text{CHP}} = (W+Q)/H \ , \quad (4)$$

where W is the mechanical power or electricity produced, Q is the thermal energy in delivered steam, and H is the input energy, usually the LHV of the fuel. In the context of CHP, the fractions of input energy that are converted to electric energy and heat can, respectively, be called electric efficiency and heat efficiency and expressed

$$\eta_{\text{el}} = W/H \quad (5)$$

$$\eta_{Q} = Q/H \quad (6)$$

These expressions are useful when evaluating the different methods of qualifying CHP.
To describe the quality difference between electricity and heat, the exergy efficiency can be defined. This is the ratio of exergy in the products

electricity and thermal energy to the exergy of the input

$$\psi = (W + E_Q) / E_F \tag{7}$$

Here, E_Q and E_F are, respectively, the exergy of the delivered thermal energy and the input exergy, while the exergy of electricity or mechanical energy is equal to its energy W.

Both thermodynamically, technically, and economically, electric energy differs from thermal energy. Several other parameters have been defined to account for this difference without making use of the exergy concept.

While electricity generation can be conducted nearly anywhere, the heat has to be generated near the user, and it has to be scaled according to the consumption. Thus, it may be useful to regard a CHP as a heat generator with surplus electricity generation. This is expressed by defining an Equivalent electrical efficiency (EEE) [3],

$$\eta_{\text{eel}} = W / (H - Q / \eta_{\text{Qref}}) \tag{8}$$

Here, the fuel energy to the CHP plant is supposed to be reduced by the fuel needed to produce the heat in a separate boiler with efficiency η_{Qref}. In the legislations of Spain and (with a slight modification) Portugal, this concept is used (cf. [4][5]). While in Eq. (8), a portion of the fuel (fuel for heating) is subtracted in the denominator, a fraction of the energy in the steam is added in the numerator in the efficiency defined by the US legislation PURPA,

$$\eta_{\text{PURPA}} = (W + 0.5 \cdot Q) / H \tag{9}$$

Also in Brazil, an efficiency close to this is used. Such efficiencies can be seen as a simplified exergy efficiency, without really taking into account the actual exergy content of the heat.

Feng et al.[6] suggested an adjusted exergy efficiency with the definition

$$\eta_{\text{adex}} = (W + E_Q + \xi \cdot (Q - E_Q)) / H \tag{10}$$

where ξ=0.12 is an adjusted exergy factor.

For all these efficiencies, an RAL can be defined according to Eq. (3). Other indicators may focus on the savings of energy or emissions. The relative primary energy savings (RPES) [3][4]can be written

$$\text{RPES} = 1 - H / H_{\text{ref}} \tag{11}$$

This is the fuel energy that is saved by the CHP when comparing to separate generation. The RPES is used as an indicator for the goodness of CHP systems in the Flemish legislation (Belgium). Other such indicators are (see [4][5]) the Relative CO_2 Emissions Savings (RCES; Walloon and Brussels-region legislations), the fuel-free electricity (Dutch legislation), and the Quality Index (QI; British legislation).

For natural-gas fired CHP, the Brussels RCES can be expressed equal to the RPES, while the Walloon RCES can be expressed equal to $\text{RPES} \cdot (H_{\text{ref}} / H_{\text{elref}})$. The RPES and the RCESs can be regarded as RALs, and the fuel-free electricity W_{free} can be related through

$$W_{\text{free}} / H_{\text{ref}} = \eta_{\text{elref}} \cdot \text{RPES} \tag{12}$$

where η_{elref} is defined below.

The Quality Index (QI) can be expressed as a relative Quality-Index improvement by

$$\text{RAL} = \text{QI} / \text{QI}_{\text{ref}} - 1 \tag{13}$$

All these RALs are based on energy considerations. At first sight, e.g. the RPES seems to represent mass of fuel and thus energy and exergy of the fuel as well. However, when the “saved” energy is evaluated, all forms of usable energy are accounted equally. That is, electric energy, fuel energy, and thermal energy in MP and LP steam are considered equal. From a thermodynamic consideration (1st and 2nd law), a system delivering an amount of heat in LP steam has higher losses than a system delivering heat in MP steam at a higher temperature. And actually, the system has a lower (1st-law) capacity when producing MP steam (see below).

2.4 Reference plants for separate generation of heat and power

For energy analyses, it is convenient to define reference plants for separate heat and power generation, with the electric and heat efficiencies η_{elref} and η_{Qref}, respectively. The reference amounts of fuel energy can be defined, $H_{\text{elref}} = W / \eta_{\text{elref}}$ and $H_{\text{Qref}} = Q / \eta_{\text{Qref}}$, and the sum $H_{\text{ref}} = H_{\text{elref}} + H_{\text{Qref}}$. These are the amounts required to produce the same electricity and heat separately in the reference plants. The ratio of the actual to the reference fuel energy is

$$H / H_{\mathrm{ref}} = (\eta_{\mathrm{el}} / \eta_{\mathrm{elref}} + \eta_Q / \eta_{\mathrm{Qref}})^{-1} \tag{14}$$

Similarly, the reference fuel exergy for separate electricity generation can be expressed

$$E_{\mathrm{F,elref}} = \alpha_{\mathrm{F}} H_{\mathrm{elref}} = \alpha_{\mathrm{F}} W / \eta_{\mathrm{elref}} \tag{15}$$

where α_F is a constant, usually close to unity (e.g. 1.04 for natural gas at standard state). The fuel exergy for separate heat generation will be discussed below.

The values of the reference efficiencies can be determined based on the notion of Best Available Technology (BAT) or based on an average of existing installations. In legislative regulations, the choice of reference values may be based on a compromise between existing technology and BAT. As the choice will affect the regarded goodness of any CHP plant, it is quite often an outcome of intense lobbying by the involved parties.

This procedure does not recognize the exergetic value or "quality" of thermal energy. The reference amount of fuel for separate heat generation is taken as the same value regardless of the temperature of the steam (or other heating media: water, oil, air, etc.). It can be argued that a conventional boiler has about the same efficiency for HP steam and LP steam, and even for hot water. Actually, this efficiency is determined more by the state of the outflow flue gas than by the state of the heating medium. However, it can be observed that for a CHP producing LP steam, the electricity generation is relatively lower than for a similar CHP producing MP or HP steam.

Moreover, low-temperature thermal energy can be generated by heat pumps. A system of separate electricity generation and heat pumps can supply an amount of heat that is larger than the fuel LHV used. Thus, for a proper exergetic comparison, the reference heat efficiency has to depend on the exergy of the heat. This corresponds to defining a reference heat-pump exergetic efficiency.

The exergy of heat can be written $E_Q = \alpha_Q Q$, which defines the exergy-to-heat ratio, α_Q. When provided by a heat pump, this heat requires the amount of work W_{QP}. These quantities can be related by the exergetic efficiency of the heat pump,

$$\psi_{QP} = E_Q / W_{QP} = \alpha_Q Q / W_{QP} \tag{16}$$

Furthermore, the heat-pump work can be assumed generated in a reference power plant as described above. Hence, the amount of fuel for separate generation of heat varies with the exergy of the steam (or other heating medium). It also depends on the exergetic efficiency of the heat pump. This efficiency may vary with the temperature levels involved but will, for convenience, be assumed constant in the following.

Two approaches can be followed to determine the reference fuel exergy for heat generation: 1) specify a reference exergy-to heat ratio, $\alpha_{Q\mathrm{ref}}$ for heat generation, or 2) specify a reference exergetic efficiency $\psi_{QP\mathrm{ref}}$ for a heat pump providing the heat.

In the first approach, the reference exergy efficiency for separate heat generation in a boiler can be expressed

$$\psi_{Q\mathrm{ref,B}} = \frac{\alpha_{Q\mathrm{ref}} Q}{\alpha_F Q / \eta_{Q\mathrm{ref}}} = \frac{\alpha_{Q\mathrm{ref}} \eta_{Q\mathrm{ref}}}{\alpha_F} \tag{17}$$

Here, the reference is separate generation of the same amount of heat at the specified exergy-to heat ratio and a specified energy efficiency. This will give a reference amount of fuel exergy for the boiler (subscript "B") approach

$$E_{F,Q\mathrm{ref,B}} = \frac{\alpha_Q Q}{\psi_{Q\mathrm{refB}}} = \frac{\alpha_F \alpha_Q Q}{\alpha_{Q\mathrm{ref}} \eta_{Q\mathrm{ref}}} \tag{18}$$

When the actual heat generation is conducted by a heat pump using electricity (work) from a reference plant for separate power generation, the heat-generation exergy efficiency is

$$\psi_{Q\mathrm{ref,QP}} = \frac{\alpha_Q Q}{\alpha_F (W_{\mathrm{QPref}} / \eta_{\mathrm{elref}})} = \frac{\eta_{\mathrm{elref}} \psi_{QP\mathrm{ref}}}{\alpha_F}. \tag{19}$$

The reference fuel exergy for separate heat generation in the heat-pump (subscript "QP") approach can then be expressed

$$E_{F,Q\mathrm{ref,QP}} = \frac{\alpha_F W_{\mathrm{QPref}}}{\eta_{\mathrm{elref}}} = \frac{\alpha_F \alpha_Q Q}{\eta_{\mathrm{elref}} \psi_{\mathrm{QPref}}}. \tag{20}$$

The two approaches can be joined by setting $\alpha_{Q\text{ref}}\eta_{Q\text{ref}} = \eta_{\text{elref}}\psi_{\text{QPref}}$. This also leads to an expression for the coefficient of performance of the reference heat pump,

$$\text{COP}_{\text{ref}} = Q / W_{\text{QPref}} = \psi_{\text{QPref}} / \alpha_{Q\text{ref}} = \eta_{Q\text{ref}} / \eta_{\text{elref}} \quad (21)$$

Although this ratio is fixed to the reference efficiencies for heat and electricity, the requirement will be more demanding as the exergy ($\alpha_{Q\text{ref}}$) increases.

Now, reference amounts of fuel exergy for separate heat and power generation are defined, and the reference efficiency can be expressed

$$\psi_{\text{ref}} = \frac{\eta_{el} + \alpha_Q \eta_Q}{\alpha_{\text{F}}(\eta_{el} / \eta_{\text{elref}} + \alpha_Q \eta_Q / (\alpha_{\text{Qref}} \eta_{\text{Qref}}))} \quad (22)$$

This procedure allows a comparison of different systems and recognizes the quality of the thermal energy. The ratio of actual fuel-exergy input to the reference input is

$$E_{\text{F}} / E_{\text{F,ref}} = (\eta_{el} / \eta_{\text{elref}} + \alpha_Q \eta_Q / (\alpha_{\text{Qref}} \eta_{\text{Qref}}))^{-1} \quad (23)$$

It is readily seen that for a heating medium with $\alpha_Q = \alpha_{Q\text{ref}}$, the fuel-exergy ratio of Eq.(23) is equal to the fuel-energy ratio of Eq.(14).

Still, the reference exergy-to heat ratio, $\alpha_{Q\text{ref}}$, (or alternatively, the reference heat-pump exergetic efficiency ψ_{QPref}) has to be specified. In this study, a value of $\alpha_Q = 0.28$ was adopted. This is the ratio of exergy to enthalpy differences for instance of steam at 2.5 bar 140 °C (LP steam), when the environmental pressure and temperature are 1 bar and 15 °C. In combination with a reference electric and heat efficiencies of 0.55 and 0.90, respectively, this corresponds to a heat-pump exergy efficiency ψ_{QPref} of 0.46 and a reference COP of 1.64. These figures are technically achievable and are chosen here to enable a quantified analysis.

This choice of “quality” for the reference is modest. An alternative choice of $\alpha_Q = 0.40$ (MP steam, 21 bar, 330 °C) corresponds to a ψ_{QPref} of 0.65. Even at this level, a reference COP of 1.64 is technically feasible. On the other side, a low-exergy reference, e.g. hot water with $\alpha_Q = 0.15$ was an alternative. The choice of reference for exergy is largely arbitrary and a matter of taste, at least within the technically possible range. The issue is whether a medium-exergy thermal system should be accounted “neutral”, “positive” or “negative”. From a pedagogical viewpoint, it is preferred to have both “negative” and “positive” categories, as the choice made here implies.

3 TEST CASES OF CHP

3.1 Cases of industrial CHP

Two different configurations for a CHP plant have been considered in this study: A boiler with back-pressure steam turbine (ST) and condensing ST (BST plant), and a plant with gas-turbine with a flue-gas heat-recovery steam generator (HRSG) and condensing steam turbine (GT-plant) [4][5].

Table 1 Cases of industrial CHP, Boiler/steam-turbine (B3-) and gas-turbine with HRSG (GT2-) series with low-pressure (LP) and medium-pressure (MP) steam delivery. From [4][5].

	Steam delivery load (tonnes/h)				
	40	55	70	85	100
B3-LP (α_Q=0.28)					
W/H	0.240	0.224	0.207	0.191	0.174
Q/H	0.281	0.386	0.491	0.597	0.702
E_Q/H	0.079	0.108	0.138	0.167	0.197
B3-MP (α_Q=0.39)					
W/H	0.144	0.128	0.111	0.095	0.079
Q/H	0.319	0.439	0.559	0.678	0.798
E_Q/H	0.125	0.172	0.218	0.265	0.312
GT2-LP (α_Q=0.28)					
W/H	0.462	0.449	0.438	0.423	0.409
Q/H	0.241	0.332	0.418	0.452	0.483
E_Q/H	0.068	0.093	0.117	0.127	0.135
GT2-MP (α_Q=0.39)					
W/H	0.410	0.396	0.373	0.351	0.332
Q/H	0.274	0.377	0.464	0.512	0.545
E_Q/H	0.107	0.147	0.182	0.200	0.213

The fuel for all cases was natural gas. The cases selected are the operational mode III of the BST plant (maintained firing, reduced condensing ST load to increase steam delivery load), and the operational mode II for the GT/HRSG/ST plant, both with LP and MP steam delivery. The fuel-energy (LHV) consumption rate was 101 MW for the BST and from 117 to 147 MW for the GT plant. Within each of the four series of cases, the steam delivery load increased from 40 to 100 ton/h. As the issue here is to investigate the efficiency indicators, most details of the plants will be left out. The key data are shown in Table 1. The RAIs for all 20 cases are seen in Fig. 1 (abscissa). Increased steam delivery load increases utilization compared to separate production. In the cases presented (except higher GT cases), reduced steam delivery was obtained by increasing load on the condensing steam turbine. It is seen that this reduces the RAI, which for the BST, becomes negative. Furthermore, it is seen that MP steam delivery gave higher RAI than LP steam, and that the GT systems gave higher RAI than the BST systems.

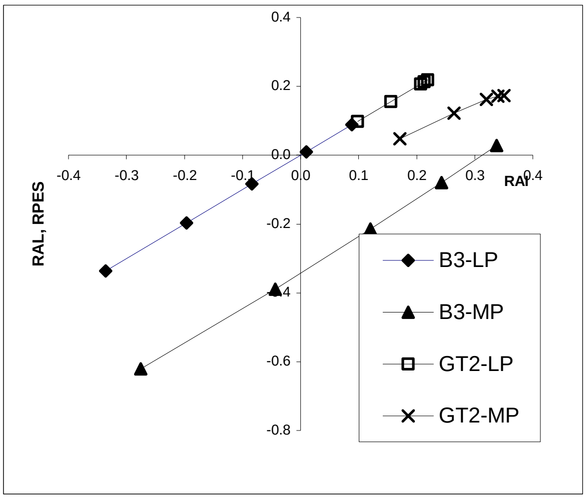

Figure 1 RAL based on the total energy (or CHP) efficiency vs. RAI for the industrial CHP cases. This RAL equals the RPES (Flandern, Brussels).

Figures 1 to 5 show the comparison between the exergy-based and energy based indicators. Here it should be noted that all indicators are defined or chosen with the purpose of promoting CHP. Each of the four series of cases has an RAI that is increasing with increasing steam delivery load. The closer a line between two cases is the diagonal line RAL=RAI, the closer the indicator resembles to the exergetic evaluation.

The Dutch fuel-free electricity (normalized with the reference amount of fuel energy) is proportional to the RPES and exhibit the corresponding behaviour.

The first graph, Fig. 1, shows the RAL based on the total energy efficiency or CHP efficiency. This RAL is equivalent to the RPES (used in Flandern legislation) and to the Brussels-region RCES. As the reference exergy-to-enthalpy ratio is chosen

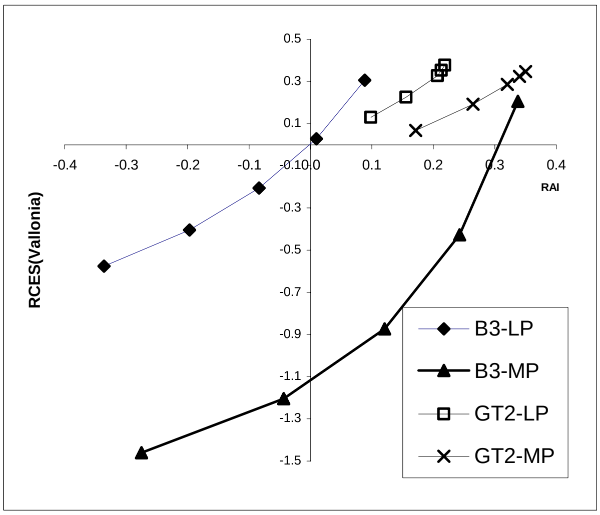

Figure 2 Walloon-legislation RCES vs. RAI.

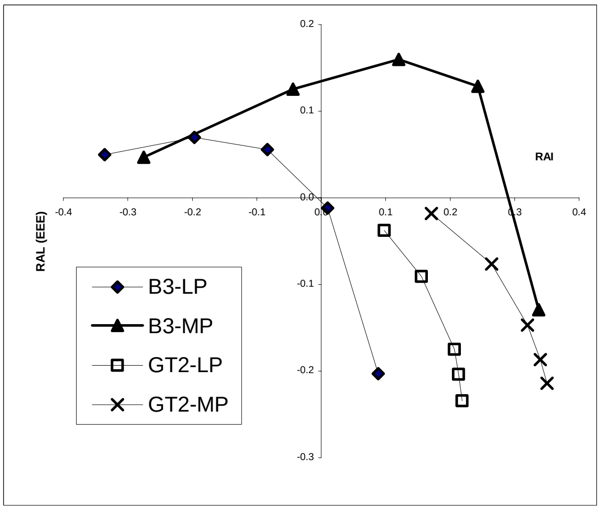

Figure 3 RAL based on EEE (Spain, Portugal) vs. RAI

equal to that of the LP steam, the LP cases lie on the line RAL=RAI. Hence, increased steam delivery for a specific plant is evaluated in accordance with exergy analysis. Improving a plant by replacing the boiler with a GT/HRSG is also encouraged by this indicator. However, it is seen that steam delivery at a higher temperature and exergy (MP steam) is punished by the energy indicator, giving a lower RAL in spite of increased RAI. The higher B3-MP cases are even found in the 4th quadrant, as the RAL takes negative values for positive RAI.

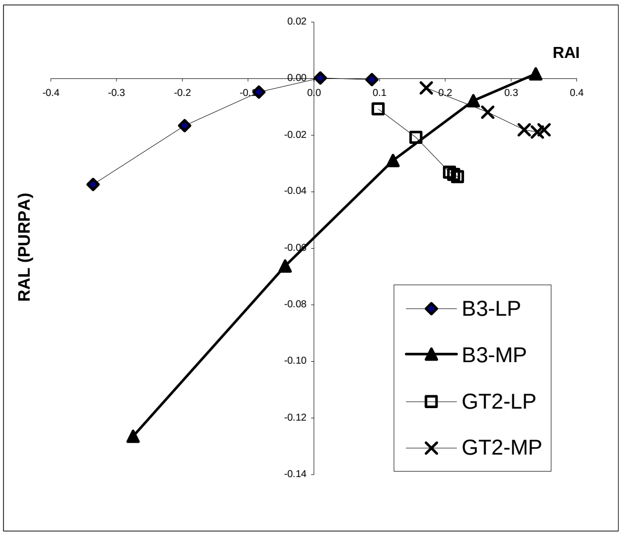

Figure 4 RAL based on US PURPA efficiency vs. RAI

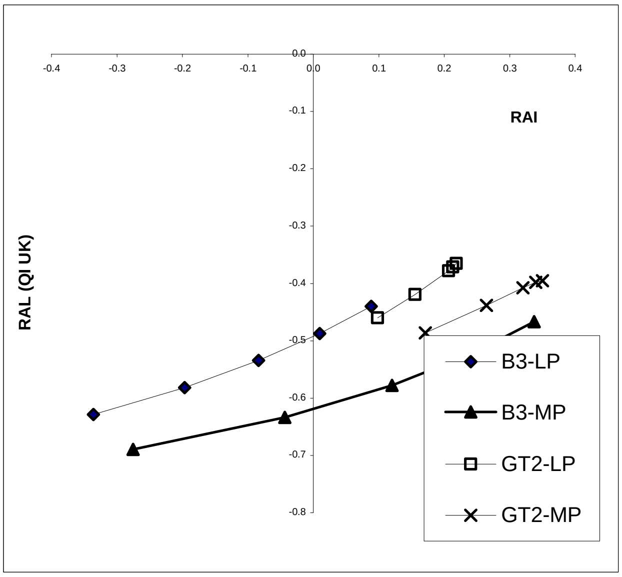

Figure 5 RAL based on British QI vs. RAI

Next, Fig. 2 shows the RCES of the Walloon legislation. This is similar to the RPES above, except that the points are moved clock-wise such that the impact of improvements are enhanced and several cases are raised above the RAL=RAI line in the first quadrant and below on the negative side.
For the present cases, with no in-house derived fuel, the efficiency of the Portuguese legislation becomes equal to the Equivalent electric efficiency (EEE), which is also used in Spain. The RAL based on this efficiency is shown in Fig. 3. This remarkable figure shows that most cases are found in the 2nd and 4th quadrant. Moreover, almost any improvement in terms of exergy utilization is answered with a poorer RAL. One exception in this picture is that the RALs for the higher boiler-MP cases are higher than those of the corresponding LP cases.

The efficiency of the US PURPA is somewhat related to the EEE above, and some of the same tendencies are seen in Fig. 4. In particular, the use of GT/HRSG is discouraged by this indicator, although not to the extent seen with the RAL based on EEE. For the BST configuration, we see some of the same picture as for the total efficiency and RPES above (Fig. 1). The efficiency proposed by Feng, Eq. (10), showed much the same picture as the PURPA efficiency, and is not included here.

The RAL based on the British Quality Index is shown in Fig. 5. It can be noted that higher steam load and higher RAI provide a less negative RAL. However, any other improvement is disregarded by this indicator.
It should be noted that the RAI values are affected by the choice of reference exergy-to-heat ratio, $\alpha_{Q\mathrm{ref}}$. A higher value will reduce the RAI, whereas the various RALs are not affected. Consequently, in all graphs, each point will be moved to the left. The change has less impact with a higher power-to-heat ratio. Nevertheless, the main picture described above will remain the same with a higher or lower value chosen for reference exergy-to-heat ratio.

3.2 Cases of CHP with district heating

In some countries, particularly Denmark, the legislation has been designed to promote small-scale CHP for district heating. This has brought forth a substantial number of natural-gas fired power-plants in the range 3-30 MW electric power, supplying their neighbourhood with space heating. Often, such plants are only operating during the heating season. A number of such cases are specified in Table 2. These data were taken from [7] and are long-term averages for plants in operation. Most of the cases are based on the K type (one B type) of natural-gas fired motor from Rolls Royce Marine Diesel of Bergen, Norway. We will regard these as representative for a number of existing plants. For such plants, the water supply and return temperatures, respectively, are typically 95°C and 50 °C. Here we have assumed $\alpha_Q = 0.19$, although the value may be lower during parts of the heating season.

Table 2 Cases of district heating (α_Q=0.19).

Case	RR1	RR2	RR3	RR4	RR5	RR6
W/H	0.419	0.416	0.397	0.407	0.413	0.450
Q/H	0.341	0.445	0.531	0.521	0.515	0.450
E_Q/H	0.065	0.085	0.101	0.099	0.098	0.086

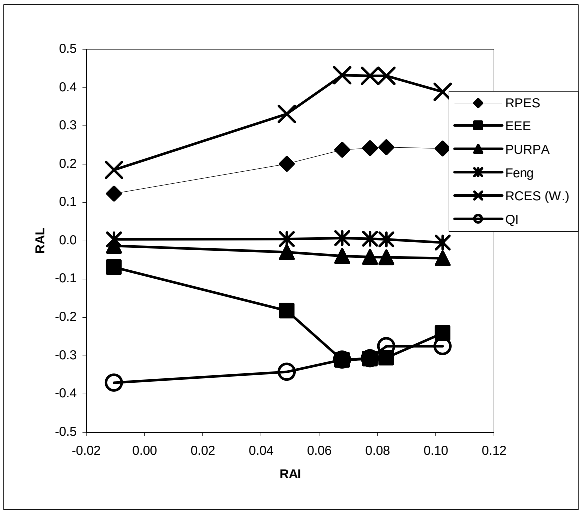

Figure 6 RAL based on various indicators vs. RAI for six cases of disctrict heating.

In Fig.6, these cases are presented from lowest (Case RR1) to highest (RR6) RAI. The corresponding RALs based on six different indicators are shown. It is seen that the total efficiency RAL (equivalent to RPES), encourage but overestimates the improvement, and the Walloon RCES even more. The RALs based on PURPA, EEE, and QI discourage improvements as five of the cases are found in the fourth quadrant of the graph. The RAL based on Feng's efficiency is close to zero for all cases.

It can be argued that for space heating, separate production will give more than 90% of the LHV. In fact, more than 105% can be achieved by using furnaces that condense some of the flue-gas water vapour. Even with his reference, the plant will turn out with positive RAL and RAI. However, the most efficient means for space heating is heat pumps. A relatively modest COP of 3.7 or less, combined with separate electricity production, will give the same RAL or fuel savings as in the cases specified. This shows that from a thermodynamic viewpoint, small-scale power plants with low-temperature heat production are advantageous to on-site heating by combustion, while the best way to provide space heating is heat pumps.

4 CONCLUDING REMARKS

The purpose of this study was to assess various 1st-law-based metrics for evaluating CHP systems. An expression for relative avoided irreversibility (RAI) was developed to enable exergetic comparison of alternative energy conversion systems. Similarly, the relative performance according to various technically or legislatively defined efficiency indicators can be expressed and compared to the RAI.

From a series of industrial and district-heating CHP test cases, it was seen that exergetic improvement (or disprovements) only to a limitied degree was captured by the various energy-based efficiency indicators. Some legislatively defined indicators appear to discourage thermodynamically based improvements.

REFERENCES

[1] EU CHP Directive 2004/8/EC 11 Feb 2004.

[2] Kotas TJ. *The exergy method of thermal plant analysis.* 2nd ed. Malabar, FL: Krieger, 1995.

[3] Horlock JH. *Cogeneration – Combined heat and power (CHP)*. 2nd ed. Malabar, FL: Krieger, 1997.

[4] Nesheim SJ. *Combined heat and power fired with natural gas - Thermodynamical, industrial, and societal consideration.* Thesis submitted for PhD. Trondheim: Norwegian University of Science and Technology, 2005.

[5] Nesheim SJ, Ertesvåg IS. *Efficiencies and indicators defined to promote combined heat and power (CHP).* To be submitted for publication, 2005.

[6] Feng X, Cai Y-N, Qian L-L *A new performance criterion for cogeneration system.* Energy Conv. Mgm. 1998;39(15):1607-9.

[7] Rolls-Royce, Power Generation `http://www.rolls-royce.com/`