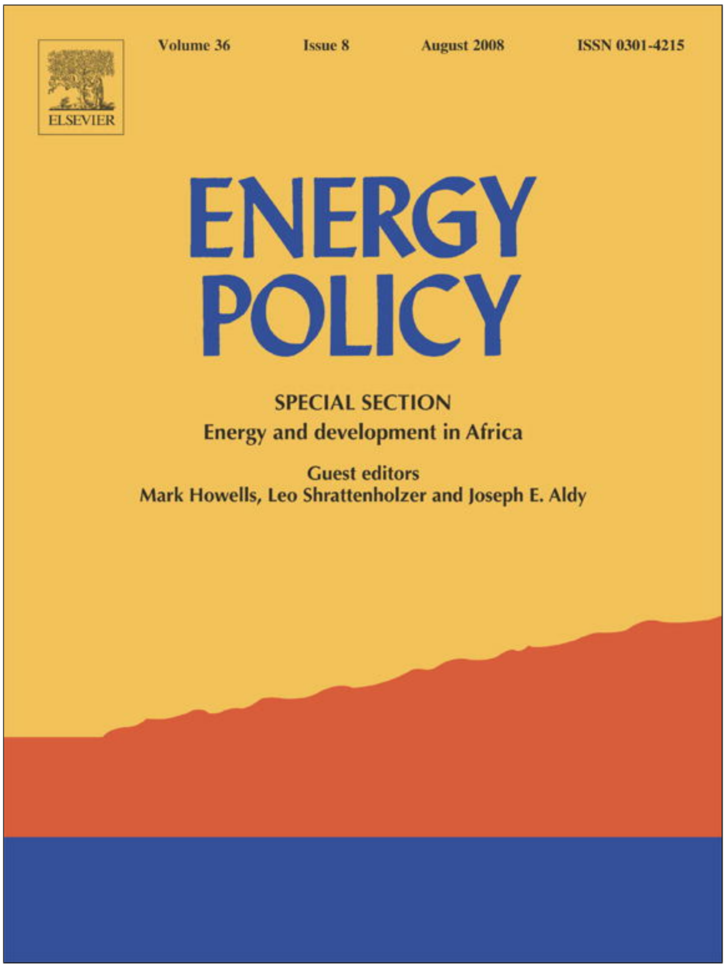
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# The merit of cogeneration: Measuring and rewarding performance

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ABSTRACT

Cogeneration or combined heat and power (CHP) is a thermal power generation cycle with the merit of recovering part or all of the heat that is fatally discarded by such cycles. This merit of higher efficiency is subject of rewarding by public authorities. When the EU enacts CHP promotion in a Directive (1997–2004), crucial measurement and qualification issues remain unsolved. CEN (coordinator of the European Bureaus of Standards) contributes in clarifying the measurement of CHP activities, but shortfalls remain, while CEN bypasses the debate on qualifying CHP performance. This article offers appropriate methods for measuring CHP activities based on design characteristics of the plants. The co-generated electric output is a necessary and sufficient indicator of CHP merit and performance. Regulators can extend this indicator, but should avoid the perverse effects of biased external benchmarking as the EU Directive entails.



## 0. Introduction

Cogeneration or combined heat and power (CHP) is as old as is its natural cradle, the once-trough condensing thermal power plant. The applications of the CHP principle are widespread, the applied technologies are diverse and the scales vary from a few kW to a few hundreds of MW. The diffusion of CHP in various countries of similar economic development is uneven, mainly the result of diverging energy policies and accompanying regulations.

Considering energy efficiency the CHP principle dominates the condensing only power cycle, providing ground for arguments that CHP warrants promotion and support. The EU[1] announced its willingness to harmonize the conditions for a promotional approach by the member states and enacted a Directive in 2004. However, many crucial issues remain unsolved and harmonization is not yet attained. This contribution discusses the major issues at stake to level the playing field for a workable harmonized approach.

Section 1 highlights the opposition in visions on the merit and the role of CHP in the energy economy, because such visions are determining for the acceptability of proposed policies. It is also revealed that quality of CHP is no other than quality of any other thermal power generation process, and therefore does not require "CHP-specific" qualification.

When a state or the state's regulator wants to promote CHP activity it is necessary to define and to measure this activity in a transparent and accurate way. Section 2 covers this issue with Section 2.1 showing that the EU Directive (EP, 2004) does not round the problem. It left open the case to home-made solutions by the member states (see e.g. Moreira et al., 2007), but also solicited CEN/CENELEC (2004) to provide a robust methodology. The propositions of the latter were published in a working paper (August 2004) and are a significant step forward compared with the Directive itself. However, important shortfalls remain and arbitrary parameter values are accepted to break through a circular reference (Section 2.2). In Section 2.3, is shown how I remedy these shortcomings by improving the theoretical framework based on the first law of thermodynamics. When the methodology is implemented one obtains accurate statistics on the real performance of CHP plants in converting fuel into power and useful heat.

Section 3 discusses whether the promotion of CHP needs further elaboration than just measuring the co-generated power output of thermal power plants. The sufficiency of the latter output as an indicator of CHP performance is investigated in Section 3.1. Arguments to also value the heat output weighed by its exergy content are also considered. In Section 3.2, the qualification of CHP outputs on external benchmarks is brought up recalling that such approach can be the source of very perverse incentives for the development of CHP.

The conclusion (Section 4) of the analysis is that the playing field for CHP policy can be levelled in a transparent and harmonized way when the EU publishes an up-scaled Directive in 2010 as it announced to do in its 2004 version.

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[1] EU in this article covers the three institutions that initiate, discuss and enact Directives, i.e. the Commission, Parliament and Council of Ministers.

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**Nomenclature**

| | |
|---|---|
| $Q$ | heat flow (Wh) |
| $Q_{CHP}$ | $=Q_{useful}$ heat recovered in thermal power generation for an end-use |
| $Q_{Cond}$ | $=Q_{waste}$ heat dissipated related to condensing thermal power generation |
| $Q_{plant}$ | heat set free at the thermal power generation process, i.e. $Q_{CHP}$+$Q_{Cond}$ |
| $E$ | electricity flow (Wh) |
| $E_{CHP}$ | electricity output from cogeneration activity of the CHP plant |
| $E_{Cond}$ | electricity output from condensing activity of the CHP plant |
| $E_{plant}$ | electricity output of the CHP plant i.e. $E_{CHP}$+$E_{Cond}$ |
| $F$ | fuel flow (Wh) |
| $F_{CHP}$ | fuel devoted to combined or back-pressure power generation in a CHP plant |
| $F_{Cond}$ | fuel spent on the condensing activity in a CHP plant |
| $F_{plant}$ | fuel consumed by the CHP plant i.e. $F_{CHP}$+$F_{Cond}$ |
| $S$ | *bliss point* of the production possibility set of a CHP process, where at maximum output of useful heat (i.e. $Q_{CHP}=Q_{plant}$), the co-generated power output is also maximized. Complex CHP processes can exhibit multiple bliss points, while they also can be virtual ( = outside the actually attainable production possibilities, when maximum $Q_{CHP}$ is below $Q_{plant}$). |
| $\sigma$ | *design* power-to-heat ratio of a CHP process. Mostly $\sigma$ is the constant power-to-heat ratio at the single bliss point $S$ of the CHP process, but more variable situations can be accommodated by writing $\sigma$ as a function (see references). |
| $\eta$ | overall energy conversion efficiency of the CHP plant $(E_{plant}+Q_{CHP})/F_{plant}$ |
| $\eta_{CHP}$ | energy efficiency of CHP activity or $(E_{CHP}+Q_{CHP})/F_{CHP}$ |
| $\eta_{Cond}$ | efficiency of the pure condensing activity of the CHP plant $(E_{Cond}/F_{plant})$ when $Q_{CHP}=0$. |
| $\beta$ | power loss factor by a heat extraction at a steam turbine (directly linked to $\sigma$ through $\eta_{Cond}$ and $\eta_{CHP}$) |
| $\alpha_E$ | the electric efficiency of the CHP plant $E_{plant}/F_{plant}$ |
| $\alpha_Q$ | the heat efficiency the CHP plant $Q_{useful}/F_{plant}$ |
| $\eta_{ERS}$ | the electric efficiency of the *reference separate* electricity generation process |
| $\eta_{QRS}$ | the heat efficiency of the *reference separate* heat process |
| *Note:* | With capacities in W (Watt) and energy in Wh, units can represent both capacities and (momentary or average) hourly energy flows. |

## 1. Visions on CHP merit and quality

Two opposite visions on the merit and the role of CHP in the energy economy are discussed first, because they help to understand why the propositions to value and reward CHP also differ widely. Next is revealed that quality of CHP is no other than quality of any other thermal power generation process. Both issues are basic but nevertheless contentious because differences in vision bifurcate the way of valuing and regulating CHP in the energy economy.

### 1.1. *Opposite visions on the merit and role of CHP*

Policy starts with a vision on the issue at hand. CHP has been subject of a broad variety of visions hold and defended by various groups in the energy field. The visions shift between a PRO and an ANTI viewpoint that express different assessments of the merit of CHP and of the role to be played by this technology (Table 1).

One favours the development of CHP when taking the position that the merit of CHP is in recovering all or part of the heat being otherwise discarded to the environment in a thermal power plant. Adding additional tests upon this basic merit leads to fencing in the application of the CHP principle. For example one can require that CHP plants perform a factor *X* better in generating power and heat jointly than the best available references of separate generation technologies (power-condensing plants and heat only facilities). While such external benchmarks provide valuable information to a would-be investor in CHP capacity and in particular to the operator of existing CHP capacities, it is not recommended to include it in the regulation of CHP as discussed in Section 3.2.

When the basic merit of CHP is recognized it is logical to attribute priority to the CHP mode above the condensing only mode for investing in thermal power plants.[2] The anti vision, often inspired by power monopolies, sees the role of CHP very restrictive to particular joint power–heat load conditions where a full heat load can be guaranteed 'all the time'. This attitude also fences the entry to the power market by setting particular tariffs for power exchanged between the CHP facility and the interconnected grid. Unfair conditions for exchanging power with the grid are main barriers to a balanced development of CHP in both the heat and the power markets. The EU Directive on the Internal Energy Market has not been very effective in resolving the market access barriers for independent generators.

### 1.2. *The quality of thermal power and of CHP*

CHP is always based on some thermal power generation cycle. The latter is its natural cradle and determinant of the performance, economics and quality of the CHP process. Every thermal power process rejects fatal heat in the environment. The merit of CHP is to recover part or all of this fatal heat and convert it into 'useful' heat. Some CHP processes (steam turbines) occasion a loss of power output when fatal heat is converted into useful heat. The loss of power is almost proportional to the temperature of the extracted heat (steam) from the turbines, and therefore it is important to minimize the required temperature of the heat applications in CHP processes. Other processes do not occasion significant power losses because the temperature of the rejected fatal heat is sufficiently high for meeting the heat end-use conditions (gas turbines, internal combustion engines, fuel cells).

The quality of CHP processes is recorded by their power-to-heat ratio, graphically shown by the slopes of the bisectors in Fig. 1. In the CHP discussion, the exact definition of this ratio has been the subject of continuous discussions. Fig. 1 shows a high-quality process and a low-quality one. For both we assume a fuel flow of 100 kW and non-recoverable losses of 15 kW. A high-quality conversion extracts 50 kW power and a low-quality one but 30 kW. The balance between fuel input and the sum of power output plus non-recoverable losses is the recoverable heat flow at

[2] In Denmark, the 1979 Heat Supply Act has made this principle reality. Since 1981 no major single condensing power station has been built in Denmark. For more detail see Grohnheit and Olsen (2001).

**Table 1**
Opposite views on the merit and role of CHP

| | Pro CHP | Anti CHP |
|---|---|---|
| CHP Merit | Use of—all or part of—the discarded fatal heat at thermal power plants | CHP has but merit when it excels above the best separate power and heat benchmarks |
| CHP Role: who first? | CHP dominates the condensing only thermal power generation cycle, and therefore is, ceteris paribus, preferred. Valid is also part recovery of fatal heat | Limit CHP to full heat loading working. As a corollary: obstruct CHP plants operating in part/full condensing mode |

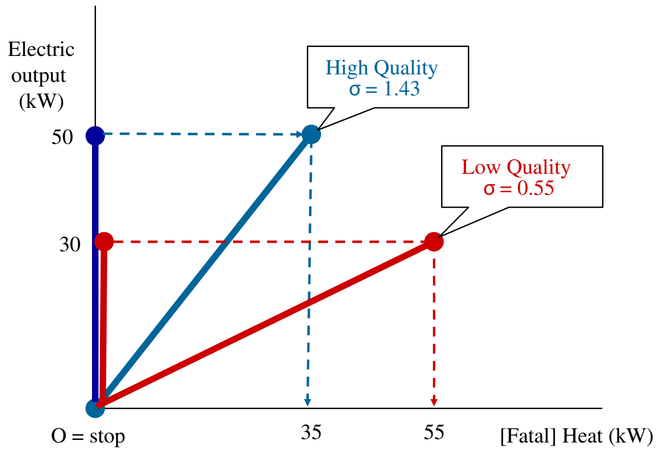


**Fig. 1.** Power/heat ratio expresses the quality of thermal power generation processes, whether condensing or CHP.

the plant. The metamorphosis of a condensing power unit into a CHP one is happening while transforming fatal heat into useful heat. It is apparent that the high- (low) quality CHP process is embedded in a thermal power plant of high (low) electricity conversion efficiency (the linkage is further discussed in Sections 2.3 and 3.1).

## 2. Measuring CHP activity[3]

Considering that the CHP process provides better fuel efficiency than the condensing only thermal power cycle, several national states have developed policies for the promotion of CHP applications. Also the EU has taken initiatives to develop a dedicated directive for the promotion of CHP. In 1997, the EU Commission started the policy construction process with a position paper (CEC, 1997). After discussing two draft versions[4] the final directive[5] is published in February 2004. The latest version of the directive still falls short in providing a harmonized and consistent approach to CHP, while such approach is the ultimate goal of EU directives. Harmonization is necessary to level the playing fields in open European markets (energy, commodities, services, etc.). Therefore, an effective and efficient EU-wide regulation is an important framework for the development of CHP in general and of independent CHP in particular, in the various member states of the European Union.

Although unexpected and seemingly odd at first sight, the bottleneck holding up an effective regulation has been the definition and so measurement of what truly is CHP *activity*. When a cogeneration plant is not equipped with condensing (heat rejection) facilities, there is no problem because all activity of the plant is combined or co-generated. However, when a plant can function in mixed modes (combined and condensing) at the same time, the problem arises how to disentangle or split up the energy flows of such plant. Not only the EU, also the USA is facing this difficulty and the Energy Information Administration (Department of Energy) is looking for improved methodologies to accurately measure cogeneration activity.[6]

Obvious arguments (see Section 3 for evidence) in protecting the quality of the CHP process provide the basis for consensus on accepting as the indicator of CHP activity the quantity of co-generated electricity $E_{CHP}$. Defining this variable and measuring it when co-generation takes place *joined to* condensing power generation, is the problem to solve. In addition, but fully overlooked in the EU regulation, is it necessary to identify and measure the share of fuel consumed for the combined activity $F_{CHP}$.

First (Section 2.1) is discussed how the identification problem is addressed by the EU (EU is the short term for the three institutes that prepare, discuss and finally adopt Directives: the Commission, the Parliament and the Council of Ministers). Then is presented the methodology proposed by the CEN/CENELEC Workshop Agreement CWA 45547 (2004). Finally, it is pointed to the weak point in the CEN/CENELEC proposals and it is shown how a better methodology remedies the weaknesses while improving transparency and regulatory incentives and answering the remaining questions of the EU Directive itself.

### *2.1. The EU CHP Directive on measuring CHP activity*

Annex II of the Directive is titled "Calculation of electricity from cogeneration" (EU-OJ, pp. L52-58). It opens with "Values used for calculation of electricity from cogeneration shall be determined on the basis of the expected or actual operation of the unit under normal conditions of use. For micro-cogeneration units the calculation may be based on certified values." Then it splits the approach in two cases. First, when the overall thermal efficiency $\eta$ of the operations exceeds 75% for steam back-pressure turbines, gas turbines with heat recovery, internal combustion engines, micro turbines, Stirling engines and fuel cells, all power generated is accepted to be co-generated. Analogously, an 80% $\eta$ efficiency threshold applies for CCGT with heat recovery and for steam-condensing extraction turbines.

Second, when overall efficiency $\eta$ falls short of the stated thresholds of 75%/80%, co-generated electricity $E_{CHP}$ should be calculated according to the formula $E_{CHP} = CQ_{CHP}$, with $C$ the

[3] Symbols used throughout the article are tabled in Nomenclature.

[4] Directive of the European Parliament and of the Council on the promotion of cogeneration based on a useful heat demand in the internal energy market (CEC, 2002).

[5] Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC. Official Journal of the European Union, 21.2.2004, L52/50-60.

[6] National Institute for Statistical Science. Statistics and Methods Group. Research project 'Combined Heat and Power Plant Fuel Allocation Methodology', Energy Information Administration, Department of Energy, USA.

**Table 2**
Range of characteristics of CHP plants

| Technology | Capacity $MW_e$ | Power-to-heat ratio[a] | Electrical efficiency % | Overall efficiency % |
|---|---|---|---|---|
| Steam turbine | 0.5–500 | 0.2–0.8 | 17–35 | 60–80 |
| Gas turbine | 0.25–50+ | 0.6–0.9 | 25–42 | 65–87 |
| CCGT | 3–300+ | 0.9–1.25 | 35–55 | 73–90 |
| Ignition engines | 0.15–20+ | 0.6–1.0 | 25–45 | 65–92 |

*Sources*: EDUCOGEN (2001), complemented by manufacturers and field data.
[a] Values are very dependent on technical designs and for steam turbines on the temperature of the extracted heat. For CCGT they also depend on the adopted convention to include—yes or no—the gas turbine output in the cogeneration activity.

power-to-heat ratio.[7] Article 3(k) of the Directive (p. L52–53) states "'power to heat ratio' shall mean the ratio between electricity from cogeneration and useful heat when operating in *full cogeneration mode* using *operational* data of the specific unit". This definition improves the versions of the first 2002-draft by emphasizing the *full* cogeneration mode for the measurement of *C*. However, the use of operational data for assessing *C* requires more detail about how to proceed for a variety of technologies and circumstances, e.g. when a steam power turbine is designed to function partially (e.g. 25%) as a cogeneration turbine. One would expect to get the necessary detail in Annex II, but there is only stated that *C* is the "*actual* power to heat ratio". And when the latter is "not known, the following default values may be used, notably for statistical purposes, …, provided that the calculated cogeneration electricity is less or equal to total electricity production of the unit [sic]". Then follows a table with *C* values: 0.95 for a CCGT with heat recovery; 0.45 for a steam back pressure and steam-condensing extraction turbine; 0.55 for a gas turbine with heat recovery and 0.75 for an internal combustion engine.

Here I limit the discussion on how the EU treats the subject of quantifying CHP activity to two points.

First, the EU Directive is very incomplete in its treatment of the subject, although good identification and measurement is a prerequisite for good regulation. Starting from the right basic principle "the amount of electricity from cogeneration power is the product of the power-to-heat ratio and the amount of useful heat from cogeneration", the Directive falls short in defining the principle clear enough and in offering solutions for the extensions of the principle to practical CHP processes, e.g. steam turbines with more than one useful heat extraction point and e.g. Combined Cycle Gas Turbine (CCGT) plants with co-generation. By lacking the right method, Annex II offers average default values by technology group, but this is "*notably for statistical purposes*". One may question the use value of very approximate statistical data, but more problematic is the lack of reliable data on the particular CHP activity of particular plants the EU wants to qualify as such. The wrong answer to the difficulties in quantifying cogeneration activity is to negate the question, and proceed without answer. This is what the EU does when in Annex III it forgets Annex II and qualifies cogeneration performance on the basis of mixed values with perverse effects for the development of CHP (Verbruggen, 2007b).

Added to the non-identification and non-quantification of $E_{CHP}$, the EU skips the problem of identifying and quantifying CHP fuel consumption $F_{CHP}$. The latter variable is also necessary to assess the efficiency $\eta_{CHP}$ of the cogeneration activity of a thermal power plant.

[7] Here the symbol *C* is maintained for the power-to-heat ratio as stated in the EU Directive, while I suggested the symbol $\sigma$ to emphasize the differences in definition and actual assessment [CEN/CENELEC also uses $\sigma$].

Second, simplifying the calculation of $E_{CHP}$ by splitting the CHP activities in two groups, as Annex II does, increases the workability of the task. Although it is true that thermal power generation surpassing overall efficiencies of 75% and 80% will be composed predominantly of cogeneration activity, threshold values and average default values are arbitrary and should be avoided in a regulation that wants to promote "high efficiency CHP". Table 2 shows the characteristics of CHP technologies currently available today, vary within wide ranges. The complement to 100% of the overall efficiency is the percent of non-recoverable losses, playing a significant role in deriving the power-to-heat ratio of a plant. It follows that regulation on the basis of the average 75%/80% values does not promote best practices being the maximization of the power-to-heat ratio through (inter alias) minimizing non-recoverable losses.

Presumably because of the many caveats, the Directive is not firm in imposing its method on the Member States. Article 12 allows for "Alternative calculations" with e.g. Section 1 stating: "Until the end of 2010 and subject to prior approval by the Commission, Member States may use other methods than the one provided for in Annex II(b) to subtract possible electricity production not produced in a cogeneration process from the reported figures." Although the EU is wise not to impose an immature method, the identification issue remains open and this will not increase harmonization, being stated as the "general objective of the Directive" ("whereas no. 15", EU-OJ, p. L52/51, where reference is made to the upcoming CEN proposals).

### *2.2. The CEN propositions for measuring CHP activity*

Already before the EU CHP Directive was published, interested stakeholders gathered at the CEN offices in Brussels to agree on a more complete methodology to identify and quantify CHP activities more accurately than the text of the Directive offers. The consensus is published as a manual and available on the internet. The approach is extensive; a flow-chart (CEN/CENELEC, 2004, p. 18) summarizes it well, and specific questions are addressed in separate sections (e.g. CEN/CENELEC, 2004, Section 9, pp. 38–40, for more complex steam turbine processes with more than one steam pass-out).

CEN admits the high importance of the CHP quantification issue as "The determination of CHP products (heat and power outputs) is important not only for the CHP Directive but also for the EU Emission Trading Scheme, State Aid guidelines for environmental improvement and the energy taxation Directive" (CEN/CENELEC, 2004, p. 6). CEN's objective "is to present a set of transparent and accurate formulae and definitions for determination of CHP (cogeneration) energy products and the referring energy inputs. The CEN/CENELEC Workshop Agreement shall simply formulate the procedure for quantifying CHP output and inputs (…). It does not include quality rankings such as assessments of fuel savings or environmental impact"

(CEN/CENELEC, 2004, p. 6). The clarity in objectives contributes significantly to the value of the work. The approach matches the analysis that I submitted in 2003 during the discussions on the drafts of the Directive. In this section, the main remaining differences[8] are discussed, and in Section 2.3 is argued where the CEN quantification can be improved.

First, CEN accepts the Annex II method of dividing CHP plant outputs in two groups, whether the overall efficiency is above or below the fixed 75%/80% thresholds, and accepting the "above ones" fully as cogeneration. Table 2 above shows a wide range of overall efficiencies (60–92%) for CHP designs. Adopting a fixed threshold as approximate method is no best practice (Section 2.3 offers a straightforward alternative).

Second, for the "below ones", CEN addresses the issue of separating CHP and non-CHP activity from the *mixed* activity and searches to quantify both $E_{CHP}$ and $F_{CHP}$ values, next to the directly measurable value $Q_{CHP}$ during a particular period. CEN hereby distinguishes cogeneration processes *with* power output loss by the extraction of useful heat at the thermal power process from the ones *without* power output loss when heat is recovered. CEN focuses on extraction-condensing steam turbines,[9] where mixed activity and power loss are prominent, with the added complexity that useful heat extraction may occur at several pressures (temperatures). I will continue on this most important and most complex CHP case (CEN/CENELEC, 2004, Section 9, pp. 38–40).

CEN proceeds through following steps:

1. Determination of the power loss coefficient(s) $\beta$ (see CEN/CENELEC, 2004, Section 9.1). There is described an extensive method to measure the $\beta$ values of specific mixed power generation and useful heat extraction activities.[10]
2. Determination of the efficiency of non-CHP power generation $\eta_{Cond}$. The latter value equals $E_{Cond}/F_{plant}$ when $Q_{CHP}=0$ (see Table 3). CEN makes here some detour by calculating the numerator as $E_{Cond}$ by $E_{plant}+\{E_{Cond}-E_{plant}\}$, the expression in brackets being the power lost by heat extraction.
3. Determination of the power-to-heat ratio $\sigma = \dfrac{\eta_{cond} - \beta\eta_{CHP}}{\eta_{CHP} - \eta_{cond}}$.
4. Determination of $E_{CHP} = \sigma Q_{CHP}$

More steps follow, but steps 3 and 4 contain a "circular reference". Obviously, $E_{CHP}$ is calculated in step 4. However, the formula of step 3 includes $\eta_{CHP}$ what requires knowledge on $E_{CHP}$ (next to $Q_{CHP}$ and $F_{CHP}$ as Table 3 shows). CEN escapes from its circular reference by applying "the CHP overall efficiency ($\eta_{CHP}$) according to Annex II of the CHP Directive" (CEN/CENELEC, 2004, p. 38), or more clearly stated: CEN adopts a fixed value of 75%/80% for $\eta_{CHP}$. Table 2 shows that fixing such constant parameters does not cover the reality of CHP technologies and applications. It is also a shortcoming to the stated objectives to deliver "transparent and accurate formulae". Next is shown that a consistent regulation has no need for arbitrarily fixed parameters.

**Table 3**
Energy flows in a CHP plant obey the first law of thermodynamics

| | CHP | +Condensing | = Plant |
|---|---|---|---|
| Fuel $F$ = | $F_{CHP}$ | $F_{Cond}$ | $F_{plant}$ |
| electricity $E$ | $E_{CHP}$ | $E_{Cond}$ | $E_{plant}$ |
| +heat $Q$ | $Q_{CHP}$ | $Q_{Cond}$ | $Q_{plant}$ |
| +losses non-recoverable | – | – | $L_{plant}$ |

The further steps of the CEN solution are:

5. Determination of non-CHP power output: $E_{Cond}=E_{plant}-E_{CHP}$.
6. Determination of fuel energy for non-CHP power output: $F_{Cond}=E_{Cond}/\eta_{Cond}$.
7. Determination of fuel energy for CHP power output: $F_{CHP}=F_{plant}-F_{Cond}$, or $F_{CHP}=(E_{CHP}+Q_{CHP})/\eta_{CHP}$, where $\eta_{CHP}$ is again the fixed parameter 75%/80%.

### 2.3. Closing the CHP measuring gap

One should start at the first law of thermodynamics with the equation

$$\text{Fuel input} = \text{power output} + (\text{recoverable})\text{heat output} + (\text{non-recoverable})\text{Losses}.$$

This universal law is valid for any thermal power plant, but requires more elaboration when cogeneration takes place. This is shown in Table 3.

With the notation of Table 3, one writes

$$F_{plant} = E_{plant} + Q_{plant} + \text{non-recoverable losses},$$

or

$$F_{CHP} + F_{Cond} = E_{CHP} + E_{Cond} + Q_{CHP} + Q_{Cond} + \text{non-recoverable losses}$$

The equations help in stating the final steps the quantification discussion should take.

First it is obvious that when $Q_{Cond}=0$, it follows $E_{Cond}=0$ and $F_{Cond}=0$, and further $E_{CHP}=E_{plant}$ and $F_{CHP}=F_{plant}$. Therefore, rather than using fixed efficiency thresholds, one better accepts all electricity as $E_{CHP}$ when the plant is not equipped with heat rejection (condensing) facilities, because there may be peculiar conditions why the overall efficiency falls short of the efficiency thresholds, e.g. when the plant is combusting waste fuels. The distinguishing property among "pure" and "mixed" CHP plants is whether they own—yes or no—"heat rejection facilities". If "no", the thermal power plant is a "pure" CHP activity and there is no CHP definition, identification and quantification problem because all useful heat, all power and all fuel relate to cogeneration. So the 75%/80% thresholds are of no use.

Second, the very issue of identification arises when the CHP activity is embedded in a plant owning heat rejection facilities. In case of joint cogeneration and condensing activity none of the variables in the equations equals zero, but directly observed are only: $Q_{CHP}$, $F_{plant}$ and $E_{plant}$. In order to split the latter two quantities in their CHP and non-CHP shares, additional information on the plant and process characteristics is necessary.

CEN adopts the fixed parameters of 75%/80% as $\eta_{CHP}$, while I propose to measure the non-recoverable losses and $\eta_{cond}$ at the thermal power plant to fix the *bliss point S* and the *design* power-to-heat ratio $\sigma$. The bliss points can be multiple and virtual, so also the ratio's $\sigma$ can be multiple, but are always real (Verbruggen, 2007a). The difference between the approaches is that CEN sets the Non-recoverable Losses in a CHP plant always equal at 25%/20% of the fuel input, while I propose to observe the real

[8] There are also some other points that can be discussed, e.g. the definition of CHP itself, e.g. the definition of the reporting periods of the measurement data (where I suggest a difference between 'accounting' and 'reporting' periods).

[9] CEN/CENELEC (2004, p. 14) considers back-pressure steam turbines as units *without* power loss, based on the argument of complementary power and heat outputs. I disagree on this classification because power loss is due to heat extraction at above ambient temperature. When designing back-pressure units and when heat is supplied at more than one pressure level, power loss factors are important parameters to optimize.

[10] Power loss is discussed widely in the technical CHP literature (see Euroheat and Power Journal), but generic statistics are published rarely because the loss factors are application specific. See, however, Fig. 1 in Harvey (2006).

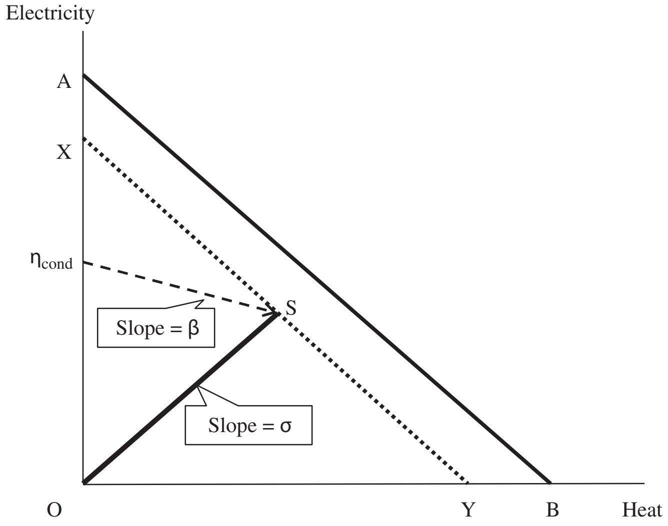


**Fig. 2.** Fixing the bliss point $S$ and power-to-heat ratio $\sigma$ of a CHP activity.

Losses at the moment of plant certification. The values in the last column of Table 2 show that overall efficiencies $\eta_{CHP}$ range from 60% to above 90%, and underpin the very straightforward argument that it is better to observe the real numbers for the particular plants. Once the characterization of the non-recoverable losses is done, one knows the share of the fuel that is converted in electricity and in recoverable heat.

Fig. 2 shows the method graphically with efficiency units on both axes. The full line $AB$ assumes 100% efficiency with all fuel converted in electricity or recoverable heat (the fictive case of non-recoverable losses being zero). The parallel line $XY$ differs from $AB$ by subtraction of the non-recoverable losses, i.e. compared with line $AB$, $XY$ represents $\eta_{CHP}$ [in the CEN approach always $XY = (0.75 \text{ or } 0.80)\ AB$].

The bliss point $S$ is to be found somewhere on line $XY$. For fixing $S$ one must observe the efficiency of pure condensing activity $\eta_{Cond}$ and the power loss factor $\beta$ of the heat extraction ($\beta$ may be zero). The two data define the dashed downward sloping line $\eta_{Cond}{-}S$, and the crossing with $XY$ fixes point $S$. The design power-to-heat ratio $\sigma$ is the slope of $OS$. The production possibility set of the CHP activity is given by the triangular area $O{-}\eta_{Cond}{-}S$.

While CEN is compatible with the methods I developed, avoiding the insertion of arbitrary threshold efficiency numbers is more accurate and transparent. Also analyzing CHP issues with the help of production possibility sets may avoid confusion.

## 3. Promoting CHP: what and how?

Once CHP activities are clearly characterized and so can be measured accurately, it is possible to discuss what aspects of that activity may be promoted,[11] and how this can be done in the most transparent and simple way in order to avoid biases and transaction costs.

### 3.1. Focus on the CHP principle itself

A CHP plant converts some fuel into power and heat outputs. There is a tendency to assess the performance of CHP processes for both: the use of particular fuels and the application of the cogeneration principle. E.g. when bio-fuels are used, waste fuels recovered, natural gas substitutes for coal, etc. additional rewarding for the CHP activity is proposed. However well intended, this practice creates confusion and often backfires when mixed with biased methods of CHP qualification are applied (Section 3.2). The principle that attaining one policy goal requires one policy instrument argues in favor of focusing exclusively on CHP activity by a CHP Directive or other promotional scheme.

Limiting for now the focus to the CHP processes, the question is what indicators best reflect CHP performance. The amount of co-generated electricity (measured in an accurate way by $E_{CHP} = \sigma Q_{CHP}$) seems necessary and sufficient as an indicator. The variable includes incentives to maximize quantity ($Q_{CHP}$) and quality (power to heat ratio $\sigma$) of the CHP activities. Using $Q_{CHP}$ as an indicator is not recommended. As the only indicator investors and operators would not be stimulated to performing cogeneration activity. Also as an additional indicator (next to $E_{CHP}$ itself) there are few arguments to include the heat output variable, even not when the quality (exergy) of the useful heat flows would be taken into account (Schaumann, 2007). While heat at higher temperature corresponds to a higher availability (quality, exergy) of the energy flows, rewarding this in CHP activities counteracts the incentives to reduce the applied temperatures of heat end-uses in buildings and processes. The lower the useful end-use temperatures of heating applications can be set, the more "nearby waste" heat flows can be recuperated, the more ambient heat sources can be included (solar heating, heat pumps) and the more efficient cogeneration systems can be inserted (in particular the ones where the power loss factor $\beta$ is non-zero and larger in absolute value with higher temperatures of the useful heat extraction at the CHP plants).

Objection against $E_{CHP}$ as indicator is that the power to heat ratio $\sigma$ could be manipulated by the most perverse effect one can imagine, i.e. by increasing the non-recoverable losses of the CHP plant. This is shown in Fig. 3. Assume that all other characteristics of the CHP process remain invariable, the simple conversion of

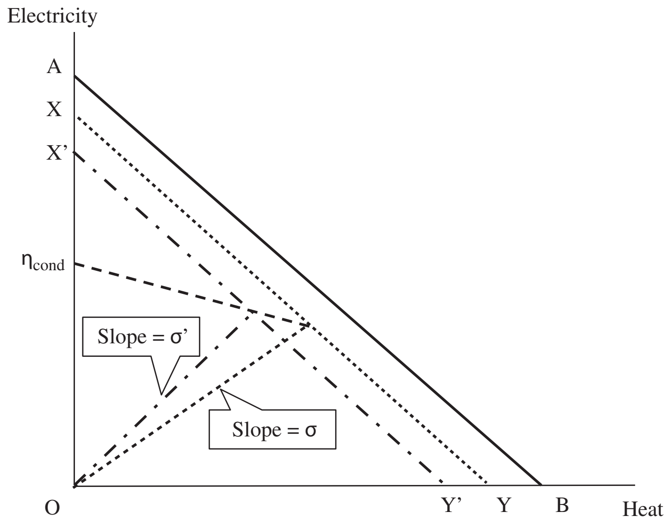


**Fig. 3.** Higher power-to-heat ratio $\sigma'$ by increased non-recoverable losses of a CHP activity?

[11] An anonymous reviewer of this article asked "Why should CHP in itself be promoted? It needs to prove a reduction in $CO_2$ emissions and/or reduction in fuel combustion. High efficiency separate heat and power generation might be better in reducing $CO_2$ than a low efficiency CHP facility." This wording of the external benchmarking argument is almost perfect, and can enjoy a majority vote. It points to the core of the discussion. First, as CEN does, I do not insist on promoting CHP in itself; it is the EU that issued a Directive to "promote CHP". My analysis focuses on identifying exactly what one is doing. Secondly, there is no problem with external benchmarking AFTER identifying and measuring CHP activity in the right way. The problems arise when this first job is not done well (see Section 3.2 and Verbruggen (2007b) for a full analysis). A metaphor can explain the dangers of external

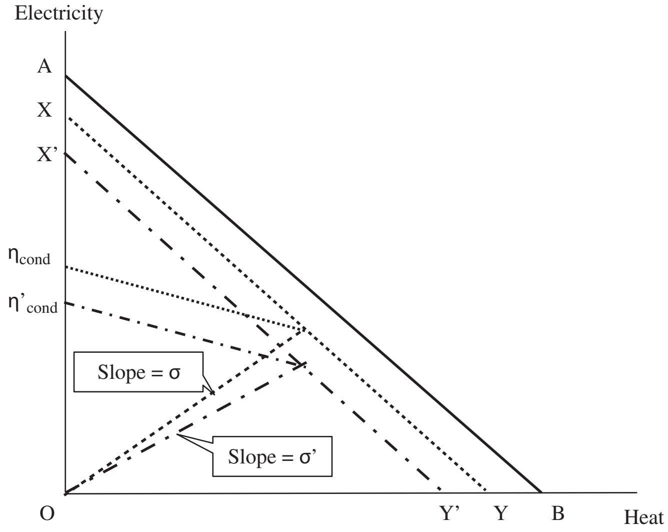


**Fig. 4.** Higher non-recoverable losses of a CHP activity are due to lower electric efficiency and do not raise the power to heat ratio.

recoverable heat in non-recoverable heat would then indeed occasion the increase of the design power to heat ratio from $\sigma$ to $\sigma'$. This would also lead to a higher reward in $E_{CHP}$ for the measured output $Q_{CHP}$ in a mixed cogeneration process. Such perverse evolution could occur at first sight, but is unlikely at second sight because the higher non-recoverable losses in thermal power plants are mostly related to bad performance in generating power, i.e. $\eta_{Cond}$ falls correspondingly to the losses. This is shown graphically in Fig. 4, revealing that there is no increase of the power to heat factor due to such higher losses.

The identification of the design power to heat value (values) in CHP plants can be subject to asymmetric information and moral hazard. Regulators can overcome both effects by imposing the right procedures for periodically measuring and reporting the energy flows at CHP plants (Verbruggen, 2007a).

When the sole quantity of (accurately measured) co-generated power is accepted as indicator of the merit and of the performance of CHP activity, a public authority may judge it recommended to support that activity by assigning some premium value to the co-generated electric kWh, quite similar to the generated quantities of renewable power. At this stage it may be found effective, efficient, or fair to assign a different premium to kWh forthcoming from different CHP plants depending on technology, size, even fuel used, adding on top of the CHP merit additional considerations. Such practices are acceptable as long as they do not bias the CHP regulation as such.

### 3.2. *External benchmarking and the EU Directive qualification*

In a business context benchmarking is "the continuous, systematic process of comparing the current level of performance against a predefined point of reference, the benchmark, in order to evaluate and improve performance" (Couder and Verbruggen, 2003). Benchmarking is applied by private or public agents assessing the own performance to improve it. Fuzzy aspects in definitions, data availability and methods applied, are ironed out by such agents.

A variety of benchmarks can be adopted: internal or external to the own organization or activity considered, local, national or international in reach, focused on a part or the whole of the organization, in a short-term or a long-term time perspective. The choice of benchmark is of crucial importance because one's own performance is measured as a 'distance-to-targets' where the benchmark characteristics function as the targets, and because the own activity is changed to resemble the benchmark as much as possible. In particular, when the benchmark is *external* to one's own activity, it requires carefully questioning whether one's own activity can or should resemble as much as possible the external reference benchmark. *Internal* benchmarking references are drawn from within the same organization or activity branch and are more akin to the own activity.

Compared with benchmarking by limited organizations, the perspective is dramatically different when benchmarking is applied in a regulatory policy context (such as an EU Directive). Then a wide range of participants (competitors) are screened and evaluated on a particular performance and remunerated or penalized in one way or another on the basis of the measured performance. In such a context the definitions must be based on argued, transparent and robust methods requiring data that are measurable in an uncontested way.

The EU CHP Directive benchmarks the energy conversion performance of CHP plants on the efficiencies of processes of separate generation of power and of heat. This is *external* benchmarking because CHP is compared with non-CHP processes. The imposed reference at the power side is the high-efficient CCGT process and at the heat side it is a high-efficiency boiler. Next to the difficulties in pointing down the "right" efficiency values, the assumption that CHP power and CCGT power are perfectly comparable and exchangeable all time of the year[12] weakens the case for applying external benchmarking (Franke, 2004). *Internal* benchmarking (particular CHP activities on best-practice CHP processes of the same technological family) is less arbitrary in gauging the performance of CHP activities. It also requires the clear identification of the CHP activity of every plant.

For clarity of the argument and because some countries based their regulation on the 2002 draft, a reminder of the qualification construct of this draft Directive (Annex III of CEC, 2002) is helpful. The construct was meant to provide an instrument to the Member States and their regulators to accept or to exclude particular CHP activity from qualification and support because they fall short of exigencies of the *quality norm*. But the construct entails particular incentives for CHP development (investment, technology, design, scale) and for the operation of existing units that are perverse.[13]

For assessing the incentives implied in *quality norm* qualification and for assessing the likely effects of these incentives, the concept of CHP production possibility sets is useful (see Fig. 2).

(*footnote continued*)
benchmarking further. Assume a public authority wants to promote bicycling in the city. It rewards this activity when all km cycled are performed faster than by car and lighter than by walking (two external benchmarks). In the inner city the cyclist can meet the criteria, but when the km cycled in the suburbs or countryside are added to the km cycled in the city it will be difficult to be faster than the car on average. So, the incentive is given not to use the bicycle outside the city (e.g. in the suburbs). This is a perverse effect obstructing cycling overall and not really promoting cycling in the inner city neither.

[12] In actual power systems, CCGT output is not constantly meeting the marginal power loads (recall that the high efficiency of CCGT is but reached at full load conditions). A common CHP plant of 35–40 percent power efficiency is of higher merit than a peak-load unit of 25–30 percent efficiency, but the CHP activity will be constrained because it falls short of the nominal 50–55 percent of its external benchmark reference. This is an example of how external benchmarking becomes perverse. It obliterates the regulatory roles. Comparing power generation performance of some CHP plant with power from the grid is to be done by a clear regulation of grid access pricing. Promoting CHP (as the EU wants) is to be done on the basis of the own merit of CHP.

[13] This analysis assumes CHP activity be constrained exactly up to the norm. When tighter norms are imposed, e.g. CHP only qualifies when it does 1.10 times better than the norm (a 10% stricter requirement as the 2004 Directive imposes), the truncation and perverse effects are amplified.

The *quality norm* links the outputs of a CHP *plant* to the efficiencies of reference separate heat and power generation processes and is defined as (see table in Annex of CEC, 2002)

$$1-1/\{\alpha_E/\eta_{ERS}+\alpha_Q/\eta_{QRS}\}$$

Verbruggen (2007b) shows that the *quality norm* entails little incentive to improve the real quality of the CHP process. This is a crucial shortcoming because the future of CHP depends on its competitive position and this in turn is dependent on the quality of the processes. The more electricity a CHP plant can generate the better for the competitiveness of CHP.

While the *quality norm* is not effective in stimulating CHP quality it is perverse in truncating the production possibilities of CHP plants. Investment in well scaled and flexible CHP capacity is choked by the qualification proposal. In existing plants, CHP operators are driven to produce smaller quantities of power either by part-loading or by shutting down capacities. Most of the negative effects are due to the amalgamation of the cogeneration and condensing activities in the CHP plants into plant quantities, and by omitting the careful identification and measurement of the actual CHP activity within such plant (see Table 3).

## 4. Conclusion

CHP is a well-known and wide-spread way of converting fuels into power and heat. When applied well it can contribute to a more efficient use of energy. It is argued that policy needs a vision, but that the visions on CHP are wide ranging and are often quite opposite. Starting from the thermal power plant as the cradle of CHP provides firm ground to the analysis.

When a public authority wants regulating a something, such as CHP, it has to define the something accurately, because "one cannot manage what one does not measure". Measuring CHP activity has shown to be particularly tricky when CHP is operated in mixed combined and condensing states. The EU Directive (February 2004) did not master the measuring problem. CEN (September 2004) did a large step forward, without, however, closing the measuring circle. How to close the gap is shown in Section 2.3.

The electric output of the CHP activity is a necessary and sufficient indicator of CHP performance. A regulator may add some extra considerations, but should focus by preference on the procedures for the accurate observation of the design power to heat ratio of CHP activities and on a good monitoring and reporting of the recovered heat flows.

The EU Directive qualification proposals use external benchmarking methods on the amalgamated outputs of cogeneration plants. This can have very perverse impacts on the development of CHP. CEN refrains from entering the qualification debate.

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