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Quantifying Combined Heat and Power (CHP) activity

Aviel Verbruggen

University of Antwerp,
Prinsstraat 13, B-2000 Antwerp, Belgium
Fax: +32 3 220 49 01
E-mail: aviel.verbruggen@ua.ac.be

Abstract: In CHP plants without heat rejection facilities power output is complementary to the recovery of heat, and all activity is cogeneration. CHP plants with heat rejection facilities can operate a mix of cogeneration and condensing activities. Quantifying the energy flows of both activities properly requires knowledge of the design power-to-heat ratio's of the CHP processes (steam and gas turbines, combustion engines). The ratio's may be multiple, non-linear or extend into the virtual domain of the production possibility sets of the plants. Quantifying cogeneration in CCGT plants reveals a definition conflict but consistent solutions are available.

Keywords: combined heat and power; CHP; co-generation; production possibility set; joint production; power-to-heat ratio; CCGT; back-pressure; extraction-condensing.

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Biographical notes: Aviel Verbruggen studied Engineering Sciences at the Catholic University of Louvain, and Economics at the University of Antwerp, where he got his PhD in 1979. He researches energy and environmental issues from an applied and interdisciplinary perspective, covering topics such as power generation, co-generation, regulation and pricing and energy efficiency. In the 1990s, he was the first President of the Flemish Environmental Council. He designed and edited the state-of-the-environment reports in Flanders, and served for two years in the cabinet for environmental policy. He is contributing to IPCC, WGIII (third and fourth assessments), and is a member, supervisor or chairman of a number of research groups and networks on energy and environmental issues.

1 Introduction

This second paper discusses how to identify and to quantify CHP activity. The manager's maxim "*you cannot manage what you do not measure*" teaches regulators that they may not be able to regulate CHP well when they do not identify and quantify it well. CHP activity is measured by three energy flows: the amount of recovered useful heat, the amount of co-generated electricity and the amount of fuel consumed therefore. The first quantity is directly measurable when agreement is reached where and how to metre the recovered heat flows (CWA CEN/CENELEC Workshop Agreement, 2004).

The quantities of co-generated electricity and of fuel consumed are not directly observable in case co-generation and condensing activities co-exist and are mingled. Assessing the quantities is subject of discussion (Euroheat & Power, 2002; CWA CEN/CENELEC Workshop Agreement, 2004). Quantifying is not a problem when the CHP plant is limited to only co-generation activity (e.g., a back-pressure steam turbine), and *cannot* operate in condensing or in mixed modes. But when mixed condensing and co-generation activities take place, one needs a method to split the co-generation activity from the condensing activity. Annex II of the EU CHP Directive (EP, 2004) addresses the issue in an unsatisfactory way. Although the basic principle "the amount of electricity from co-generation power is the product of the power-to-heat ratio and the amount of useful heat from co-generation" is right, 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, CCGT plants with co-generation. By lacking the right method, Annex II offers average default values by technology group, but this very approximating approach is not stimulating efficient investments and efficient operations.

A clear division rule for splitting the power output in condensing and combined parts is needed, with solutions in case the power-to-heat ratio is not a single constant, but a function of heat loads or takes on multiple (functional) values. Also the special case of co-generation at a CCGT plant requires specific attention. The developed methods must obey three criteria:

- *Workable*. Every procedure that must be applied EU wide in all member states and in a numerous number of installations and applications should be transparent and as simple as possible. Opaque formulas and calculations difficult to implement should be avoided. The methods should support cheap monitoring and enforcement.
- *Correct*. The methods must identify what is to be identified, i.e., the combined (share of) power generated in CHP plants and the related fuel consumption. The amounts should be estimated within a rather small fault margin.
- *Right incentives*. The EU Directive is meant to stimulate CHP development not to nip it in the bud. Incentives are important at the moment of investment when technology, design and scale are fixed, and during operation. CHP investors should be stimulated to opt for high-quality processes and correctly dimensioned plants with the installation of condensing facilities whenever technically and economically feasible to enlarge the production possibility sets. CHP operators should be stimulated to recover the maximum amount of heat. Avoid including average parameter values or thresholds that protect laggards and refrain pioneers.

After a short reference to the 2004 CHP Directive (Section 2), Section 3 shows the basic division rule for assessing the quantity of co-generated electricity and of fuel consumed. Then the basic rule is extended for accommodating special cases one encounters in practical technologies (Sections 4–6). In particular, the embedding of a CHP activity in a large condensing plant (Section 7) and the placement of a gas turbine ahead of a steam turbine run as co-generation unit (Section 8) require specific solutions. A brief conclusion rounds up the paper (Section 9). A common set of symbols is used throughout the analysis (Table 1).

Table 1 CHP nomenclature

Q	Heat flow (Wh)[†]
$Q_{\mathrm{CHP}} = Q_{\mathrm{useful}}$	Heat recovered in thermal power generation for an end-use
$Q_{\mathrm{Cond}} = Q_{\mathrm{waste}}$	Heat dissipated related to condensing thermal power generation
Q_{plant}	Heat set free at the thermal power generation process, i.e., $Q_{\mathrm{CHP}} + Q_{\mathrm{Cond}}$
E	Electricity flow (Wh)[†]
E_{CHP}	Electricity output from combined or 'back-pressure' 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., $E_{\mathrm{CHP}} + E_{\mathrm{Cond}}$
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., $F_{\mathrm{CHP}} + F_{\mathrm{Cond}}$
CQ	Heat recovery capacity (W)[†]
CQ_{CHP}	Maximum heat recovery capacity given the parameters of the CHP process
CQ_{real}	Realised heat recovery capacity of the CHP process
CE	Electricity supply capacity (W)[†]
CE_{Cond}	Electric capacity in pure condensing operation
CE_{CHP}	Electric capacity in CHP operation, for a given level of heat recovery
h	Number of hours of co-generation activity within a given accounting period
q	Heat load factor = $Q_{\mathrm{CHP}}/(h \cdot CQ_{\mathrm{real}})$
S	*Bliss point* of the production possibility set of a CHP process, where at maximum output of useful heat the co-generated power output is also maximised. Complex CHP processes can exhibit multiple bliss points, while they also can be virtual (= outside the actually attainable production possibilities)
σ	*Design* power-to-heat ratio of a CHP process. Mostly σ 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 σ as a function (see analysis)
η	Overall energy conversion efficiency of the CHP plant $(E_{\mathrm{plant}} + Q_{\mathrm{CHP}})/F_{\mathrm{plant}}$
η_{CHP}	Energy efficiency of CHP activity or $(E_{\mathrm{CHP}} + Q_{\mathrm{CHP}})/F_{\mathrm{CHP}}$
η_{Cond}	Efficiency of the pure condensing activity of the CHP plant $(E_{\mathrm{Cond}}/F_{\mathrm{plant}})$ when $Q_{\mathrm{CHP}} = 0$
β	Power loss factor by a heat extraction at a steam turbine (directly linked to σ through η_{Cond} and η_{CHP})
α_E	The electric efficiency of the CHP plant $E_{\mathrm{plant}}/F_{\mathrm{plant}}$
α_Q	The heat efficiency the CHP plant $Q_{\mathrm{useful}}/F_{\mathrm{plant}}$
η_{ERS}	The electric efficiency of the *reference separate* electricity generation process
η_{QRS}	The heat efficiency of the *reference separate* heat process

[†] With capacities in W (Watt) and energy in Wh, the axes of the Electricity-Heat graphs can represent both capacities and energy flows per hour (momentary or average values).

2 The EU directive 2004/8/EC on identifying/quantifying CHP activity

Annex II of the EU Directive is titled "Calculation of electricity from co-generation" (EP, 2004, p.L52/58). It opens with "values used for calculation of electricity from co-generation shall be determined on the basis of the expected or actual operation of the unit under normal conditions of use". Then it splits the problem in two cases. First, when the overall thermal efficiency 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% efficiency threshold applies for a CCGT with heat recovery and for a steam condensing extraction turbine.

Second, when overall efficiency falls short of the stated thresholds, co-generated electricity E_{CHP} is calculated according to the formula $E_{\mathrm{CHP}} = C \cdot Q_{\mathrm{CHP}}$, where C is the power-to-heat ratio. Article 3(k) of the Directive (p.L52/53) states

> "'power-to-heat ratio' shall mean the ratio between electricity from co-generation and useful heat when operating in *full co-generation mode* using *operational* data of the specific unit."

This definition improves the versions of the first draft (CEC, 2002) by emphasising the *full* co-generation mode for the measurement of C. The use of operational data for assessing C requires more detail about how to proceed for a variety of technologies and circumstances. One would expect to get this in Annex II, but there is 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 co-generation electricity is less or equal to total electricity production of the unit."

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.

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 activities surpassing overall efficiencies of 75% and 80% will be composed predominantly of co-generation, threshold values are arbitrary. It would be better to *accept all electricity as* E_{CHP} *when the plant is not equipped with heat rejection (condensing) facilities*, because there may be particular conditions why the overall efficiency falls short of the efficiency thresholds, e.g., when the plant is combusting waste fuels and/or operates under difficult circumstances.

The real problem of identification arises when the CHP activity is embedded in a plant with condensing facilities that is operated in mixed mode during a significant part of the year. Here the Directive offers unsatisfactory guidance, because what is the "actual power-to-heat ratio" of the various CHP plants? Also it is not very consistent to define the actual power-to-heat ratio on operational data, supplying in the meantime default values that relate to some average design/tombstone characteristics of particular plant types. Furthermore, such default values are quite arbitrary and do not entail incentives for investors and operators to optimise CHP processes.

Presumably because of the remaining 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 co-generation 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 harmonisation, being stated as the "general objective of the Directive" (see the "whereas no. 15", p.L52/51). This paper discusses a unified method to identify and quantify E_{CHP} and F_{CHP} for the broad variety of CHP technologies.

3 Basic division rule for identifying CHP activity

The problem at hand is splitting the outputs of the joint CHP activity in co-generated outputs and in non-co-generated (condensing) outputs. For heat, distinction between useful and wasted heat is easy to observe (CWA CEN/CENELEC Workshop Agreement, 2004). For electricity, distinction between co-generated and condensing power is not evident and subject of much confusion. Fuel consumption correspondingly must be split in a part used for CHP activity and a part used for condensing activity (Franke, 2004).

The *first* step in this process is to distinguish CHP units that do not own heat rejection (condensing) facilities from the ones that own such facilities. All electricity forthcoming from the former group of CHP processes can be labelled univocally as CHP power and all fuel used as CHP fuel, without further consideration on efficiency or whatever. Examples of such processes are pure back-pressure turbines, engines or gas turbines without condenser equipment, etc.

Direct certification of such CHP processes is favoured without further bureaucracy. The 75% and 80% (EU Directive Annex II) threshold values in overall thermal efficiency should not be maintained because there may have been good reasons that the values could not be reached.

A *second* step addresses the real issue of splitting power flows and fuel consumed when co-generation and condensing generation modes co-exist. In its mixed operational states, a CHP plant converts fuel into *three* products: E_{CHP} (co-generated power), E_{Cond} (condensing power) and Q_{CHP} (recovered heat).

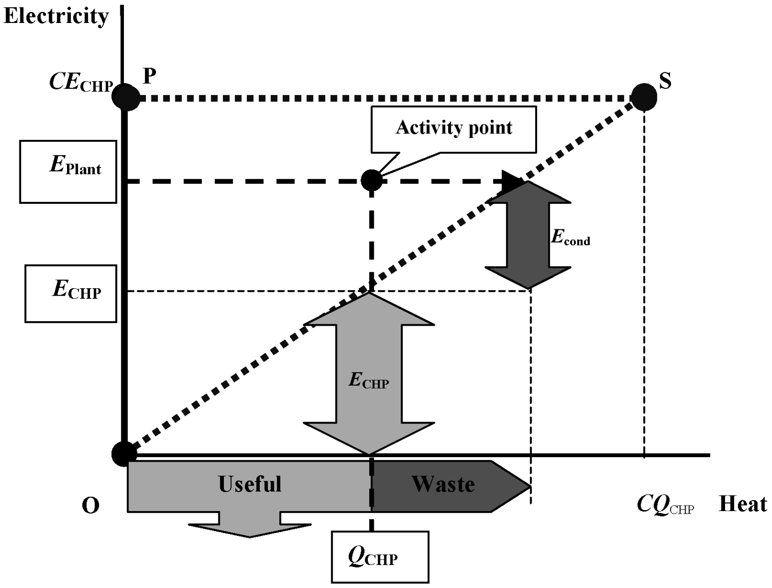
Because CHP promotion requires promoting the possibility for a CHP plant to also function in a non-fully co-generation mode, this blended mode in itself should not be penalised by the qualification procedure. So for every given period the batch of electricity generated can consist of any proportion from 0% to 100% co-generated vs. condensing power. CHP qualification however can only be based on the co-generated part of power and on the fuel used for the co-generated activity (see *Qualifying CHP Activity*).

The CHP plant must submit two sets of data to the regulator:

- The *parameters* of the technology and equipment involved, mostly fixed in the *design phase* of a CHP plant. CEN/CENELEC details the type of data necessary to assess the power loss parameters β of CHP units (CWA CEN/CENELEC Workshop Agreement, 2004), and our method needs similar information to obtain the design power-to-heat ratio's σ and η_{Cond} (electric efficiency of the pure condensing mode).
- Dividing the year in distinct *accounting sub-periods* (Hours? Days? Weeks? Months? Seasons?). These function as the reference time spans for adding the energy flows on which the regulation applies. The division rule is little dependent on the sub-period choice but finer accounting offers regulatory benefit. *Reporting and evaluation* can occur after a large number of accounting periods, e.g., adding to a year.

The basic division rule to be applied on the electricity batches per unit period uses the *design* ratio σ of the CHP process (Figure 1). The design ratio is measured at the *bliss point* of the unit. This is the point where the sum of useful heat CQ_{CHP} and power CE_{CHP} capacities are maximised, because there the maximum power capacity is delivered at the moment the maximum useful heat flow is or could be recovered, or $\sigma = CE_{\mathrm{CHP}}/CQ_{\mathrm{CHP}}$.

Figure 1 Splitting the mixed (joint) activity of a CHP plant into a co-generation part and into a condensing part



In this proposal, σ is a *design or tombstone characteristic* of every particular CHP plant that has to be certified. In this certification process, the regulator can start from reference values valid in the year the CHP plant is built and registered, leaving for the CHP investor the proof that his plant exhibits better characteristics than the reference values. Annex II of the CHP Directive grossly (because only a few crude average values are applied) accepts this practice.

The quantity of co-generated electricity in every accounting period is assessed by multiplying the metred amount of useful heat during the same period with the σ ratio.

So the basic division rule is:

$$E_{\text{CHP}} = \sigma \cdot Q_{\text{CHP}}.$$

The division rule is derived from the production possibility sets of CHP technologies (see CHP Essentials). It is based on the distinction between co-generation and condensing operational modes. For every point in the area OSP one must find how much of the mixed activity gets the label 'co-generation' and how much is labelled 'condensing'. The principle of the division rule is shown in Figure 1.

In an accounting period, the metred variables are the fuel consumed by the plant F_{plant}, the electricity generated in the plant E_{plant}, and the useful heat recovered from the plant Q_{CHP}. With the tombstone parameters σ and η_{Cond}, the division rule is based on the equal portioning principle $Q_{\text{CHP}}/Q_{\text{Cond}} = E_{\text{CHP}}/E_{\text{Cond}}$ or $E_{\text{CHP}}/Q_{\text{CHP}} = E_{\text{Cond}}/Q_{\text{Cond}}$.

In addition, the *design power-to-heat ratio* σ is equal to the above ratios, or:

$$E_{\text{CHP}} = \sigma \cdot Q_{\text{CHP}},$$

and

$$E_{\text{Cond}} = E_{\text{plant}} - E_{\text{CHP}}.$$

One must also split the plant fuel input into a part for the co-generation activity and a part for the condensing activity (Franke, 2004). When *PS* is (almost) horizontal (engines, gas turbines, fuel cells) one can continue the portioning principle, but when PS is sloping downward (steam turbines), the allocation of the fuel consumption is only accurate when the substitution of heat for power (power loss) is accounted for. This is taken care of by:

$$F_{\text{CHP}} = F_{\text{plant}} - (E_{\text{Cond}} / \eta_{\text{Cond}}).$$

The division rule assesses co-generated power E_{CHP} and co-generation fuel consumption F_{CHP} in a transparent and reliable way. Basing regulation on these values, assessed correctly as the division rule prescribes, also entails the right incentives to the CHP plant designer and CHP plant operator. When designing CHP units, the investor gets a stimulus to search for the plant with the highest σ or quality. When operating the plant, the operator will recover the maximum of heat Q_{CHP} to give it a useful destination.

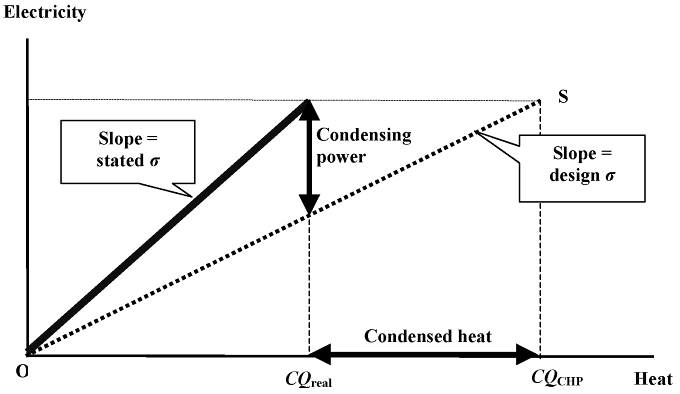
The division rule is most simple when proportionality of the co-generation process along ray OS prevails. Considering the expansion of fluids in turbines and the functioning of reciprocating engines, proportionality is the logical working hypothesis. The German CHP Association argues similarly and was also critical of the vagueness of the draft Directive's power-to-heat ratio definition (B.KWK, 2002).

However, it is necessary to investigate the existence and uniqueness of the design ratio σ measured in the bliss point *S*, in relation to the production possibility sets of CHP processes. Complex processes require extensions to the basic method that must remain transparent and straightforward to perform. The main cases are addressed in Sections 4–8.

4 Reporting bias of the design σ

When a CHP plant investor or owner learns about the basic division rule for quantifying and for later qualifying CHP power, there will be a positive incentive to maximise the power-to-heat ratio of the plant when designing a CHP plant and to maximise the heat output when operating the unit. But given the tombstone character of σ for a given plant, the incentive exists to exaggerate the value of the ratio during the process of certification, by e.g., withholding from declaration part of the accessible useful heat capacity CQ_{CHP} or by exaggerating the corresponding CE_{CHP} at the bliss point, in particular when the bliss point of the plant is virtual because one does not apply the full heat recovery opportunities (Figure 2).

Figure 2 Real heat recovery capacity is less than feasible maximum



The first cheat could be attempted for a CHP engine where the heat recovery is staged (motor jacket cooling, lubrication oil cooling and flue gas cooling at various levels of gas temperatures) with some range $CQ_{\text{real}} < CQ_{\text{CHP}}$ can take on. The bias consists in hiding some part of the heat recovery capacity CQ_{CHP} stating a faulty, higher design σ value based on e.g., CQ_{real}. The incomplete information may result from investors not exhausting all recovery capabilities of their plant. Also, some with full recovery capabilities can after certification of an overestimated σ value operate their larger heat recovery capacity for producing more Q_{CHP}, being the second factor of the multiplication in the division rule for assessing E_{CHP}.

This bias can be contravened by some provisions in the regulation. First, the regulator should rely on independent and certified institutions to investigate and certify the production possibility set of a plant that solicits qualification. Most existing plants own a report on acceptance of delivery of the plant where the design capacities are specified, but assessment of virtual bliss points will mostly lack and require some additional certification work in assessing the extent of the foregone heat recovery capability of the plant ($CQ_{\text{CHP}} - CQ_{\text{real}}$ in Figure 2).

Cheating when $CQ_{\text{real}} = CQ_{\text{CHP}}$ can be penalised by adding a calculation. Noting the operating hours h during the accounting periods, one computes the *heat load factor* q on the basis of the declared CQ_{CHP} value that was used in the σ fixing. The heat load factor q is the metred useful heat flow during the accounting period divided by the maximum flow that could have been generated when the maximum heat capacity was delivered during

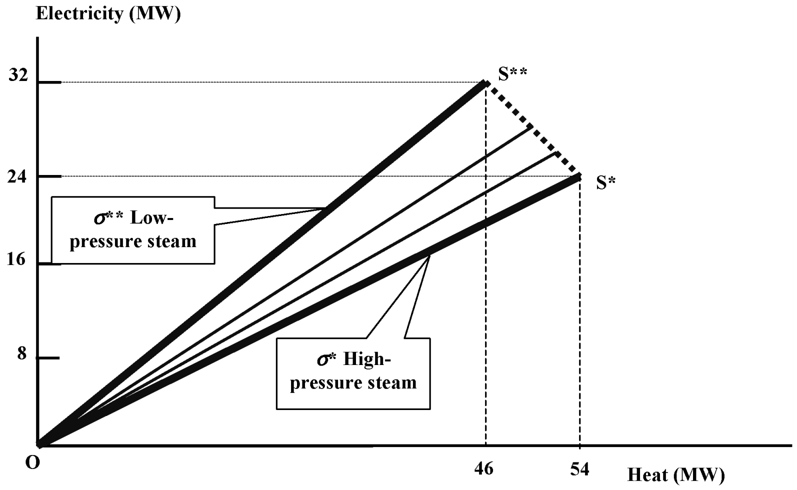
h hours, or: $q = Q_{\text{CHP}}/(h \cdot CQ_{\text{stated}})$ and by definition q must be less or equal to 1. When $q > 1$ during a particular accounting period, it proves that a too low value of CQ_{CHP} had been declared. Then, the measured heat flow Q_{CHP} would be truncated to a lower value to make the heat capacity factor equal to 1 (or to some lower penalty value when cheating should be condemned more firmly). One will also adapt the first set σ value based on the too low reported value to a new one based on the evidently higher CQ_{CHP} value found by dividing Q_{CHP} by h. For using the heat load factor as a control on the true CQ_{CHP} value and for adjusting the quantification of flows on it, it helps the periods of accounting CHP performance should be taken sufficiently short.

The second way of trying to bias the design σ is to exaggerate the CE_{CHP} capacity at the bliss point, e.g., by increasing the gas inlet temperatures of a gas turbine to the overdrive levels. In principle this type of cheating can be overcome by reliable plant certificates and if necessary by a control of the process imposing overdrive conditions upon nominal working conditions.

5 Multiple and shifting design ratio’s

In some CHP processes the design ratio σ is not unique but shifts with the characteristics (pressure/temperature) of the recovered heat. Typical example is the steam turbine with steam exhausts at several points in the expansion path (Euroheat & Power, 2002; CWA CEN/CENELEC Workshop Agreement, 2004). The possibility set of such a CHP unit is shown in Figure 3 where the back pressure part of a steam turbine is shown while omitting the condensing mode on top of it. The incomplete picturing of the full production possibility set is for didactical reasons and not to be seen in conflict with Section 3 where it was proposed that all power from a pure back-pressure cycle by definition is CHP power and so the division problem is of no relevance. One should read Figure 3 as the bottom part of the production possibility set of an extraction-condensing unit (see Figures 6–8 in CHP Essentials) where the division problem is real.

Figure 3 Production Possibility Set of an extraction-condensing steam turbine (only back-pressure part shown) with two hot water condensers



When a steam turbine is equipped with two hot condensers, steam can be exhausted at high pressure cutting off a larger segment of the power generating steam expansion path (line OS^* in Figure 3). When the steam is allowed to expand further to the next hot condenser more power will be generated but also less useful heat (OS^{**}). Indeed the law of conservation of energy teaches that steam energy not converted into electricity will show up as heat at the condensers. When one can balance the steam extraction between the two condensers the power-heat combinations follow the segment S^*S^{**} (full load operation) or any of the rays ending on this segment (part load back-pressure operation). Given that the slope of such a ray is the σ of the process in that mode, it is obvious that there are many σ's. In Figure 3 there is a shift of σ from 0.4444 (high-pressure steam) to 0.6956 (low-pressure steam).

How to handle this problem?

Some cases could be solved in convening an average σ per accounting period (CWA CEN/CENELEC Workshop Agreement, 2004, p.38, e.g., proposes average power loss coefficients). For example, a district heating steam turbine with two hot water condensers (one for summer regime at low temperature and pressure and one for winter regime at higher temperature and pressure) may be assigned a different σ for every month of the year. This is an acceptable approach in some cases but sensitive to fraud and protracting discussions, and it will require regular certification (high transaction costs).

An accurate solution consists in the definition of more than one design power-to-heat ratio σ for the unit, and in the measurement of the useful heat flows in separate temperature and pressure classes as CWA CEN/CENELEC Workshop Agreement (2004, p.31) proposes. So, at the various hot condensers or extraction points the heat flows are measured separately and their contribution to the generation of combined power is obtained by multiplication with the suitable design ratio. In the example of Figure 3, two flows have to be measured and multiplied by respectively σ^* and σ^{**}.

More generally for *i* types of useful heat recoveries, one can state:

$$E_{\text{CHP}} = \sum_i \{\sigma_i \cdot Q_{\text{CHP}i}\}.$$

For assessing the co-generation fuel consumption, the formula $F_{\text{CHP}} = F_{\text{plant}} - (E_{\text{Cond}}/\eta_{\text{Cond}})$ remains valid, with $E_{\text{Cond}} = E_{\text{plant}} - E_{\text{CHP}}$.

6 The design power-to-heat ratio is not constant at part-load and/or partial back-pressure operation

Another objection against the use of a constant design ratio at the bliss point as the basis for identification of CHP activity will be that the co-generation operational mode does not follow the straight ray from the bliss point *S* down towards the origin, i.e., the proportionality is not perfect in part-loading conditions. Past studies (Bach, 1978; Verbruggen, 1982) of possibility sets revealed that part-load functioning in pure back-pressure mode causes but a small deviation from proportionality when part-load does not fall below particular thresholds (40% of the capacity). Below the thresholds efficiency loss can be significant up to the point of having to shut down the unit.

One must distinguish *partial* co-generation from *part-load* operation. Coming down the OS curve means effective *part-load* charging of the unit. In plants equipped with condensing facilities *partial* co-generation operation is feasible with the plant fully loaded. Only the latter type of plants can operate in a mixed mode where the CHP identification problem is real.

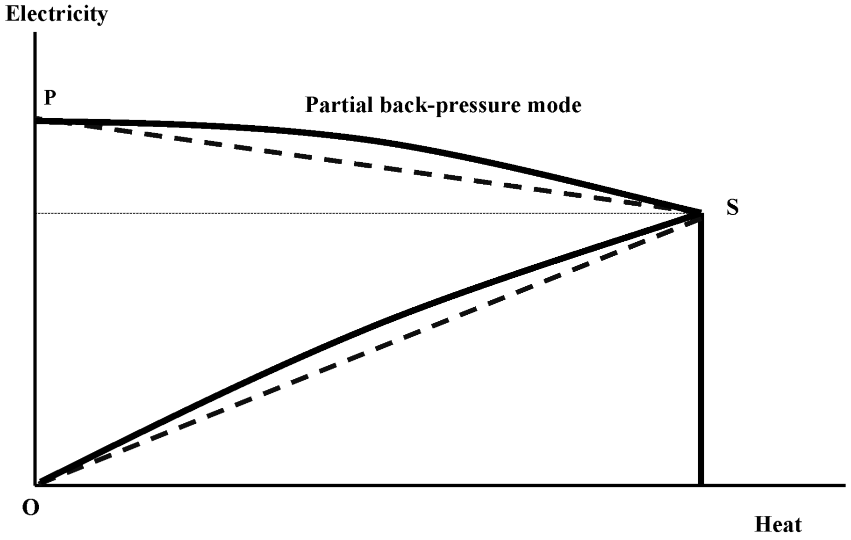
In extraction-condensing steam turbines (with mixed mode) loading of the unit is generally high, but one still may argue non-proportionality. The regulator can provide the opportunity to such operators to reveal the true curve $\sigma(q)$ and once the curve known the procedure is straightforward. For every accounting period one calculates the *heat load factors* q_i of the i CHP activities. With the results of Section 5 the division rule is extended to:

$$E_{CHP} = \sum\nolimits_i \{\sigma_i(q_i) \cdot Q_{CHPi}\}.$$

Where the power-to-heat ratios are represented as analytical functions $\sigma_i(q_i)$ with as argument q_i being the heat load factor of heat flow i or $q_i = Q_{\mathrm{CHP}i}/(h_i \cdot CQ_{\mathrm{real},i})$ where $Q_{\mathrm{CHP}i}$ is the heat amount recovered at point i and h_i is the number of hours the hot condenser or extraction point i with heat recovery capacity $CQ_{\mathrm{real},i}$ is operated.

In extraction-condensing steam turbines *partial* CHP loading is of higher interest. There is little evidence that the power/heat substitution line PS is non-linear as the curve in Figure 4 shows. CHP interests may argue that the partial back-pressure curve is situated above the ray, and ask for a higher power-to-heat ratio than the one of the bliss point. This is the implicit statement in the Euroheat & Power (2002) approach, but CWA CEN/CENELEC Workshop Agreement (2004) only deals with linear power loss coefficients.

Figure 4 Production Possibility Set of an extraction-condensing CHP unit with full back-pressure capability and with non-proportionality in partial back-pressure working



Eliciting in a direct way, the non-proportional part-load back-pressure curve *OS* is difficult or impossible for many plants. But it is feasible to monitor the electricity performance of a fully fuel loaded extraction-condensing steam turbine when it shifts the useful heat recovery regimes from zero recovery (point *P*) to the maximum recovery (the bliss point *S* or a point to the left of it when $CQ_{\text{real}} < CQ_{\text{CHP}}$) (CWA CEN/CENELEC Workshop Agreement, 2004, p.39). This is the curve *PS* that is considered mostly as linear, but that may also show a slight curvature (upwards or downwards the straight line). Figure 4 illustrates the upward case (favourable to CHP). The standard rule accepts that the curvature on the top line *PS* is forthcoming from a curvature on the back-pressure line *OS*. Figure 4 shows the congruence.

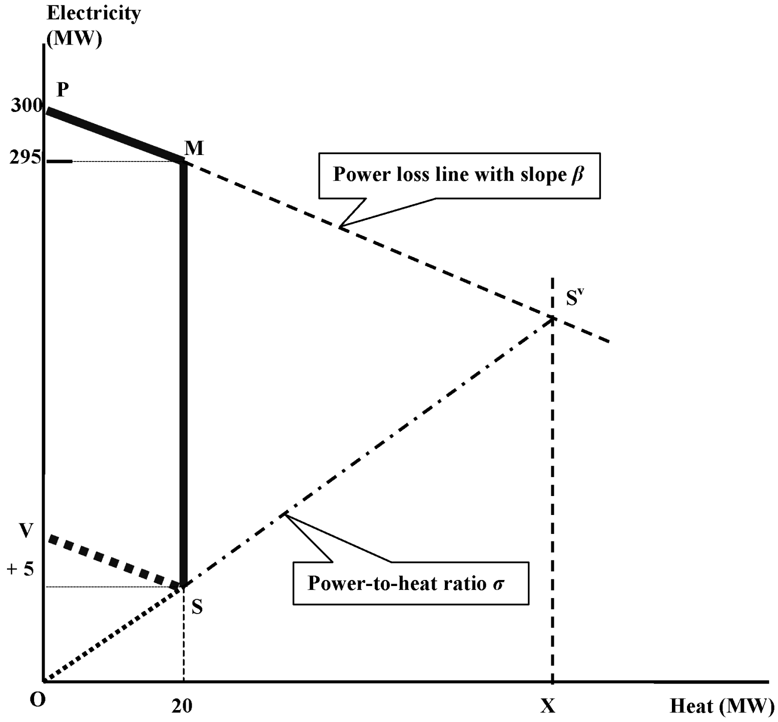
Deviations from proportionality prove to be small in practice and one can deny the small differences. For CHP plants where the real curve is below the straight line no protest will be heard. Others can do the effort to reveal and let certify the true curve.

7 The CHP process is embedded in a larger condensing power unit

Most problems in fixing the true design power-to-heat ratio's come up at condensing power units with a limited CHP capability built into the larger condensing plant. In Section 4 this was discussed for a plant without power loss by heat recovery (Figure 2). More important are the large-scale steam power plants that include a small CHP activity by extracting part of the processed steam at one or more points at the turbines.

Figure 5 shows the example of a 300 MW condensing unit that allows the delivery of 20 MW of useful heat by giving up 5 MW of electricity (power loss $\beta = 0.25$). Let the live steam flow to the unit equal 690 MW at full load.

Figure 5 Production Possibility Set of a condensing turbine with a small CHP activity



The points observable are the full condensing operational modes on segment *OP* and the mixed states on *PM*, with *M* as the maximum useful heat recovery of 20 MW with a loss of 5 MW in electric output. But what is the applicable design power-to-heat ratio σ of this CHP activity? To explain our method, a small CHP possibility set OSV is drawn inside and at the bottom of the much larger CHP + condensing set OSMP. Because the extraction can occur at several points (different pressure and temperature) shifting power-to-heat ratios (Section 5) may occur here too, and we will work this out further.

Directly fixing point *S* is not possible because no clear maximum back-pressure condition can be observed. Therefore one extrapolates the small CHP activity on the whole live steam flow.

Graphically one extends the power loss line PM with slope β down point *M*, and one calculates the maximum heat output corresponding to the virtual bliss point S^v of the unit. Where both lines cut one has found S^v. Next, point S is pinned down on the ray OS^v at the abscissa $CQ_{\text{real}} = 20$ MW. The algebra is based on the first law of thermodynamics (neglecting non-recoverable losses from heat radiation that are mostly small):

Live steam flow = electric output + useful heat output + lost heat output.

This equation is solved for the condition of full back-pressure operation, making the last term of the above equation equal to zero. In the virtual bliss point S^v the live steam flow is at its maximum or nominal value. With the numbers of the example one finds the so far unknown maximum feasible heat recovery CQ_{CHP} by:

$$690 = \{300 - (5/20)CQ_{\text{CHP}}\} + CQ_{\text{CHP}}$$

or

$$CQ_{\text{CHP}} = 520 \text{ MW}.$$

The (*E*, *Q*) coordinates of S^v are therefore (170, 520) and the design power-to-heat ratio σ equals 0.327. Point *S* has coordinates (6.54, 20). This example shows that the necessary information for stating the design σ or σ's requires the same effort as the measurement of the power loss coefficients of the CHP units (CWA CEN/CENELEC Workshop Agreement, 2004).

One further can call upon the full Mollier diagrams (Reynolds and Perkins, 1977) of the process cycle and assess more empirically the position of points S^v and *S*. However, the division rule is not blocked when such extensive calculations would not be feasible.

Once *S* is fixed it is possible to construct the possibility set of the OSV CHP process consisting of a condensing mode and a back-pressure mode that meet at point *S*. The possibility set is represented by the triangle OSV in Figure 5.

In pure condensing mode, the CHP process would generate 6.54 + 5 = 11.54 MW. This is 3.85% of the total condensing capacity. The fuel consumption of the CHP process also equals 3.85% of the nominal fuel consumption of the plant (e.g., equal to 780 MW). Continuing the example, the overall efficiency at point *S* would equal (6.54 + 20)/{(0.0385) · (780)} or 88.5% (compared to 38.5% in pure condensing mode).

CEN/CENELEC publishes a method to solve the CHP jointness problem. The CWA method is also based on design parameters of the CHP plant, i.e., the power loss coefficient(s) β and η_{cond} but introduces a fixed value of 80% for η_{CHP}, the energy efficiency of CHP activity, to exit a circular logic in the formulas. One of the case studies

(CWA CEN/CENELEC Workshop Agreement, 2004, pp.64–66) is comparable to the situation of Figure 5, and here their method is compared with the division rule.

Table 2 shows the data of the CWA case with addition of the symbols used in this paper. Table 3 shows the outcomes of the two methods, with the differences in italics.

Table 2 Numbers of the CWA case-study

Variable	*Value*	*Our symbol*
Fuel use of the CHP plant	800 GWh	F_{plant}
Efficiency of the live steam boiler	90%	–
Pure condensing power efficiency	29.375%	η_{Cond}
Power generated by the plant	200 GWh	E_{plant}
Heat recovered at the plant*	150 GWh	Q_{CHP}
Power loss of heat extraction*	0.233 (=35/150)	β

*The CWA case uses two extractions but then adds the two and averages the power loss factors (Section 5).

Source: CWA CEN/CENELEC Workshop Agreement (2004, pp.64–66)

Table 3 Results from the CWA method and from the division rule (differences in italics)

Variable	*CWA method*	*Division rule*
Live steam use of the CHP plant	720 GWh	720 GWh
Power-to-heat ratio	*0.212*	*0.138*
CHP Power E_{CHP}	*31.728* GWh	*20.722* GWh
Condensing power E_{Cond}	*168.272* GWh	*179.278* GWh
Fuel for condensing power F_{Cond}	*572.840* GWh	*610.308* GWh
Fuel for CHP activity F_{CHP}	*227.160* GWh	*189.692* GWh
Overall efficiency of the plant η	43.75%	43.75%
Efficiency of the CHP activity η_{CHP}	*80%*	*90%*

Even on this stylised problem, the differences are significant (more than 50% in the crucial outcomes), forthcoming from the last line in Table 3. CWA adopts a fixed 80% conversion efficiency of the CHP activity, and the division method derives the 90% from the energy balance “live steam in = power + heat out”.

Graphically it means that CWA fixes always the bliss point of the CHP process where the total plant efficiency equals 80%. It follows that the CWA method cannot solve CHP cases with efficiencies higher than 80%, the threshold in the EU Directive. Such arbitrary fixings overestimate CHP power generated when in practice efficiencies are higher (Section 4). The CWA definitions for the power-to-heat ratio (CWA CEN/CENELEC Workshop Agreement, 2004, p.18, 38) are more transparent when written directly as $\{[80(1-\beta)]/[80-\eta_{\text{Cond}}]-1\}$ when $\beta \neq 1$, and $\eta_{\text{Cond}}/[80-\eta_{\text{Cond}}]$ when $\beta = 0$, making the role of the fixed 80% value becomes more clear.

Compared to the EU Directive 0.45 default value as power-to-heat ratio of steam turbines, the results of the above case study are very different. This does not mean that the default value is not a well chosen compromise of realistic β and η_{Cond} values, but the spread around the mean compromise is significant and therefore incentives are needed to surpass this mean. The CHP activity quantification method should include the design parameters of the particular units stimulating high design σ values through high η_{Cond} values and low β values. For example, within the CWA-method (fixed η_{CHP} at 80%) and with accessible efficiencies $\eta_{\text{Cond}} = 40\%$ and $\beta = 0.15$, then $\sigma = 0.70$ (the division method would reveal a lower value with $\eta_{\text{CHP}} > 80\%$).

8 The CHP process is embedded in a CCGT cycle

A combined gas turbine-steam turbine cycle is an application of heat flows used in cascade. The hot gases leaving the gas turbine can be either wasted (dissipated in the ambient air), or recovered for the supply of process steam or heat (CHP gas turbine), or recovered for the generation of live steam for feeding a steam turbine that generates power (standard CCGT). The latter also can be designed as a CHP unit delivering useful heat. When heat loads fluctuate over time the CHP steam turbine will be an extraction condensing one in order to guarantee a continuous takeoff of the gas turbine exhaust gases in the heat recovery steam boiler. This boiler may be equipped with additional firing to boost the live steam flow to the steam turbine by burning excess air in the hot exhaust gases from the gas turbine or for complementing the heat output of the gas turbine when the latter would function in part-load (a rather unlikely situation owing to poor part-load performance of gas turbines and the loss in power generated). Other additional firing for enhancing the live steam flow falls out of scope of the CCGT cycle itself, and is not considered here.

The stapling of a Brayton and a Rankine cycle requires additional clarification on what is considered to be CHP activity and what not. Figures 6–8 shows respectively the Production Possibility Sets (PPS) of

- a gas turbine with recovery of the hot exhaust gases
- an extraction-condensing steam turbine
- the stapling of both sets towards one overall set.

The numbers are chosen to reflect real-life efficiencies.

Figure 6 Production Possibility Set of a gas turbine with recovery of the hot exhaust gases (assume fuel input = 100 MW)

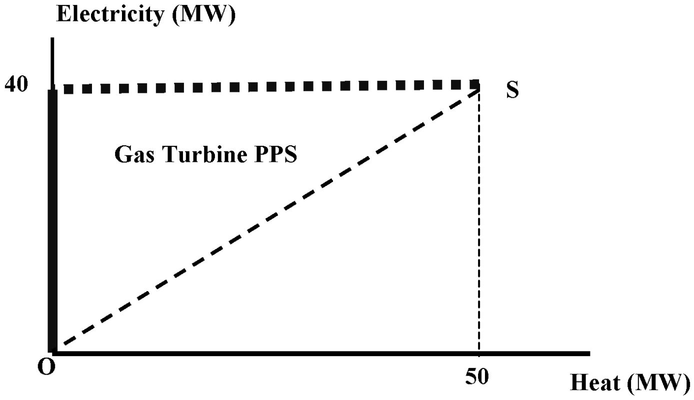


Figure 7 Production Possibility Set of an extraction-condensing steam turbine with maximum back-pressure opportunity as bottoming cycle of the gas turbine of Figure 6 and without additional firing

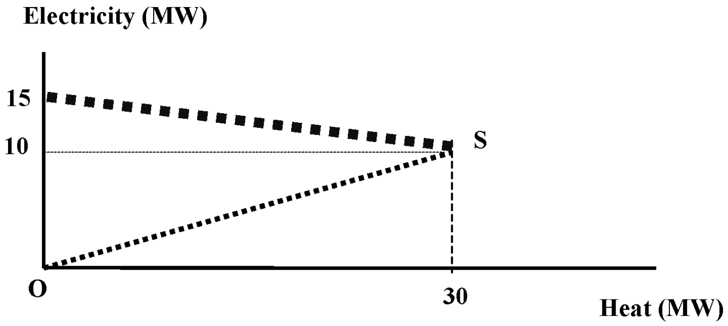
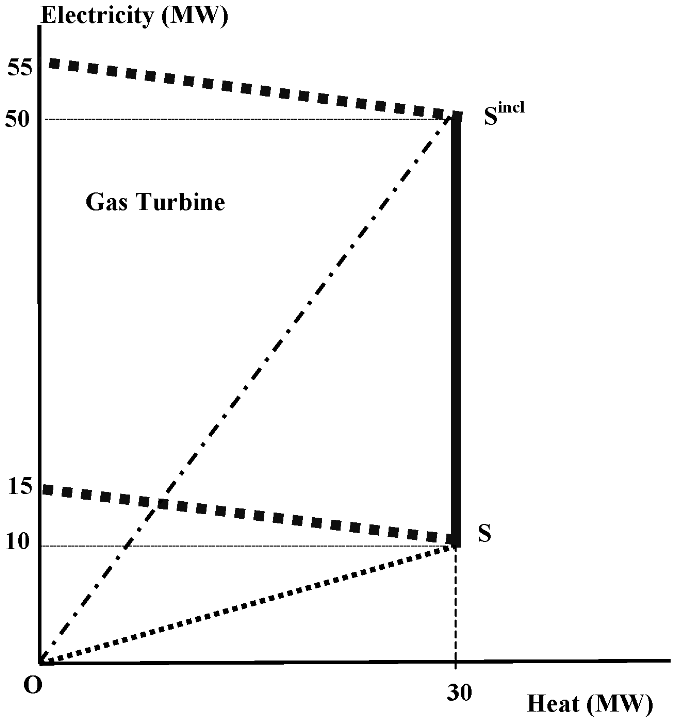


Figure 8 Production Possibility Set of a stapled gas turbine and an extraction-condensing CHP steam turbine as bottoming cycle



Given the poor part-load operation of gas turbines (proportionally more of the fuel is converted in heat instead of power) the real power-to-heat line will lie below the *OS* ray as has been discussed in Section 6. In CCGT stations full loading of the gas turbine is the rule to keep the efficiency at the high reference levels.

In Figure 7, the numbers are approximate to represent the results obtained with the live steam flow recovered from the gas turbine exhaust shown in Figure 6. Additional firing would extend the shown possibility set. Figure 8 staples the *full load* possibility set of Figure 6 on the set of Figure 7, what is the most likely operational mode.

Figure 8 shows the choice one has to make regarding the definition of CHP activity and performance of such a combined cycle CHP plant. There are two positions:

(1) ***All** power from the gas turbine is labelled as CHP power*. The power-to-heat ratio of the integrated CCGT is the slope of the steep ray OS^{incl} and the accounting result for CHP activity will be high. All fuel consumed by the plant is considered CHP fuel or $F_{\text{CHP}} = F_{\text{plant}}$.

(2) ***No** power from the gas turbine is labelled as CHP power*. The power-to-heat ratio is the slope of the shallow ray OS and the accounting result for E_{CHP} will be low. One must assign part of the plant fuel F_{plant} to the CHP activity as F_{CHP}.

So far, position (1) has been commonly stated and accepted assuming that the quality of a Combined Cycle CHP plant is expressed by the sum of the power-to-heat ratios. But this practice entails its own problems. First, for consistency reasons there is the case of assigning also CHP output certificates to every conventional CCGT plant without heat recovery at the steam turbine but because of the hot exhaust gases recovery at the outlet of the gas turbine (not for heat end-uses but for power generation). Secondly, in adding the gas turbine power output as a power output of the integrated CCGT-CHP cycle, there is an overestimation of the CHP performance of the gas turbine unit. Considered on its own the power-to-heat ratio equals 40/50 = 0.80 (Figure 6). Embedded with the steam turbine CHP activity the addition factor equals 40/30 = 1.33 (in Figure 8 the difference between the slopes of ray OS^{incl} and ray OS). There is some double counting in this addition because part of the recovered gas turbine hot gases output is recovered again as useful heat in the steam turbine unit. Thirdly, the practice blurs the core definition of CHP being the simultaneous supply of power + heat, not of power + heat/power + heat (CWA CEN/CENELEC Workshop Agreement, 2004).

Annex II of the EU CHP Directive holds an overall power-to-heat ratio of 0.95 as default value for a CCGT-CHP plant (EP, 2004), but the argument about this value is missing. The CWA method applied on the numbers of Figures 6–8 (that show $\eta_{\text{CHP}} = 80\%$), gives $\sigma = 1.67$ (for $\beta = 5/30$). Objecting the power loss is too little, $\beta = 0.25$ still gives $\sigma = 1.4$.

Given the above considerations, our preference is to limit the identification of CHP activity of such a combined cycle CHP plant to the back-pressure activity at the steam turbine unit, i.e., being based on the design ratio of bliss point S in Figures 7 and 8.

When this principle is accepted, one assesses the share of the integrated CCGT plant fuel assigned to the CHP steam turbine plant by debiting the power loss owing to non-condensing activities at the bottoming steam cycle on the steam turbine section, or:

$$F_{\text{steam turbine CHP plant}} = F_{\text{CCGT plant}} - E_{\text{gas turbine}} / \eta_{\text{Cond}}.$$

η_{Cond} expresses the efficiency of a CCGT cycle at maximum condensing power output, and $F_{\text{steam turbine plant}}$ is the fuel consumption assigned to the bottoming steam turbine CHP plant (F_{plant} in the general notation; see Table 1).

With the numbers of Figures 6–8 and $\eta_{\text{Cond}} = 0.55$ the following results are obtained:

$$\begin{aligned} F_{\text{CCGT plant}} &= 100 \text{ MW} \\ E_{\text{gas turbine}} &= 40 \text{ MW} \\ F_{\text{steam turbine plant}} &= 27.3 \text{ MW}. \end{aligned}$$

The $F_{\text{steam turbine plant}}$ fuel flow is split further in a part assigned to the CHP activity and a part to the condensing activity by applying the fuel-splitting rule of Section 3.

For example, let the heat recovery at the steam turbine Q_{CHP} equal 18 MW (instead of the maximum CQ_{CHP} = 30 MW), one derives (Figure 7 or 8):

$$E_{\text{plant}} = 15-(0.167)\cdot 18 = 12 \text{ MW (because } \beta = 5/30)$$

$$E_{\text{CHP}} = \sigma \cdot Q_{\text{CHP}} = (0.33)\cdot 18 = 6 \text{ MW (because design } \sigma = 10/30)$$

$$E_{\text{Cond}} = E_{\text{plant}} - E_{\text{CHP}} = 12-6 = 6 \text{ MW}$$

$$F_{\text{CHP}} = 27.3-(6/0.55) = 16.4 \text{ MW.}$$

This final result is consistent with the fuel splitting rule of Section 3 applied on the integrated CCGT-CHP plant [verify: $F_{\text{CHP}} = F_{\text{CCGTplant}} - E_{\text{Cond}}/\eta_{\text{Cond}}$ or $16.4 = 100-(40+6)/0.55$].

Reducing the CHP arena of a CCGT co-generation unit to the bottoming steam turbine unit, limits the amount of power that is identified as being CHP. It however saves one from nasty problems regarding the condensing only CCGT plants and from double counts. It remains advantageous to link a co-generation steam turbine at a topping gas turbine, because of the high fuel efficiency that spills over to the co-generation part of the plant. This advantage is to be cashed when the identified CHP activity is qualified on the basis of energy savings realised (see Qualifying CHP Activity).

9 Conclusion

A good regulation starts from an accurate definition and measurement of the object to be regulated. This is no easy task when dealing with CHP and the 2004 EU Directive did not address sufficiently the jointness issue. The proposals are not consistent yet but not definite either, leaving room to Member States to develop own methods until 2010.

This paper contributes to the development of a comprehensive approach starting from the *division rule*, i.e., the same point of departure as Annex II of the EU Directive. However we clearly define the power-to-heat ratio as the *design ratio at the bliss point* of CHP activities, and we offer methods to assess E_{CHP} accurately for all relevant CHP technologies. The rule encompasses the CEN/CENELEC approach that is based also on design parameters of the CHP plants, but adopts a fixed 80% combined efficiency to derive the power-to-heat ratios.

For CHP plants with particular properties (e.g., non-constant design ratio, virtual bliss point, multiple ratio's, CCGT co-generation with the stapling of two thermodynamic cycles) the basic division rule is extended. Eventually a curve representing the partial back-pressure pattern may be substituted for the single number ratio (linear substitution), but this occurrence will be exceptional. For a neat application and for regulatory control it is recommended to consider the *heat load factor* being the useful heat flow divided by the maximum flow (the heat recovery capacity installed at the plant times the operational hours during the accounting period). The application of rather short (from daily to maximum monthly) *accounting* periods is also advised. Detailed follow-up of the CHP activity and energy flows is anyhow necessary to operate CHP units in a competitive way. The *reporting* period can encompass several accounting periods and equal e.g., the year.

The proposed approach is *workable* and applicable on all CHP technologies: simple for small and non-complex plants, while extensions are tractable by few additional steps for complex CHP plants. The results will be *quite correct* because co-generated power is distinguished precisely from condensing power. Cheating behaviour by CHP owners is recognised earlier by use of heat load factors and short accounting periods. The method also estimates the *fuel use of the CHP activities* measured (needed for qualifying co-generation as the EU Directive proposes).

The method provides the *right incentives* by identifying only – but fully – the real CHP activity of CHP plants. So a reliable measurement of the *merit of CHP* happens. Investors are stimulated to search high-quality CHP designs and to provide ample heat recovery facilities, and operators to maximise useful heat recovery.

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