Combined Heat and Power (CHP) essentials

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Abstract: 'CHP essentials' introduces the concept of power and heat 'production possibility sets', starting at the cradle of CHP, i.e., the thermal power generation plant. The latter always occasions 'fatal' heat that is either recovered (the 'merit' of CHP) or wasted (condensing). This split paves the way to defining the production possibility sets of CHP plants, shown for steam turbines, internal combustion engines and gas turbines as main CHP technologies. Three indicators are widely used to monitor CHP performance: the overall conversion efficiency (quantity indicator), the (mostly ill-defined) power to heat ratio (quality indicator), the 'quality norm' advertised by the EU Directive 2004/8/EC. The paper levels the field for discussing the crucial issue of identifying and quantifying CHP activity

Keywords: cogeneration; power-to-heat ratio; gas turbine; steam turbine; internal combustion engine; production possibility set; feed-in prices; joint outputs; heat recovery; performance indicators.

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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, cogeneration, regulation and pricing, 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 member, supervisor or chairman of a number of research groups and networks on energy and environmental issues.

1 Introduction

The EU developed over the period 1997–2004 a Directive to support and promote CHP within the new setting of liberalised electricity markets in Europe. In 1997, the process started with a position paper (CEC, 1997) and culminated in the 2004 Directive after discussing two draft versions (CEC, 2002, 2003; EP, 2002, 2004). The final Directive, however, still falls short in reaching a harmonised and consistent approach to CHP.

A triptych of papers discusses

- 'CHP essentials' bringing clarity on the issues of joint production
- 'quantifying CHP activity' for splitting cogeneration from condensing power output and fuel consumption

- 'qualifying CHP activity' for obtaining a valid reference when regulators would want to support CHP developments.

A common vocabulary and set of symbols (Table 1) are used throughout the three contributions.

Table 1 Symbols used throughout the analysis

Q	Heat flow (Wh)†
Q_{CHP}	$=Q_{\text{useful}}$ Heat recovered in thermal power generation for an end-use
Q_{Cond}	$=Q_{\text{waste}}$ Heat dissipated related to condensing thermal power generation
Q_{plant}	Heat set free at the thermal power generation process, i.e., $Q_{\text{CHP}} + Q_{\text{Cond}}$
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., $E_{\text{CHP}} + E_{\text{Cond}}$
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., $F_{\text{CHP}} + F_{\text{Cond}}$
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 cogeneration activity within a given accounting period
q	Heat load factor = $Q_{\text{CHP}}/(h.CQ_{\text{real}})$
S	Bliss point of the production possibility set of a CHP process, where at maximum output of useful heat the cogenerated 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 $(E_{\text{plant}} + Q_{\text{CHP}})/F_{\text{plant}}$
η_{CHP}	Energy efficiency of CHP activity or $(E_{\text{CHP}} + Q_{\text{CHP}})/F_{\text{CHP}}$
η_{Cond}	Efficiency of the pure condensing activity of the CHP plant $(E_{\text{Cond}}/F_{\text{plant}})$ when $Q_{\text{CHP}} = 0$
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 $E_{\text{plant}}/F_{\text{plant}}$
α_Q	The heat efficiency the CHP plant $Q_{\text{useful}}/F_{\text{plant}}$
η_{ERS}	The electric efficiency of the reference separate electricity generation process
η_{QRS}	The heat efficiency of the reference separate heat process

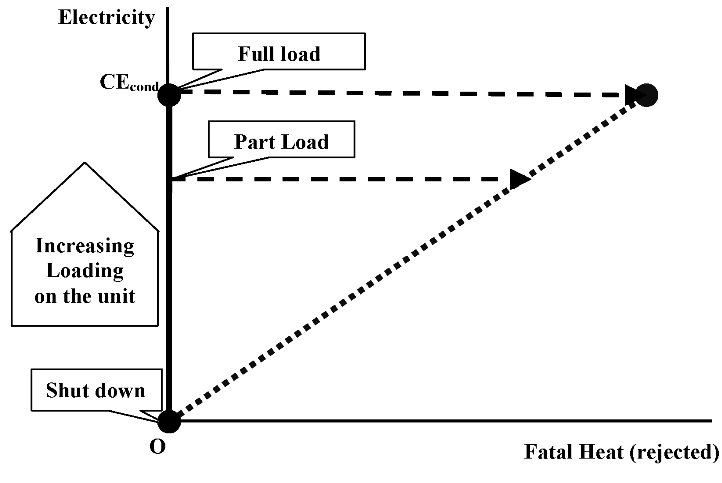
†With capacities in W (Watt) and energy in Wh, the axes of the Electricity-Heat graphs can represent both capacities and energy flows per hour (momentary or average values).

'CHP essentials' introduces step by step the basic concept of a CHP 'production possibility set' starting at the cradle and the natural biotope of CHP, i.e., the thermal power generation plant. The latter always occasions 'fatal' heat that is either recovered (CHP) or wasted (condensing). The 'merit' of CHP consists in converting wasted fatal heat into recovered useful heat (Section 3). Understanding the fatal heat property paves the way to the definition of the production possibility set of CHP plants (Section 4). The set concept, familiar to economists, is explained for the main CHP technologies (steam turbines, internal combustion engines and gas turbines). In Section 5, fuel consumption is added to the graph of the power and heat possibility sets. The paradox that CHP investors and operators face because they control but one process for meeting two demands – power and heat – is discussed in Section 6. Section 7 introduces three indicators that are widely used to monitor CHP performance. In addition to the overall conversion efficiency (quantity indicator) and the mostly ill-defined power-to-heat ratio (quality indicator), the 'quality norm' was advertised as the single yardstick encompassing all CHP aspects. Section 8 reminds some major variables and parameters determining CHP competitiveness. The concluding remarks follows in Section 9.

2 Thermal power and fatal heat

In 1824, Sadi Carnot has shown that the extraction of power from heat flows requires one to get rid of the part of the heat flows that cannot be converted into work (see Reynolds and Perkins (1977) for a discussion of Carnot's findings). A thermal power generation process always discharges amounts of heat one may call 'fatal' heat because it cannot be avoided. This basic fact of physics can be represented graphically (Figure 1).

Figure 1 Thermal power generation always brings along the output of fatal heat



The vertical axis represents the condensing electricity output of the plant depending on fuel input (assumed is a load increase from zero to full load; see Section 5). At every charge or load condition the generation of electricity is accompanied by the discard of a proportional amount of fatal heat (see arrows). The amount of fatal heat is marked on the abscissa.[1]

For the same consumption of fuel, there are thermal power generation processes where the generation of electricity brings along a large quantity of fatal heat and there are processes with smaller quantities of fatal heat, as shown in Figure 2. The smaller the quantities of fatal heat the better, because this implies that more power is extracted from the fuel (given non-recoverable losses, such as radiant heat from equipment, remain constant). The first law of thermodynamics indeed teaches us that:

Fuel energy = Electricity + Heat + non-recoverable losses.

Figure 2 Thermal power generation processes differ in amount of fatal heat discarded

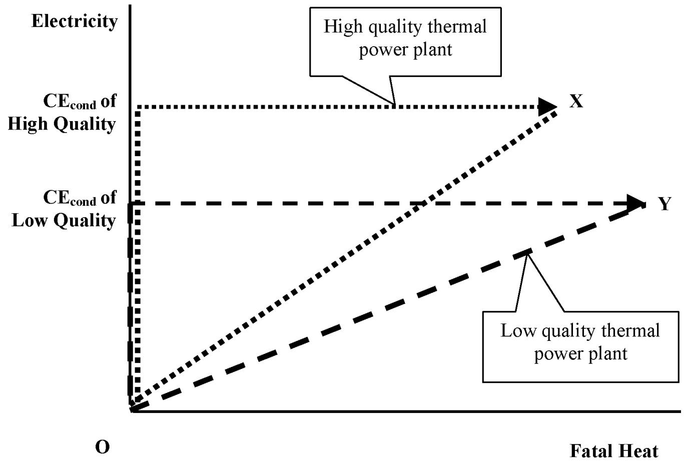


Figure 2 shows a process where the *ratio of electricity to heat* is high (e.g., a plant with top live steam conditions, high-technical lay-out and near vacuum condensing) and one where this ratio is lower (e.g., a plant where live steam conditions, lay-out and condensing are of lower quality). Experts recognise the concept of electric efficiency or η_{ERS} behind the graphs. Indeed a 'high-quality' condensing plant has a high electricity to heat ratio (slope of OX in Figure 2). This is no other for a 'high-quality' CHP plant. Analogously for a 'low-quality' thermal power plant (slope OY in Figure 2).

3 The merit of CHP

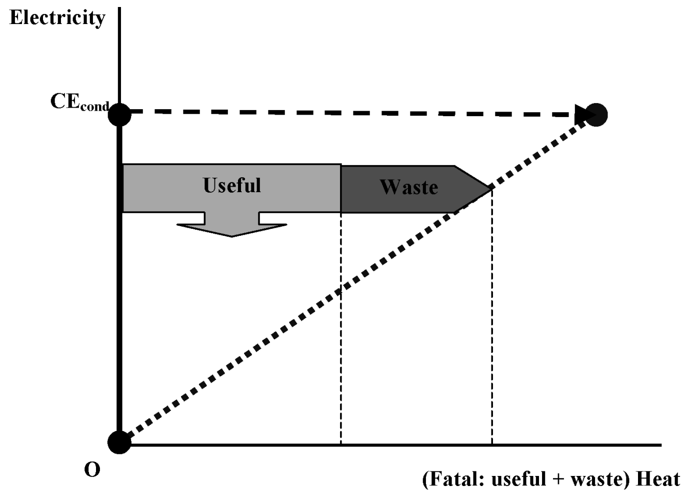
The next evident question is: how is one getting rid of the fatal heat? Will it all be dissipated or wasted in the environment or can it (or part of it) been directed to a useful end-use because our cities and factories need so much heat? When (part of) the fatal heat is recovered as useful heat one enters the realm of CHP (DEFRA, 2004). This is shown in Figure 3.

The recovery of fatal heat is the basic merit of the CHP process, and is an argument to in principle (economists would say 'ceteris paribus' – all other things being equal) prefer CHP above plain condensing power generation.

In some applications the CHP process is designed to recover all of the fatal heat. This is the preferred solution but not always economically feasible when there is no sufficient economic demand for the heat. Also a plant with a full fatal heat recovery capacity installed will mostly not be charged at full heat load continuously in time.

When heat demand is lower, the plant will work more in condensing mode (when at least heat rejection equipment is installed) with wasting a corresponding part of the heat flows.

Figure 3 CHP transforms part of the fatal heat in useful heat



Regarding heat recovery, the thermal power processes will split into two groups, depending on the temperature of the fatal heat flows in reference to the required temperature of the heat end-uses being served. The temperature of rejected waste heat for some technologies is high (gas turbines, some types of fuel cells), medium (internal combustion engines, some types of fuel cells), low (some types of fuel cells) ambient (condensing steam turbines). When the temperature of the fatal heat supplies is above the temperature of the end-use requirements, the use is 'free'. In the other case, it is necessary to increase the temperature of the recovery heat. In steam turbines such increase occasions a loss in the power generation that encroaches on the merit of recovering a large quantity of condensing (latent) heat.

> Concluding: The virtue of CHP is to convert (part of) the fatal heat flow of thermal power generation into a useful destination. This virtue is encroached when the act of heat recovery involves a reduction in power generated, but generally suffices to rank CHP – ceteris paribus – higher than power only thermal generation of the same technology.

One is to extend slightly the content of the variable on the horizontal axis. It is still an amount of heat, but transiting from a single condensing plant to a CHP plant, adds the labels 'useful heat', 'CHP heat', 'waste heat', 'condenser heat' to the label 'fatal heat'. The output on the abscissa now partly becomes a valuable economic product (also because it has the right temperature to serve particular end-uses).

In daily practice, one generally uses the label 'heat' but one must be aware of its double character, partly useful and partly waste. This double character of the abscissa of the electricity–heat graphs requires high attention of the reader, but it is the key to splitting the output on the ordinate in its components cogenerated power (E_{CHP}) and condensing power (E_{cond}) as shown in 'quantifying CHP activity'. The capabilities of a particular CHP plant in providing the demanded products electricity and useful heat are represented by a 'production possibility set'.

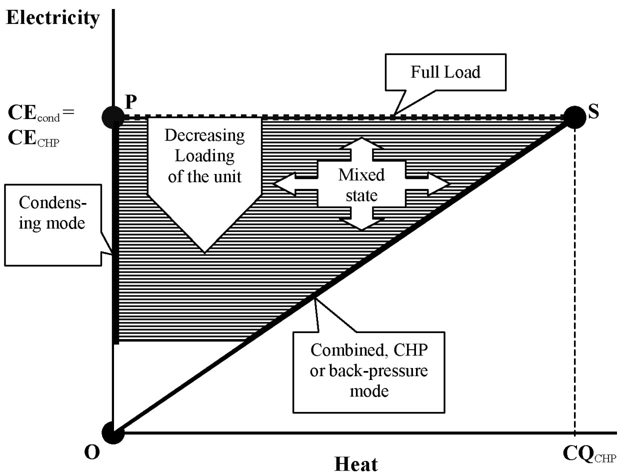
4 CHP production possibility sets

The operational flexibility in supplying power and heat by a CHP plant is expressed by its (*E*, *Q*) production possibility set (Bach, 1978; Verbruggen, 1982; Anonymous, 1996). There are two main cases. The first (A) represents CHP technologies that can supply useful heat without a (significant) change (loss) in power output, e.g., internal combustion engines recovering heat from cooling water, oil coolers and flue gases or gas turbines recovering heat from the hot exhaust gas flow. The second (B) refers to CHP technologies that can recover heat at above ambient temperatures only by giving up some power output, e.g., steam turbine cycles.

A Heat recovery without trade-off for electricity generated

Figure 4 shows a production possibility set of a thermal power plant equipped with on the one hand full facilities to recover heat and on the other hand full facilities to reject all surplus heat in the environment.

Figure 4 Production possibility set of a CHP plant when heat recovery has no effect on power output



The ordinate axis shows power output of the pure condensing mode from standstill (point O) to full load (point P), wasting all the heat. Point S is the *bliss point* of the plant, with the highest power output CE_{CHP} combined to the *feasible maximum* heat recovery CQ_{CHP} when the plant is running at full load.[2] The slope of ray OS represents the *design power-to-heat ratio* $\sigma(=CE_{CHP}/CQ_{CHP})$ of the cogeneration activity. This ratio reflects the thermodynamic quality of the process and one should – ceteris paribus – opt for the steepest ray (see Section 2).

When the actually installed heat recovery equipment falls short of the capacity CQ_{CHP}, bliss point *S* is a virtual point and the possibility set is truncated to the left of *S* (see Section 6 in quantifying CHP activity). When heat rejection facilities are unavailable the possibility set is reduced to the bisector ray OS (in practice truncated at the lower end because loads below e.g., a quarter or a third of the nominal capacity are not accessible). In point S the plant is fully loaded. In all other points on OS the plant is partly loaded. In O it is out of service. Along ray OS the recovery of heat and the output of power are complements. By the law of physics (Carnot) power can but be generated with discarding the heat outlet and when the plant has no heat rejection facilities, it follows power can only be generated when there is a useful heat demand for absorbing the heat outlet. In this case, power and heat outputs are joined in a sticky way, posing no real problems to the analysis of the joint-ness issue. The design power-to-heat ratio 'σ' equals the actual power-to-heat ratio of the CHP plant.

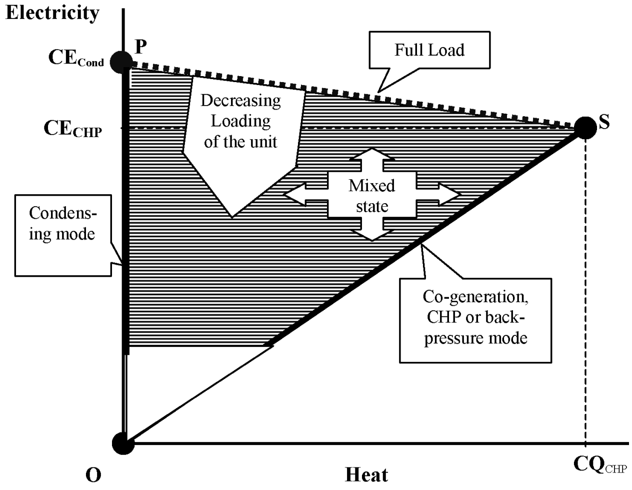
The complex case arises when heat rejection facilities are installed for enlarging the CHP production possibility set from OS to the triangular area OSP. Then, a CHP plant can supply combined (E, Q) loads in all combinations within the dashed area OSP. When operating on the top line PS, the unit is fully loaded. In going from P (pure condensing) to S (fully combined) one recovers a larger and larger share of the heat. This continues up to capacity CQ_{CHP} at bliss point S when OSP is not truncated by a shortage in heat recovery equipment (Section 6 in Quantifying CHP Activity). All points below line PS mean a part-load functioning of the unit.

On line OS the maximum cogeneration effect is maintained. This is the *cogeneration or CHP* operation mode. All other points of the possibility set involve a deviation from the maximum CHP principle, where part of the available heat has to be rejected because there is no useful demand for it.

B Heat recovery with trade-off for electricity generated

In CHP processes based on steam turbines there is trade-off between power output lost and useful heat recovery making the full load line downward sloping from *P* towards *S* (Bach, 1978; Verbruggen, 1982; Grohnheit, 1996). This makes the analysis slightly more complicated, as shown in Figure 5. One now must distinguish more clearly between CE_{Cond} and CE_{CHP} because the two values may diverge significantly (CWA, 2004).

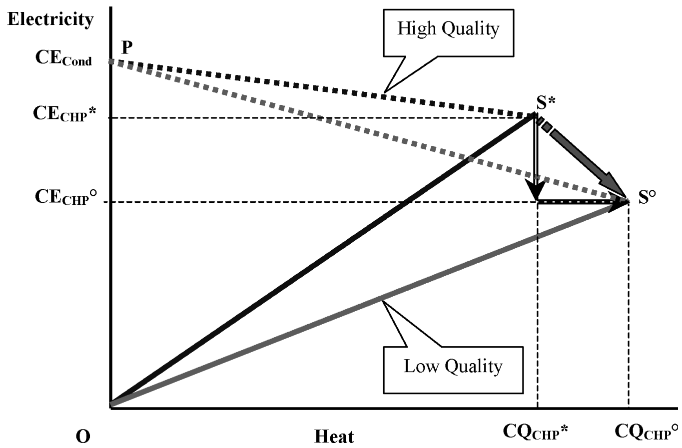
Figure 5 Production possibility set of a CHP plant (example of an extraction–condensing steam turbine with a single back-pressure feasibility)



The full-load line PS slopes down. The downward slope indicates the loss in power that occurs by extracting the steam from the turbine above condensing conditions (the latter being near vacuum pressure and near ambient temperature). The higher the pressure and the temperature of the heat extraction are the more power that is lost for every Joule of heat recovered. One is willing to incur such loss because CHP sets all the recoverable heat (including the latent condensing heat) in the extracted flow to use. Obviously, one opts for the shallowest slope of the PS line and can be successful in this when the temperature of the useful heat applications can be kept as low as possible.[3]

Figure 6 shows the impact of raising pressures–temperatures of the steam extracted from a steam turbine on the production possibility set of the CHP unit and on the quality of the CHP process. This figure also highlights that the quantity and quality aspects of CHP units can be represented by means of production possibility sets. When useful heat is extracted at two different points at the turbine (meaning two different pressure–temperature levels) the unit has multiple bliss points and the design power-to-heat ratio is no longer unique.

Figure 6 Loss of quality by exigent useful heat temperature (pressure) in a steam turbine or by sub-optimal design



While loss in quality in steam turbine CHP units is due mainly to the pressure–temperature exigencies of the heat end-uses, quality loss can also result from bad designs. The latter also can occur in engine and gas turbine driven CHP units where – within limits – the useful heat pressure–temperature conditions have no significant impact on the generation of power.

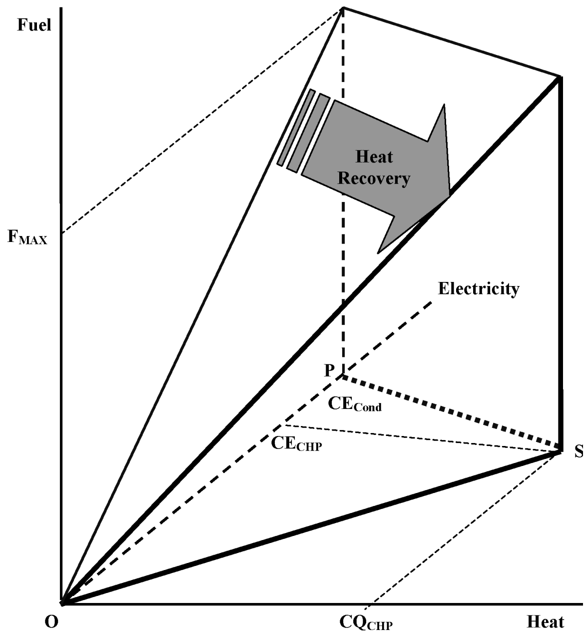
The *design quality* of a CHP process is measured by the power-to-heat ratio $CE_{\text{CHP}}/CQ_{\text{CHP}}$, i.e., by the slope of the line OS. One should avoid CHP processes as the one shown with bliss point S° in Figure 6, when the one with bliss point *S** was technically and economically also feasible. Loss of quality means the substitution of amounts of (low-grade) heat for equal amounts of (high-quality) power, as the arrows in the graph show (CWA, 2004; Annex B; pp.41, 42). The variety in CHP processes depending on the availability of heat recovery/heat rejection capacities as discussed in Subsection 4.1, also shows in Subsection 4.2. Pure back-pressure processes own no heat rejection facilities (complementary heat recovery–power output); extraction condensing steam turbines can cover the full OSP production possibilities or a truncated part of it when heat recovery facilities are limited (Section 6 in Quantifying CHP Activity).

The discussion on CHP performance is quite simple when limited to the pure states either back-pressure along line OS or condensing along line OP, but becomes confusing when both states are mixed up (area OSP). One must find an acceptable principle to divide or split the mixed activity into on the one hand *cogeneration activity* and on the other hand *condensing activity*. The former has merit in recovering fatal heat flows. The latter has no such merit because it dissipates the heat in the environment. In separate papers on *Quantifying CHP Activity* and on *Qualifying CHP Activity* these questions are discussed in detail.

5 CHP fuel consumption

Figure 7 projects the fuel consumption of an extraction-condensing steam turbine on top of the possibility set of supplying electricity and useful heat. Full load conditions along PS imply F_{MAX} fuel use. Along OS part-load prevails, and fuel consumption is also part of the F_{MAX} value. There is a difference between *part-load CHP* operation and *partial CHP* operation. In the part-load mode one comes down the fuel axis. In the partial mode one stays at an equal fuel consumption level, but comes down the heat axis meaning that less heat is recovered. While part-load working may deteriorate the technical efficiency of the conversion, partial load will not entail such technical losses.

Figure 7 (E, Q) possibility set of an extraction–condensing turbine and Fuel consumption



6 Joint outputs

CHP is an activity that wants to satisfy two energy demands: non-storable electricity and difficult to store and convey heat. When designing the plant, the difficulty of targeting such two goals with one instrument is best addressed by "*dimensioning the CHP activity on the heat loads while maximising the electric power output*". Why is the latter a good guiding principle?

In CHP, priority for heat loads is necessary because heat loads are a prerequisite for the cogeneration principle (DEFRA, 2004). Of course power loads are also a necessity, but when power can be transmitted over existing power lines, the interconnected grid functions as an unlimited market to every single CHP-project. This statement is valid when the access to the grid is not denied or impeded by a number of barriers and when the sum total of CHP power output is not covering the whole or a dominant part of the power market. The latter situation would require a significant increase of market share of cogenerated electricity in most countries (CEC, 1997).

CHP has a high preference for low-grade heat demand i.e., heat at low-temperature (below 100°C). Some technologies only can deliver low-grade heat (e.g., some fuel cells, engines without flue gas heat recovery). The quality of other technologies (steam turbines) is inversely related to the height of the temperature–pressure of the delivered heat (steam). Only gas turbines naturally exhaust the waste heat at high temperatures but when heat loads are to be met at high-steam conditions, one has to forgo the combined cycle option, today the basis of the better performance of CCGT plants over other fossil fired power units.

The other output of a CHP plant is electricity of maximum thermodynamic quality that enjoys a high willingness-to-pay in the market. Electricity is more valuable and – most of the time – can be valorised at higher prices than heat. In the joint products case of CHP, the CHP investor and operator must squeeze the maximum electricity out of the process. This guiding rule will maximise as well the thermodynamic quality as the economic quality of the process. Especially in *investing (fixing design and scale)* in CHP capacities, all barriers should be removed to avoid low-quality combined processes. In particular, low feed-in prices for CHP power provide incentives to CHP investors to build either a too small unit or when the plant is dimensioned on the heat loads a bad-quality unit.

When *operating* the plant a CHP owner must benefit from the maximum degrees of freedom to optimise the financial return of the investment. The instant operational priorities are fully determined by the prices of heat, power and fuel, but *the operational flexibility is constrained by the production possibility set of the plant at hand*. In addition, CHP is operating in a difficult environment on the edge between the power and heat markets, and must watch continuously both sides (Verbruggen, 1996).

7 Indicators of CHP performance

Established practice in monitoring the performance of a CHP unit is to handle a ‘quantity’ indicator and a ‘quality’ indicator.

- The *quantity* indicator is the overall conversion efficiency of the process, defined as:

  (Electricity output + Part of the fatal heat recovered for end-use)/Fuel input

  Or:

  $(E_{\text{plant}} + Q_{\text{CHP}})/F_{\text{plant}}$.

- The *quality* indicator expresses how much high-quality energy (electricity) is generated vs. how much low-quality (heat) is recovered along. One mostly (e.g., CWA, 2004) uses the ratio between electricity output and useful heat output, or:

E_{plant}/Q_{CHP}.

This practice is a source of enormous confusion because it mingles the condensing and the cogeneration activities of a CHP plant. Only when the formula is applied on pure back-pressure or CHP processes the ratio based on the power and heat outputs will (nearly) be the same as the one based on design capacities. When the formula is applied on energy output flows, and the unit is condensing a part of the heat (that part therefore is no longer included in the useful heat flow of the denominator), *the ratio is biased and actually meaningless*.

For sake of clarity and precision *the power-to-heat ratio σ should be defined on the design conditions in the bliss point or in the bliss points of a CHP unit* (see 'quantifying CHP activity'). Therefore it may be better to substitute 'bliss capacity' for 'output' in the formula (see Figures 4–6), i.e., expressing quality by:

$\sigma = CE_{CHP}/CQ_{CHP}$.

The quality of CHP activity is measured by the ratio 'σ' and one cannot solve the CHP quantification problem without addressing the exact definition and metering of this ratio. The EU Directive drafts (CEC, 2002, 2003) and the final Directive (EP, 2004) err in passing this issue. The EU Parliament amendment in November 2002 (EP, 2002) placed the issue in the centre of the discussion again, but followed a method (Euroheat and Power, 2002) that falls short in transparency and accuracy. CEN/CENELEC (CWA, 2004) provides the way for measuring the design 'σ' but does not make a right use of the results (in fact CEN focuses on measuring the design 'power loss' β of steam turbines and this is akin as measuring 'σ').

- A third ratio links the outputs of a CHP plant to the efficiencies of reference separate heat and power generation plants by the so-called '*quality norm*' (see Table of Symbols):

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

  It is an *external* benchmarking tool for a CHP plant but not for a CHP process or activity because it confuses cogeneration and condensing operation in a plant. Therefore, it fails as a qualifying tool for CHP and can imply perverse effects for the development of CHP as explained in *Qualifying CHP Activity*.

8 The economics of CHP

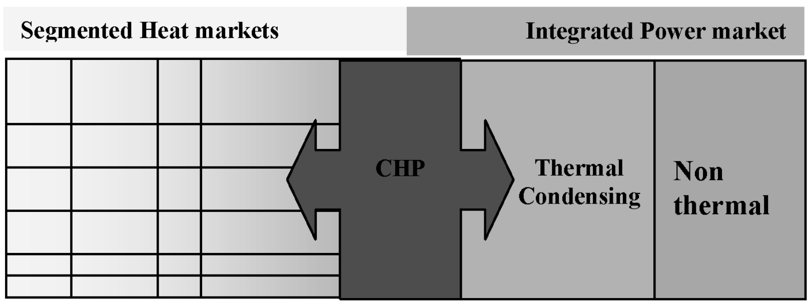
Investing in and operating CHP plants is not a charity but an economic activity expecting financial return. Profit is the difference between revenues and costs. Revenues depend on quantities and prices of electricity and useful heat generated. Costs are the sum of fixed capital and operational costs and of variable fuel and maintenance costs. In particular, the *utilisation time* and the *full-load conditions* of the plant must be maximised to keep CHP competitive.

CHP covers a broad range of institutional arrangements such as utility CHP, independent CHP and partnerships, with a distinct access to the electricity grid. CHP projects owned or controlled by an electricity company interact smoothly with the power grid. Independents generally face problems because electric companies have a natural drive in defending market share and in fencing off their market from competitors.

Independent producers better face the competition from incumbent, specialised, large-scale and endowed power companies when they can create a competitive advantage in a market niche. An important niche for independent production in industrialised societies is the recovery of fatal heat from thermal electricity generation processes, i.e., CHP. In the stalemate on controlling this niche in Europe the various power companies followed different strategies. Where some of the utilities have met the own CHP duties properly by developing District Heating and related CHP, e.g., in Denmark the 1979 Heat Supply Act has imposed on electric utilities the obligation to give preference to CHP above single condensing plants and since 1981–2000 no major single condensing power station has been built in Denmark (Grohnheit and Olsen, 2001). Other power companies mainly have been fighting the independent growth of the CHP market or have safeguarded and extended the market control by enforcing partnerships on upcoming independent producers, e.g., by applying discriminatory back-up power tariffs (Verbruggen, 1990).

Figure 8 shows CHP on the crossing of segmented (local) heat and integrated (international) power markets. A public economic point of view argues that CHP should cover all heat market segments when technically and economically a better choice than separate supplies (arrow Left/West). But related is the question how much condensing power the CHP units may deliver *next to and on top of* their pure CHP functioning (arrow Right/East). When CHP stations – in cogeneration or condensing mode – supply power to the grid simple condensing power plant capacity and activity can be saved. Therefore the condensing activity by CHP plants, either utility controlled or independent should rather be promoted than obstructed by regulations or by market power from incumbent companies. Progress on the West and progress on the East fronts are very much interrelated. CHP will be able to cover a larger share of the heat market when the conditions for generating and selling surplus power in the electricity market are favourable (DEFRA, 2004).

Figure 8 CHP on the crossing of heat and power markets

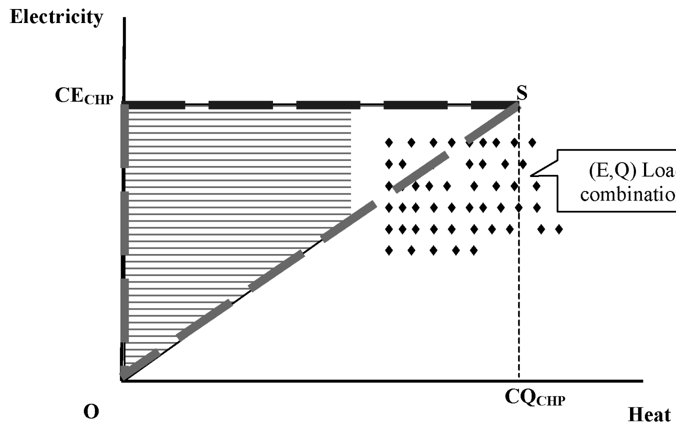


However, some incumbent power companies are very reluctant in adopting the public economic vision on distributed power, and fence off their markets. Also liberalisation has not levelled the playing field in most EU countries. But when CHP owners have to operate increasingly in the free-power markets of tomorrow, full flexibility in *investing* and in *operating* the plants is a prerequisite for success. Bohn (2005) offers an overview of the multitude and variety of technologies and their combinations in decentralised power systems.

CHP investment means *designing and scaling* the CHP units. When CHP should cover an important share of the heat market, the various CHP plants should be designed and scaled to cover the major share of the heat loads in particular market niches. Referring to the production possibility sets of CHP units one should select CHP technologies and scale the units such that their production possibility sets cover most of the heat load frequency (e.g., 95%). This is shown in Figure 9, where the diamonds represent (*E*, *Q*) load pairs forthcoming from the site served by the CHP plant. Heat loads can be met by the CHP plant or by separate sources (boilers). Electric loads can be met by the CHP plant or by purchasing kWh at the grid, but in addition electric load on the CHP plant can be raised when surplus kWh can be exported to the grid at fair terms. The latter condition is crucial for safeguarding the quality of the thermal power generation process by keeping the OS ray as steep as technically possible (Verbruggen, 1996).

However, a good design and scale decision at the moment of investment can turn into a nightmare if in the operational phase flexibility is truncated. If selling surplus power to the grid is made impossible by technical, economic, institutional or regulatory barriers the CHP operator will be compelled to match the electric load at any time. For the load points below the OS cogeneration line in Figure 9, the operator will shift westwards to the point on the line OS at height of the electric load. Burning fuels for providing complementary boiler heat will be required. For (*E*, *Q*) loads above OS matching the electric load is impossible without condensing equipment. Than the operator is caught by the heat load and must descend southwards to the OS cogeneration line while purchasing make-up power at the grid.

Figure 9 CHP design and scale should cover most of the heat loads while maintaining the maximum quality (power-to-heat ratio)



In such cases, the operator is driven to a part-load operation of the CHP process. Here, the conflict between CHP sanctity and real-live economics comes at light clearly. When operating on the OS line all the time the cogeneration mode is maintained and the CHP effect is maximised. However, running the plant in part-load deteriorates the finances of the operation. First the conversion efficiency comes down, although this loss is minor for most technologies when the part-load stays above 50% of full load. Some technologies (e.g., gas turbines) are, however, more sensitive to part load functioning. But more important is the economic effect owing to low utilisation of the plant. Wear and tear and depreciation of many CHP technologies is accounted by the running hour whether the unit is fully or partly loaded. This fixed cost must be spread over the generated electricity and useful heat, and this group of money gainers becomes smaller when one slips away from full load operation.

In addition, operating in quasi real-time and reacting swiftly on volatile and largely fluctuating variables (such as the power price fixings) is a necessity when one must survive in the future power markets (Hughes and Parece, 2002). This requires the power supply capacity to be almost continuously fully available. When the heat load is not almost constant for most of the time, CHP units should dispose of condensing equipment whenever technically feasible and economically warranted, and there should be no truncation of the flexibility in operating the CHP plants. The danger of reducing the scale and of leading CHP operation to part-load exploitation is real with the EU Directive regulation (see qualifying CHP activity) what will jeopardise the financial viability of many CHP projects.

No regulation, and a fortiori no regulation that claims to support the development of CHP should diminish the flexibility and the degrees of freedom in CHP operation. On the contrary all should be done for extending the flexibility and the freedom of choice for CHP plants.

9 Conclusion

CHP is an activity integrated in a thermal power generation process that because of basic physical laws (Carnot), always brings fatal heat. The merit of CHP is to transform (part of) the fatal heat flow into useful heat. A variety of thermodynamic cycles and derived power systems can house a CHP activity. The power and heat generation opportunities of the various systems can be represented with the help of (E, Q) production possibility sets. They highlight the difference between cogeneration and condensing operational modes, and show that several technologies may cover a large set of mixed states of partial CHP activity and of part-load activity. Because a single plant is used to meet the demand for two energy flows – power and heat – one often has to assign priority to one of both. When investing, the CHP activity should be dimensioned on the heat loads because meeting heat loads is a prerequisite for cogeneration. When operating, the priority to heat or power demand will depend on prices of fuel, heat and electricity at that moment, constrained by the production possibility set of the plant. When there are no or only limited useful heat loads present and the CHP unit is equipped with condensing facilities, one can operate the unit as a single or almost single power unit. From a public economic point of view it is recommended to enlarge the power production capabilities of CHP. Whether it is financially recommended to do so depends mainly on regulatory and market variables.

The performance of CHP is measured by three indicators: overall thermal efficiency, power-to-heat ratio’s and the quality norm. The first measure is based on energy quantities regardless their quality. The second points to quality and is crucial but mostly not well defined. The third places a CHP plant in a context of external benchmarking and can give rise to perverse effects when used as the qualifying standard as the EU Directive proposes. Quantifying CHP activity is the first task because Qualifying CHP activity must build upon a good quantification.

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Notes

[1]To keep the discussion simple all figures show a direct proportional link between fatal heat and power output (i.e., the dotted line in Figure 1 and the following figures is a ray starting at the origin of the diagram). Owing to efficiency losses in part load functioning of plants the actual relationship will be somewhat different. This has no influence on the basic arguments that can be extended to non-linear and to multiple relationships, and to truncated production possibility sets (see *Quantifying CHP Activity*).

[2]The constant full load energy balance equation $F_{\text{plant}} = E_{\text{plant}} + Q_{\text{plant}}$ + non-recoverable energy losses (boiler loss, heat radiation of equipment, leakages) is used to measure during one hour the four energy flows of the thermal power plant. The number measured for Q_{plant} (MWh) from the balance equation = CQ_{CHP} (MW).

[3]One of the beneficial spill-over effects of CHP supplies is the redesign and reengineering of heat end-uses for the least temperatures. With such innovations energy flows and in particular heat flows can be used in cascade (CHP is already such an example) increasing the opportunities for heat integration (pinch technology developed by Linhoff) and for implementing solar heat.