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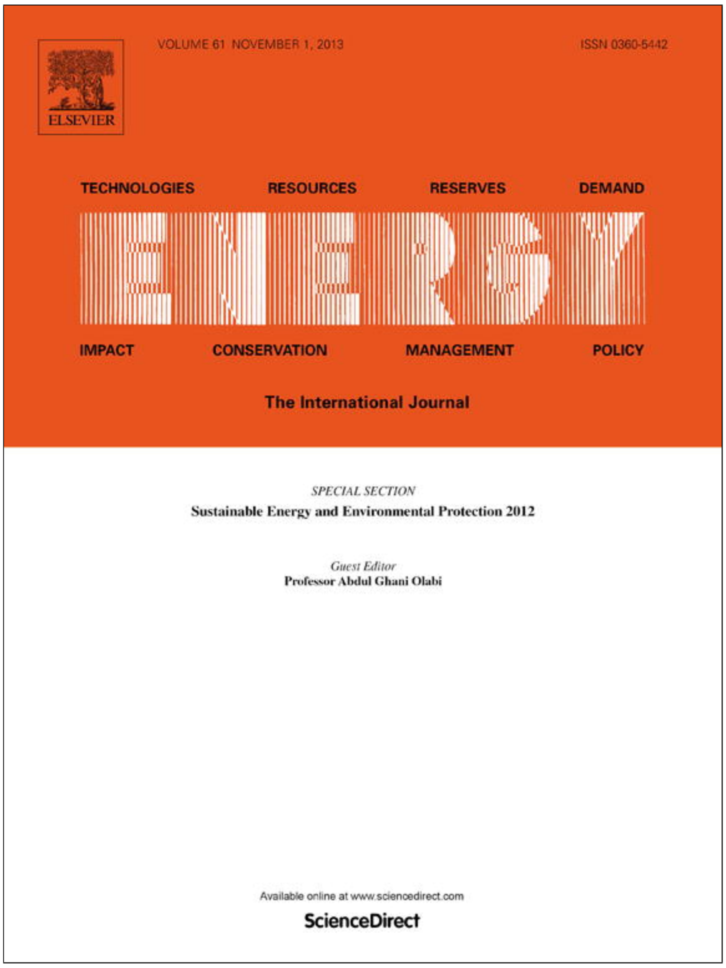

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Unveiling the mystery of Combined Heat & Power (cogeneration)

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A B S T R A C T

The article unveils the mystery of cogeneration. Cogeneration is an *add-on or embedded activity* in thermal power plants, with as merit the use of part or whole of their point source heat exhausts. EU's talk of "high-efficiency cogeneration" is an unfounded transfer of responsibility from the hosting thermal power generation plant onto CHP (Combined Heat & Power) activity. The quality of a CHP activity is univocally defined by its *design* power-to-heat ratio $\boldsymbol{\sigma}$, a tombstone parameter derived from the design characteristics of the power plant. A thermal power plant may house more than one cogeneration activity. Identifying $\boldsymbol{\sigma}$ requires positioning the *bliss point* in the *electricity–heat production possibility set* of the cogeneration activity. The bliss point is where after electric output is maximized, the sum of that output and the *maximum recoverable* quantity of heat occurs. Once CHP's mystery of *virtual bliss points* is unveiled, the proper $\boldsymbol{\sigma}$ are found. With known $\boldsymbol{\sigma}$ by CHP activity, the quantity of cogenerated electricity is reliably assessed as best indicator of cogeneration performance. Our analysis is applicable on all relevant thermal power cycles that host CHP activities, and illustrated with a numerical example. Our lean method is necessary and sufficient for proper CHP regulation.

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1. Introduction

Cogeneration or CHP (Combined Heat & Power) is as old as its natural cradle, the thermal power plant. CHP is applied in thermal power plants employing diverse technologies and ranging from a few kW to a few hundreds of MW [1]. Cogeneration diffusion in countries with similar economies is uneven, due to diverging energy policies and related regulations [2,3]. Dedicated sector organizations (COGEN Europe, Euroheat & Power, International District Energy Association) support CHP deployment. The overwhelming breakthrough has not yet arrived. CHP is not fancy. Now and then, it is embraced by policy circles [4], kindling the hope for a boost of its application. Public policy in favor of efficient fuel use, argues support for cogeneration. This was intended by the EU CHP directive 2004/8/EC [5], but not realized by lack of effective and efficient regulation. The EU [6] admitted that the 2004 CHP directive "failed to fully tap the energy saving potential", but shows no assessment of the flaws in its regulation. The EU continues the 2004 framework, now incorporated in the Energy Efficiency Directive [7], without any improvement in answering the essential questions that impede improved regulation of cogeneration activity and its support: What is quality of CHP? What is CHP merit? How exactly to monitor and measure CHP performance? A partial remedy was suggested by CEN (European Committee for Standardization) [8], but failed on crucial points [9].

The adage of this article is "everything should be made as simple as possible, but not simpler". We care extremely about didactic transparency in communicating insights on the paradoxes of joint electricity–heat generation processes [10]. Cogeneration only exists when heat from the plant is recovered and used (what supports the idea of 'priority to heat'); yet net power output always should be maximized ('priority to power'). This double priority is also called the CHP paradox.

Effective communication is based on clear terminology, now missing in CHP's world. It starts with the proper definition of what cogeneration/CHP is, of the power-to-heat ratios, of cogenerated electricity, etc. We add a few essential concepts to develop our analysis of CHP for unveiling its mystery: Electricity–Heat (E–Q) *production possibility sets*, and *bliss points* [9,11]. We also invoke vocabulary from the environmental sciences, like point source and nonpoint source pollution [12].

The article is developed along the logic summarized in the abstract. Section 2 defines CHP or cogeneration as an activity added

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Variables, symbols and acronyms

E	electricity, power (MWh, MW);
F	fuel energy, flow (MWh, MW);
Q	heat energy, flow (MWh, MW);
L	losses of energy in a diffuse way (MWh, MW);
CHP	Combined Heat & Power or Cogeneration;
BP	backpressure;
S	bliss point;
cond	condensing;
plant	thermal power generation unit wherein cogeneration activity is embedded;
β	power loss factor, or better: 'used heat for generated power substitution' rate;
σ	design power-to-heat ratio of a CHP activity;
η	conversion efficiency;
CEN	European Committee for Standardization

on or embedded in a thermal power generation process. Fig. 1 illustrates that CHP activity may convert part or all of the point source (and so recoverable) thermal pollution of the power plant into used heat. This leads to the proper definition of CHP being the recovery and use of all or part of the point source heat exhaust, otherwise being rejected to the ambient environment, by a thermal power generation plant. CHP is comparable to other environmental mitigation activities. CHP activity is not responsible for the power conversion efficiency of the hosting thermal power plant. EU's talk of "high-efficiency cogeneration" and its "Primary Energy Saving" approach are unfounded transfers of responsibility from the hosting thermal power generation plant onto CHP activity. Section 3 explains that the design power-to-heat ratio of a CHP activity parallels the electricity conversion efficiency of the hosting power cycle. It shows that the design ratio is the necessary and sufficient indicator of CHP quality. For identifying the proper design power-to-heat ratios, the positioning of bliss points is necessary. Here CHP analysts go astray when they overlook that most bliss points in practical CHP applications are virtual. The bliss point is where after electric output is maximized, the sum of this maximum and the *maximum recoverable* quantity of heat is reached (CHP paradox). Section 4 states the basic merit of CHP activity being the use of part or all of a thermal power plant's point source heat exhaust, reducing heat rejection to the environment, and avoiding the use of other energy sources to obtain the used heat. Yet, the quantity of used heat is not adopted as the proper indicator of CHP performance because this implies incentives to downgrade a (expensive) power plant to the supply of heat that less expensive heat plants can deliver. The proper indicator is the quantity of cogenerated electricity, being the product of the design power-to-heat ratio and the recovered quantity of heat. As such this indicator overarches the CHP paradox, because the more heat is recovered and the more electricity is generated, the better scores the indicator. Section 5 offers applied analysis. With the help of five graphs, the concepts and indicators proposed in the previous sections are implemented for all major power generation cycles: gas turbines, internal combustion engines, and extraction-condensing and backpressure steam turbines. Classing the cycles by temperature of their point source heat exhausts separates CHP activities without impact on the power output of the plant (e.g. CHP on reciprocating engines or gas turbines), from the ones with impact (e.g. CHP on steam turbines). Section 6 is a short numerical example of the methods explained in Section 5. A few comments on the regulation of cogeneration activities are offered in Section 7, mainly recommending caution on the perverse impacts of the EU's external

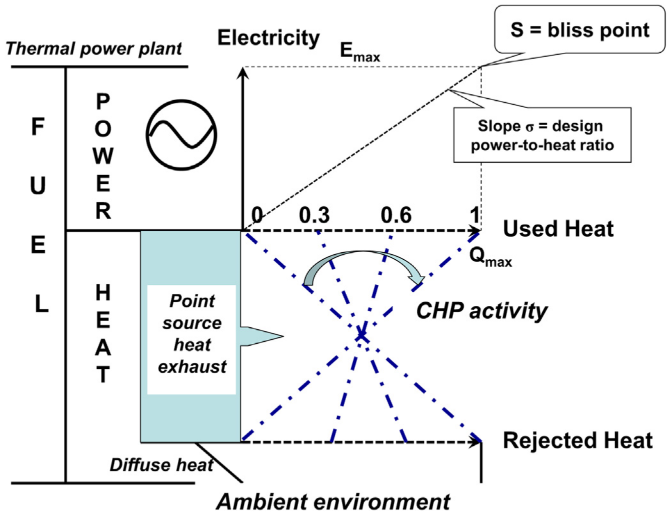

Fig. 1. Thermal power generation: CHP is the recovery of (a share of) the point source heat exhaust.

benchmark approach, because the latter leads to unfounded "high-efficiency" calls. A conclusion is added in Section 8.

Because the analysis breaks ground on an accurate definition of what cogeneration really is, and because several basic concepts (electricity–heat production possibility sets, real and virtual bliss points, design power-to-heat ratios) are explained, perseverance and patience are requested from the reader to process the consecutive sections. Some proof readers of the article get the "eureka" by the numerical example of Section 6, but it is not possible to provide the example without prior description of the concepts and methods.

2. CHP is an activity added on/embedded in a thermal power generation process

In a thermal power generation plant, fuel is converted into a high temperature heat flow, partly turned into power, and partly discarded from the process as residual heat at lower temperature [13] (Fig. 1, left side). The power obtained from steam turbines, gas turbines, or internal combustion engines, is convertible into electricity.[2] Heat rejection to the ambient environment is called thermal pollution [12]. Pollution is often classed as point source or nonpoint source pollution. A point source is a single identifiable localized source, from which flux or flow is emanating, manageable for capture, treatment, or storage. Nonpoint sources cause diffuse emissions, spreading and mixing with flows and mass in the ambient environment.

In thermal power generation cycles, point sources are the condensers at the end of the steam expansion in steam turbines, outlets of gas turbines, and radiators for engine mantle and oil cooling. Flue gas stacks are thermal point sources when heat is still recoverable, or are diffuse sources when non-recoverable. Heat radiation at various parts of the process is also considered non-recoverable.

CHP or cogeneration is *the recovery and use of all or part of the point source heat exhaust, otherwise being rejected*, by a thermal power generation plant. Fig. 1 represents CHP activity as a valve splitting the point source heat exhaust flow in a used and rejected

[2] Few applications are direct drive (for example running a compressor on a turbine's shaft power), except for delivering torque or thrust for transport (vehicles, ships, planes). Fuel cells also convert (hydrogen) fuel in power and heat, but are not widely applied yet.

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share: in position 0 no heat is used/all heat is rejected to the ambient environment; in position 0.3 thirty percent of the heat is used/seventy percent is rejected; in position 0.6 sixty percent is used/forty percent rejected; in position 1 all heat is used/no heat is rejected to the environment. The continuum of positions reflects all imaginable operational CHP activities.

In practice CHP activity may be constrained by the design and the availability of specific facilities for recovering or for rejecting heat. For example, a steam turbine thermal power plant may be designed as a condensing power unit without possibility of using the point source heat exhaust (fixed at position 0); when designed as full backpressure unit it is fixed at position 1 and cannot reject point source heat to the ambient environment; when facilities are installed for recovering a maximum of thirty percent of the point source heat exhaust, CHP activity can range over all positions between 0 and 0.3, but not beyond the latter. In the latter case, confusion arises, and is strengthened by dense but misleading terminology. The physical phenomenon "*CHP/cogeneration activity added on or embedded in a thermal power generation plant*" is mostly shortcut as "*CHP/cogeneration plant*".[3] The shortcut obscures that CHP is an added or embedded facility to recover point source thermal pollution; as such CHP is similar to other mitigation techniques (for example scrubbers removing SO_2 from the flue gases of coal plants). The properties of the polluting installation may affect the mitigation facility, but the latter carries no responsibility for those properties. Unfounded carrying over of responsibility from the hosting thermal power generation plant onto the CHP activity is the EU's and others talk about "high-efficiency cogeneration" [7]. The merit of CHP activity is in recovering as much as possible of the point heat source exhaust. CHP activity is not responsible for the power conversion efficiency of the hosting thermal power plant.

3. The quality of CHP and how to measure it

The quality of a thermal power generation process is the efficiency η in generating power from the fuel, measured by the ratio ***E*/*F***. In case of CHP, the cogeneration efficiency $(E+Q)/F$ is often used as efficiency yardstick. This yardstick assigns equal weight and value to electricity and heat. However, electricity and heat do not have the same value. From the thermodynamic point of view, electricity can be entirely converted into heat or work while the conversion of heat into work is limited by the second principle of thermodynamics. From the economic point of view, expensive power plants are required to produce high-quality power while low temperature heat can be produced with not so expensive combustion facilities (burners, furnace, boilers, etc…). Optimizing a thermal power cycle with cogeneration activities requires maximizing the output of electricity per unit of heat produced for given fuel inputs.

Applying the first principle of thermodynamics on a thermal power plant leads to $F = E + Q + L$. When the diffuse losses L are stabilized at their minimum level, the efficiency ratio E/F is paralleled by the ratio E/Q called the *design power-to-heat ratio* and denoted σ. The latter is a crucial variable for understanding cogeneration. When η goes up, so does σ, and vice versa. The quality of thermal power generation processes is reflected by the capacity to generate relatively more electricity than heat, with the ratio E/Q reflecting the quality of cogeneration. There exists a general consensus that cogeneration quality is given by the power-to-heat ratio. However, confusion is widespread on the precise definition of that ratio and on the methods to quantify the ratio. Fig. 1 provides the basic elements to resolve the confusion, with extended arguments and methods for assessing σ values discussed in Section 5.

The northeast corner of Fig. 1 formats an electricity–heat (E, Q) diagram; the ordinate is the quantity of electricity (E) generated; the abscissa is the heat (Q) that *may have been recovered* from the point source heat exhaust. The words in italic in the previous sentence reveal that Q is an unsettled variable. Full recovery occurs in only a few power plants; in most power plants a (small) share of the point source heat exhaust is recovered for use.

For the proper analysis of a CHP activity, the corresponding *bliss point S* needs identification. A bliss point in a (E, Q) diagram is the point where after E is maximized, the sum $E_{max} + Q_{max}$ (Q_{max} being the *maximum recoverable* quantity of heat) is also at its maximum. In positioning the bliss point S, abstraction is made of the actual use of the point source heat exhaust. When for example, the plant is equipped to only use at maximum 30% of the point source heat exhaust of the power plant, S will be a *virtual bliss point*. The recognition and identification of virtual bliss points, not directly observable, unveils the CHP mystery, what is crucial for the evaluation of partial CHP activity.

Once the bliss point S of a CHP activity is marked in the (E, Q) diagram of a power plant, the design power-to-heat ratio σ is calculated as the slope of the vector O–S. Because σ is a design attribute of the plant, σ is a tombstone parameter, easy to reveal from the as built plans of the power plant with its various equipment and installations to manage and optimize the energy flows. When public policy meddles in the world of cogeneration, it should come up with regulations that support the maximization of σ, the real quality parameter, decided during the design phase of the plant [9]. This implies the maximization of electricity output, because the first goal of expensive power plants remains the provision of high-quality power, not low-quality heat. Therefore heat recovery maximization is always secondary to power maximization (see: CHP paradox and bliss point definition).

4. The merit of CHP and how to measure it

Public policy may support specifically CHP activity when demonstrating particular merit (Section 4.1). In case of support, what outcomes of CHP activity are adopted as proper performance indicators (Section 4.2)?

4.1. Specifying CHP activity merit

The visions on the merit of cogeneration in the energy economy are not universal, leading to diverging and even opposite policies ranging from stimulating to actually destroying cogeneration's role and development [9]. The basic merit of CHP activity is the use of part or all of a thermal power plant's point source heat exhaust, reducing heat rejection to the environment, and avoiding the use of other energy sources to provide the used heat. Ceteris paribus, this merit is sufficient for ranking thermal power plants with heat recovery facilities principally higher than its counterparts without such facilities. Adopting this merit is rooted in preferences for efficient above wasteful energy use practices that cause greenhouse gas emissions [7]. The argument is weakly strengthened by reference to the reduction of local climate change effects caused by concentrated waste heat releases [14].

Few countries have enacted or enforce a policy with a preference for cogeneration activities. An exception is Denmark where the 1979 Heat Supply Act has made this priority real. The important role of cogeneration in the Danish electricity system is evident [3].

[3] This resembles shortcut language "*heat*" and "*work*" for the proper scientific terms "*energy transferred as heat*" and "*energy transferred as work*", emphasized by e.g. Reynolds and Perkins [13].

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4.2. Indicators of CHP performance

Although the merit of CHP is in recovering all or part of the rejected point source heat, the recovered quantity of heat ($\boldsymbol{Q}_{\text{used}}$) is not recommendable as indicator, because for investors and operators rewarding $\boldsymbol{Q}_{\text{used}}$ holds no stimulus to maximize the design power-to-heat ratio. Amazingly, the 2009 adaptations to the emissions trading scheme [15] have changed the allocation rules for CHP generation, such that from 2013 onwards CHP plants will receive only allowances for the used heat and no longer for cogenerated power. Westner and Madlener [16] assess the negative impact of this rule on future investment in large-scale CHP plants. Presumably, the reason of the EU adaptation is due to persisting lack of reliable and easily auditable methods for calculating the cogenerated power output. This article offers the approach to close this gap.

Including $\boldsymbol{Q}_{\text{used}}$ as an additional indicator with accounting for the quality of the recovered heat is proposed by experts in thermodynamics [17]. While heat at higher temperature corresponds to a higher availability (quality) of heat flows [13], 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 smaller is β, the used heat for generated power substitution rate and the higher is $\boldsymbol{\sigma}$, the power-to-heat ratio of CHP activities embedded in steam turbines.

The necessary and sufficient CHP performance indicator is the accurately assessed amount of cogenerated electricity $\boldsymbol{E}_{\text{CHP}}$. The $\boldsymbol{E}_{\text{CHP}}$ variable is not directly observable when condensing and cogeneration activities are mixed, which is the dominant practice because few power plants face a sufficiently high heat demand to recover their full point source heat exhausts. $\boldsymbol{E}_{\text{CHP}}$ is a part of the measured $\boldsymbol{E}_{\text{plant}}$ and has to be assessed. Generally accepted is the rule $\boldsymbol{E}_{\text{CHP}} =$ **"power-to-heat ratio"** $\times\ \boldsymbol{Q}_{\text{used}}$ but lacking are definition and assessment of the proper power-to-heat ratio [7–9].

Section 5 provides the methods for assessing the proper $\boldsymbol{\sigma}$ for every CHP activity added on or embedded in various thermal power generation units. With measurements of the $\boldsymbol{Q}_{\text{used}}$ flows, the accurate $\boldsymbol{E}_{\text{CHP}} = \boldsymbol{\sigma}.\ \boldsymbol{Q}_{\text{used}}$ is calculated. The remainder ($\boldsymbol{E}_{\text{plant}} - \boldsymbol{E}_{\text{CHP}}$) is condensing electricity. Rewarding $\boldsymbol{E}_{\text{CHP}}$ includes incentives to maximize $\boldsymbol{E}_{\text{CHP}}$, what also means investors and operators are stimulated to maximize the design quality ($\boldsymbol{\sigma}$) of the CHP activity and to maximize the quantities of recovered heat ($\boldsymbol{Q}_{\text{used}}$). This is the appropriate way to address the joint production paradox.

5. Monitoring and measuring CHP activity

The temperatures of used heat demanded have a significant impact on some CHP activities, and on the choice of the hosting thermal power generation plants. Heat use is characterized by the required temperature, needed for performing intended functions, such as space heating, washing, cooking, drying, etc. Useful heat is heat available at temperature sufficiently above ambient temperature to provide useful functions. Banding heat demand by temperature is recommended, for example: lowest (above ambient temperature to 50 °C), low (50°–100 °C), medium (100°–200 °C), high (200°–400 °C), very high (above 400 °C).

Depending on the thermal power generation process, point heat source exhausts deliver at different temperatures. Gas turbine outlets range in the very high temperature band; at stacks of engines medium to high temperature heat is recoverable, and low temperature heat at mantle and oil coolers; the cold condensers of steam turbines offer massive heat flows in the lowest band. Only a miniscule part of the latter is useful for some nearby activities, such as greenhouse or tropical fish culture. The height of the temperature of the point source heat exhausts is a crucial discretionary variable for classifying cogeneration activities in two groups: CHP activities without impact on the power output of the plant, and CHP activities with impact. The former refer to "added on", and the latter to "embedded in" CHP activity.

5.1. CHP activities without impact on the power output of the plant

Gas turbines and internal combustion engines deliver heat flows at sufficient high temperature to match demand by a wide variety of applications. Gas turbine outlets are sufficiently hot to deliver pressurized steam for driving a steam turbine (the Combined Cycle Gas Turbine – CCGT (combined cycle gas turbine) plant). Directing their point source heat exhaust to used heat does not significantly affect the electricity output of such plants. Fig. 2a and b show representative shapes of their (E, Q) production possibility sets. In these cases, the coefficient β is zero. When running the plant at full load, and an electricity output of $E_{\max}$ is obtained, the discarded point source heat $Q_{\max} = F - E_{\max} - L$. The bliss point S is located at the coordinate ($Q_{\max}$, $E_{\max}$). When all that heat is used, the "bliss point" S is actually reached, maximizing the energy conversion efficiency $(E + Q)/F$ of the plant. The design power-to-heat ratio $\boldsymbol{\sigma}$ of this CHP activity is the slope of the vector O–S.

In practical settings the demand for used heat at the plant may always be lower than the maximum recoverable heat flow $Q_{\max}$, and the capacity of the heat recovery facilities will be limited to the peak heat demand $Q_{\text{peak demand}}$. The production possibility set is

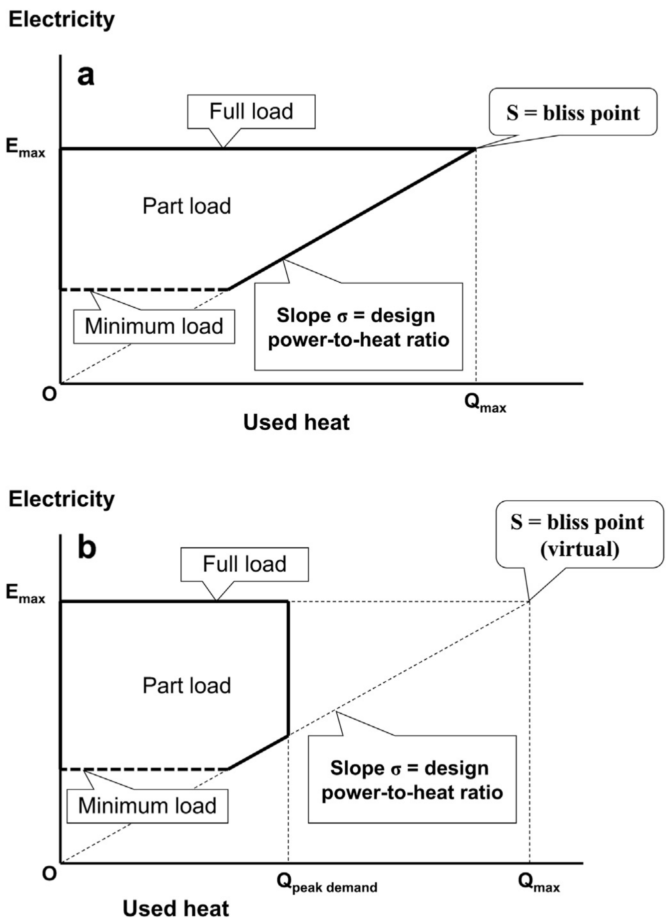

Fig. 2. (a) Cogeneration (E, Q) production possibility set of gas turbines and of internal combustion engines. (b) Truncated cogeneration (E, Q) production possibility set of gas turbines and of internal combustion engines.

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truncated. The bliss point becomes a virtual point, which results in it being overlooked. However, identification of the virtual bliss point is a necessity for a proper assessment of the design power-to-heat ratio $\boldsymbol{\sigma}$.

5.2. CHP activities with impact on the power output of the plant

Steam turbines are the main hosts of CHP activities. The temperature of their point source heat exhaust is scantly above the ambient temperature, hence not widely useful, although the flows are massive due to the latent heat of condensing the steam rejected at the end of the turbine. Practical heat uses require higher than near ambient temperatures, which necessitates steam extraction at higher temperature and pressures. For optimizing steam cycles, small steam flows are extracted from the turbines, and re-used in the cycles. Steam extracted for external heat demand before the end of a turbine where cold condensing conditions prevail, shortens the expansion path, i.e. reduces the work delivered and the power generated [13]. A Mollier diagram offers a visible steam expansion path, which segment lengths reflect the amount of power extracted.

Fig. 3a shows how cogeneration is embedded in a steam cycle that is equipped with cold condensers (approaching near vacuum pressure conditions for the steam outlet) to function as an only cold condensing plant. For clarity of the argument here it is assumed all steam flow can also be extracted either at a low or at a high backpressure (BP). To describe the production possibility sets of CHP activities, first consider the full cold condensing status of the turbine: $\boldsymbol{E_{cond}}$ electricity is generated, and the point heat source exhaust equals $\boldsymbol{Q_{cond}}$. Because $\boldsymbol{Q_{cond}}$ has no economic value, one increases the temperature of the exhaust, viz. the backpressure to BP-low. This reduces the electric output to $\boldsymbol{E_{BP\text{-}low}}$, and enlarges the point source heat flow to $\boldsymbol{Q_{BP\text{-}low}}$; this substitution of used heat for generated power is generally called "*power loss*" (we prefer the term "*used heat for generated power substitution*"), with β as common symbol. The value of β is evidently dependent on the backpressure experienced by the turbine's steam flow [18].

Fig. 3a shows two levels of backpressure (low and high), with production possibility sets respectively triangle $\mathbf{O} - \boldsymbol{E_{cond}} - \boldsymbol{S_{BP\text{-}low}}$, and $\mathbf{O} - \boldsymbol{E_{cond}} - \boldsymbol{S_{BP\text{-}high}}$ (both truncated by minimum plant load constraints). Their used heat for generated power substitution rates differ, with as a corollary that their design power-to-heat ratios differ. Generalizing the argument reveals that a continuum of backpressures or hot condensing temperatures are feasible, each one defining another CHP activity embedded in the steam turbine power plant. Every CHP activity is characterized by its specific β and $\boldsymbol{\sigma}$, crossing in the specific bliss point $\boldsymbol{S_{BP}}$. Fig. 3a also shows the continuum of bliss points, as a segment of the line reflecting the first principle of thermodynamics $F - L = E + Q$, with the diffuse losses L stabilized at their minimum level [9]. The ratio of latent to sensible heat in the total heat flow decreases with higher backpressure, as visually shown by more declining $\boldsymbol{E_{cond}} - \boldsymbol{S_{BP}}$ lines (caused by higher β values). The incremental heat for power substitution, by higher backpressure relative to a lower backpressure, is reflected in the (equal to -1) slope of the set of bliss points.

In practice, a steam turbine may have two major hot condensers for steam extraction. Assuming all steam can be extracted at all three condensers (one cold + two hot), the production possibility set of the steam plant is shown by area $\mathbf{O} - \boldsymbol{E_{cond}} - \boldsymbol{S_{BP\text{-}low}} - \boldsymbol{S_{BP\text{-}high}} - \mathbf{O}$. Generally, the heat extraction capacity at large steam plants will be limited by the demanded heat capacity of the end-uses (e.g., the base load of a district heating system). This is shown in Fig. 3b, derived from Fig. 3a. The actual possibility set of the plant is the solid bordered pentagon, as a cut from the wider set discussed in Fig. 3a. When only viewing the smaller set without the virtual components underlying the set, it is difficult to recognize the crucial parameters, such as the proper design power-to-heat ratio.

Assessing $\boldsymbol{E_{CHP}}$ is done first by CHP activity: the heat recovery $\boldsymbol{Q_{used}}$ at every hot condenser is measured and multiplied by the

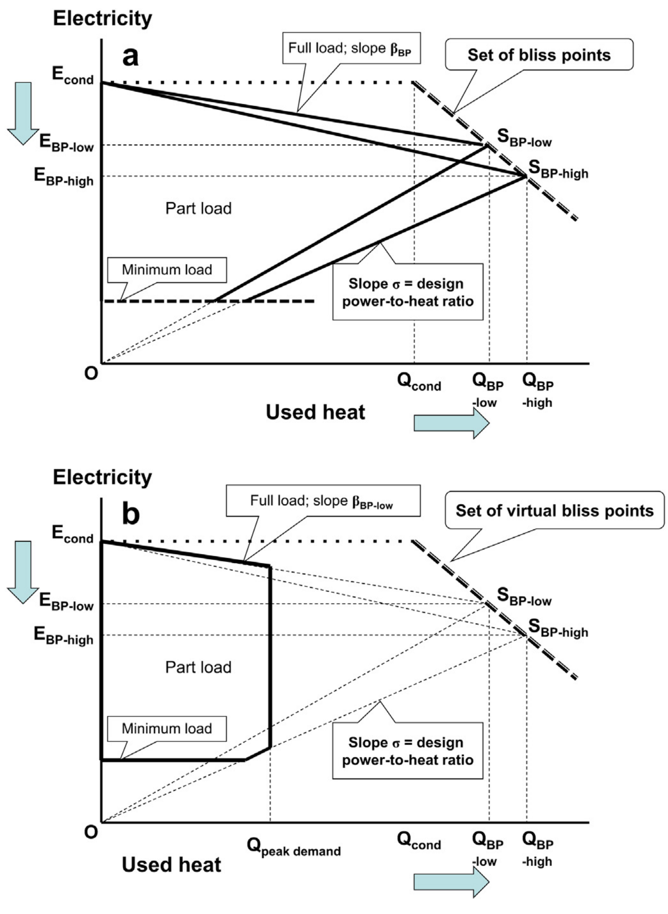

Fig. 3. (a) Cogeneration (E, Q) production possibility set of extraction-condensing steam turbines. (b) Truncated cogeneration (E, Q) production possibility set of extraction-condensing steam turbines.

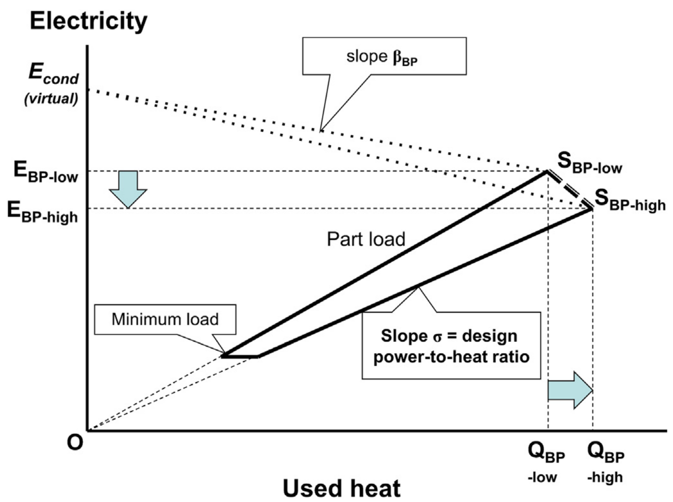

Fig. 4. Cogeneration (E, Q) production possibility set of pure backpressure steam turbines.

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corresponding power-to-heat ratio σ. The separate results are added to obtain the total quantity of cogenerated electricity.

The pure backpressure steam turbine is not equipped with a cold condenser; all steam is exhausted at backpressure. Its production possibility set depends on the number of hot condensers installed. When there is just one, the (E, Q) set is an O–S line segment. With two or more hot condensers, which loads can be modulated, creates a possibility set as shown by the solid bordered quadrangle in Fig. 4, derived from Fig. 3a. The condensing part of Fig. 3a is virtual, again confusing experts. For example the European CEN commission considers backpressure steam turbines as units *without* power loss [[8], p.14]. This CEN position violates the laws of thermodynamics.

The inherent attribute of a pure backpressure turbine is to recover all the point source heat exhaust of the steam cycle, i.e. the installed heat capacity is the maximum one. As such the bliss points are naturally revealed real points, and the assessment of the proper power-to-heat ratios is automatically right. The case is indeed simple because no mixed condensing-cogeneration activities occur, as in extraction-condensing steam turbines. As argued in Refs. [9], power plants without facilities to reject heat to the ambient environment are simple cases, because E_{CHP} is equal to the standard measured variable E_{Plant}.

6. Numerical example: identifying the virtual bliss point and the power-to-heat ratio of a CHP activity embedded in a larger steam power plant

Fig. 5 provides a numerical example with energy flows of a large condensing steam power plant supplying heat for the district heating of the nearby city. The nominal fuel flow to the plant is 1000 MW, converted in a supercritical steam boiler. In full cold condensing mode the plant generates 460 MW electricity, with 450 MW condensed heat rejected. Boiler, radiation and other non-recoverable losses sum up to 90 MW. The plant embeds a cogeneration activity delivering at maximum 150 MW heat at modest temperature to the city's district heating network. Extracted steam provides 1 MW heat for 0.1 MW forgone power output ($\beta = 0.1$). The nominal cogeneration efficiency is 59.5% ((445 + 150)/1000) and, according to the actual EU's directives, is not considered as a high-efficiency cogeneration. The Directives enacted two limits: one of 75% and one of 80% [5,7].

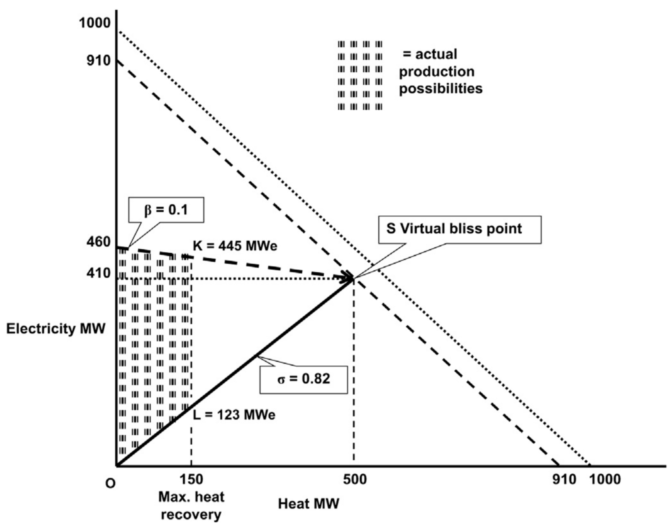

Fig. 5. Numerical example of a steam power plant with cogeneration activity of limited capacity: determining virtual bliss point S and design power-to-heat ratio σ.

The E–Q set is divided in an attainable part and a virtual part. The bliss point is a virtual point, not identifiable without the proper concepts and analysis developed in the previous sections. The partly virtual power-heat production possibility set of the plant is the triangle O – 460 – S – O. Point 460 on the ordinate is the design full condensing power output. From this point the line 460–0.1 $\boldsymbol{Q}$ is drawn and its crossing with the sloping line 910–910, is the bliss point S at $\boldsymbol{Q} = 500$, $\boldsymbol{E} = 410$. The design power-to heat ratio $\sigma = 0.82$. The production possibility set is the dashed area (trapezium O – 460 – K – L – O). The K ordinate equals 445 MW power and the L ordinate 123 MW power, when the plant runs at full load with maximum feasible cogeneration activity (150 MW heat recovered). The measured plant power output (445 MW) consists of 123 MW $\boldsymbol{E}_{CHP}$ (calculated as 0.82 × 150 MW $\boldsymbol{Q}_{used}$), and 445–123 = 322 MW is $\boldsymbol{E}_{Cond}$.

Applying the external benchmark formula, as recommended by the EU Directives [5,7], requires the identification of the conversion efficiency of separate power and of separate heat delivery. Mostly is assumed 55% for power (the CCGT cycle) and 90% for heat (a high-efficiency steam boiler). Then, the fuel value for the obtained output flows by the plant with embedded CHP activity would be at best: (445 MW electricity/0.55) + (150 MW $\boldsymbol{Q}_{used}$/0.90) = 976 MW fuel, being less than 1000 MW used by the plant. Adding on top the arbitrary requirement by the Directive that CHP should save at least 10% compared with the reference for separate production [[7], p.31], i.e. in the example falling below 878 MW fuel, this valid and efficient recovery of wasted heat is labeled low-efficiency by the Directive. This shows the perverse impact of 'Primary Energy Saving' approaches, when not applied in the proper way. The EU Directive and the practice in some EU member states showcase such impacts.

The only issue with the identification of virtual bliss points resides in the fact that they cannot be operationally measured because plants cannot operate at these virtual bliss points. But the positions of virtual bliss points are easy to derive from the thermal power plant designs and commissioning parameters.

7. Improving CHP regulation

Except for the few cases (for example Denmark) that assign priority to power plants with CHP activity, public regulation of cogeneration in most countries is not well developed. The EU directives fail on crucial criteria of appropriate regulation [9]. After a few general considerations about independent power activity regulation (Section 7.1), the pitfall of external benchmarking as the core of the EU's approach is highlighted (Section 7.2).

7.1. Sound regulatory approach

Every meaningful regulation starts by correctly and precisely defining what actually is regulated, in case: cogeneration activity added on/embedded in thermal power plants. Up to now, regulations failed in properly identifying CHP activity [19]. This is of particular concern when condensing and cogeneration power generation occur simultaneously. By appropriate identification and measurement of the relevant parameters and energy flows, cogeneration activities are clearly characterized. Then it is possible to discuss what aspects of that activities may be promoted and supported, and how this can be done in the most transparent and effective way.

The promotion of cogeneration as a competitive activity and accessible to independent power producers should address salient aspects like: optimization of technical characteristics with priority for high power-to-heat ratio designs; stimulation of economies of scale and high capacity factors for the generation plants by opening

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a large market for both outputs of power and heat; guaranteeing fair terms for exchanges of power (as surplus, make-up, or back-up flows) with the grid. The latter terms significantly affect the development of any independent and decentralized power generator. Unfair conditions for exchanging power with the grid are main barriers to a balanced development of cogeneration in both the heat and the power markets [20,21]. But for cogeneration difficulties increase because the joint outputs power and heat are delivered to separate energy markets (end-users) [10]. When regulations explicitly or implicitly fence in cogeneration's freedom of operating in the energy markets, the electricity market in particular, the economics of cogeneration deteriorate [9].

7.2. External benchmarking pitfall

The quality and merit of CHP activity are individually defined in Sections 3 And 4. Adding other considerations and tests to vest cogeneration's merit confounds the case and implies obstructions to the full deployment of cogeneration activity. The obstructions may range from weak to strong, arrive unintended or deliberate, and be overt or hidden veiled by high-efficiency talk. The latter is the case with the "high-efficiency cogeneration" of the EU directives [5,7] based on dubious external benchmarking practices.

We were first in applying external benchmarking for assessing CHP's reduction in CO_2 emissions [22]. Benchmarking is '*the continuous, systematic process of comparing the current level of own performance against a predefined point of reference, the benchmark, in order to evaluate and improve the own performance*' [23]. The choice of benchmarks is crucial because the individual project performance is measured as a 'distance-to-targets' or gap between the benchmark characteristics as targets. For reducing the distance to targets and resembling the adopted benchmark as much as possible, the individual project activity is changed. When benchmarking is applied in a private context, the actor controls the selection of targets and the degree and pace of change, accommodating fuzzy aspects in definitions, data availability and methods applied.

However, in a public regulatory context external benchmarking is precarious. Public regulation needs uncontested defined concepts and indicators, measured by argued, transparent and robust methods. Notwithstanding the caveats, the EU directives propose to benchmark cogeneration plants on the high-efficient combined cycle gas turbine (CCGT) and high-efficiency boilers. Next to the difficulties in fixing appropriate efficiency numbers of the external benchmarks, the false assumption that any cogenerated power and CCGT power are perfectly comparable and exchangeable any time of the year weakens the case for applying external benchmarking [24]. EU's external benchmarking exerts perverse effects on the deployment of CHP activities [25]. It restricts investment in cogeneration because the regulation penalizes cases with not continuous full or almost full heat load. Penalizing operation in mainly condensing mode cuts the utilization time of the capital investment. It also impedes economies of scale in power generation when maximum heat load is limited in capacity. Hostile positions to independent cogeneration developments fence or constrain their entry into electricity markets by applying unfair tariffs for surplus and back-up power exchanges [21]. Driving independent investors to low-quality investments is the worst effect that may occur.

8. Conclusion

This contribution demonstrates a lean method to accurately identify and measure the quantity of cogenerated power $\mathbf{E_{CHP}}$ for every power plant hosting CHP activity. The method is practical by using only design characteristics of the power plant and energy flows that are normally monitored and inventoried. For attaining these exceptional results, we had to make a few steps: first, clarify what CHP activity actually is; second, construct power-heat production possibility sets; third, focus on the efficiency frontier of such sets and in particular on the salient bliss point; fourth, identify the design power-to-heat ratio of every cogeneration activity. It is argued why $\mathbf{E_{CHP}}$ is a necessary and sufficient indicator of CHP performance, and the failures of the EU CHP Directives are highlighted.

The ambitions of this article are eliminating the confusing talk about CHP/cogeneration, and formulating a clear and effective alternative. It proved necessary to start with the proper definition of what CHP/cogeneration is and does. Looking at CHP as a mitigation facility for the point source thermal pollution of thermal power generation plants, clarifies its position as an activity added on or embedded in a thermal power generation process. CHP activity converts part or all of the point source thermal pollution of the power plant into used heat. Policy directed at CHP promotion, will focus on CHP activity, and will avoid unfounded transfer of responsibility from the hosting thermal power generation plant onto CHP activity.

EU's talk of "high-efficiency cogeneration" is a pitiful example of confounding host and guest.

The second task is accurately identifying and describing the CHP activities as added on or embedded in thermal power generation plants. The common concepts of power-to-heat ratio and power loss factor are revisited. Crucial is the insight that every CHP activity owns a single, clearly identifiable, design power-to-heat ratio, as tombstone characteristic of a power plant equipped with point source heat recovery facilities. When a plant is commissioned, those characteristics are simple to reveal. The method to do this properly is explained for the common thermal power generation cycles: gas turbines, internal combustion engines, and steam turbines. For this, earlier proposed concepts of (Electricity–Heat) production possibility sets and bliss points [9,11] needed refinement and improved definition. The bliss point is the salient point on the efficiency frontier of the production possibility set: after maximizing electricity output, it includes all the recoverable point source heat. In particular, the finding of bliss points being virtual points for most CHP activities, unveils the mystery of cogeneration. Only by positioning the – virtual – bliss point, the correct design power-to-heat ratio is observed. For a reliable assessment of the quantity of cogenerated electricity, the measured quantity of recovered heat by the CHP activity is multiplied with its design power-to-heat ratio. The method is extensively explained and then illustrated with a numerical example.

The design power-to-heat ratio of a CHP activity parallels the electricity conversion efficiency of the hosting plant, and is a necessary and sufficient indicator of the real quality of the CHP activity. Without proper attention for its real quality, CHP can turn out to be unprofitable, even if subsidies are provided [26]. Addition of external benchmark requirements is a wrong practice with possible perverse effects for the real quality of CHP activities and for its economic conditions, as the experience with the EU directives reveals [9,25].

This article also cares about appropriate cogeneration vocabulary. It builds on commonly used symbols and terminology. Sometimes it was considered necessary to improve some terms, for example β: generally called "power loss factor", but "used heat for generated power substitution rate" is more telling; also the necessary inclusion of "design" when "power-to-heat ratio" $\boldsymbol{\sigma}$ is mentioned, will avoid confusion. We also reconfirmed the use of terminology carried over from environmental and economics sciences, e.g.: point source, production possibility set, with efficiency

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frontier. The concept "bliss point" is fostered for referring to the point where the joint production CHP paradox is best addressed. This article again may inspire scholars in the field [27], and hopefully they refer and comply with the established vocabulary.

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References

[1] EDUCOGEN. An educational tool for cogeneration. In: SAVE EU programme 2001 [Brussels].
[2] Westner G, Madlener R. Development of cogeneration in Germany: A mean-variance portfolio analysis of individual technology's prospects in view of the new regulatory framework. Energy 2011;36:5301–13.
[3] Ostergaard PA. Regulation strategies of cogeneration of heat and power (CHP) plants and electricity transit in Denmark. Energy 2010;35:2194–202.
[4] Siciliano GF. Combined heat and power and district energy in the U.S. IEA/GSEP-CHP/DHC joint Workshop. USA; February 12, 2013.
[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.
[6] Proposal for a Directive of the European Parliament and of the Council on energy efficiency and repealing Directives 2004/8/EC and 2006/32/EC. European Commission COM; 2011. 370 final.
[7] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. Official Journal of the European Union; 14.11.2012.
[8] Workshop Agreement CEN/CENELEC. Manual for determination of Combined Heat and Power (CHP). CWA 45547; September 2004. Brussels.
[9] Verbruggen A. The merit of cogeneration: measuring and rewarding performance. Energy Policy 2008;36:3069–76.
[10] Verbruggen A. An introduction to CHP issues. International Journal of Global Energy Issues 1996;8:301–18.
[11] Verbruggen A. A system model of combined heat and power generation. Resources and Energy 1982;4(3):231–63.
[12] Masters GM. Introduction to environmental engineering and science. New Jersey, USA: Prentice Hall; 1991.
[13] Reynolds W, Perkins H. Engineering thermodynamics. New York, USA: McGrawHill; 1977.
[14] Zevenhoven R, Beyene A. The relative contribution of waste heat from power plants to global warming. Energy 2011;36:3754–62.
[15] Directive 2009/29/EC of the European Parliament and of the Council amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community. Official Journal of the European Union; 23.4.2009.
[16] Westner G, Madlener R. The impact of modified EU ETS allocation principles on the economics of CHP-based district heating systems. Journal of Cleaner Production 2012;20:47–60.
[17] Schauman, G. Energy efficiency in industry. Keynote lecture at 4th European congress on economics and management of energy in industry, iPorto, 27–30 November 2007.
[18] Harvey D. Clean building feature. Cogeneration and On-Site Power Production; September-October 2006. p. 107–15.
[19] Verbruggen A. Quantifying combined heat and power (CHP) activity. International Journal of Energy Technology and Policy 2007;5:17–35.
[20] Toke D, Fragaki A. Do liberalized electricity markets help or hinder CHP and district heating? The case of the UK. Energy Policy 2008;36:1448–56.
[21] Verbruggen A. Pricing independent power production. International Journal of Global Energy Issues 1990;2:41–9.
[22] Verbruggen A, Wiggin M, Dufait N, Martens A. The impact of CHP generation on CO_2 emissions. Energy Policy 1992;20(12):1207–14.
[23] Couder J, Verbruggen A. Technical Efficiency measures as a tool for energy benchmarking in industry? Energy & Environment 2003;14:705–24.
[24] Franke U. Die Thermodynamik der KWK aus systematischer Sicht. Euroheat & Power 2004;33:28–33.
[25] Verbruggen A. Qualifying combined heat and power (CHP) activity. International Journal of Energy Technology and Policy 2007;5:36–52.
[26] Radulovic D, Skok S, Kirincic V. Cogeneration – investment dilemma. Energy 2012;48-1:177–87.
[27] Frangopoulos CA. A method to determine the power to heat ratio, the cogenerated electricity and the primary energy savings of cogeneration systems after the European Directive. Energy 2012;45-1:52–61.