Assessing Cogeneration Activity in Extraction–Condensing Steam Turbines: Dissolving the Issues by Applied Thermodynamics

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Extraction–condensing steam turbines mix cold-condensing and cogeneration activities making the respective power and fuel flows not directly observable. A flawed assessment of the flows is causing confusion and bias. A steam expansion path on a Mollier diagram reveals the design characteristics of a thermal power plant and of its embedded combined heat and power (CHP) activities. State variable data on a unit mass of steam, entering the turboset as life steam and leaving it at one of the heat extraction exhausts, provide the roster of the power-heat production possibility set of the plant. The actual production possibilities are drawn from the roster by applying capacity data and constraints on the heat extraction points. Design power-to-heat ratios of CHP activities are univocally identified, allowing accurate assessments of cogenerated power. This information is needed for proper incentive regulation of CHP activities, pursuing maximization of CHP quality and quantity. Quality is gauged by the power-to-heat ratio, principally a design (investment) decision. Quantity is gauged by the operational amounts of recovered heat exhausts. Optimal regulatory specificity is attained through setting generic frameworks by technology, accommodating investment and operational decisions by plant owners. Our novel method is explained and applied with numerical data, also revealing the flaws in present regulations. [DOI: 10.1115/1.4033424]

Keywords: extraction–condensing steam turbine, design power-to-heat ratio, regulatory specificity, EU CHP Directive

1 Introduction

CHP is an evergreen topic in engineering analysis. Most studies focus on the investment appraisal of the proposed CHP activities [1,2] or on the operational analysis of power plants with CHP activity [3,4]. The major CHP activities are embedded in extraction–condensing steam turbines, implemented for various applications of electricity and heat generation in industry, for example, petrochemical complexes [5], also studied by Zhang et al. [6], and in district heating systems [7]. CHP is also part of the electric power transition pathways [8].

This article is different in nature. It addresses a long-standing, unsolved problem in the CHP literature and practice: how to accurately measure the share of the cogenerated electricity in the total power output of an extraction–condensing plant. The solution builds upon the results of our earlier work [9,10] and more recent developments [11]. The analysis is framed with the graphical tool of electricity–heat (E,Q) "production possibility sets" of thermal power plants. Cogenerated heat is the heat that would otherwise be a waste from thermal pollution point sources of a power plant, but is instead recovered. Depending on the temperature of the exhausted heat and on the thermodynamic cycle, heat recovery may be accompanied by "power loss" [12,13] or more accurately by "useful heat for generated power substitution." All the power generated in the plant equals cogenerated power (E_{CHP}) when the plant reduces point sources thermal pollution to zero [11]. However, when the reduction of point-source thermal pollution is not 100% because only part of the recoverable heat is actually recovered, the plant power output consists partly of condensing power and partly of cogenerated power, without possibility to directly observe or meter the shares. The question is: How to precisely identify and assess the shares, in particular the quantity of cogenerated electricity E_{CHP}? Production possibility sets are instrumental in answering the questions. But a major issue remains: How to graph the possibility sets for a real thermal power plant with embedded CHP activities? This missing link is provided by this article and illustrated with a numerical example.

This article is organized as follows: Sections 2 and 3 are composed of several subsections, they both open with a more detailed description of their contents. Sections 4 and 6 are kept concise, with more elements about regulating CHP activity brought up in Sec. 5.

2 Material and Methods

Here, we clarify the problem statement of our analysis. It starts with defining CHP activity itself as "added on" or "embedded in" thermal power plants (Sec. 2.1). For identifying the activity, some energy flows are not observable (Sec. 2.2), in particular the quantity of cogenerated electricity E_{CHP}, while this is the appropriate indicator of CHP performance (Sec. 2.3). The principle to find E_{CHP} is reminded (Sec. 2.4), but the methods to properly assess E_{CHP} are not available in the official and academic literature (Sec. 2.5).

2.1 Defining CHP Activity.

At the outset, defining cogeneration as such is necessary. Although most scholars and practitioners use the shortcut CHP/cogeneration plant, it is useful to note that CHP/cogeneration is an activity added on or embedded in a thermal power generation unit [11]. The CHP activity is added on when it has no impact (or only a minor impact "of footnote significance") on the electric power output of the unit; technically, the

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Contributed by the Advanced Energy Systems Division of ASME for publication in the JOURNAL OF ENERGY RESOURCES TECHNOLOGY. Manuscript received May 6, 2015; final manuscript received April 2, 2016; published online May 12, 2016. Editor: Hameed Metghalchi.

"used heat for power substitution rate" (mostly named "power-loss factor") equals zero ($\beta = 0$). The term embedded in is applied when the useful heat from the unit has an effect $\beta > 0$, i.e., there is "power loss," When and why the difference occurs? For $\beta = 0$, thermal plants (mostly gas turbines or engines) reject point-source waste heat at a sufficiently high temperature for serving targeted thermal end-uses. For $\beta > 0$, thermal plants (mostly steam power plants) exhaust the heat via condensers at nearly ambient temperature. The latter heat sources are only useful for a few limited low-temperature end-uses, e.g., fish farms and greenhouses. For most industrial and urban end-uses, the temperature must be significantly higher than ambient temperature, requiring steam extraction at a pressure above the near vacuum pressure of the cold condenser. This truncates the steam expansion path of this share of the steam; the truncating impact on power output is proportional to the backpressure and temperature of the heat exhaust [14]. Also, a backpressure steam turbine plant, not owning a cold condenser, is to be classified as a cycle with power loss, notwithstanding it is impossible to observe a β rate because the cold-condensing state is absent. The impossibility of direct observation of β is not a valid argument for describing backpressure steam turbines as units without power loss as CEN/CENELEC [12] and Urošević et al. [13] do.

2.2 Energy Flows in a Steam Power Plant With Embedded CHP Activity. The accounting constraints of the first law of thermodynamics provide consistency in the quantities of the various energy flows in a steam power plant. Table 1 shows how CHP activity and condensing activity sum to the plant activity, and how separate summing applies to the major flows of fuel, electricity, and point-source heat emissions, with nonrecoverable diffuse energy losses mentioned only at the plant level (it is not possible nor necessary to split diffuse losses over activities). Table 1 is helpful in several ways to keep track of the flows and to classify practical cogeneration activity cases. In a CHP analysis, every fuel, electricity, and heat flow need one of the subscripts "plant," "CHP," or "cond" to avoid confusion and faulty formulas. Of the ten flows mentioned in the table, only four can be directly monitored and measured: F_{plant}, E_{plant}, Q_{CHP} (also called Q_{used} or $Q_{\text{recovered}}$), and Q_{cond} (this latter flows are generally but inventoried at larger plants, for example, because of reporting obligations on thermal pollution). The flows shown in Table 1 in square brackets are not directly observable or measurable. They have to be assessed with the help of measured flows, formulas, and parameters describing the CHP activity. The most central variable to know is the quantity of cogenerated power E_{CHP}, because it is considered as the appropriate indicator of CHP performance.

2.3 The Quantity of Cogenerated Power E_{CHP} as Appropriate Indicator of CHP Performance. The rate E_{CHP} gauges CHP activity and, when calculated properly, reflects the rating of CHP performance. The basic merit of CHP is its ability to recover otherwise wasted point-source heat in thermal power generation processes. Reducing thermal pollution and a higher fuel conversion efficiency are arguably positive activities in the public interest. Basing the performance of a CHP activity on the sole variable of recovered heat Q_{CHP} is, however, not satisfactory, because it lacks incentives to improve and maximize the quality of CHP. This quality is reflected by the design power-to-heat ratio σ of the CHP activity.

Like adopted by CEN/CENELEC [12], E_{CHP} is the necessary and sufficient indicator to properly gauge CHP activity. E_{CHP} is not directly observable in power plants with mixed condensing and backpressure activities. The assessment of E_{CHP} has been a source of confusion, flawed logic, and biased (even perverse) regulations. This article shows that the only right approach is based on the quantity of recovered heat Q_{CHP}, multiplied by the design power-to-heat ratio σ, as quality measure of a particular cogeneration activity. The indicator E_{CHP} bundles operational performance (the amounts of recovered heat Q_{CHP}) with the result of investment decisions (the design power-to-heat ratio σ, reflecting the loss of power generation by the heat recovery).

Table 1 First law of thermodynamics: energy flows in a thermal power plant with mixed CHP and condensing activity (energy flows in [brackets] cannot be metered; their assessment needs a computational procedure)

Activity Energy flows	CHP	+ condensing	= plant
Fuel, $F =$	$[F_{\text{CHP}}]$	$+ [F_{\text{cond}}]$	$= F_{\text{plant}}$ $=$
+ Electricity, E	$[E_{\text{CHP}}]$	$+ [E_{\text{cond}}]$	$+$ $= E_{\text{plant}}$
+ Point source heat, Q	Q_{CHP}	$+ Q_{\text{cond}}$	$+$ $= [Q_{\text{plant}}]$
+ Losses nonrecoverable	—	—	$+ [L_{\text{plant}}]$

2.4 Identifying the Quantity of Cogenerated Power E_{CHP}. Table 1 illuminates the first steps in addressing the problem of identifying E_{CHP}. When either the column of the activity CHP (a condensing power plant not equipped with cogeneration facilities) or the column of the activity condensing (a backpressure steam plant without heat rejection facilities) is empty, the problem of identification vanishes: the observed energy flows in the plant own a clear, singular label. In all the other cases, cogeneration and condensing activities may occur simultaneously, and E_{CHP} is no longer directly observable or, in other words, the observed flow E_{plant} has to be split via calculation into E_{CHP} and E_{cond}. For splitting, the proportionality principle is generally accepted and applied in official regulations [15,16]: $E_{\text{CHP}}/E_{\text{cond}} = Q_{\text{CHP}}/Q_{\text{cond}}$ or rewritten: $E_{\text{CHP}} = \{E_{\text{cond}}/Q_{\text{cond}}\} \times Q_{\text{CHP}}$. The term in brackets is called the "power-to-heat ratio" (called C in the EU Directives; here named σ to emphasize, it should be the design power-to-heat ratio of a CHP activity) and is not observable because E_{cond} is not directly measurable (with also Q_{cond} generally not being measured). Finding and implementing the right power-to-heat ratio σ are sources of confusion.

2.5 Literature and Practice in the Identification and Assessment of Cogeneration Activity. The problem of identifying and assessing cogeneration activity plainly emerged with the first EU CHP Directive [15]. This directive failed in delivering a correct definition of the proper power-to-heat ratio σ. The directive states that the power-to-heat ratio C "shall mean the ratio between electricity from cogeneration and useful heat when operating in full cogeneration mode using operational data of the specific unit." Here, the circular logic has entered, because one needs to know the power-to-heat ratio to assess "electricity from cogeneration," the latter being proposed by the EU Directive as input for calculating the ratio. Because the directive does not deliver a solid method for assessing E_{CHP} and even does not refer to the assessment of F_{CHP} at all, it neither can assess the right cogeneration efficiency of a CHP activity, being by definition: $\eta_{\text{CHP}} = (E_{\text{CHP}} + Q_{\text{CHP}})/F_{\text{CHP}}$. The directive therefore adopts arbitrary efficiency numbers (75% and 80% depending on the technology). CEN/CENELEC [12] clarified the EU Directive approach, but remained captured in the same circular logic.

Earlier analysis [17] revealed the obvious issues in the 2004 EU and CEN/CENELEC proposals and suggested alternative methods. Later, colleagues noted our publications but neither criticized the analysis nor accepted it as a proper framework. Frangopoulos [18] followed our explicit focus on the first law of thermodynamics to avoid nonsensical energy flows that could result from the EU Directive's approach. He adopted the division rule for splitting plant power in condensing power and cogeneration power. However, his Sec. 3 used E as an amalgamation of condensing power and cogeneration power, precluding a meaningful application of the division rule. For indentifying E_{CHP}, the quantity of cogenerated electricity, he followed the CEN/CENELEC proposal, including its circular logic (his subsection 4.2 and Appendix B). CEN/CENELEC escapes from the self-created circular confinement by adopting the arbitrary "cogeneration efficiency" numbers 75% or 80%. The necessary escape is concealed by Frangopoulos by shifting the meaning of the nondefined variable E.

Urošević et al. [13] found that our critical analyses and indications of deficiencies in the 2004 Directive lead to "clearly advocating the need for more complex CHP measurements," what is certainly not the case. On the contrary, our method is straightforward and transparent, using known or measured variables. The literature review by Ye and Li [19] ends with: "Though many methods have been suggested so far, these methods cannot meet the requirements of practical applications owing to some intrinsic limitations," but the authors do not clarify what they mean by "intrinsic limitations."

The method we present in Sec. 3 is free of arbitrary numbers to escape a self-created circular logic, does not include confusing variables, and the measurements are not at all complex. The method applies thermodynamics in a straightforward, transparent way.

3 Theory/Calculation

The observation that accurate identification of E_{CHP} remains unresolved in the CHP literature and EU regulation [16] was the stimulus to refresh the analysis of CHP activities [11]. In focusing on didactic goals, accurate vocabulary, and comprehensive coverage, we nevertheless omitted the discussion on the thermodynamics of the methodology and neglected the provision of guidelines for practical use. The most intricate CHP activities, i.e., the ones embedded in extraction–condensing steam turbines [13,20], are selected as cases. The steam expansion path in a Mollier diagram supplies the required design characteristics of a steam cycle with CHP activities (Sec. 3.1). From the design data, the (E,Q) production possibility set for unit mass flows is derived (Sec. 3.2). The practical (E,Q) set is obtained by applying capacity design data on the unit mass roster, and the practical calculations are illustrated with a numerical example (Sec. 3.3). The applied case also reveals that the EU Directives [15,16] are a source of erroneous and biased regulation.

3.1 Mollier Diagram Showing the Steam Expansion Path in an Extraction–Condensing Turbine With CHP Activities. Figure 1 shows the steam expansion path of a Rankine cycle with reheating and embedded CHP activities, in a Mollier diagram (specific enthalpy h in kJ/kg versus specific entropy s in kJ/K kg). When CHP activity is embedded in a Rankine cycle, one or two (more is feasible but unusual) hot condensers are installed in the low-pressure part of the steam expansion path. Isentropic (vertical line segments) and actual (dashed bending-off curves) expansion path segments are shown: the left segments refer to the high-pressure turbine, followed by a reheating at constant 40 bar pressure, and then, the expansion in the low-pressure turbine to 0.06 bar (point S_0).

Two hot water condensers are placed at, respectively, S_1 and S_2. The enthalpy values of the start and the end points of the actual expansion segments characterize the power cycle and the CHP activities embedded in it. For the high-pressure turbine segment, the specific enthalpies are 3500 and 3100 kJ/kg. The specific enthalpy at the entry of the low-pressure turbine is 3600 kJ/kg, and for the steam exhausts, Fig. 1 shows the specific enthalpies to be 2300 kJ/kg at S_0, 2675 kJ/kg at S_1, and 2865 kJ/kg at S_2. The data are design data of a steam power plant with heat extraction.

3.2 (E,Q) Production Possibility Set for Unit Mass Flows. Figure 2 draws the (E,Q) production possibility set of the plant in kJ/kg values by following a unit mass flow's path [14] along the steam expansion curves in the Mollier diagram. The horizontal top line ending in point S_0 represents the cold-condensing state ($\beta = 0$). The height on the ordinate is 1700 kJ/kg = (3500 − 3100) + (3600 − 2300), reflecting the maximum E_{cond} output with no cogeneration activity. The specific enthalpy of the exhaust heat flow is 2300 kJ/kg, but not useful because it is at ambient temperature. Changing ambient air or water conditions slightly shifts point S_0, causing slight shifts in the value of power-loss factors β depending on the position of S_0. This is an argument for avoiding power-loss factor information when not necessary in assessing the quantity of cogenerated power E_{CHP}.

When steam flow is extracted at a condition higher than S_0, substitution of heat for power occurs, in principle at the rate of 1 kJ/kg electricity given up for one additional kJ/kg heat used. In the first step, all condensing heat is recovered. When this step can be

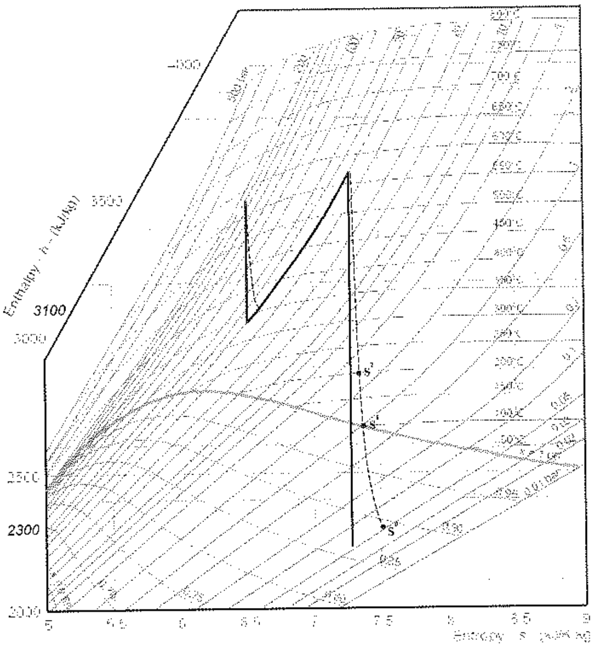

Fig. 1 Example of steam expansion in a Mollier diagram with a reheat step and two hot condensers (situated at S_1 and S_2) in addition to the cold condenser (S_0). The source of the background Mollier-diagram is engineeringtoolbox.com.

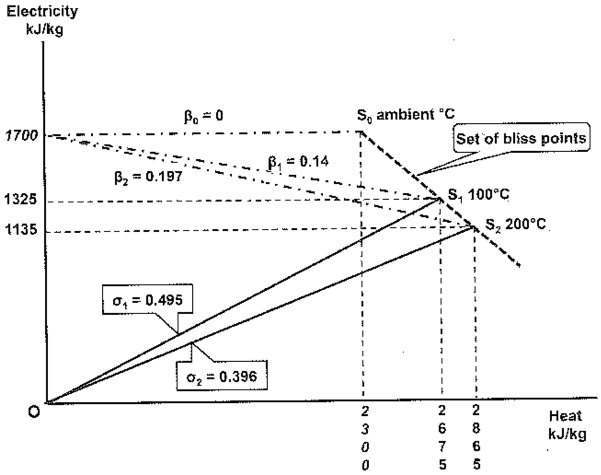

Fig. 2 (E,Q) production possibilities in kJ/kg of the Rankine cycle example steam expansion and extractions, as shown in Fig. 1

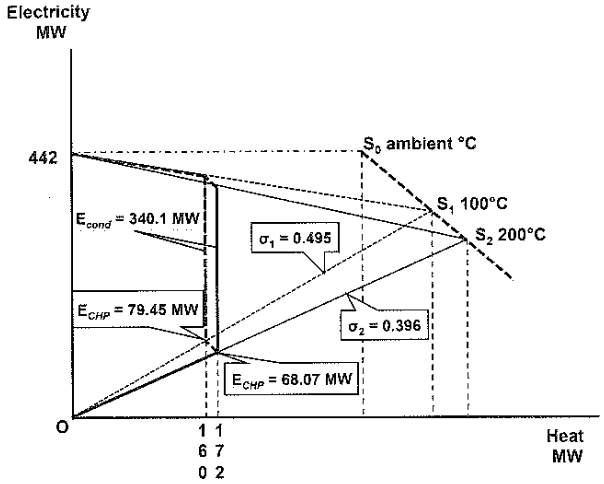

Fig. 3 Extraction–condensing steam turbine: truncated form of the (E,Q) production possibilities for a maximum steam mass flow of 60 kg/s over both hot condensers S_1 and S_2

kept very short (assume S_1 just above S_0 in Fig. 1, which means that the energy is at a temperature slightly above the ambient temperature), the gain in useful heat is significant because it is predominantly latent condensing heat and the β loss in power is small. After recovering the latent condensing heat, only a one-to-one substitution of sensible heat remains feasible. Therefore, the slope of the line of the bliss point set equals 1. Two cogeneration activities are embedded in the shown Rankine steam cycle and described by the points S_1 and S_2. At S_1, heat at 100 °C is made available. Compared to the full condensing status, the heat for power substitution rate β is 0.14 and the power-to-heat ratio σ_1 is 0.495. Similarly for S_2 where heat at 200 °C is delivered, β equals 0.197 and σ_2 equals 0.396.

3.3 The Practical Assessment of E_{CHP}. In drawing Fig. 2, the states like S_1 and S_2 are examined following the path of 1 kg mass fluid. In reality, a turbine in full (nominal) load processes tens to hundreds of kg/s of fluid, depending on the plant capacity. The fluid leaves the low-pressure steam turbine mainly via the exits at S_0, S_1, and S_2. A steam turbine has some minor steam outlets for preheating water flows and for purging. CEN/CENELEC [12] discussed the minor outlets in detail. From a regulators' perspective that encompasses all steam turbines with cogeneration activity in a state or on the continent, limiting the analysis to the major cold and hot condensers keeps the approach feasible and controllable and still sufficiently accurate for incentive regulation and for obtaining valid statistical data. In an extraction–condensing turbine, the cold condenser at S_0 can pass all the fluid and requires a minimum flow during operation of the turbine; the flow over the hot condensers is physically limited and the maximum flow is designed for given maximum deliveries of useful heat. Figure 2 is used to construct Fig. 3 by including information on the maximum steam flows and related power and heat capacities.

We consider a practical case. Let the maximum nominal life steam flow rate be 260 kg/s (at 180 bar and 580 °C, implying the input energy rate is about 910 MW, with 9% of primary fuel input converted in nonrecoverable losses). From the total flow rate, 60 kg/s can pass through the hot condensers working in series. The flow is shifted from S_1 toward S_2 when demanding a higher temperature for the used heat. At S_1, the flow can deliver 160.5 MW (= 60 kg/s × 2675 kJ/kg) of useful heat; at S_2 the useful heat delivery rate may reach 171.9 MW (= 60 kg/s × 2865 kJ/kg). The difference in useful heat capacity of 11.4 MW is due to the higher extraction pressure/temperature at S_2 compared to S_1 and signifies a loss rate of 11.4 MW electricity generated (which is the substitution of heat for power effect). Leaving at S_1, the 60 kg/s steam flow has contributed 79.45 MW of power to drive the electric power generator; when the 60 kg/s flow exits at S_2, its contribution to power supply is curtailed to 68.07 MW. The nonextracted steam flow delivers condensing power of 340.1 MW for full-load states of steam extraction at the hot condensers.

Table 2 Energy inputs and outputs (GWh/year) of the extraction–condensing process, described in Figs. 1–3

Activity	Fuel	Q_{CHP}	E_{CHP}	E_{cond}	E_{plant}
S_0	1400	0	0	618.80	618.80
S_1	3000	480	238.35	1020.30	1258.65
S_2	1000	172	68.07	340.10	408.17
Sum	5400	652	306.42	1979.20	2285.62

Note: Plant capacities are shown in Fig. 3. The example is based on a plant load factor of 61.64%.

During exploitation, the distribution of the steam flow exhausting over the three major steam outlets may vary over time. The combinations of outputs that can be generated are shown by the (E,Q) production possibility set in Fig. 3.

The size (full-load or part-load operation) and distribution of the flows have to be monitored and measured to evaluate the corresponding value(s) of E_{CHP}. The distribution of the steam flow of 60 kg/s can vary over the two hot condensers (for example, in district heating systems operated with gliding temperature of the delivered heat during winter). Then, E_{CHP} is a weighed average of the cogenerated power flows at S_1 and S_2. Let α be the share of the steam exhausted at S_1 with Q_1 the heat extracted at S_1, and let Q_2 equal the heat extracted at S_2, then E_{CHP} equals $\alpha \cdot \sigma_1 \cdot Q_1 + (1-\alpha)\sigma_2 \cdot Q_2$. This can be rewritten as $\sigma_2 Q_2 + \alpha(\sigma_1 Q_1 - \sigma_2 Q_2)$. Referring to the values for the full-load conditions shown in Fig. 3, $E_{\mathrm{CHP}} = 68.07 + \alpha(11.38)$. The use of β values has been avoided in the calculations, because they depend on the cold-condensing conditions that vary with meteorological conditions, which determine the performance of the cold condenser and the quantity of E_{cond}. This improves the theoretical and practical strength of our approach.

The obtained numerical results in Fig. 3 are the basis for calculating the performance of the studied extraction–condensing cycle over a period of, for example, 1 year. Exemplary results are shown in Table 2.

The load factor over the year equals 61.64% (5400 hrs of full load/8760 hrs). The second column in Table 2 shows how the loads are spread over the three steam exhausts; in the following columns, the outputs are given. The overall CHP activity results in 306.42 GWh cogenerated power (E_{CHP}). This value summarizes the quantitative (652 GWh heat used) and qualitative (the average $\sigma = 0.470$) performance of the extraction–condensing cycle. Because of the high accuracy of the assessment, this outcome is a valid basis for further regulation.

3.4 The EU CHP Directive: Source of Erroneous and Biased Regulation. EU CHP regulation is prescribed in the Directives of 2004 and 2012 [15,16]; mainly their (unchanged) Annexes I and II are informative. Annex I starts by calculating the mixed efficiency of the extraction–condensing plant as $(Q_{\mathrm{CHP}} + E_{\mathrm{Plant}})/\ F_{\mathrm{Plant}}$ (in our example case, this would be $0.54 = (652 + 2285.62)/5400$). When this efficiency falls below 80% (as in our example), an arbitrary average power-to-heat ratio is applied, in case of the extraction–condensing technology being 0.45. This arbitrary power-to-heat ratio differs significantly from the σ_1 (0.495) and σ_2 (0.396) of the two CHP activities in the example (Figs. 2 and 3). When over the year the two CHP activities are combined, the average σ of the combination lies somewhere between 0.495 and 0.396, but the probability it would equal 0.45 is small. Adopting the arbitrary average excludes stimuli for investors and operators to move from the low-end σ_2 (0.396) to the high-end σ_1 (0.495) and even exceed the latter by reducing the required temperatures of heat end-uses.

Annex II adds to the confusion by introducing an opaque external benchmarking process, covered up as a method to select "high-quality CHP," but implies several perverse effects based on erroneous numbers [10]. For example, the incorrectly assessed "electricity production from cogeneration" in Annex I is used in estimating the "electrical efficiency of the cogeneration production" without a method to split the plant fuel consumption in its composing elements (Table 1). Due to lack of this method, one will generally use $E_{\text{Plant}}/F_{\text{Plant}}$ as electric efficiency indicator. When implementing Annex II in this way, external references of 90% conversion efficiency of heat only generation and 55% of power only generation are adopted. In the example, for the used cogenerated heat, the reference heat process would require $652/0.9 = 724.44$ GWh fuel and the plant-generated electricity demands $2285.62/0.55 = 4155.67$ GWh fuel, or together 4880.12 GWh fuel. For being adopted as "high-efficiency cogeneration," the CHP plant should do 10% better than the separate benchmarking fuel consumption. In the analyzed case, it would be rejected as a high-efficiency cogeneration activity, given the ratio $4880.12/5400 = 0.90$ and not 1.10 as the Directive's Annex II imposes. By erroneous identification of what CHP activity means and by missing a correct method to reveal the power-to-heat ratio of every single CHP activity (being a tombstone design parameter of CHP units), CHP regulation by the EU has become a mess of perverse incentives.

4 Results

Our methodology is necessary and sufficient to accurately assess the quantities of cogenerated power E_{CHP} for all the major thermal power technologies and installed plants. It needs two sets of data. First, the design data available in the technical file and/or the commissioning report of the plant, for constructing once the necessary diagrams (Figs. 1–3). Second, on a regular basis, the measured, observable energy (eventually also mass) flow data of the plant (Q_{CHP}, E_{plant}, and F_{plant}) for assessing corresponding E_{CHP} flows. This may be in real time when the power system operator performs fine-tuned system optimization, but rather it will occur monthly or yearly when the regulation is limited to ex-post support of CHP activity or for statistical purposes.

5 Discussion

For whatever purpose (science, policy, operations, and statistics), a CHP process is considered, it is a prerequisite for the issue one is dealing with, i.e., cogenerated power flow E_{CHP} is precisely identified and accurately quantified. Surprisingly, regulators and scholars are failing to assess E_{CHP} via scientifically rooted and verifiable methods. Our method fills this gap by applying engineering thermodynamics in a transparent and verifiable way.

Once E_{CHP} is accurately assessed, it is a sufficient indicator of qualitative and quantitative performance (and CHP merit), because it includes the design power-to-heat ratio σ of the CHP activity and the recovered heat flows, otherwise rejected to the environment.

The vision adopted by EU Directives [15,16] that a CHP plant has merit only when it performs better than the best separate power and heat generation benchmarks is flawed, even it is concealed by the cloak of high-efficiency cogeneration. Without accurate assessment of E_{CHP} and F_{CHP}, the call for "high-efficiency" impedes the deployment of cogeneration activities. Practically, the selection of the "best" separate benchmarks is arbitrary [20]. Logically, it is meaningless to only support an activity under the condition it outperforms the best systems on its right and left sides. It resembles the practice of supporting a pupil only when s/he outperforms the others in class in theoretical courses (mathematics, philosophy, and literature) and in practical courses (sports and workshops).

Because our methodology is transparent and excludes arbitrary choices and circular flaws, it is administratively simple. It also avoids the pitfalls of external benchmarks and their inherent counterproductive effects when E_{CHP} and F_{CHP} values are not accurately defined [9,10].

The discussion can be extended to the possible roles of public regulation of electricity supply issues, including CHP as a particular power generation activity [21,22]. All the regulations are served by an accurate definition of what type of activity cogeneration really covers and by accurately assessed E_{CHP} results.

For example, regulators could instruct power system operators to assign preference ("must run" status) to plants performing cogeneration activity (generating E_{CHP}) in the merit order ranking of integrated power supply systems. However, for non-CHP power (E_{cond}) of that same plant, a similar priority cannot be argued on the basis of CHP merit. The system operator can but follow the detailed merit order priorities if E_{CHP} and E_{cond} are properly distinguished.

For example, CHP activity can be viewed as a mitigation technique of point-source thermal pollution [23]. There is a vast body of literature and experience on environmental regulation for controlling point sources of pollution. Mostly, regulators are said to apply "stick and carrot" incentives. The carrot means rewarding the performance of cogeneration activity, for example, a pecuniary subsidy per MWh E_{CHP}. The stick could imply a more restrictive permit policy for thermal power plants without CHP activity (mitigation options). Such policy has been implemented in Denmark, which imposes CHP as default thermal power plant [7]. A levy on thermal pollution could be used as a price stick.

The quality of regulation is correlated with its attainment of "optimal specificity." Optimal specificity requires well-balanced solutions between, on the one hand, generic frameworks applied on comparable cases and, on the other hand, discretionary power assigned to regulated investors and operators to optimize their economic activities (investments, operations, and practices) within the frameworks. Optimal specificity should also contribute to minimizing administrative burdens.

This article has focused on the extraction–condensing steam turbine power plant as the most intricate class, but our methods apply for all the CHP activities. Once the basic concept of power-heat production possibility sets is mastered, the separate CHP activities in a plant are modeled. For every class of thermal power plant, the analytical framework can be specified. Within this framework, every CHP entrepreneur's plant can be located, depending on its design parameters. This enhances efficiency and fairness. Because the crucial indicator of CHP performance is the value of E_{CHP}, the plant operator is stimulated to recover the maximum of otherwise wasted heat, which raises the effectiveness of the regulation.

High scores on effectiveness, efficiency, and fairness criteria are stimulated by optimal specificity. This means: within generic frameworks applied on all, individual cases can optimize their performance by adapting the particularities of their systems or operations. The most warranted approach often is to base regulations on nominal values and design parameters of systems and equipment, because this allows accurate and reliable monitoring, reporting, and verification of performance. The analysis here targets optimal specificity in CHP regulation by providing a scientifically unified framework (keeping the regulator distant from arbitrary choices and messy exemptions), while attaining good detail and accuracy for the variety of CHP systems and plants in applying the framework.

6 Conclusions

By the applied engineering thermodynamics, power-heat (E,Q) production possibility sets of any thermal power plant with CHP activity are derived. Then, the truncated sets become visible when the capacity constraints are included. This article provides the practical method to obtain the proper (E,Q) graph for extraction–condensing steam turbines, with identification of the various CHP activities embedded in the turbines. The graph provides the actual design power-to-heat ratio of every separate CHP activity (without necessity of using power-loss factors). By measuring the quantity of recovered heat for every CHP activity, one obtains accurate values for the cogenerated electricity E_{CHP}. The latter variables are important inputs for economic (incentive) regulation of CHP activity in thermal power generation.

The presented methodology provides the necessary and sufficient foundation for public regulations that meet the principles of optimal specificity, combining generic imposed frameworks with full discretionary decision-making by regulated agents. This allows the regulating principal to perform well on efficacy, efficiency, fairness, and administrative transparency. It is shown that the EU regulation on CHP is flawed and needs overhaul.

Nomenclature

BP = back pressure
CEN = European Committee for Standardization
CHP = combined heat and power (or cogeneration)
E = electric power (MW)
F = fuel flow rate (MW)
hot condenser = device to extract steam for external heat uses from a steam turbine at above near vacuum pressure (also called backpressure condenser)
L = loss rate of energy in a diffuse manner (MW)
Q = heat flow rate (MW)
S = bliss point, i.e., the point at which the sum of the maximum electric output (after electric output is maximized) and the maximum recoverable heat is attained

Greek Symbols

β = power-loss factor, i.e., substitution rate of useful heat for generated power
η = conversion efficiency (generic use)
σ = design power-to-heat ratio of a CHP activity

Subscripts

CHP = cogenerated
cond = condensation at ambient temperature
plant = thermal power generation unit in which cogeneration activity is embedded

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