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Energy Procedia 116 (2017) 481–489

Energy Procedia

www.elsevier.com/locate/procedia

The 15th International Symposium on District Heating and Cooling

Practical and accurate measurement of cogenerated power

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Abstract

The performance of CHP activity is measured by the amount of cogenerated electricity (E_{CHP}) during a considered period. It is the proper yardstick because it combines attributes of quality (power-to-heat ratio $\boldsymbol{\sigma}$) with those of quantity (recovered heat Q_{CHP}), given that $E_{CHP} = \boldsymbol{\sigma} \times Q_{CHP}$ is a commonly accepted identity. In practical applications of the formula, problems arise in finding the appropriate numerical values of power-to-heat ratios. The EU Commission, expert groups, and published literature expose circular logics, concealed by flawed approximations. The enigma is most relevant for extraction-condensing steam turbines, which mix cold condensing with one or more cogeneration activities, making the power flow E_{CHP} not directly observable. This paper presents a generic and neat solution to the E_{CHP} measurement problem. It starts with a clear problem statement. Then, the components of the solution are exposed. First, in a Mollier diagram the unit mass flow expansion path of a Rankine steam cycle with backpressure heat extraction(s) ahead of the cold condenser is noted. Second, the characteristic points on the expansion path provide the contours of the (Electricity E – Heat Q) production possibility set of the steam power plant. Third, the real capacities of the steam flows of the power plant are mapped on the possibility set expressed in electricity and heat capacity (Watt). It shows how limits on extracted steam flows truncate a significant part of the theoretical possibility set in an extraction-condensing turbine. By merging the extraction capacities with design characteristics of a plant, the accurate measurement of cogenerated power becomes self-evident. The method is documented with numerical cases. Applying the presented, transparent and accurate, method is prerequisite for regulations being effective in promoting optimal CHP plant investments and operations. Promotional support may imply subsidies for energy efficiency, priority ranking of cogenerated power in merit orderings of integrated power systems, among others.

Keywords: Extraction-condensing steam turbine; quantify cogenerated power; power-to-heat ratio; production possibility set; incentive regulation

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Peer-review under responsibility of the Scientific Committee of The 15th International Symposium on District Heating and Cooling.
10.1016/j.egypro.2017.05.095

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1. Introduction

Combined Heat & Power (CHP) plants are one of the major heat sources in District Heating (DH) systems. In 2014, 61.1% of Danish thermal electricity production was produced simultaneously with heating, and 68.9% of district heating was produced with electricity [1]. Large-scale DH networks often source the major share of the distributed heat from large steam power plants, designed as extraction-condensing Rankine cycles. This type of plants likely delivers the major part of globally cogenerated electricity. The word 'likely' in the preceding sentence is necessary because there is no agreement about a standard method for measuring the quantity of cogenerated electricity in plants where cogeneration and condensing activities occur simultaneously. At the plant's alternator but one current is sent out and metered by the plant operator. The metered quantity is the sum of two electricity flow components: cogenerated plus condensing power. Splitting the metered flow requires a computational method. The purpose of this paper is to illustrate a generic, proper and accurate splitting method [2]. The method is rooted in basic engineering thermodynamics [3], and the description is documented with a numerical example to emphasize the accuracy and the practicality of the approach.

In common language we speak about CHP plants when they deliver power and heat for end-uses. However, it is more accurate to specify that CHP is an activity occurring in a thermal power generation plant [4]. The activity may be added on (with no power output loss) or embedded in (with some loss of power output) the thermal power generation process. The plant may be equipped with one, or with more than one, opportunity to perform CHP activity. The CHP activities recover all or part of the point-source heat exhausts of the thermal conversion process. In this way, CHP also mitigates local thermal pollution, in addition to improving the overall efficiency in converting primary energy. Such advantages are the basis for public authorities eventually supporting CHP. Support systems function best when they apply effective and fair regulations, providing incentives to CHP actors to optimize performance and results [5-6].

The novelty of this paper is the combination of straightforward technical know-how (thermodynamic cycles) with concepts of economic analysis (production possibility sets), to develop a generic and accurate method solving the long-standing issue of splitting electricity flows metered in CHP plants. The method is applicable for all cogeneration technologies, and is fully transparent and manageable by regulators. It dissolves the present confusion forthcoming from differing practices adopted in various regions. For example, the European Union has formulated an approach in a Directive of 2004 [7], reconfirmed in 2012 [8].

Nomenclature

CHP	Combined Heat & Power
E_{CHP}	Cogenerated electricity
Q_{CHP}	Recovered heat
β	Power loss factor (heat for power substitution rate)
σ	Power-to-heat ratio

2. Background

The central indicator of performance of a CHP activity is the amount of cogenerated electricity (E_{CHP}) during a considered period. The amount of cogenerated electricity is linked to the amount of recovered heat (Q_{CHP}) from the thermal conversion process, by the equation $E_{CHP} = \sigma \times Q_{CHP}$, where σ is called the "power-to-heat ratio". Because Q_{CHP} is readily measured, for obtaining E_{CHP}, the crucial unknown is σ, representing also the quality of the particular CHP activity recovering the measured Q_{CHP}.

Although the basic merit of CHP is its ability to recover otherwise rejected and wasted heat, one should avoid measuring the performance of a CHP activity by the sole variable of recovered heat Q_{CHP}. Maximizing only Q_{CHP} entails perverse effects because efforts to raise the power-to-heat ratio, i.e. the thermodynamic quality of the process, are not stimulated. There is a broad consensus that CHP activity should be gauged by the quantity of cogenerated electricity E_{CHP} [9, 10]. This yardstick combines performance in quality (power-to-heat ratio) with performance in quantity (recovered heat).

The task to fulfil is straightforward: find the quantity E_{CHP} for a considered period (for example, one year). In practice, fulfilling the task is simple in some cases, but intricate and confusing in other cases. The simple cases are cogeneration plants without facilities to reject heat to the ambient environment, such as backpressure steam turbines not owning a cold condenser, or a gas turbine with flue gas heat exhaust coupled to a heat recovery boiler without a bypass to directly reject part of the flue gases to the ambient environment. In this case all electricity from the plant is cogenerated electricity. It is not necessary to know the power to heat ratio σ; on the contrary, the value of σ may be derived by dividing the quantity of electricity generated in the plant by the quantity of heat recovered during the same period.

The real challenge is to assess E_{CHP} when cogeneration and condensing power generation occurs simultaneously in a thermal power plant. As exemplary case an extraction-condensing steam cycle is selected. For clarity the following assumptions are made:

- 1000 MJ/s (MW) maximum fuel input, with 8% non-recoverable losses (stack flue gas, diverse heat radiation, etc.)
- Full load cold condensing generates 442 MW electricity, with 478 MW rejected condenser heat
- Large heat extraction is feasible at two points in the low-pressure turbine: 160 MJ/s at 100°C or 172 MJ/s at 200°C, reducing the electricity supplies to respectively 419.5 MW and 408.2 MW at full load plant operation

All the above numbers belong to the standard metered variables at a managed power plant. They help in drawing the electricity-heat (E-Q) production possibilities set of the plant, shown in Figure 1.

In an (E-Q) quadrant the electricity and heat capacities at full load make up the efficiency frontier(s) of the production possibilities set(s). The ordinate point at 442 MW shows the cold condensing electricity output, without any heat recovery. Heat can be recovered up to the maximum flow at the hot condensers. When the heat capacity flow is entirely extracted at 100°C it delivers 160 MW heat and 419.5 MW electricity, respectively at 200°C useful heat increases to 172 MW and electricity decreases to 408.2 MW. The numbers of the metered electric output are the sum of E_{CHP} plus $E_{CONDENSING}$, not discernable without a division rule like $E_{CHP} = \sigma \times Q_{CHP}$. Figure 1 contains the relevant Q_{CHP} values, but not the relevant power to heat ratios. Obviously wrong is the use of the slopes of the rays through point O shown in Figure 1 as values for the unknown σ. It is necessary to develop an appropriate computational method to find the right σ values.

In the professional and academic literature [9, 11-13] no consistent method has been provided. The flaws have been highlighted in [10] and [2], with the latter publication also offering the arguments and theoretical development of an appropriate computational method, although only explained for the extraction-condensing cycle.

The focus of this publication is on highlighting the practicability of the method. It also shows the generic validity of the method by illustrating its extension to gas turbines with CHP activity (internal combustion engines or fuel cells are not discussed here, but generalizing the assessment method is feasible by collecting information about the equipment and by applying the constituent calculations).

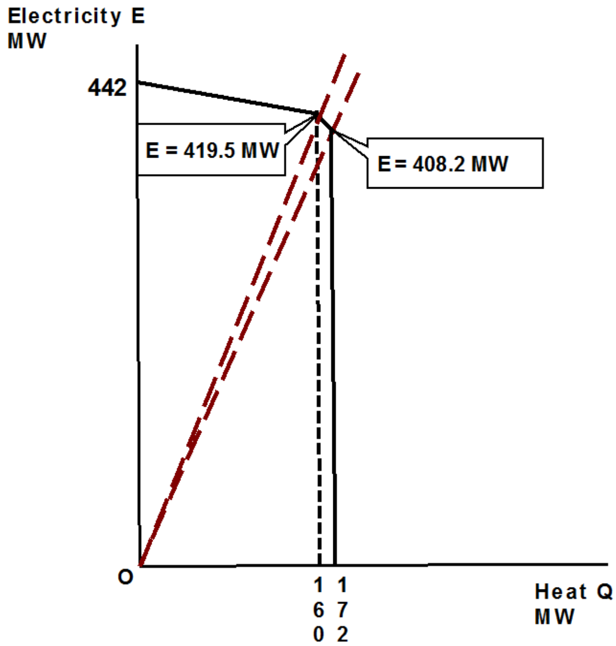

Figure 1. Electricity-Heat Production Possibilities of Extraction-Condensing Steam Cycle with two hot condensers ahead of the cold condenser

3. Results

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 in Figure 2: 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 a near-vacuum pressure of 0.06 bar (point S°).

Two hot water condensers are installed to extract steam at respectively S^1 and S^2. The enthalpy values of the start and of the end points of the actual expansion segments characterize the power cycle and the CHP activities embedded in it.

The steam expansion enthalpy data of Figure 2 allow to picture the paths followed by a unit mass. The (E-Q) production possibilities of the unit mass are shown in Figure 3. The horizontal top line ending in point S^0 represents the cold condensing state ($\beta = 0$ i.e., there is no power loss due to steam extraction). Variable temperature/pressure conditions of ambient air/water cause slight shifts in the height of the horizontal line ending in point S^0, i.e. power loss factors change when steam is extracted. The slight shifts and changes are an argument for avoiding the use of power loss factor information in the method for assessing the quantity of cogenerated power ECHP. When steam flow is extracted at pressure conditions higher than at S^0, substitution of heat for power occurs, in principle at the rate of one given up kJ/kg electricity for one additional kJ/kg heat used. In the first step all condensing heat is recovered. When this step can be kept very short (assume S^1 just above S^0 in Figure 2, 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 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 S points line equals -1. Two cogeneration activities are embedded in the shown Rankine steam cycle, and described by the points S^1 and S^2.

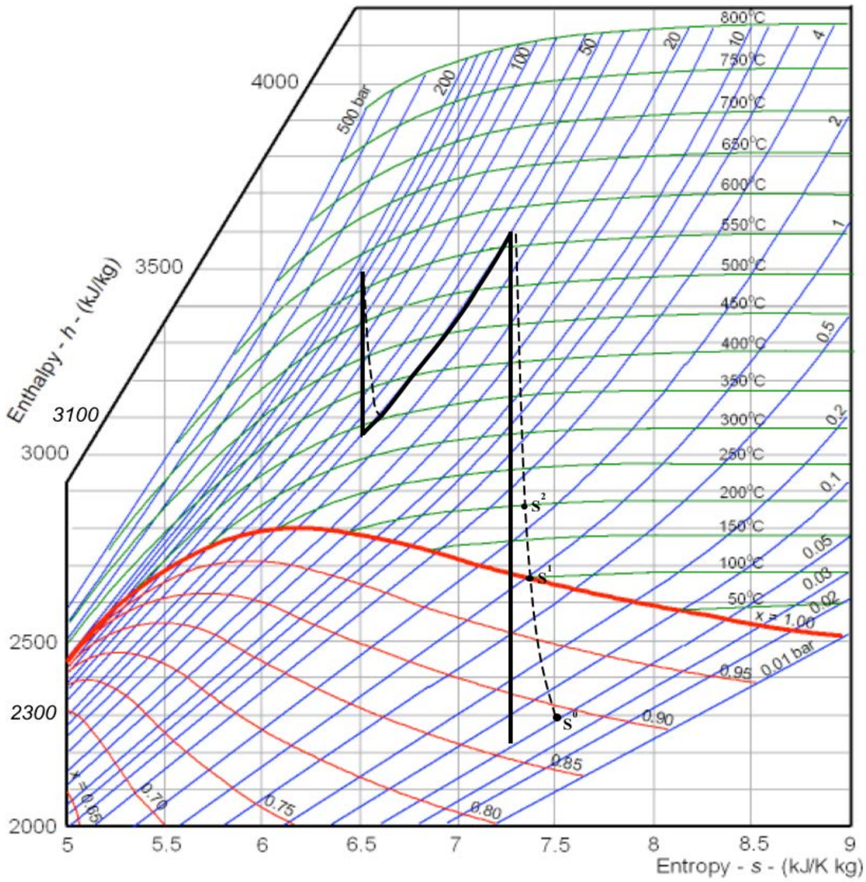

Figure 2. Rankine extraction-condensing steam cycle. Isentropic and actual steam expansion with reheat, hot condensers (S^1, S^2) and cold condenser S°

In drawing Figure 3, the states like S^1 and S^2 are examined following the path of one 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 [9] discusses the minor outlets in detail.

The method presented does not require too detailed, difficult to monitor calculations. The method is generic and encompasses all steam turbines with cogeneration activity and also other thermal power processes with CHP activity (see the example of a gas turbine further down in this section). Limiting the analysis to the major cold and hot condensers keeps the approach feasible and controllable.

In an extraction-condensing turbine, the cold condenser at S^0 can pass all the fluid at full load of the plant 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. It follows that in practice the points S^1 and S^2 are virtual points, not observable by monitoring actual total flows [9]. But the observations are not necessary because one only needs the computational results with the help of σ values (σ_1 and σ_2). The merger of Figures 1 and 3 is shown in Figure 4. It shows graphically how the quantity of cogenerated power E_{CHP} is assessed contingent on the quantity of recovered heat Q_{CHP}.

The numbers in Figure 4 focus on the borderlines of the production possibility sets. The method is robust for part load heat recovery operation. When yearly numbers of power plant production are reported, one often adds capacity factors or full load hours to better inform readers. Table 1 illustrates the method further with a numerical example of an E_{CHP} calculator, based on the properties of the exemplary plant as shown in Figures 1 to 4.

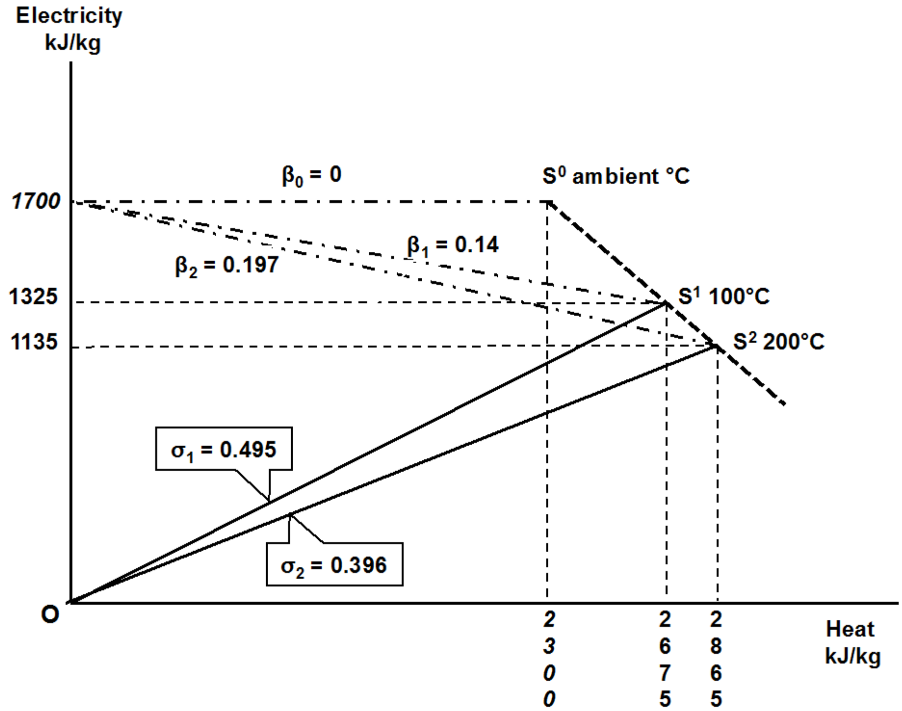

Figure 3. Electricity-Heat Production Possibilities of a Unit Mass for the Steam Expansion with three Major Exhaust Points as shown in Figure 2

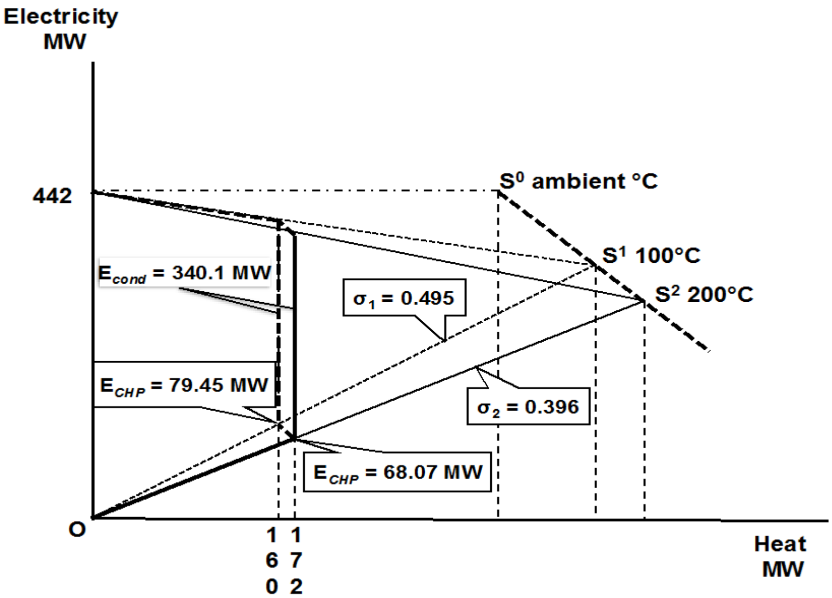

Figure 4. Electricity-Heat Production Capacities (Figure 1) merged with the Roster of Figure 3

Table 1 is composed of two parts. The top part holds the design (tombstone) parameters for describing the actual layout and capacities of power generation and heat recovery. This information is inventoried at the moment of plant commissioning or of major retrofit, and remains valid for long periods (the lifetime of the plant). The second part holds operational data and is regularly updated depending on the reporting intervals (monthly, yearly). First two rows are metered plant data on recovered heat (separately per CHP activity) and generated electricity. The numbers on the following three rows are assessed and derived from combining tombstone parameters and metered flows.

Table 1. Numerical results of the performance during a year of an extraction-condensing steam plant with two CHP activities embedded

E-CHP calculator

Design (tombstone) properties per major steam exhaust	Cold condensing S^0	Hot low back pressure S^1	Hot high back pressure S^2	
Work E kj/kg (Fig. 2)	1700	1325	1135	
Work Q kj/kg (Fig. 2)	2300	2675	2865	
Power to heat σ (Fig.3)	0,739	0,495	0,396	
Steam flow rates kg/s	260	60	60	
Electric capacity CPH MW (Fig.4)	0	79,5	68,1	
Electric capacity Condensing MW (Fig.4)	442	340	340	
Electric capacity total MW (Fig.4)	442	419,5	408,1	
Heat recovery capacity MW (Fig.4)	0	160,5	171,9	
Operational data				**Totals**
Recovered Heat GWh:y (metered)	0,0	503,0	237,6	740,6
Plant electric output GWh/y (metered)	747,9	1314,7	564,0	2626,6
CHP electric output GWh/y (assessed)	0,0	249,1	94,1	343,3
Condensing electric output GWh/y	747,9	1065,6	469,9	2283,3
Full load hours per exit S	1692	3134	1382	6208

For the development and illustration of the method, the extraction-condensing cycle with two hot condensers has been employed as the reference. Not only is this an important case of cogeneration, it has proven to be the most challenging case for identifying and measuring the quantity of cogenerated electricity. Especially in the European Union, the EU Commission failed in providing a scientifically robust approach when publishing the related Directive in 2004 and 2012 [7, 8]. CEN/CENELEC neither knew how to avoid the pitfall of a circular referencing [9, 10].

The method is not only valid for steam turbines, but also applicable on other cogeneration plants. This is shown for the open gas turbine with flue gas heat recovery in an added steam boiler. Because the temperature of the flue gases is in a range of 400 to 800°C, there is no power loss when their energy content is recovered. There is also but one exhaust of the heat, i.e., one CHP activity and one design power to heat ratio. The (E-Q) possibility diagram, similar to the one in Figure 4, becomes very simple, as shown in Figure 5.

Mostly all heat of a gas turbine equipped with a recovery boiler will be fully used. Then E_{CHP} is equal to all the electricity production of the turbine. When the heat is not fully used, some share (for example about 20% in Figure 5) is rejected to the environment. The amount of cogenerated power is calculated with the quantity of recovered heat (40 MW), multiplied by the design power to heat ratio σ (being 0.815 in Figure 5), or E_{CHP} = 32.6 MW.

The logic applied is the same as with steam turbines. The logic is generic for all cogeneration activities, allowing the addition of the assessed E_{CHP} quantities.

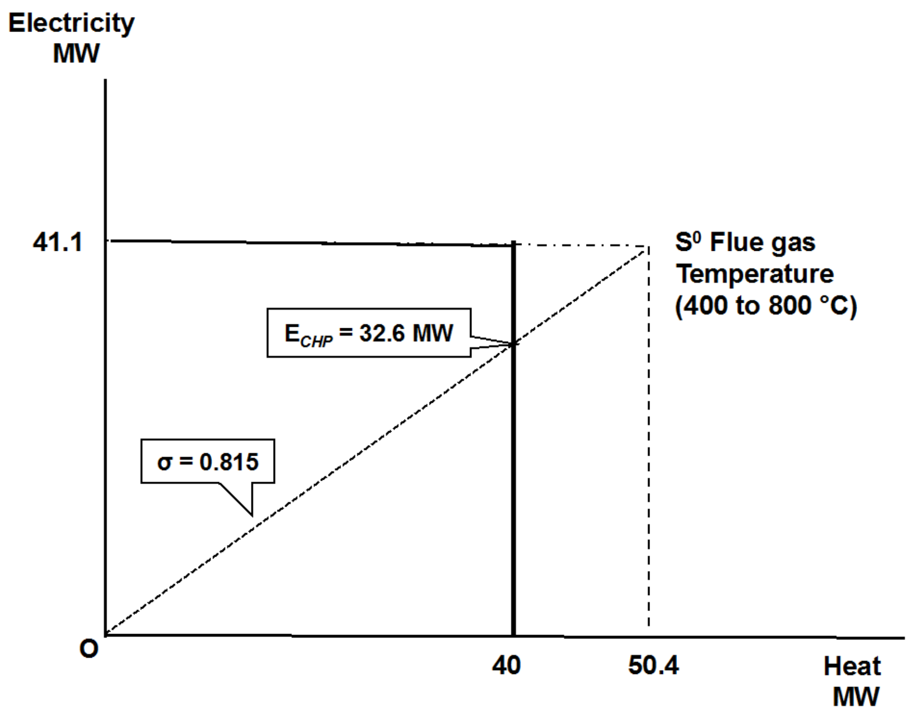

Figure 5. Electricity-Heat Possibility Set of an Open Gas Turbine with Flue Gas Heat Recovery

4. Conclusion

The contribution builds on established know-how in thermodynamics and economics. The novelty of the presentation is the combination of solid know-how and concepts, for addressing and solving a long-standing issue in the management and regulation of CHP activities. The issue is the correct identification and accurate measurement of the quantities of cogenerated electricity E_{CHP} for the various CHP processes. The issue is of high relevance because E_{CHP} is the crucial, necessary and sufficient, indicator of CHP's merit in the energy economy. For whatever purpose (science, policy, operations, statistics) a CHP process is considered, the issue one is dealing with, i.e. the cogenerated power flows E_{CHP}, should be identified precisely and quantified accurately. Once E_{CHP} is accurately assessed, it is a sufficient indicator of qualitative and quantitative performance (and of CHP merit). E_{CHP} includes the design power to heat ratio σ of the CHP activity (the proper yardstick of thermodynamic quality) and the quantitative count of recovered heat Q_{CHP} at the thermal power process. Obviously, the prerequisite for E_{CHP} to assume the central role is the reliable measurement of its value.

The method for reliable measurement is explained and illustrated with graphs and practical examples. The method dissolves the fuss about E_{CHP} identification and measurement. It owns several valued attributes:

- Transparent by identifying CHP activities added-on or embedded in thermal power processes
- Accurate by clear definition and quantification of design power to heat ratios **σ**
- Generic, applicable on all CHP activities in all kinds of thermal power conversions
- Easy and cheap to apply in practice

Energy administrators and regulators can enact specific incentive regulations. Investors and operators can focus on the essential parameter σ and flows Q_{CHP}. The method supports good policies. When certified and widely adopted, it will establish a common practice with results that are comparable. As a corollary, consistent statistical data are obtained about the performance of all types of thermal power plants with cogeneration activities. Reliable E_{CHP} data are needed for effective, efficient and fair support mechanisms for CHP activities (if public authorities decide to favor CHP). This would relief the sector from arbitrary, biased and perverse regulations, as the EU Directives on CHP entail.

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