HIGH-QUALITY CHP: DEFINITION, MEASUREMENT, AND REGULATION

Verbruggen A.
Department of Engineering Management,
University of Antwerp,
Prinsstraat 13, 2000 Antwerp
Belgium,
E-mail: aviel.verbruggen@uantwerpen.be

ABSTRACT

CHP (Combined Heat & Power) is a vested term referring to thermal power generation with heat recovery. The lack of clear terminology on CHP activities causes confusion and suboptimal regulation, what impairs investment decisions. An improved discourse on CHP is significant in addressing the issues. It starts at the basic definition of CHP itself. A proper definition is instrumental in identifying what the real merit of CHP is, also questioning whether *high-quality CHP* is a valid term. The proper yardstick of CHP performance is quantities of cogenerated electricity. In extraction-condensing steam turbines, being the most applied thermal power processes, the quantities are not directly observable. The scientific community failed to provide practical methods to assess the quantities. Basic engineering thermodynamics suffice to construct the needed methods, easy to apply and supporting investment in high-quality thermal power units and daily maximization of heat recovery. The epilogue questions the role thermodynamic machinery may play in future electric power generation.

INTRODUCTION

Combined Heat & Power (CHP) 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]. CHP diffusion in countries with similar economies is uneven, due to diverging energy policies and related regulations [2, 3]. Public policy in favour of efficient fuel use, argues support for CHP. This was intended by the EU CHP directive 2004/8/EC [4], but not realized by lack of effective and efficient regulation. The EU [5] admitted that the 2004 CHP directive "failed to fully tap the energy saving potential", but the assessment of the flaws in its own regulations is not provided. Moreover, the EU continues the 2004 framework, now incorporated in the Energy Efficiency Directive [6], without improvement in answering the essential questions that impede better regulation of CHP activity and its support: What is quality of CHP? What is CHP merit? How to monitor and measure CHP performance more exactly? A partial remedy was suggested by CEN (European Committee for Standardization) [7], but failed on crucial points [8].

CHP is tricky business when considered to be a joint generation process, what is often the case. Joint production (economics textbooks use meat & wool as favoured example) poses difficult issues about joint cost allocation over the outputs. Similarly it creates the CHP double priority paradox. CHP only exists when heat from the power generation process is recovered and used, what supports the idea of *priority to heat*. Yet because the process is a power generation cycle, net power output should be maximized, what means *priority to power*. Better semantics may largely dissolve tricky situations. It starts with the proper definition of what CHP is, of the power-to-heat ratios, of cogenerated electricity, etc. Also I will invoke vocabulary from the environmental sciences, like point source and nonpoint source pollution [9].

The article is developed along the logic of the abstract. First CHP is defined as an activity *added on* or *embedded in* a thermal power generation process. Figure 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 mitigation of environmental pollution. CHP activity is not responsible for the power conversion efficiency of the hosting thermal power plant. The EU [4, 6] approach of *high-efficiency CHP* and *Primary Energy Saving* using external benchmarks are unfounded transfers of responsibility from the hosting thermal power generation plant onto CHP activity. By figure 2 is revealed that the *power-to-heat ratio of CHP* parallels the electricity conversion efficiency of the hosting power cycle. CHP activity (added on or embedded in a thermal power plant) is considered a better term than the shortcut CHP plant.

In the next section is argued that the quantity of cogenerated power is the proper indicator of CHP performance and the necessary and sufficient indicator of CHP merit. Measuring the quantities remains a tricky issue when a power plant simultaneously produces condensing power and CHP power. Then, accurately assessing the quantities of CHP power requires knowledge of the proper *design power-to-heat* ratios. The concept of bliss point S is introduced as the point where, after electric output is maximized, the sum of this maximum and the *maximum recoverable* quantity of heat is reached. Analysts go astray when they overlook that most bliss points in practical CHP applications are virtual.

The final section shows how the design power-to-heat ratio of every separate CHP activity in an extraction-condensing steam cycle can be identified. It starts with the steam expansion pattern of the specific plant in a Mollier diagram (figure 3). For useful heat extraction so-called hot condensers have been installed. Their position also fixes the (in most cases: virtual) bliss points in an (E, Q) output diagram (figure 4). Virtual bliss points in electricity-heat production possibility sets, helpful in identifying the proper design power-to-heat ratios of CHP activities, are basic concepts of a comprehensive CHP glossary.

In the Results and Conclusion section the developed methods are reviewed and compared with the propositions of the EU Directives dealing with CHP regulation. It emphasizes the importance of clear terminology and of avoiding circular logic when addressing the tricky situation of processes delivering two useful outputs.

NOMENCLATURE

E	[Wh, W]	Electricity, power
F	[Wh, W]	Fuel energy, flow rate
Q	[Wh, W]	Heat energy, flow rate
L	[Wh, W]	Losses of energy (mostly heat) in a diffuse way
S	[-]	Bliss point (where the sum of generated power + point source heat exhaust is at its maximum)

Special characters

β	[-]	Used heat for generated power substitution rate; mostly called power loss factor
σ	[-]	Power-to-heat ratio (design property of power generation without or with CHP activity

Subscripts

CHP	Combined Heat & Power (also named cogeneration, or back-pressure in steam plants)
cond	Condensing activity
plant	Plant (thermal power unit with CHP activity)

CHP IS AN ACTIVITY ADDED ON / EMBEDDED IN A THERMAL POWER GENERATION PLANT

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 [10] (Figure 1, left side). The power obtained from steam turbines, gas turbines, or internal combustion engines, is convertible into electricity[1]. Heat rejection to the ambient environment is called thermal pollution [9]. 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 heat is non-recoverable. Heat radiation at various parts of the process is also considered non-recoverable.

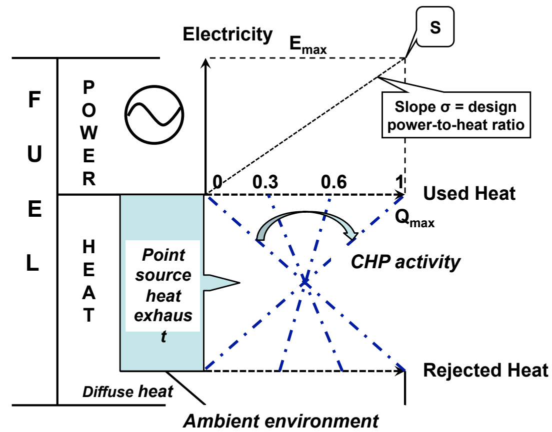

Figure 1 Thermal power generation: CHP is the recovery of (a share of) the point source heat exhaust [12]

CHP is *the recovery and use of all or part of the point source heat exhaust, otherwise being rejected, by a thermal power generation plant*. Figure 1 represents CHP activity as a valve splitting the point source heat exhaust flow in a used and rejected 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 case of partial CHP, confusion arises, and is strengthened by dense but misleading terminology. The physical phenomenon *CHP activity added on or embedded in a thermal power generation plant* is mostly shortcut as *CHP plant*[2]. 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

[1] 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.

[2] This resembles shortcut language *heat* and *work* for the proper scientific terms *energy transferred as heat* and *energy transferred as work*, as Reynolds and Perkins [10] emphasize.

mitigation facility, but the latter carries no responsibility for those properties.

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 *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 $\beta > 0$, 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 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 alias temperature of the heat exhaust [10]. 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 did CEN/CENELEC [7] and again recently Urošević et al. [11].

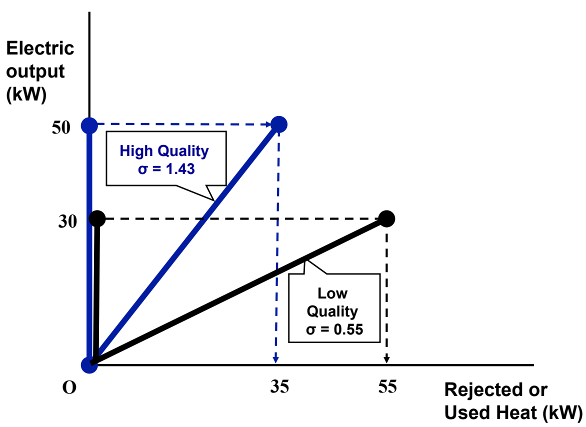

Figure 2 Power-to-heat ratio expresses the efficiency of thermal power generation processes, either only condensing or with CHP activity

Summarizing so far, the usual term *CHP plant* is to be avoided and better replaced by *CHP as activity added on or embedded in* a thermal power generation plant. CHP is then not analyzed as a joint production process, but as mitigation of thermal pollution at point sources. This hierarchical relationship frees CHP from being responsible for the power conversion efficiency of the hosting thermal power plant. This empties the term *high-efficiency CHP*, staying central in the EU's regulation intended to promote CHP [7]. Actual conversion efficiencies are set by the hosting thermal power generation process, and measured by the design power-to-heat ratio σ (Figure **2**). High quality conversion (high σ) delivers a lot of power and less heat, and vice versa for low quality conversion (low σ).

THE QUANTITY OF COGENERATED POWER E_{CHP} AS MERIT INDICATOR

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. However, basing the performance of a CHP activity on the sole variable of recovered heat Q_{CHP} is not satisfactory. Maximizing Q_{CHP} may entail perverse effects by neglecting efforts to raise the design power-to-heat ratio σ of the power generation process (figure 2); the focus on Q_{CHP} lacks incentives to improve and maximize the generation of power. This generally leads to non-economic investments and practices.

Therefore, for gauging CHP activity and performance the rate of cogenerated power E_{CHP} is a better yardstick. Also CEN/CENELEC [7] adopts that E_{CHP} is the necessary and sufficient indicator to gauge CHP activity. The major issue now is that E_{CHP} is not directly observable and measurable in steam power plants with simultaneous condensing and CHP activities. Table 1 provides an overview of all energy flows in a thermal power plant with CHP activity. Energy flows in [brackets] cannot be measured directly.

Activity Energy flows	*CHP*	+ *condensing*	= *plant*
Fuel F =	$[F_{CHP}]$	$+ [F_{cond}]$	$= F_{plant}$ =
Electricity E	$[E_{CHP}]$	$+ [E_{cond}]$	$= E_{plant}$
+ Point source heat Q	Q_{CHP}	$+ Q_{cond}$	+ $= [Q_{plant}]$
+ Losses non-recoverable	-	-	+ $[L_{plant}]$

Table 1 First law of thermodynamics: thermal power plant with CHP and condensing activity.

MEASURING QUANTITIES OF E_{CHP}

Table 1 illuminates the first steps in addressing the problem of identifying E_{CHP}. When either the column of the activity CHP is empty (a condensing power plant not equipped with cogeneration facilities) or the column of the activity condensing is empty (a backpressure steam plant without heat rejection facilities), the observed plant energy flows are equal to flows with a clear, singular label E_{cond} or E_{CHP}. In all other cases, cogeneration and condensing activities may occur simultaneously, and E_{CHP} is not directly observable. Assessing E_{CHP} needs a computational method for splitting the observed flow E_{plant} into E_{CHP} and E_{cond}. Here, the proportionality principle is generally accepted and applied [4, 6, 7]: $E_{CHP}/E_{cond} = Q_{CHP}/Q_{cond}$, or rewritten: $E_{CHP} = \{E_{cond} / Q_{cond}\} \times Q_{CHP}$.

The term in brackets is called the *power to heat ratio* (named C in the EU directives [4, 6]; here named σ referring to the *design power to heat ratio* of a particular CHP activity [12]). In steam turbines where CHP activity causes power loss, the ratio is not observable. Finding the right power to heat ratio **σ** is a source of confusion, spilling over on the assessment of E_{CHP} and causing biased (even perverse) regulations. Otherwise, the properly assessed value E_{CHP} bundles operational performance (= quantity of heat recovered Q_{CHP}) with investment decision-making on the design σ (= electricity generation efficiency).

THERMODYNAMICS OF EXTRACTION-CONDENSING STEAM CYCLES

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 3: 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 pressure of 0.06 bar (point S°).

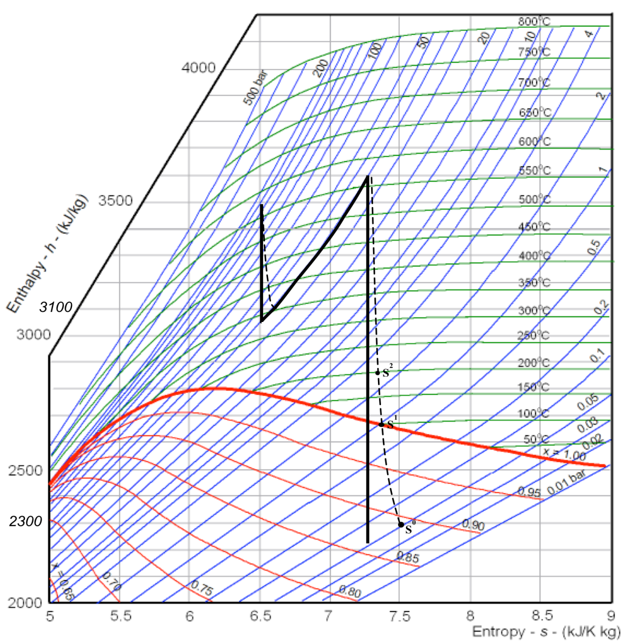

Figure 3 Isentropic and actual steam expansion with reheat, hot condensers (S^1, S^2) and cold condenser S°

Two hot water condensers are placed 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 3 allow to picture the paths followed by a unit mass. The (E,Q) production possibilities are shown in figure 4.

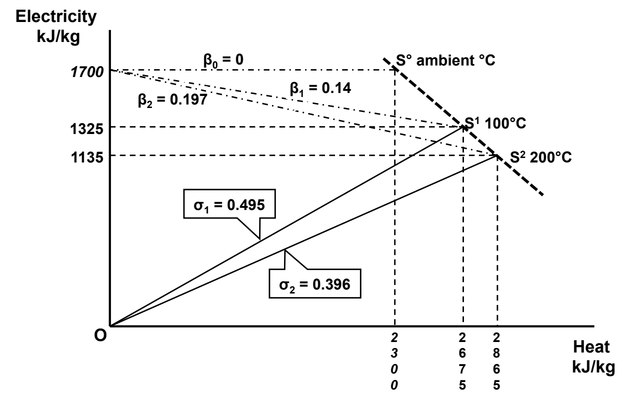

Figure 4 (E, Q) production possibilities in kJ/kg of the steam cycle expansion and extractions of figure 3.

The horizontal top line ending in point S^0 represents the cold condensing state (β = 0). 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 one 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 kept very short (assume S^1 just above S^0 in Figure 3, 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 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.

In drawing Figure 4, 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 [7] discusses the minor outlets in detail. From a regulators' perspective which encompasses all steam turbines with cogeneration activity in a state or in a union of states, limiting the analysis to the major cold and hot condensers keeps the approach feasible and controllable, and still sufficiently accurate for incentive regulation and statistical data.

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. This makes that in practice the points S^1 and S^2 are virtual points, not observable by monitoring actual total flows [12]. But the observations are not necessary because one only needs the computational results on σ values (σ_1 and σ_2).

RESULTS AND CONCLUSION

The developed method is necessary and sufficient to accurately assess the quantities of cogenerated power E_{CHP} for all 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 (Figures 3 and 4). Second, on a regular basis, the measured, observable energy (eventually also mass) flow data of the plant (Q_{CHP}, E_{plant}, F_{plant}) for assessing corresponding E_{CHP} flows. This may be in real time when the power system operator performs fine-tuned system optimisation, but rather it will occur monthly or yearly when the regulation is limited to ex-post support of CHP activity, or for statistical purposes.

For whatever purpose (science, policy, operations, statistics) a CHP process is considered, it is prerequisite that 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 the laws of 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 [4, 6] 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* [8]. Without accurate assessment of E_{CHP} and F_{CHP} values, the call for *high-efficiency* impedes the deployment of cogeneration activities. Practically, the selection of the *best* separate benchmarks is arbitrary [13]. 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, literature) and in practical courses (sports, workshops). Our method is transparent and excludes arbitrary choices and circular flaws. It is administratively simple and avoids the pitfalls of external benchmarks and their inherent counterproductive effects when E_{CHP} and F_{CHP} values are not accurately defined.

The presented method 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 fundamental corrections on its most essential parts.

EPILOGUE

CHP is an activity inherently connected to thermal power generation plants. The CHP activity recovers part or all of the point source heat pollution of the power conversion processes. This recycling of waste heat is a worthwhile practice with merit that is favoured by public policy and may also be rewarded to some degree or mandated as default option when thermal power generation occurs. Rewards for recycling may on occasions stimulate the creation of waste. This danger is real when CHP is treated as a joint production process of two valuable outputs, power and heat. Emphasizing that CHP is a point source pollution mitigation activity is helpful in reducing this danger. More effective is the broadly accepted rule that the merit and performance is measured by the quantities of CHP power E_{CHP} and not simply by the quantities of recovered heat Q_{CHP}. Nevertheless, the EU's Emissions Trading Scheme makes an exception in its selection of Q_{CHP} as reference for emissions reductions [14].

Several studies have identified CHP as a major 'technology' to reduce carbon dioxide emissions in the energy conversion sector [15]. This is based on the substitution of otherwise wasted heat flows for the conversion of virgin fuels to obtain heat. Nowadays one observes a fast evolution to substitute non-thermal renewable power sources for thermal electricity generation from fossil fuels (and from nuclear fission) [16]. The future 100% renewable electricity supplies will predominately be based on the direct conversion of mechanical power and light into electric current. The thorough transition may leave little room for thermal power. There are references to geothermal sources, fuel cells with hydrogen as feedstock obtained from converting excess renewable power, and bioenergy fuelled power cycles [17]. Their share in the power mix may be modest, for example because biofuels will cover higher valued demand (transport, bio-chemical feedstock). This all makes that CHP as an activity of high industrial and economic interest may fade.

After a PhD thesis in 1979 on district heating and heat supplies by CHP activities, I continued to research the economics and policy aspects of CHP on an irregular time allocation basis as an academic researcher and as a consultant. With 'Unveiling the mystery of CHP' [12] and the present manuscript, I round up my research on CHP. Maybe, giving the fast transition to sustainable renewable power supplies, my research investment will quickly depreciate. This dwindling market for CHP expertise does not upset me, because the preservation of the atmosphere and of climate stability is many times more important for the future of mankind than the depreciation of personal assets. Maybe I join a club of industrial archaeology to preserve obsolete thermodynamic machinery of the 20th century.

REFERENCES

[1] EDUCOGEN. An educational tool for cogeneration. 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, 36:5301-5313
[3] Ostergaard PA. Regulation strategies of cogeneration of heat and power (CHP) plants and electricity transit in Denmark. *Energy* 2010, 35:2194-2202
[4] 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
[5] 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
[6] 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
[7] CEN/CENELEC. Workshop Agreement. Manual for Determination of Combined Heat and Power (CHP). CWA 45547. Brussels, September 2004
[8] Verbruggen A. The merit of cogeneration: measuring and rewarding performance. *Energy Policy* 2008, 36:3069-3076
[9] Masters G.M. Introduction to environmental engineering and science. Prentice Hall, New Jersey, USA,1991
[10] Reynolds W., Perkins H. Engineering Thermodynamics. McGrawHill, New York, USA, 1977
[11] Urošević D., Gvozdenac D., Grković V. Calculation of the power loss coefficient of steam turbine as a part of the cogeneration plant. *Energy* 2013, 59: 42-651
[12] Verbruggen A., Dewallef P., Quoilin S., Wiggin M. Unveiling the mystery of Combined Heat & Power (cogeneration). *Energy* 2013, 61: 575-582
[13] Klaassen R.E., Patel M.K. District heating in the Netherlands today: A techno-economic assessment for NGCC-CHP (Natural Gas Combined Cycle combined heat and power). *Energy* 2013, 54: 63-73
[14] 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
[15] IPCC- Intergovernmental Panel on Climate Change. Fifth Assessment Report, Working Group III, Chapter 7. Cambridge University Press 2014 (www.ipcc.ch)
[16] Agora Energiewende, 12 Insights on Germany's Energiewende, 2013 http://www.agora-energiewende.de
[17] IPCC- Intergovernmental Panel on Climate Change. Renewable energy sources and climate change mitigation. Working Group III Special Report. Cambridge University Press 2012 (www.ipcc.ch)