A STUDY ON UTILIZATION IMPROVEMENT OF COGENERATION POTENTIAL IN A COMPLEX INDUSTRIAL STEAM AND POWER PLANT

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Annotation
Efficient cogeneration is widely acknowledged as one of measures reducing primary energy use and emissions of greenhouse gases and other pollutants. This contribution bears on analyses of complex industrial power plants, incorporating the concept of exergetic and exergoecomic balances – a concept that has been rarely utilized in Slovakia up to day. Emphasis is laid on synergic use of marginal and exergoeconomic analysis, thus assessing the economics of various complex cogeneration units' operational modes. The whole study, together with resulting recommendations for cogeneration efficiency improvement of the given unit is an excerpt of corresponding author's doctoral thesis.

Keywords
Efficient cogeneration, marginal analysis, exergoeconomic cost, combined cycle power plant

1 INTRODUCTION

The combined heat and power producing units are commonly evaluated in terms of electric and heat efficiency, their sum being the cogeneration efficiency. Despite growing share of wind and photovoltaic power sources, the traditional cogeneration still belongs to successful concepts of achieving both high overall efficiency and substantial greenhouse gases emissions. Important parameters evaluated in common cogeneration systems are: specific steam consumption (t/MWh) in steam turbines based cogeneration, or heat rate (kJ/kWh) in gas turbines based systems. These parameters, despite their usefulness, may fail to help to find operational optimum or may lead to incorrect results in assessing economics of various performance improvement options of a cogeneration unit. More useful approach to such tasks is to obtain marginal performance parameters [1,2], especially in cases when the profit function is flat and the improvement is compromised by uncertainties about one or more profit function inputs. With their help, optimal operational conditions are readily estimated [3]. As proven in [1,2], marginal analysis approach can be successfully implemented on various complexity and scale levels, beginning with operation of a single cogeneration unit, through management of one or more complex energy systems to evaluation of national or international primary energy consumption reduction strategies. Such analysis, however, is seldom performed in Slovakia's industry, with the energy management divisions relying on their own insight into the process, often limited by process complexity and by internal barriers to information transfer [4]. The exergetic and exergoeconomic analysis [5,6] has been employed in systems performance analysis even more rarely. Their combination, the marginal exergoeconomic analysis, moreover yields costs of produced energetic media, based on exergy and not energy accounting. Such concept has been successfully tested [7] in several industrial cogeneration units in Slovakia, thus striving to support knowledge transfer between the academy and industry. Several of the in [7] presented cogeneration potential improvement possibilities were set into reality and perform very well, proving the appropriateness of the chosen approach and the obtained results.

2 DESCRIPTION OF SYSTEM UNDERSTUDY

The doctoral thesis [7] utilizes data from three steam and power plants of which one is of municipal character and the two other of industrial one with some share of heat delivered to nearby municipalities. A brief characterization of the most complex plant understudy is given by Tab.1 and a global view on it is provided by Scheme 1. As can be recognized from the brief characterization given in this table, the operation of subsystem 1 is governed directly by the National Dispatch Centre, as it is among the power units provisioning the SRV ancillary service. Flue gas content is utilized to raise high pressure steam which is partly led to an oversized backpressure steam turbine and partly consumed in the gas turbines in form of steam injections reducing the NO_x formation rate. The steam boiler in *1* is just a backup, operated in times the subsystem *2* or *3* is shut down due to

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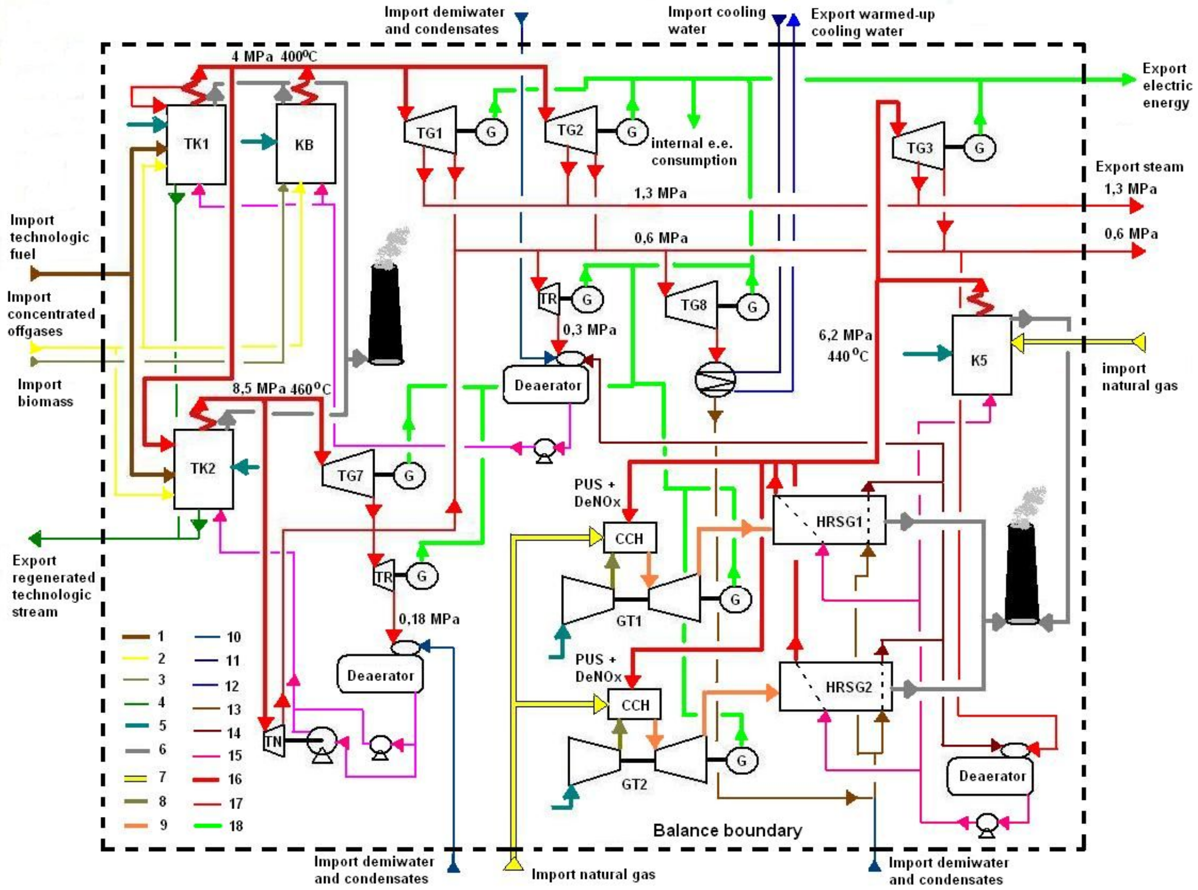
maintenance. The backpressure steam turbine is sized to consume all steam produced in the HRSGs and the backup boiler, thus at prevailing low steam load it is operated inefficiently. The electric efficiency of subsystem *1* reaches only 30 to 33 % and the overall efficiency does not exceed 70 %. As the gas turbines maintenance cost steadily increases while the ancillary services provisioning revenues drop, the GTs are envisaged to be set out of order soon. While the gas turbines load varies, the steam output of *1* is, especially in winter, required to cope with the industry's heat demands as well as with the steam delivery to the nearby municipality. In such cases the steam balance is kept by flexible supplementary firing operation able to provide a steam surplus up to 90 t/h.

Tab.1 Industrial steam and power plant subsystems characterization. GT = gas turbine; ST = steam turbine; BP = backpressure (steam turbine); C = condensing (steam turbine); HRSG = heat recovery steam generator; *- such steam parameters are reached only at GT's high load or with supplementary firing

Characterization parameter	Subsystem		
	1 ("paroplyn")	*2* ("stará energetika")	*3* ("nová energetika")
Power generating devices	2 GTs; 1 BP ST with optional steam extraction	2 BP STs with steam extraction; 1 C ST	1 BP ST
Steam generators	2 HRSGs + 1 steam boiler	2 steam boilers	1 steam boiler
Steam produced, MPa/°C	6/440*	4/400	8/455
Steam delivered to industry, MPa abs./ t/h	0,6 /30 to 120 (1,3 MPa steam extraction optional)	0,6/up to 100; 1,3/20 to 80	0,6/120 to 150
Ancillary services provisioning	SRV, TRV	TRV	TRV



Scheme 1. Global view on the cogeneration plant understudy, after installation of two TRs. Legend: CCH – combustion chamber, G – generator, HRSG – heat recovery steam generator, K – boiler, KB – biomass boiler, TG – turbogenerator, TK – technologic boiler, TR – small simple steam turbine. 1 – technologic fuel, 2 – concentrated offgases, 3 – biomass, 4 – regenerated technologic stream, 5 – combustion air, 6 – flue gas, 7 – natural gas, 8 – compressed air, 9 – flue gas from GT, 10 – cooling water, 11 – warmed up cooling water, 12 – demiwater and condensates, 13 – steam condensate, 14 – preheated water, 15 – boiler feedwater, 16 – live steam, 17 – middle and low pressure steam, 18 – electric energy

Subsystems *2* and *3* are operated more steadily, as they are in direct material connection with the industry's production: two of the boilers are technologic boilers, participating in the production cycle by recovering chemicals; the third boiler is fed by biomass, partly able to respond to seasonal steam demand variations. A few years ago *2* has been reinforced by a new condensing steam turbine, utilizing part of the exhaust steam from the backpressure turbines that is in excess to industry's steam demand. *3* is the newest subsystem, producing valuable high pressure superheated steam in a highly efficient technologic boiler. As this fact is recognized by plant managers, steam production of *3* is sought to be maximized and the corresponding backpressure steam turbine is operated near its nominal load point or even beyond it.

3 SYSTEM ANALYSIS METHODS

First analysis step was obtaining characteristics of gas and steam turbines. Efficiency curves for steam boilers could not be exactly estimated as the fuel quality both is not monitored continuously and varies depending on the plant production. The characteristics were subjected to marginal analysis, which yielded the characteristics slopes, termed marginal steam consumption (t/MWh), which happened to be constants over the whole turbines operating area. For gas turbines it yielded marginal heat rate (kJ/kWh) as a function of turbines load. The obtained data are shown in Tab.2. It must be stressed that marginal parameters generally differ from the often employed average parameters. As elucidated before, utilizing average parameters instead of marginal ones enables to fall wrong decisions about the optimal system operation.

Tab.2 Marginal operational parameters of gas and steam turbines installed in the system understudy. BP STs: steam expansion to 0,6 MPa abs.; $^{\&}$: steam expansion to 8 kPa abs.; $^{\#}$: at 100 % load; $^{\$}$: at 40 % load; *: below 125 t/h load; $^{+}$: above 125 t/h load

	Subsystem				
	1		2		3
Turbine	GT (identical GTs)	TG3	TG1,2	TG8	TG7
Marginal parameter	$6300^{\#}$ to $8200^{\$}$ kJ/kWh	7,14 t/MWh	8,12 t/MWh	6,55 t/MWh$^{\&}$	6,56 t/MWh*; 10,03 t/MWh^{+}

Based on the estimated characteristics and marginal parameters, exergetic and marginal exergetic analysis could be conducted with its results being more deeply described in [7].

4 ANALYSIS OUTCOMES AND THEIR INTERPRETATION

Tab.2 provided insight into operation of installed power sources. Considering TG7 it has been proved that, indeed, its characteristics can be split into two linear dependences with different intercepts and slopes, meeting at 125 t/h turbine steam load. Below this load, more electricity is obtained from one ton of steam expanding in TG7 than in TG1,2. Above this load, however, TG1,2 appear to be more effective in electric energy production, despite lower inlet steam parameters. As an appropriate solution, we recommended to install a short steam pipeline, leading the excess steam from TK2 to TG1,2, in order to match with the TG7 optimum load. The electricity production surplus is in the range 250 to 500 kW. As has later become known, the TG7 comprises an internal steam by-pass, whereby a portion of the expanding steam can by-pass the last turbine stages. Such device's aim is to prevent condensate droplets formation on the last turbine stage which might occur at high turbine loads. It has been installed additionally, after it became obvious that the steam boiler, providing steam for TG7, produces colder steam than was its design. Thus the kink in the turbine characteristics relates to by-pass activation.

Marginal analysis was applied to boiler feed water preparation system as well. All three subsystems used 0,6 MPa abs steam for feed water heating and deaeration. However, feed water temperature was just 116 °C in subsystem *3* and 125 to 145 °C in subsystem *2.* Past record have shown that subsystem *2* has been operated with feedwater temperature of 150 to 155 °C; utilizing 1,3 MPa steam in the deaerator. Later, following a saving proposal, the temperature has been decreased to lower stack losses and deaerators begun to be operated on 0,6 MPa steam. Thus it has been proposed either to increase the feed water temperature which would help the boilers to raise more steam and consequently to produce more electricity, the obtained surplus 0,6 MPa steam being utilized to increase the feed water temperature. Despite increased stack losses it would enable to produce up to 1,5 MW electricity more at a marginal price well below that of electricity bought from outer grid. Such approach is well known for decades and is termed "Carnotization of the Clausius-Rankine cycle" explaining, that it helps to shift the conventional power production cycle towards the theoretical Carnot cycle, thereby boosting its efficiency. It is implemented in large industrial and municipal cogeneration units as well as in large power plants, where the boiler feedwater is heated in up to 9 stages to a final temperature of more than 240 °C. Due to the above mentioned communication barriers [4] the plant managers could not be persuaded about the benefits of this proposal. The industry decided instead to implement another, less favorable proposed option, namely to install two small steam turbines (TRs), utilizing the steam pressure differential between 0,6 MPa steam and the deaerator pressure, to produce 500 to 700 kW of cheap electricity. Marginal analysis, dealing separately with benefits of feedwater temperature increase and of TRs installation, as well as with the synergic effect of both proposals, demanded to recalculate the steam balance of the whole system. An example of such calculation, comprising just the biomass boiler with its feedwater preparation system, is provided in Tab. 3. Results of complex calculations are shown in Chart 1.

Tab. 3 Calculation example of elevated boiler feedwater impact on the whole steam and electricity balance, considering just one steam boiler and its feedwater preparation. Chosen reference state for water: 0 °C, (l). * - based on past boiler operation records

Operational parameter	Base case	Elevated boiler feedwater temperature
Water to deaerator, t/h / °C / kJ/kg	93,22 / 85 / 356	92,16 / 85 / 356
Steam to deaerator, t/h / MPa abs / °C / kJ/kg	6,78 / 0,6 / 200 / 2850	11,52 / 0,6 / 195 / 2840
Boiler feedwater, t/h / °C / kJ/kg	100 / 125 / 525	105,24 / 150 / 632
Steam production, t/h / °C / MPa / kJ/kg / GJ/h	100 / 400 / 4 / 3220 / 322,0	103,68 / 400 / 4 / 3220 / 333,8
Heat consumed in boiler, GJ/h	269,5	268,3
Combustion air, t/h / °C	156,4 / 60	159,2 / 40*
0,6 MPa steam for combustion air preheating, t/h	2,85	1,46
Combustion temperature, °C	1150	1140*
Fuel consumption, GJ/h	306,3	311,7
Flue gas, t/h / °C	187 / 180	190,3 / 190*
Steam turbine output, MW	9,85	10,30
0,6 MPa steam to industry, t/h, GJ/h	90,37 / 257,6	90,70 / 257,6
Fuel to electricity ratio, GJ/MWh	31,10	30,26
Marginal fuel to electricity ratio, GJ/MWh	-	12

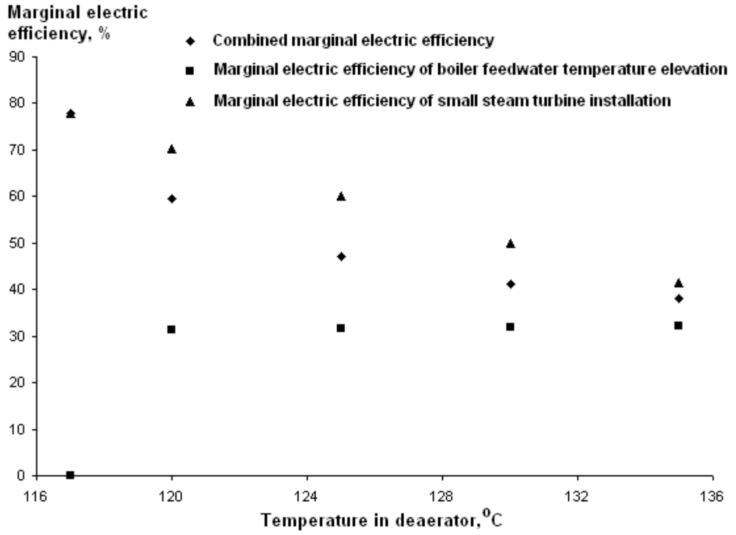


Chart 1. Marginal analysis results of both feedwater temperature elevation and small steam turbine installation, in subsystem *3*

The marginal efficiencies were calculated by (1) as a ratio of the system's electric output increase, expressed in GJ/h and of the corresponding system's fuel consumption increase in terms of its lower heating value.

$$\eta_{el,m\arg} = \frac{\Delta P_{el,system}}{\Delta \dot{Q}_{fuel}} \, [\%] \tag{1}$$

From the above results a general conclusion can be drawn that solely increasing the feedwater temperature in this particular system results in electric output increase with marginal electric efficiency of approximately 30 %. Such figure is wholly comparable with marginal electric efficiency of combined KB + TG1,2 + TG8 operation; moreover, in contrary to TG8 installation, it requires no capital expenses. Installation of small steam turbine fed by steam to deaerator is characterized by even higher marginal electric efficiency, slowly decreasing with increasing deaeration temperature due to lowering pressure ratio available. Above approximately 135 °C, the steam pressure ratio is already too low to allow for an economic steam turbine operation; the combined marginal efficiency then equals to the marginal efficiency of feedwater temperature elevation. The plant managers decided to implement just the small steam turbines installation in the end. Their operation history and the electric energy produced resulted in a simple payback period of approximately 2 years, which thus represents an exceptionally attractive investment in the field of the Energetics.

Marginal exergoeconomic analysis was used in evaluation of subsystem *1* and in its revamp possibilities [8]. To sum up briefly the concept of exergy, one is referred to the second law of thermodynamics, postulating the qualitative inequality of heat and work. Based on the studies performed by Carnot, definition of exergy states it is such a part of energy, convertible to useful work by theoretical (Carnot) cycle. Thus, a substance in physico-chemical equilibrium with its surroundings has zero exergy, which helps to define exergy of a substance as its ability to react (interact) with its surroundings, or, from the environmental point of view, as its ability to harm it. Exergy is not a conservative quantity; it gets lost in real (non equilibrium) processes, for example in form of heat degradation in heat transfer, in form of friction losses in fluids transportation or by irreversibility of chemical reactions such as combustion. The relationship for specific exergy of steam (water) stream is given by (2a) and that of an ideal gas, or an ideal gas mixture, disregarding the mixing exergy is given by (2b) with $_1$ denoting the state of the given stream and $_o$ denoting the reference state. Explanation of symbols used is provided in the List of symbols and abbreviations used chapter.

$$b = h_1 - h_o - T_o(s_1 - s_o) \tag{2a}$$

$$b = \left[\int_{To}^{T_1} c_p(T)dT - T_o.\int_{To}^{T_1} \frac{c_p(T)}{T} dT + RT_o.\ln\left(\frac{p_1}{p_o}\right)\right].\frac{1}{M} \tag{2b}$$

Cost, on the contrary to exergy, is a conservative quantity. Basic theses of exergoeconomy [5] enable the specific cost of a stream to be calculated on the basis of its exergetic and not energetic content. The reader is referred to [5] for further information, here we present just the final relationship (3) for the unit exergoeconomic cost of a product stream $c_{P,i}$, valid for i-th sequential process with one feed and one product stream.

$$c_{P,i} = \frac{\left(c_{F,i}.\dot{F}_i + \dot{Z}_i\right)}{\dot{P}_i} = c_{F,i}.k_{P,i} + \frac{\dot{Z}_i}{\dot{P}_i} \quad [euro/kJ] \tag{3}$$

The term $\left(c_{F,i}.\dot{F}_i + \dot{Z}_i\right)$ represents the sum of cost related to feed stream and that of externalities $\dot{Z}_i$ related to the i-th process (for example emissions cost, waste disposal cost or ancillary services revenues). Explanation of symbols used is provided in the List of symbols and abbreviations used chapter. By simultaneous solving of material, heat and exergoeconomic balances, one can calculate cost of all product or internal streams of a production process. The advantage of such approach is documented in Chart 2, while more results can be found in [8].

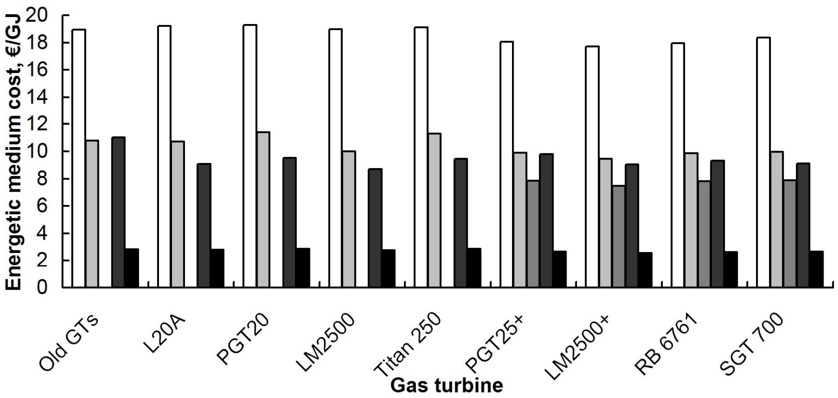


Chart 2. Obtained energetic cost of various energetic media in €/GJ energy, after performing the exergoeconomic costing procedure, produced in subsystem 1 after revamp with different gas turbines. White – electric energy from a new gas turbine, light grey – high pressure steam (6 MPa) from a new HRSG, medium grey – medium pressure steam (1,3 MPa) from a new HRSG, dark grey – 0,6 MPa steam from TG3, black – preheated pressurized water from hot water section of a new HRSG

As is obvious, the unit energetic cost decreases along with decreasing unit exergy content of a stream. Let’s compare the cost of high and medium pressure steam. Traditional costing procedure assigns the same cost €/GJ to both streams, however the exergoeconomic costing assigns higher cost to the stream with higher exergetic content, namely the high pressure steam. The advantage of such outcome is straightforward: it penalizes utilization of energetic media with higher quality and promotes low quality media consumption, thus directly supporting the exploitation of cogeneration potential of the given plant. On the other hand, separating the electricity and steam cost by traditional costing, does not respect the different quality of steam at various pressure levels, thus making no contribution to cogeneration plant efficiency improvement. The risk of subsequent irrational operations is the bigger the more autonomous the industrial power plant is in the production structure of the industry, the less information are exchanged between the energetic media producer and consumers and the less the plant managers understand the purpose of central steam and power plant operation.

As an extreme example how far it can lead, we briefly describe following case: A production unit of a certain industrial complex needed for its operation 30 t/h of 1,7 MPa steam on average. Normally it has been produced by a boiler, located directly on the given production unit. After the boiler had to be turned down because of its bad technical state, the production unit begun to import the needed steam amount from outer 3,5 MPa steam main. The 3,5 MPa steam is produced in the central steam and power plant on backpressure turbines with extractions. As a result, the 3,5 MPa steam production capacity has been exceeded and on average 10 to 30 t/h of 3,5 MPa steam had to be produced in a let-down station directly from live 9 MPa steam. The “best” solution the plant experts could propose was to commission a new steam boiler. We proposed both cheaper and more effective solution, comprising installation of a thermocompressor, which is intended to produce 1,7 MPa steam by thermocompression of 1,0 MPa steam from outer main with the help of 3,5 MPa steam from outer main. Such measure enables to produce more than 1 MW of backpressure electricity in the central steam and power plant, thus better exploiting its cogeneration potential. It could backwards be concluded, that such simple solution could not be thought of by plant managers or energy efficiency experts because of lack of communication and because of employed traditional steam pricing.

5 CONCLUSIONS

This contribution presented the main findings in optimization of a complex industrial cogeneration unit by employing marginal and exergoeconomic analysis. Such analysis has de facto not been performed on a power and heat source in Slovakia and the joint approach together with obtained results represents an important pillar of one of the author’s doctoral thesis [7]. Its usefulness has been demonstrated on optimization of various subsystems performance from a global point of view, with resulting exploitation of reserves in cogeneration potential utilization by potential increase of cogenerated electric output by more than 1,5 MW. Part of the proposals has already been set into reality, with power output increase of 500 to 700 kW and a documented simple pay back period of around two years. However, the presented approach is not restricted just to performance optimization of cogeneration units; after being suitably modified it can be adopted in optimization of any industrial process consuming and / or producing energy in any technically exploitable form. We can only hope that the presented approach will be more frequently made use of in evaluation of possible cogeneration potential improvements of both new and existing cogeneration units. Thus we hope to have contributed to knowledge transfer between academia and industry, the already achieved results making it the more interesting for our future industrial partners.

6 LIST OF SYMBOLS AND ABBREVIATIONS USED

b	specific exergy	kJ/kg
BP	backpressure (steam turbine type)	
c	cost	€/kg
C	condensing (steam turbine type)	
c_p	molar heat capacity	kJ/kmol/K
CCH	combustion chamber	
$\dot{F}$	exergetic flux of an inlet stream (feed)	kW
G	generator	
GT	gas turbine	
h	specific enthalpy	kJ/kg
HRSG	heat recovery steam generator	
k	unit exergetic cost	kJ/kJ
K	boiler	
KB	biomass boiler	
M	molar mass	kg/kmol
p	pressure	kPa

$\dot{P}$	exergetic flux of an outlet stream (product)	kW
$P_{el,system}$	electric output of a system	kW
$\dot{Q}_{fuel}$	lower heating value flux of fuel used	kW
R	universal gas constant	8,314 kJ/kmol/K
s	specific entropy	kJ/kmol/K
ST	steam turbine	
T	thermodynamic temperature	K
TG	turbogenerator	
TK	technologic boiler	
TR	small steam turbine	
$\dot{Z}$	Externalities cost flux	€/s

Subscripts and superscripts

F	related to an inlet stream (feed)
i	i-th sequential process
P	related to an outlet stream (product)
o	reference (thermodynamic) state
1	actual (thermodynamic) state

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