EXERGY BASED METHODS FOR ECONOMIC AND ENVIRONMENTAL ANALYSIS APPLIED TO A 320 MW COMBINED CYCLE POWER PLANT

Matteo Rocco*, Claudia Toro°

*Politecnico di Milano, Department of Energy, via Lambruschini 4, Milan, Italy
°Università di Roma "Sapienza", Department of Mechanical and Aerospace Engineering, via Eudossiana 18, Rome, Italy

ABSTRACT

In the last decades, the growing scarcity of non-renewable resources led analysts and researchers to sharpen Second Law analysis methods in order to understand how to minimize the consumption of natural resources on the part of energy conversion systems. Thermoeconomics demonstrates to be a proper and promising framework to evaluate and optimize exergetic and economic costs of energy systems products. Understanding the relation between the economic cost and its natural resource counterpart is likely to be a key factor in future research activities.
This paper presents an Exergy and Thermoeconomic analysis of a 320 MW Dual Pressure Combined Cycle Plant, aimed to identify the optimal design configurations of the system with respect to its specific objective functions: second law efficiency, economic cost and natural resource consumption cost of the generated unit of electric energy. The natural resource consumption of the system is computed according to the Cumulative Exergy Consumption (CExC) method.
The CCPP plant simulations have been performed by using CAMEL-Pro™ Process Simulator and the sensitivity study of the plant behaviour and its optimization as a function of the selected parameters have been developed by using the Proper Orthogonal Decomposition procedure. Our results confirm that the optimal design configuration is strictly dependent on the considered objective function, and helps to investigate the relationship between the thermodynamics, the economics and the resource consumption of the system, thus giving a more comprehensive understanding of its performance from different perspectives.

INTRODUCTION

Combined Cycle Power Plants (CCPPs) are well proven and reliable technology for electricity production. CCPPs are widely used in the Italian grid network and their design and optimization are today more and more relevant.

This paper presents an original implementation of the Thermoeconomics framework for the optimal design analysis of a 320 MW Dual Pressure CCPP. The purpose of the study is to identify the possible optimal design configuration of this system, including thermodynamic, economic and environmental perspectives.

As a first step, modelling and simulation of the system is performed. Secondly, economic and environmental perspectives are assessed performing exergy based specific analyses. Exergy analysis (EA) is used to determine the second law efficiency of the system, whereas Thermoeconomic framework is used to assess both the economic and the environmental costs of the product. In the case study electricity is considered as the unique product of the system. Economic optimal cost of product is assessed with the Thermoeconomic analysis (TA-ECO), finding the best trade-off between investment and operative economic costs [1]. On the other hand, Thermoeconomic analysis is also used to assess, in an environmental cost perspective, the primary exergy consumed in order to produce the system product (TA-EXER). The primary exergy may represent the natural resources consumed [2].

As will be shown, the optimal design configuration is strictly dependent on the considered objective cost function. The paper shows how changing the objective function of the analysis (efficiency, monetary cost or primary exergy cost) can influence the optimal design of the system, and proposes a key to understanding the relationship between economic and environmental costs of energy systems.

CASE STUDY: DUAL PRESSURE COMBINED CYCLE POWER PLANT

Plant layout and simulation

As a case study, the *Neka* CCPP power plant operative data have been used [3]. The main components of this combined plant are two gas turbines, two air compressors, two HRSGs with a supplementary fired unit (duct burner), one steam turbine and one surface condenser with a seawater cooling system. The total output power is 320 MW, 130MW produced by the steam turbine and 190 MW two gas turbines.

Table 1. CCPP fixed operative parameters.

Parameter	u. m.	Value
Outlet Power	MW	160
Gas Turbine Adiabatic Efficiency	%	87.7
Compressor Adiabatic Efficiency	%	88.0
Steam Turbine Efficiency	%	78.0
Condenser inlet pressure	kPa	14
HRSG Low Pressure	kPa	1029
HRSG High Pressure	kPa	11425
Turbine Inlet Temperature	K	1383
Plant Availability	h/y	2628

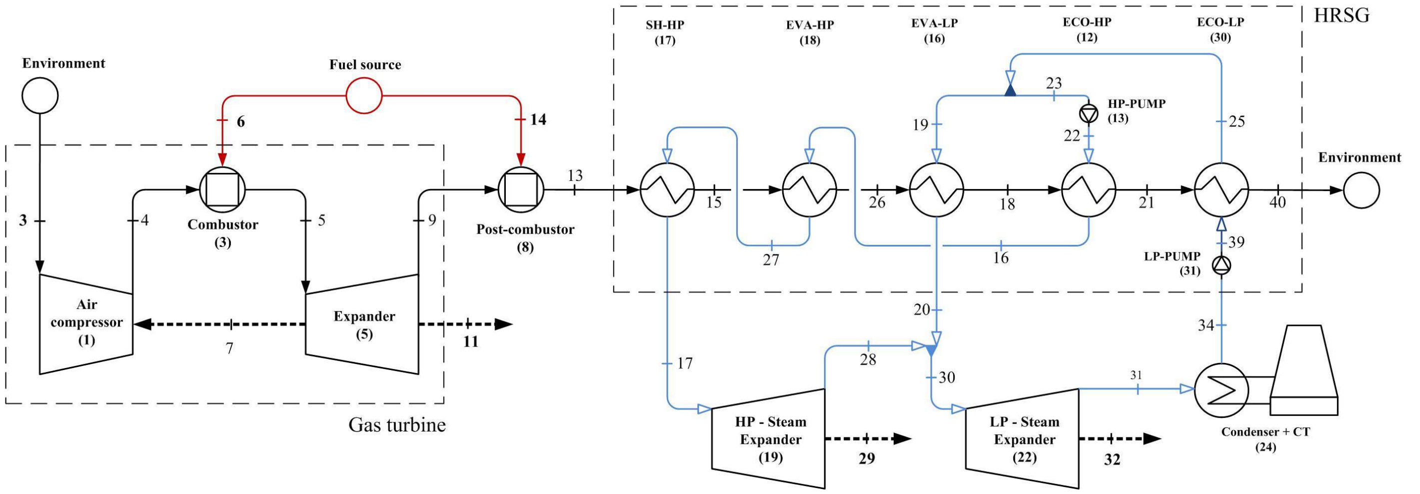

Figure 1. Plant layout.

The power plant was modeled with CAMEL-Pro™ process simulator [4]; its layout consist in two identical blocks, each generating half of the total output: all simulations were performed accordingly for one single block with an output net power of 160 MW. The layout of the simulated plant is reported in Figure **1** and the operative conditions (steady state operation being assumed throughout) are reported in Table **1**. The low Load Factor (2628 hours per year) reflects the actual operative conditions of the average Italian CCPPs.

Table 2. Selected design variables and their respective ranges.

Process variables	Symbol [u. m.]	Min. value	Max. value
Air pressure ratio	β_C [-]	10	21
Post-Firing fuel	$\dot{m}_{14}$ [kg/s]	1	2

To proceed with the optimization of the plant, two process variables have been selected: the gas turbine pressure ratio β_C and the duct burner fuel mass flow rate $\dot{m}_{NG,pf}$ ($\dot{m}_{14}$) Their respective possible ranges of variation are reported in Table **2**.

Determination of the plant behavior: Proper Orthogonal Decomposition method (POD)

The sensitivity study of the plant behavior and the optimization with respect to the selected process variables and the objective functions have been developed by using the Proper Orthogonal Decomposition mathematical procedure (POD – RBF). The POD Method is a is a statistical method that aims to provide a compact representation of the data by projecting the data set into a lower dimensional space. The POD-RBF procedure has been previously tested on the optimization of a simple MSF desalination plant [5] and of a single pressure CCGT [6] plant and the very satisfactory results obtained for these plants suggested extending its application to more complex configurations and to different processes. Moreover, the POD enables designers to extrapolate functions linking the variables to be optimized with the selected process variables.

More details about POD as well as an introductory mathematical explanation of its conceptual basis are provided in [7]. In the case study here presented the objective functions are minimized considering the constraints listed in Table **3**.

Table 3. Constraints for plant operation.

Parameter [u. m.]	Device / Pipe no.	Lower limit	Higher limit
$\Delta T_{pp,LP}$ [°C]	16	5	35
$\Delta T_{pp,HP}$ [°C]	18	5	35
$\Delta T_{ap,LP}$ [°C]	16,30	10	-
$\Delta T_{ap,HP}$ [°C]	17,18,12	10	-
T_{40} [°C]	40	100	-

EXERGY BASED METHODS ANALYSES AND OPTIMIZATION

Thermodynamic evaluation: exergy analysis

As stated in [2], in order to perform the exergy analysis for a generic energy system, it is convenient to set up its productive structure, or functional diagram. Using the physical model of the system as reference and grouping all the energy and material flows for every component of the system, and therefore for the whole system, the productive structure is completed according to the *Resources–Product–Wastes* (R/P/I) criterion. For the generic *j-th* system component, exergy balance is:

$$\dot{\mathbf{E}}_{R,j} = \dot{\mathbf{E}}_{P,j} + \dot{\mathbf{E}}_{I,j} + \dot{\mathbf{E}}_{D,j} \tag{1}$$

For every system consisting of *n* components connected by *m* streams, the exergy balance system can be expressed in matrix form by (2), where **A** is the *n*×*m* incidence matrix of the system, defined in [2]:

$$\mathbf{A}_{(n\times m)} \cdot \mathbf{E}_{(m\times 1)} = \mathbf{E}_{\mathbf{D},(n\times 1)} \tag{2}$$

For each component of the system, exergy efficiency is defined as the ratio between exergy of products over exergy of the resources and it represents a criterion for evaluating the thermodynamic performance of the component. The objective of the exergy analysis is to find the combination of the selected process variables β_C and $\dot{m}_{14}$ that provides the highest exergy efficiency for the whole system, defined as (3).

$$\eta_{II,tot} = \frac{\dot{\mathbf{E}}_{P,tot}}{\dot{\mathbf{E}}_{F,tot}} = \frac{\dot{W}_{el,net}}{(\dot{m}_6 + \dot{m}_{14}) \cdot \mathbf{e}_{NG}} \tag{3}$$

This goal has been reached applying the POD procedure on simulated plant results, which allows extrapolating the exergy efficiency (3) as a function of the selected process variables β_C and $\dot{m}_{14}$. Figure 2 shows the exergy efficiency as function of these process variables, normalized within their own range.

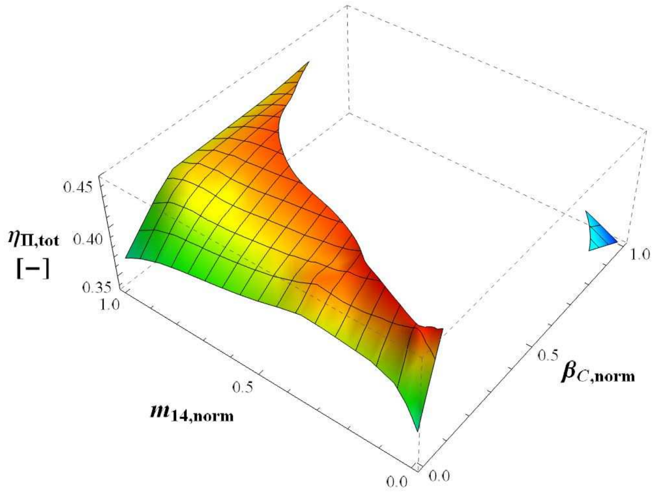

Figure 2. Overall plant exergy efficiency map.

For the plant given in the case study, the best exergy efficiency results around 44.8 %, corresponding to β_C = 14.36 and $\dot{m}_{14}$ = 1.6 kg/s.

Thermoeconomic design analysis for Economic cost evaluation and optimization (TE-ECO)

According to productive structure adopted for exergy analysis, the economic cost rate balances for the *i-th* plant component is:

$$\dot{C}_{eco,R,i} + \dot{Z}_{eco,i} = \dot{C}_{eco,P,i} + \dot{C}_{eco,I,i} \tag{4}$$

Where $\dot{C}_{eco,i}$ represent the economic cost rate associated with each exergy transfer, and $\dot{Z}_{eco,i}$ represents the sum of capital investment, operating and maintenance cost rates for the *i-th* system component. Exergy costing principle (5) allows to compute the economic cost rate of every *j-th* material or energy flow entering the *i-th* system component as the product between its average monetary cost per unit of exergy $c_{eco,j}$ (in *€/kJ*) and its exergy content:

$$\dot{C}_{eco,j} = c_{eco,j} \cdot \dot{\mathbf{E}}_j \tag{5}$$

The complete thermoeconomic system can be rewritten in matrix form as follows:

$$\mathbf{A}_{(n\times m)} \cdot \mathbf{C}_{eco,(m\times1)} + \mathbf{Z}_{eco,(n\times1)} = \mathbf{0}_{(n\times1)} \tag{6}$$

If the considered system has n components and m streams, $\mathbf{C}_{eco}$ is the $m\times1$ economic cost rates vector and $\mathbf{Z}_{eco}$ is the $n\times1$ investment cost rates vector of system components. In order to close the equations system, it is therefore necessary to write other *m-n* auxiliary monetary costs equations [1]: some of them depends on the adopted branchings and cost allocation criteria [2], whereas the others are defined by the boundary conditions, such as market prices. In the case study the following auxiliary equations were adopted:

$$c_{eco,6} = c_{eco,14} = c_{eco,NG} \tag{7}$$

$$c_{eco,3} = 0 \tag{8}$$

$$c_{eco,40} = 0 \tag{9}$$

The specific cost of the natural gas (7) was computed on the base of the Italian market average price, and it was considered constant for the entire lifetime of the plant. With the auxiliary equation (9) it comes out that all the economic costs of exiting flue gases are charged to the HRSG, thus on the cost of the product. Other standard assumptions have been made to distribute costs among internal streams [8].

Table 4. Economic parameters.

Parameter	Symbol [u. m.]	Max. value
Interest rate	i [%]	5
Plant lifetime	t [years]	30
Natural gas cost	$c_{eco,NG}$ [€/Nm^3]	0.35

The main parameters of the economic analysis are reported in Table 3. To calculate equipment costs as a function of the main plant operation parameters, the Frangopoulos capital costing equations have been used: values obtained with these equations could be considered acceptable approximations of real values which usually are not given by industry as a function of components parameters [9].

The main result of the thermoeconomic plant optimization, obtained by the application of the POD-RBF procedure, is the combination of the process variables which lead to the attainment of the most convenient compromise between plant efficiency and economic costs.

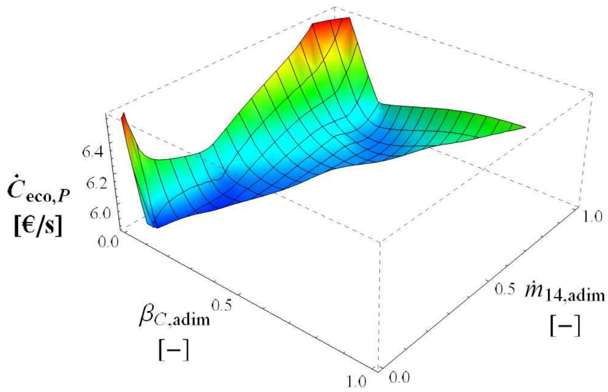

Figure 3. Economic cost map of the system product.

Figure **3** shows the economic cost map of electricity as a function of the normalized selected process variables β_C and $\dot{m}_{14}$. For this plant, the minimum cost results 5.90 €/s, corresponding to values of β_C = 13.32 and $\dot{m}_{14}$ = 1.84 kg/s.

Thermoeconomic design analysis for Environmental cost evaluation and optimization (TA-EXER)

According to literature [10], the impact of energy systems on environment is mainly related to: natural resource consumption in the whole life cycle of the system (a) and polluting effect of all the waste emissions in water, atmosphere and soil (b).

Exergy is widely accepted as a common measure of natural resources consumption and it can be therefore used as an indicator for the environmental impact [11, 12]. Indeed, several attempts have been made to combine exergy analysis and Life Cycle Assessment (LCA) to quantify the natural resources consumption (a) of industrial processes [13, 14]: such as Cumulative Exergy Consumption (CExC) [15], Thermo - Ecological Cost (TEC) [16], Exergetic Life Cycle Analysis (ELCA) [17], Cumulative Exergy Extraction From Natural Environment (CEENE) [18] and so on. All these indicators are development of the "embodied energy" paradigm, well explained in [19]: they differ from each other in the definition of the resource cost factors included into the accounting and in the analysis time window.

On the other hand, one of the main weakness of exergy analysis is that the exergy of waste emissions hardly reflects the magnitudes of the environmental impact [20]. For this reason, some authors propose to evaluate the waste emissions polluting effect (b) as the additional natural resource consumption needed to reduce the exergy content of the effluents to zero: CExCT [21], Zero-ELCA [22] and Extended Exergy Accounting [14] are examples of this approach.

In this paper the authors propose the adoption of the Cumulative Exergy Consumption (CExC) indicator for evaluating the natural resource consumption of the system as partial evaluation of the environmental cost of energy systems. This approach accounts only for energy and materials resources (renewables and non-renewables), as well as human labour, involved in the production of a unit of energy or material products [16]; it does not includes other externalities.

The thermoeconomic cost rate balance (4) for each *i-th* plant component is rewritten according to the same productive structure and input data adopted in 0, replacing economic costs rates of Resources, Products, Wastes and Plant components with their respective exergetic costs:

$$\dot{C}_{ex,R,i} + \dot{Z}_{ex,i} = \dot{C}_{ex,P,i} + \dot{C}_{ex,I,i} \tag{10}$$

Where $\dot{C}_{ex,i}$ represent the resource cost rate embodied in each exergy transfer, and $\dot{Z}_{ex,i}$ represents the resource cost embodied in the *i-th* system component. Exergy costing principle (11) allows to compute the resource cost rate for every *j-th* material or energy flow entering the *i-th* system component as the product between its exergy content and its CExC (represented here by $c_{ex,j}$, in kJ/kJ):

$$\dot{C}_{ex,j} = c_{ex,j} \cdot \dot{\mathbf{E}}_j \tag{11}$$

In a dual way of paragraph 0, the complete thermoeconomic system can be rewritten in matrix form (12).

$$\mathbf{A}_{(n\times m)} \cdot \mathbf{C}_{ex,(m\times1)} + \mathbf{Z}_{ex,(n\times1)} = \mathbf{0}_{(n\times1)} \tag{12}$$

Where $\mathbf{C}_{ex}$ is the $m\times1$ thermoeconomic costs vector and $\mathbf{Z}_{ex}$ is the $n\times1$ investment cost rates vector of system components. Here, the same rules for branchings and cost allocations adopted in 0 were used, and auxiliary relations necessary to close the equation system were computed relying to Simapro 7.3.3 software [23] and Szargut database [15].

$$c_{ex,6} = c_{ex,14} = c_{ex,NG} \tag{13}$$

$$c_{ex,3} = 0 \tag{14}$$

$$c_{ex,40} = 0 \tag{15}$$

CExC of the Ecoinvent unit process "*Natural gas, high pressure, at consumer/RER U*" is 1.069 MJ/MJ and was adopted as specific exergy cost of the natural gas (13). Like TE-ECO analysis, with the auxiliary equation (15) comes out that all the exergetic costs are charged to the HRSG, thus on the cost of the product. Exergy cost functions for plant and O&M costs ($\dot{Z}_{ex,i}$) have been extrapolated from Ecoinvent database as a function of the size, weight and the operative parameters of the plant components [24]. In case of data scarcity, average value for primary exergy consumption of European Machinery and Equipment production sector have been extrapolated from European Input-Output tables (year 2003) and result to be 50.21 MJ/kg [25]. Like the investment economic cost functions, the exergy cost functions could be considered acceptable approximations of real values.

Exergy costs of system product were obtained as a function of the selected process variables β_C and $\dot{m}_{14}$ by applying the POD-RBF procedure.

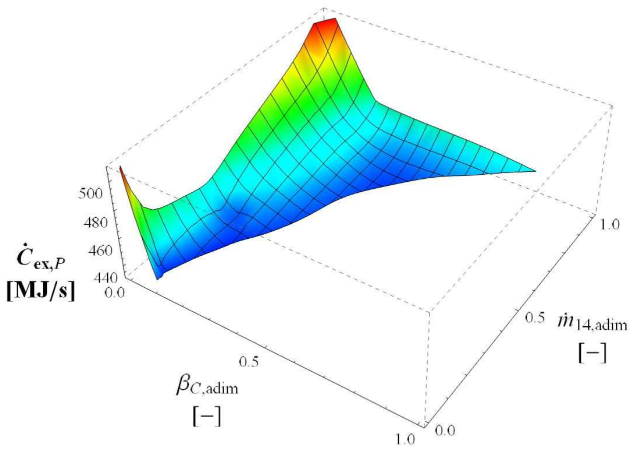

Figure 4. Exergetic cost map of the system product. Values in x and y axes are normalized between 0 and 1.

Figure **4** shows the exergetic cost map of electricity as a function of normalized process variables β_C and $\dot{m}_{14}$. For this plant, the minimum resources consumption results to be 434.5 MJ/s, corresponding to values of β_C = 14.29 and $\dot{m}_{14}$ = 1.75 kg/s. It is noteworthy that, starting from this thermoeconomic analysis, an extension of the traditional second law efficiency can be introduced:

$$\eta_{CExC,tot} = \frac{\dot{\mathbf{E}}_{P,tot}}{\dot{C}_{ex,R,tot} + \dot{Z}_{ex,tot}} \tag{16}$$

Since it takes into account also for the production processes of the fuel and the plant equipment, efficiency defined in (16) is an extended insight of the overall energy conversion process. For this plant, best CExC-efficiency is about 0.36, obtained in correspondence with the minimum resource consumption as previously described.

RESULTS AND DISCUSSION

Exergy based methods results

As previously explained, three different exergy based optimization criteria have been applied to the specific case study. For each identified optimal configuration, it is therefore possible to calculate all the corresponding process variables, summarized in Table 5. As expected, the three couples of β_C and $\dot{m}_{14}$ variables that define each optimal configuration are different; therefore, also the other operative parameters such as efficiency, exergetic and economic costs differ.

Considering a plant availability of 2628 hours per year, the minimization of the economic cost of electricity ($\dot{\mathbf{C}}_{\mathbf{eco,opt}}$) allows to reduce the annual cost of electricity by 336 k€/year with respect to the optimal efficiency configuration ($\boldsymbol{\eta}_{\mathbf{II,opt}}$), and by 219 k€/year with respect to the optimal exergy cost configuration ($\dot{\mathbf{C}}_{\mathbf{ex,opt}}$).

On the other hand, considering as design point the optimal exergy cost of electricity ($\dot{\mathbf{C}}_{\mathbf{ex,opt}}$), the global resource consumption of the plant is reduced by 84,5 toe/year and 1070 toe/year if compared respectively with the optimal efficiency ($\boldsymbol{\eta}_{\mathbf{II,opt}}$) and economic ($\dot{\mathbf{C}}_{\mathbf{eco,opt}}$) configurations.

Table 5. Results of CCPP exergy based optimizations.

Parameter	u. m.	$\eta_{II,opt}$	$\dot{C}_{eco,opt}$	$\dot{C}_{ex,opt}$
β_C	-	14.36	13.32	14.29
$\dot{m}_{NG,pf}$	kg/s	1.60	1.84	1.75
$\dot{m}_{NG,tot}$	kg/s	9.24	9.41	9.25
$\dot{m}_{Air}$	kg/s	282.76	280.47	282.70
η_{II}	-	0.448	0.438	0.449
η_{CExC}	-	0.358	0.353	0.36
$\dot{C}_{eco,el}$	€/h	21373	21245	21328
$\dot{Z}_{eco}$	€/h	6149	5712	6106
$\dot{C}_{eco,NG}$	€/h	15305	15586	15315
$\dot{C}_{ex,el}$	toe/h	37.39	37.76	37.36
$\dot{Z}_{ex}$	toe/h	4.27	3.97	4.24
$\dot{C}_{ex,NG}$	toe/h	33.51	34.12	33.53

To comprehensively evaluate the relationship between the three optimisation functions it is therefore necessary to investigate the relation between thermodynamic, economic and environmental costs of the product.

Coupling procedure for global optimization

Figure **5** depicts a general simplified 2-D representation of this optimization problem: the economic optimization of the plant design (**Eco,opt**) leads to an additional consumption of resources ($\Delta\dot{C}_{ex,P}$ = 0.41 toe/h) while the resource cost optimization (**Ex,opt**) causes an increment of the economic cost of the product ($\Delta\dot{C}_{eco,P}$ = 83.63 €/h).

The subsequent question that arises is whether it is possible to link these two aspects. Referring to Table 5 data, and assuming an average oil barrel market price of 623 €/toe (2011) [26] as a proxy for the primary exergy market price, the CCPP operating in the optimal economic cost design absorbs 0.407 toe/h more with respect to the exergy optimal design. This primary energy surplus purchased by society at its market price would results in 253.76 €/h which is grater then the difference of costs between the economic optimal design and the exergy optimal design ($\Delta\dot{C}_{eco,P}$ = 83.63 €/h). Therefore, this CCPP plant "pays" the primary exergy less than the commercial price: for the societal niche in which this CCPP operates, it is convenient to invest (perhaps by means of a specifically aimed incentive policy) in systems designed to minimize the exergetic primary resources rather than the economic costs: saving resources costs globally less than producing them.

Even if today we still live in world where the objective function is the monetary cost, and therefore the most probable configuration chosen at the end of the process would be the optimal economic cost configuration (**Eco,opt**), the current analysis open a window over a new chance for evaluating resource consumption as an environmental cost for the society. The evaluation of the optimal exergy cost configuration (**Ex,opt**) add another set of information to Decision Makers for having a more comprehensive understanding of the overall impact of the total system for the whole society.

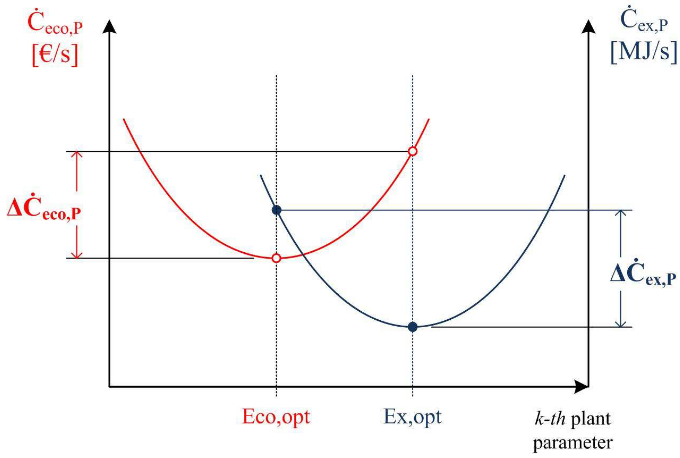

Figure 5. 2-D schematic comparison among economic and exergetic cost function of product.

CONCLUSION

Results of the presented exergy based analyses confirm the existence of substantial differences in designing the CCPP plant considering the optimization of second law efficiency, economic or exergy costs of system product.

Thermoeconomics proved to be an appropriate framework to evaluate both economic and exergy cost of system product. In particular, exergy cost evaluation was expanded in order to include the embodied exergy of resources and equipment into the analysis, as shown by eq. (12), according to CExC method. This improvement gives a better insight of the overall energy conversion process with respect to a standard exergy analysis. Moreover, it has been proposed a criterion for determining the relation between the economic and the environmental costs of the product linked to the consumption of resources (i.e. cost of the primary exergy), giving therefore different perspectives to Decision Makers. In the current economic asset, the optimal economic cost configuration will be probably selected but a number of information can be obtained by comparing the optimal efficiency configuration and the optimal exergy cost configuration.

On the other hand, some drawbacks can be identified and they indicate possible further research directions to improve Thermoeconomic analysis from practical point of view. They fall under two major categories: need for standardization, refinement and extension of the CExC database, and a more accurate socio-economic model to compute the primary exergy market price.

NOMENCLATURE

Symbol	Quantity	SI Unit
c	Specific cost	€/J – J/J
$\dot{C}$	Cost rate	€/s – J/s
$\mathbf{e}$	Specific exergy	J/kg
$\dot{\mathbf{E}}$	Exergy rate	J/s
i	Interest rate	%
m	Total system streams	-
$\dot{m}$	Mass flow rate	kg/s
n	Total plant components	-
T	Temperature	°C
t	Plant lifetime	years
$\dot{W}$	Work	J/s
$\dot{Z}$	Investment cost rate	€/s – J/s
β_C	Air pressure ratio	-
η	Efficiency	-

Subscripts

adim	Adimensional
D	Destruction
eco	Economic
el	Electricity
ex	Exergetic
i	Plant component no.
I	Waste
II	Second Law
j	Material / Energy flow no.
P	Product
pf	Post-firing
R	Resource
tot	total

REFERENCES

[1] A. Bejan, G. Tsatsaronis, M.J. Moran. Thermal Design and Optimization: Wiley, 1996.

[2] E. Querol, B. González-Regueral, J.L.P. Benedito. Practical Approach to Exergy and Thermoeconomic Analyses of Industrial Processes: Springer, 2012.

[3] P. Ahmadi, I. Dincer. Thermodynamic analysis and thermoeconomic optimization of a dual pressure combined cycle power plant with a supplementary firing unit. *Energy Conversion and Management*. 2011;52(5):2296-308.

[4] Università di Roma "La Sapienza", CAMEL-Pro Users Manual, v.4. *wwwturbomachineryit*. 2008.

[5] R. Melli, E. Sciubba, C. Toro, A. Zoli-Porroni. An Improved POD technique for the optimization of MSF processes. *International Journal of Thermodynamics*. 2012;15(4):231-8.

[6] R. Melli, E. Sciubba, C. Toro, A. Zoli-Porroni. An example of Thermo-Economic optimization of a CCGT by means of the Proper Orthogonal Decomposition Method. *Proceedings of the ASME IMECE2012 November 9-15, 2012, Houston, TEXAS, USA*.

[7] V. Buljak. Proper Orthogonal Decomposition and Radial Basis Functions for Fast Simulations. Inverse Analyses with Model Reduction: Springer Berlin Heidelberg; 2012. p. 85-139.

[8] A.a.T. Lazzaretto, G. . On the quest for objective equations in exergy costing. *in ML Ramalingam, JG Lage, Vc Mei, and JN Chapman (eds), Proceedings 'if the ASME Advanced Energy Syrems Devision, 37, ASME, New York, 197-210*. 1997.

[9] C.A. Frangopoulos. Comparison of thermoeconomic and thermodynamic optimal design of a combined-cycle plant. *in: DA Kouremenos (Ed), Proceedings of the International Conference on the Analysis of Thermal and Energy Systems, Athens*. 1991.

[10] S.E. Jorgensen, B. Fath. Encyclopedia of Ecology, Five-Volume Set: Elsevier Science, 2008.

[11] G. Wall. Conditions and tools in the design of energy conversion and management systems of a sustainable society. *Energy Conversion and Management*. 2002;43(9–12):1235-48.

[12] M.A. Rosen, I. Dincer. On Exergy and Environmental Impact. *International Journal of Energy Research*. 1997;21(7):643-54.

[13] J.-F. Portha, S. Louret, M.-N. Pons, J.-N. Jaubert. Estimation of the environmental impact of a petrochemical process using coupled LCA and exergy analysis. *Resources, Conservation and Recycling*. 2010;54(5):291-8.

[14] E. Sciubba. Can an Environmental Indicator valid both at the local and global scales be derived on a thermodynamic basis? *Ecological Indicators*. 2013;29(0):125-37.

[15] J. Szargut, D.R. Morris, F.R. Steward. Exergy analysis of thermal, chemical, and metallurgical processes: Hemisphere, 1988.

[16] J. Szargut. Exergy Method: Technical And Ecological Applications: WIT Press, 2005.

[17] R.L. Cornelissen, G.G. Hirs. The value of the exergetic life cycle assessment besides the LCA. *Energy Conversion and Management*. 2002;43(9–12):1417-24.

[18] B. De Meester, J. Dewulf, S. Verbeke, A. Janssens, H. Van Langenhove. Exergetic life-cycle assessment (ELCA) for resource consumption evaluation in the built environment. *Building and Environment*. 2009;44(1):11-7.

[19] S. International Federation of Institutes for Advanced. IFIAS Workshop Report, energy analysis and economics. *Resources and Energy*. 1978;1(2):151-204.

[20] R.U. Ayres, L.W. Ayres, K. Martinás. Exergy, waste accounting, and life-cycle analysis. *Energy*. 1998;23(5):355-63.

[21] P. Zhu, X. Feng, R.J. Shen. An Extension to the Cumulative Exergy Consumption Applied to Environmental Impact Analysis of Industrial Processes. *Process Safety and Environmental Protection*. 2005;83(3):257-61.

[22] G. Hirs. Thermodynamics applied. Where? Why? *Energy*. 2003;28(13):1303-13.

[23] Simapro 7.3.3, site: http://www.pre.nl/simapro/. Pré Consultants.

[24] X. Feng, G. Zhong, P. Zhu, Z. Gu. Cumulative exergy analysis of heat exchanger production and heat exchange processes. *Energy & fuels*. 2004;18(4):1194-8.

[25] S. Suh. Handbook of Input-output Analysis Economics in Industrial Ecology: Springer London, Limited, 2009.

[26] B. Petroleum. Statistical Review of World Energy. 2012.