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An Integrated Approach to the Assessment of Energy Conversion Plants*

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Abstract

An integrated approach to the assessment of energy systems behaviour with regard to energetic, economic and environmental viewpoints is suggested. For each aspect, suitable performance indicators are defined, evaluated and then normalised in order that the same numerical value is calculated for qualitatively equivalent performances even if related to different aspects; application of these indicators can address policy makers, designers and plant operators towards a fair compromise among such important aspects. In this paper the method is applied to different types of plants (thermal power, gas-steam combined, co-generative, geo-thermal power, hydroelectric) and results are compared and discussed. The procedure can be effective in both determining standard performances for each class of plants and analysing the deviations of a particular plant from the average behaviour of its class.

Key words: Multicriteria approach, exergy, thermoeconomics, emergy

1. Introduction

Shortage of energy resources, environmental pollution and increasing costs of energy are three major aspects of the energetic problems in the modern society; therefore, methods aimed at evaluating the performances of energy systems should take into account the so-called "3 E's" (Energy - Environment - Economics). Many approaches have been suggested by scientists and engineers to assess performances from different viewpoints: 1st Law and 2nd Law (exergetic) calculations, thermoeconomic methods, environmental impact assessment, embodied energy (emergy) analysis, economic evaluation, *Life Cycle Assessment* (LCA), etc.

More effective and general indications can be drawn from integrated analyses, considering many aspects simultaneously. With this aim, several theories have been introduced by many authors. These contributions resulted in a valuable conceptual background for the presented approach.

The *Thermoeconomic Theory* , El Sayed et al. (1983), Frangopoulos (1984), Tsatsaronis et al. (1985), Von Spakovsky et al. (1990), Lozano et al. (1993), considers the internal structure and parameters of the plant and determines the economic costs of its internal energy flows and its products, based on their exergy. The results are helpful in choosing and improving the plant configuration by the evaluation of thermodynamic inefficiencies and their costs. Valero (1998) recently introduced the concept of *exergoecological cost* to take also into account the contribution of natural resources directly and determine a more comprehensive exergetic cost of products. Yet, he acknowledges that quantifying this contribution is difficult and proposes to further investigate the problem of evaluating the exergoecological costs.

The *Cumulative Consumption of Exergy* (CExC) by Szargut (1991), (1999) and the *Extended Exergy Accounting (EEA*) *Theory* by

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Sciubba (1999), still using exergy as the basis for cost accounting, suggest a formulation of the environmental costs of both input resources and clean-up activities.

The *Environomic Theory* by Von Spakovsky at al. (1993) is an extension of the thermoeconomic theory, considering the environmental resources. Contributions of raw materials, plant manufacturing, operation, maintenance, decommissioning, recycling and clean up activities are expressed in monetary units. Anyway, great difficulties are related to the evaluation of the cost parameters required by this analysis.

The whole lifetime of the plants, "from the cradle to the grave", is considered by the LCA method (Badino et al., 1998). This method, very popular in the industrial field, works only on first-law energy balances. Conversely, the ExLCA (Exergetic Life Cycle Assessment) is still in an early stage to understand its real practical value.

Similar viewpoints were introduced by Odum (1995), later Brown and Ulgiati (1997), (1998), in the *Embodied Energy* (*Emergy) Analysis* (see § 2.3 and note 5)

Although several theoretical approaches for the global assessment of energy conversion plants were suggested, as shown, very few examples of application of these theories can be found in the literature. One reason is the very recent introduction of these approaches but there are also strong difficulties in gathering the large amount of data required and uncertainties in quantifying the intrinsic cost of natural resources and the effects of pollution by means of a common measurement unit.

An effective tool for evaluating plant performances considering different points of view (energy, environment and economy) is presented in this paper.

Proper techniques are used to focus on different aspects and an appropriate set of indicators, suitable to supply distinct key information about plant performances, is defined. Indicators are then transposed in a proper non-dimensional scale to make each one comparable with the others. In this way the same numerical value of different indicators supplies equivalent qualitative information about the plant performances; i.e., equal values of different parameters express similar "degrees of effectiveness" related to the corresponding aspects.

Indicators can be effectively evaluated without knowing the internal structure of the plant, using comprehensive data that are normally available from on-line monitoring or design data.

Information provided by this method is useful to compare different technical solutions in an immediate and effective way. Both policy makers at governmental level and energy managers at company level might be interested in this application. Information can be also used by plant operators to select appropriate criteria to improve plant operation. Finally, in the design of energy conversion plants, the tool can be used to obtain some guidelines for design improvements of structure, components and parameters.

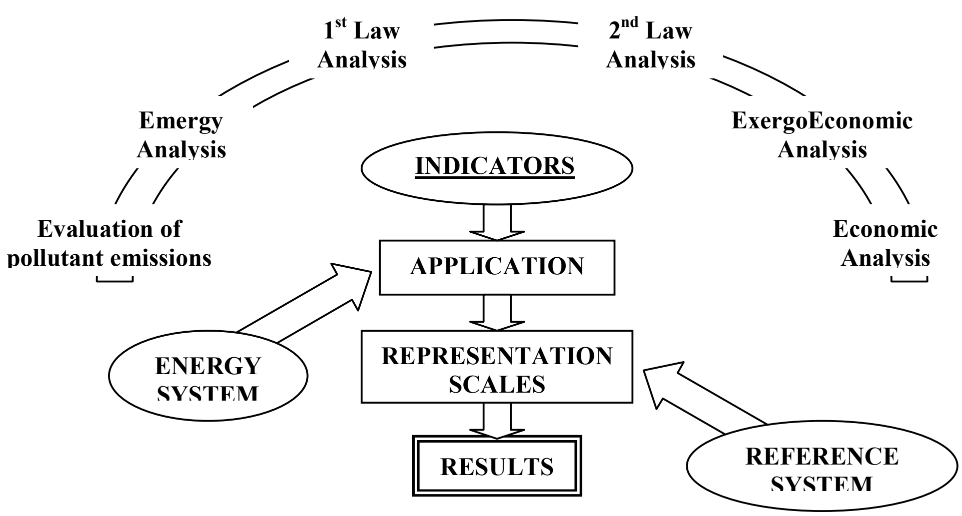

Figure 1. Basic structure of the integrated approach method

2. General Description of the Tool

Energy conversion systems, due to their complexity, require great attention to be paid to the energetic, economic and environmental aspects. Many strong interconnections exist among these aspects and this makes the analysis difficult to be performed. Anyway, important information can be derived from separate investigations, using different methods, provided that, at the end, the results are examined simultaneously.

The proposal integrates results of the methods described in *Figure 1*. They focus on different time and scale windows; for this reason the tool provides comprehensive information about plant performances.

Each method has a particular field of application and has to be used in accordance with the correct time and space scales to provide valuable results. To do this, a careful definition of time and space boundaries has to be performed. Considering that comprehensive characterization of the system is a time-consuming activity usually hard to be achieved, insights on process dynamics should be adequate to the information required. For each method of analysis, time and space boundaries of interest are shown in TABLE I. As can be inferred, some methods are used with several levels of boundaries. Moreover, other boundaries can be used for particular applications that are not considered in this paper.

TABLE I. TIME AND SPACE BOUNDARIES FOR DIFFERENT METHODS

TIME				SPACE		
From the cradle to the grave	Operation life	Present conditions		Physical borders	Regional	Biosphere
	■	■	1st Law Analysis	■		
	■	■	2nd Law Analysis	■		
	■	■	Exergoeconomic Analysis	■		
	■		Economic Analysis	■	■	
	■	■	Eval. of pollutant emissions	■		
■	■		Emergy Analysis		■	■

Each method supplies the basis to define certain indicators that express, quantitatively, various kinds of interesting performances. In choosing the indicators some features or requirements have been considered: they should be concise, reliable and easily applicable to actual plants (using data currently available). Some of them are already known, so can be used with confidence, others have been introduced by the authors. In so doing all the indicators should supply complementary information. In the following paragraphs selected indicators are described.

2.1 Energetic (thermodynamic) indicators

Energy and exergy analysis are important to explain how energy flows interact with each other and how the energy content of resources (both renewable and non-renewable) is exploited.

1st Law efficiency $\boldsymbol{\eta}$ (eq. 1), supplies information about the efficiency in using energy resources to get the products.

$$\eta = \frac{\sum_{j=1}^{n} E_j}{E_{in}} \qquad (1)$$

2nd Law efficiency $\boldsymbol{\zeta}$ (eq. 2), is used to explain efficiency from the exergetic point of view. These two indicators have a wide range of application (system and component level, even though the last one is not considered in this paper).

$$\zeta = \frac{\sum_{j=1}^{n} B_j}{B_{in}} \qquad (2)$$

Raw energy conversion coefficient $\boldsymbol{\varepsilon_{raw}}$ (eq. 3), is introduced by the authors to quantify the amount of raw energy resources used to obtain the final products and is related to the amount of raw (non-renewable) energy saved for not using fossil fuels to get the same products. Its numerical value can range between η (no energy saved) and ∞ (best use, no raw energy used at all).

$$\varepsilon_{raw} = \frac{\sum_{j=1}^{n} E_j}{E_{raw}} \qquad (3)$$

Potential 2nd Law efficiency $\boldsymbol{\zeta_{pot}}$, (eq. 4), is a measure of the potential further exploitation of the process, from the exergy point of view, if outlet flows, which are generally discarded because of their low exergy content, were used when considered as useful products (consider, for example, the heat released with flue gases when low temperature heat is not needed nearby).

$$\zeta_{pot} = \frac{\sum_{j=1}^{n+t} B_j}{B_{in}} \qquad (4)$$

2.2 Economic and exergoeconomic indicators

Economic performances involve many aspects. First of all the convenience of the plant as an investment must be checked and the "Discounted Cash Flow" method provides some useful indicators.

Profit Index ***IP*** (Eq. 5), is a measure of the convenience of the investment considering the complete plant operating life; the calculation of IP implies the choice of a proper value for the discount rate *i*, because it affects the calculation of NPV (*Net Present Value*).

$$IP = 1 + \frac{NPV}{I_o} \tag{5}$$

Internal Rate of Return ***IRR*** (Eq. 6), expresses the internal convenience point of the investment and has to be compared with the actual market conditions. Unlike IP, IRR is not influenced by the value of *i*. Generally, the decision makers should consider these indicators altogether, since each one supplies different information.

$$IRR = i \Rightarrow (NPV = 0) \tag{6}$$

Exergoeconomics (or Thermoeconomics) is a powerful combination of exergy and cost analysis. This theory allows the analyst to calculate the cost at which all the exergy streams are generated within the plant. The model proposed here considers the plant as a whole and the inefficiencies of components are not detailed.

Exergoeconomic factor ***f*** (Eq. 7), introduced by Tsatsaronis et al. (1985), represents a compromise between exergy and economics. With this indicator plant capital costs are compared with those associated to the irreversibilities linked with the process. The range for this indicator is between 0 and 1: if f is close to 0, the cost of irreversibilities is predominant (high I, which is the sum of plant irreversibilities and exergy losses, low η_{ex}, i.e. low efficiency), while the capital cost is predominant when f is close to 1. Generally, in plants running on fossil fuels, a good compromise is reached when intermediate values occur; but in the authors' opinion this indicator is really useful in comparing plants belonging to the same class.

$$f = \frac{Z}{Z + c_F \cdot I} = \frac{Z}{Z + \Pi_F (1 - \eta_{ex})} \tag{7}$$

Economic cost of products ***c****,* on exergy basis (eq. 8), explains the manufacturing efficiency of the process in economic terms (i.e. allocation of the unit exergy cost of product). It is evaluated considering the operating life of the plant.

$$c = \frac{Z + c_F \cdot F}{P} \tag{8}$$

2.3 Environmental indicators

Environmental impact assessment is concerned both with the production and emission of pollutants and with the use of resources (renewable and non-renewable). Therefore, two classes of parameters are considered. The first class is used to characterise the emissions of pollutants, whereas the second one is useful to evaluate both emissions and rate at which resources are consumed.

Environmental factors $\boldsymbol{EF_{air}}$ *and* $\boldsymbol{EF_{water}}$ (eq. 9), were proposed[1] by the authors, see Tonon (1998). They represent an effective way to quantify pollutant emissions and can be referred to instant conditions or average values (operating periods). Parameters are referred to the main aspects of pollution in air and water[2]. The set of polluting substances and the *emission limits* L_i (see TABLE II) have been chosen according to the in-force laws[3] and with respect to the peculiarities of energy conversion plants. For the air indicator, both the *Emission Levels* S_i and the emission limits L_i are referred to the exergy of products, thus considering the favourable effect of better energy conversion efficiency. Conversely, water pollution is assessed by considering the level of harmful substances in the water system receiving the discharge flow, since the relation between pollution effects and emission level is very complex.

$$EF_{air}, EF_{water} = \max\left(\frac{S_i}{L_i}\right)$$
$$\left\{\begin{matrix} i = SO_2, NO_x, PM, CO & \text{for} & EF_{air} \\ i = \Delta T, DO, TDS, pH, N, Me. & \text{for} & EF_{water} \end{matrix}\right\} \tag{9}$$

[1] See also the *Harmfulness factor* f_P used in the *Environomic analysis* by Von Spakovsky et al. (1993) and the *Pollutant Standard Index PSI* introduced by EPA (1999), used in monitoring air quality.

[2] Other types of environmental impact (ground, biological, health, psychological and sociological) should also be discussed, but they cannot be directly ascribed to a certain plant, because they also depend on the environment. On the other hand, our indicators are aimed at evaluating plants; so, these aspects are not considered. As to the acoustic pollution, it is not a key factor, because it can be generally reduced if needed and is more related to comfort and safety of personnel.

[3] The influence of each pollutant on the environment is not only related to its own level but also to the interaction among several pollutants which produces effects hard to be evaluated; these interactions have already been considered by the regulations.

TABLE II. POLLUTANTS AND LIMITS CONSIDERED

Air[4]

Fuel type		Coal	Oil	Gas
PM	Particulate Matter	50	42	4
SO_2	Sulfur Dioxide	400	334	26
CO	Carbon Monoxide	250	211	184
NO_x	Nitrogen Oxides	647	376	258

Water

ΔT	Temperature increase	3 °C
TDS	Total dissolved solids	80 mg/l
DO	Dissolved Oxygen	> 5.0 mg/l; < 9.0 mg/l
pH	Acidity	5.5
N	Ammonia	15 mg/l
	Nitrate	0.6 mg/l
	Nitrite	20 mg/l
Me	Metals	3 mg/l

The environmental impact in a more general sense is qualified by parameters taken from the embodied energy (emergy) analysis[5]. Emergy based indicators are evaluated using emergy values of the environmental and economic, renewable and non-renewable, local and imported input flows, as suggested by Brown et al. (1998).

Transformity ***Tr*** (eq. 10), is the ratio of the total emergy used to the exergy of the considered products. It accounts for the chain of convergent processes.

$$Tr = \frac{Em_{in}}{B_Y} \tag{10}$$

Emergy Sustainability Index ***ESI*** (eq. 11), is an aggregate measure of economic performance and sustainability of the system considering both the contribution of renewable vs. non-renewable resources and the need of feedbacks to drive the process. The performance and the sustainability of the process are therefore evaluated with reference to the global scale of the biosphere (both in its space and time perspectives).

$$\begin{aligned} ESI &= \frac{Em_Y}{Em_F} \cdot \frac{Em_R}{Em_F + Em_N} \\ &= \frac{Em_F + Em_R + Em_N}{Em_F + Em_N} \cdot \frac{Em_R}{Em_F} \end{aligned} \tag{11}$$

3. Setting a Reference

Each indicator previously defined has been handled and reported in a proper scale, to get homogeneous numerical values. In such a way, the same value of different "normalised" indicators supplies equivalent qualitative information about the plant performances; i.e., equal values of different parameters express similar "degrees of effectiveness" related to the corresponding aspects.

The scales, expressed by analytical functions, are defined in order to have a standard range [–1,+1] for each normalised indicator, which is also forced to hold the value 0 when the indicator is equal to its reference value, while –1 corresponds to the worst possible conditions and +1 to the best (see TABLE III). The scales depend on the reference system, identified as the ensemble of these zero values. More than one reference system can be defined, according to the purpose of the analysis.

Let us consider an example (TABLE III):

- current technology of plants and devices;
- average conditions of the present financial market;
- emissions limits taken from the in-force EU regulations (TABLE II).

With these values a direct comparison between classes of plants is established. Policy makers can get valuable information to address strategies, whereas designers may obtain helpful data in selecting plant components, their arrangement and working parameters.

Other reference systems can be considered. It is reasonable that different users will choose different reference systems, depending on the information they need.

If a specific class of energy conversion systems is being studied, it is possible to stress the features of an actual plant by using a particular reference system consisting of average values of the indicators typical for that class. Besides a global assessment of the plant given by the ensemble of indicators, it is possible to focus the attention of the analyst on specific deviations of parameters and look for possible improvements. A policy maker, interested in the future implications due to the introduction of a

[4] All air emission limits are expressed in mg/MJ of output exergy; values are obtained from 1998 EU regulations for plants of new construction (EU Directive, 1988 and 1994) assuming η=0.38 as reference value for the electricity conversion process.

[5] Emergy accounting theory is aimed at evaluating the environmental support required by the system. Emergy is, by definition, the amount of available energy (exergy) of one kind (usually, solar) that is (and was) directly and indirectly required to make something; it is expressed in (solar) emjoules (abbreviated sej). Emergy is a measure of the global past and present processes required to produce something in units of a given energy form, Odum (1995). Thus, emergy represents a new and different concept of energy quality.

particular type of plant in an existing context, should consider as reference an "average" old plant which would be replaced by the new ones. On the other hand, plant operators are more concerned with the overall behaviour during the operating period compared to the expected one: in this case the reference system has to be consistent with the design conditions.

TABLE III. INDICATORS AND REFERENCE VALUES USED

Ind.	Wst	Ref	Best
η	0	0.38 Average efficiency for thermal power plants	1
ζ	0	0.38 Average efficiency for thermal power plants	1
ε_{raw}	η	0.38 Average efficiency for thermal power plants	∞
ζ_{pot}	0	0.38 Average efficiency for thermal power plants	1
Tr	∞	$1.50\ 10^5$ Reference transformity for electrical energy	0
ESI	0	1 No benefit to society is obtained	∞
EF_{air}	∞	1 Emissions in compliance with regulations	0
EF_{water}	∞	1 Emissions in compliance with regulations	0
IP	0	1 No economic profit is obtained	∞
IRR	0	0.06 Average value in financial market	∞
c	∞	14.3 €/GJ 1998 average estimated Italian production price of electricity	0
f	0 - 1	0.5 This scale is valid only for plants running on fossil fuels	0.5

4. Graphical Representation

A graphical representation of the indicators allows the analyst to formulate an immediate and intuitive judgement on the plant behaviour from every viewpoint.

This representation (*Figure 2*) consists of a pie-shaped chart with radial axes, one for each indicator. In this way all the results of the analysis are visualised simultaneously, properly grouped for each aspect. With this structure it is easy to check graphically the best (outer circle), the worst (inner circle) and the reference conditions (middle circle) and, by looking at the line connecting the values of all the indicators, the global behaviour of the plant can be quickly verified.

5. Examples of Application

An application of the model to some actual energy conversion plants (whose main features are reported in TABLE IV) is presented here.

TABLE IV. ENERGY SYSTEMS EVALUATED

Type, location and main features
Thermal power - Porto Tolle, Italy 4 x 660 MW sections running on oil, super-critical steam cycle. Condenser cooled with seawater. NO_X and SO_2 abatement systems not yet installed at the time of investigation.
Co-Generative - Turin, Italy 1 extraction-condensation steam turbine (136 MWe) running on natural gas; 1 gas turbine (35 MWe) with heat recuperator to power a district heating system
Geo- Thermal Power - Tuscany, Italy Standard section (20 MWe) based on a geo-thermal system mostly consisting of superheated water. The plant has cooling towers and a system for cold gases re-injection.
Gas-Steam Combined - Verona, Italy Gas turbine (topping, 21 MWe) coupled with a co-generative steam turbine (8.5 MWe) by means of a recovery boiler. The system also includes a district heating system.
Hydroelectric - Castrocucco, Italy 2 Pelton turbines on vertical axis (45 MWe each). The related water system holds a natural productiveness of 140 GWh on a yearly basis

Results are shown in *Figure 2* and lead to some observations according to each viewpoint. Even if separate information are already well known, in this paper the attention is paid to the understanding of the relative importance and the mutual influence of performances.

The high energy and exergy efficiencies (in a wide sense) for the hydroelectric plant are concerned with a conversion process where input and output energy have the same quality in exergy terms. ε_{raw} shows the convenience in using a renewable form of energy as primary input (hydro and geo-thermal). For the plants powered by fossil fuels, i_S and ε are useful to evaluate the fuel exploitation, which is particularly good in combined cycles and co-generative plants.

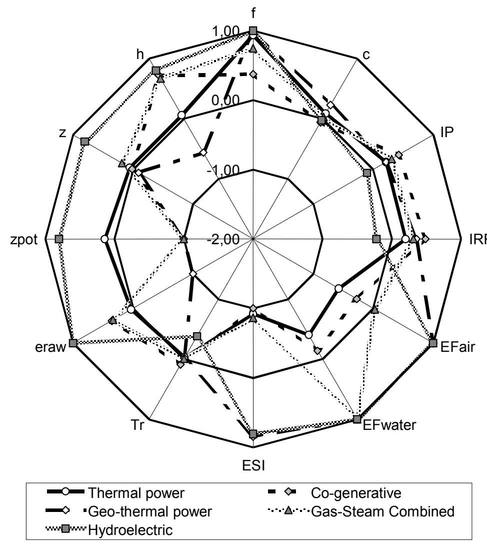

Figure 2. Graphic representation of the results for the case studies

Because of the production of more than one useful outputs, combined and co-generative plants are attractive from the economic point of view. The thermal power plant is penalised by the large number of facilities typical of an oil plant, more complex and expensive than in a gas fuelled plant. Concerning the hydroelectric plant, even if generalisation about investment cost is almost impossible since every site involves different civil and hydraulic works, some considerations are worthwhile. The economic analysis is not favourable mainly because the real construction time for the plant at hand was much longer than estimated and so were the costs.

The exergoeconomic factor f shows the convenience of recent and advanced plants, like combined and thermal power (the considered co-generative plant is rather old). This parameter is not very significant for the hydroelectric and geo thermal power plants.

Considering the emission of pollutants, it is evident that the hydro plant is the most favourable. Also the geo- thermal power has a good behaviour but it must be observed that the air quality indicator does not evaluate some polluting substances, peculiar for this class: other specific parameters should be considered. Plants running on natural gas have reduced emissions among the combustion plants; but the emergy analysis shows low sustainability (even lower than that of the oil plant), probably because a large amount of non-renewable resources and imported resources are used

Moreover, emergy analysis shows that the natural resources involved in the hydro plant are relevant (greater than in the geo-thermal plant).

In evaluating the indicators, according to each theory, some considerations, based on the previous analysis, can be employed. Several studies have been carried out about the importance of operation compared to construction and decommissioning phases; Riva et al. (1998) showed that, when fossil fuels are used, the influence, in economic terms, of environmental pollution during the operation process is far greater than that due to decommissioning. Brown et al. (1998) came to analogous conclusion using the emergy analysis showing that the operating phase heavily affects sustainability of power plants running on fossil fuels and, in general, the importance of the construction emergy input is inversely proportional to the concentration of emergy in the supporting emergy flow.

This paper stressed the importance of using several indicators of performance to provide clear and easy-to-understand key information. Nevertheless, a *global parameter* γ of the overall plant performances may be calculated by averaging the normalised values of the indicators. However, because of the relevant simplification implied by this operation, the information obtained might be misleading.

TABLE V. EVALUATION OF A GLOBAL PARAMETER γ: AN EXAMPLE

Plant type	Average	Stressed parameters		
		Environment	Economy	Energy
Thermal power	-0.017	-0.133	0.078	0.005
Co-generative	0.088	-0.017	0.142	0.138
Geothermal	0.401	0.478	0.413	0.312
Combined	0.247	0.195	0.273	0.275
Hydroelectric	0.540	0.556	0.445	0.617

When some priorities have to be explained, a “scale of relevance” for each indicator, or for a group of indicators, could also be supposed, thus leading to a weighted sum. By assigning double counting value to the stressed parameters, several examples of weighted average are proposed in TABLE V.

Although the hydroelectric plant generally has good behaviour, its convenience decreases when economic issues are stressed. Geo-thermal power, co-generative and combined plants are generally convenient when economic results have great importance.

6. Conclusions

A method for an effective evaluation of energy conversion plants, considering the energetic, environmental and economic aspects, has been proposed. The assessment of energetic performances, environmental impact and economic cost can be obtained by means of suitable indicators, each one emphasising a specific aspect, or taking into account the overall behaviour, as a matching of all the previous parameters. The indicators selected by the authors are taken from well-known methods or defined in the paper and are able to supply different quality or degree of information. A proper combination of all the indicators and their visual representation in a circular chart helps the policy maker address his/her choices, the engineer improve the design, the plant manager or operator perform the operation of a plant correctly.

No method allows automatic plant optimisation: in the authors' opinion, trials to obtain this result may not be successful, because too many constraints and variables are involved in the choice of a plant, in the design and arrangement of its components, in the selection of its operation modes. The method suggested here can help find a good compromise among different requirements, remembering that the "best absolute solution" of this problem, probably, does not exist.

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Nomenclature

Roman Characters

c_F	Fuel cost per exergy unit, €/J
i	Discount rate
B	Exergy, W
E	Energy, W
Em	Emergy, semJ
F	Fuel exergy, W
I	Exergy losses, W
I_o	Capital cost, €
L_i	Emission limit
NPV	Net Present Value, €
P	Exergy of delivered products, W
S_i	Emission level
Z	Rate of levelized capital and O&M cost, €/s

Greek characters

η	Energetic efficiency
ζ	Exergetic efficiency
€	Euro
Π_F	Fuel cost, €/s

Subscripts

i	i-th pollutant substance
in	Input
n	Delivered products
out	Output
raw	Raw, non renewable energy (exergy)
t	Non-used products
F	Feedback
N	Non-renewable
R	Renewable
Y	Yield

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