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An integrated assessment of energy conversion processes by means of thermodynamic, economic and environmental parameters

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Abstract

A comprehensive method of analysis based on energetic, exergetic, emergetic and economic evaluations is proposed in the paper and the application presented. The method is applied to selected energy conversion processes (hydroelectric and thermoelectric ones and bioethanol production). Results are presented and compared while general considerations about the effectiveness of the different approaches are suggested. Emissions to the environment are also evaluated. Suitable performance indicators developed within the proposed methodological framework are defined and discussed accordingly.

The method proposed here is addressed to policy makers, operators and designers working in the field of energy supply and conversion. In the authors' opinion, by jointly applying and comparing all of the methods suggested in the paper, valuable information about plant performance and possible areas of improvement are obtained. This can be helpful in the decision-making process.

1. Introduction

Energy-related problems are likely to become more and more important in the forthcoming millennium. The increasing energy demand from emerging economies versus the day-by-day decreasing

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Nomenclature

Roman characters

i	Discount rate
c_F	Fuel cost per exergy unit (€/J)
B	Exergy (J)
B_F	Exergy of the fuel (J)
DCF	Discounted cash flow (€)
DDGS	Distillers dried grains with soluble
E	Energy (J)
ELR	Emergy loading ratio
EYR	Emergy yield ratio
Em	Emergy (seJ)
I	Exergy losses (J)
Inv	Capital investment (€)
L	Emission limit of the jth pollutant
NO_x	Nitrogen oxides
NPW	Net present worth
s	Environmental factor
S	Emission level of the jth pollutant
SO_2	Sulphur dioxide
Z	Rate of levelized capital and O&M cost (€/s)

Subscripts

i	jth Pollutant substance
in	Input
n	Life of the investment (yr)
out	Output
raw	Raw, non-renewable energy (exergy)
t	Delivered products
w	Non-used outputs
F	Feedback
N	Non-renewable
R	Renewable
Y	Yield

storages of energy resources, the rising cost of fossil fuels and the considerable environmental impact connected with their exploitation are implications that policy makers cannot any further disregard.

These problems involve major aspects: the energetic concern about a more rational use of resources, the environmental impact due to the emission of pollutants, the use of non-renewable resources, the inter-generation equity and finally the economic issues related to both investment decisions and political actions (taxes, incentives, etc.).

The complexity of the problems that should be taken into account when evaluating energy systems within societal and environmental dynamics suggests the combined and integrated use of several methods, each one addressing specific aspects and providing only one piece of the whole mosaic. Additionally, since explicit relations between different aspects of the same process are very hard (if not impossible) to find, useful indications about system behaviour can be obtained by comparing empirical and calculated parameters and indices supplied by different but complementary techniques.

Several methods have been suggested to perform analyses of energy conversion systems and supply information from different viewpoints. In the area of energy investigations, especially worth mentioning are the *Life cycle assessment (LCA) method* [18], its exergetic version *ExLCA* [4], the *thermoeconomic theory* [5,8,9,16], further extended to include environmental implications [1], the *cumulative exergy cost accounting (CExC)* [14], the *extended exergy accounting (EEA)* [13], the *environomic theory* [19] and the *emergy accounting* [11].

Except for the LCA method, rather popular in several industrial circles but unable to characterize the quality of energy according to second law balances, and the classic Thermoeconomic theory, both not aimed at evaluating the process demand for environmental support, very few examples of application of the other methods have been published, due to the relatively recent introduction of most of them.

In this paper, an effective tool for evaluating the performance of energy conversion processes from different points of view is presented and a set of suitable indicators is proposed for a multicriteria assessment. The parameters are carefully selected and normalized to facilitate the interpretation of results. Several approaches already in use for energetic, economic and the environmental analyses are considered, in order to show the value added by their joint use and the comparison of performance. Anyhow, the authors recognize that distinct methods (exergetic analysis, emergy accounting, etc.) have further areas of application in addition to those considered here. An original graphic representation is also proposed as a synthetic and integrated tool to visualize the complexity of system behaviour and its key aspects.

As the indicators evaluate overall performances, the system might be considered as a black box. In this way, plant components do not need to be described in detail, and the computational effort is reduced; in addition, the data needed to calculate the proposed indicators are normally available as design or working data, as needed.

2. Goals and boundary definitions. Spatial and time scales

According to the goals of the investigators and the specific task that each approach is able to accomplish, accurate drawing of the boundary of the investigated system is required. Space and time scale definitions are crucial for the correct application of each approach and the reliability of results.

The first step of any evaluation (energetic, economic and environmental) is therefore a clear identification of the space-time window of interest (see Fig. 1). While the spatial scale is related to the choice of boundaries, the time scale is also related to the nature of inputs and the actual goals of the investigation (for instance, assessing short term and long term sustainability). Some approaches focus on the process (and the process details) while others concentrate on the relation between the plant and the ecosystem in which the process takes place.

In short, when the purpose of the evaluation is to minimize the amount of input (energy, material or money) required per unit output, a system boundary might well be its physical borders. When

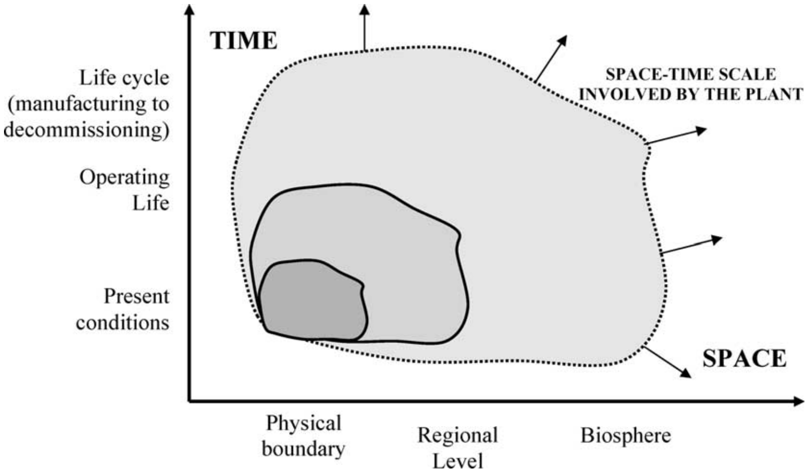

Fig. 1. Boundary definitions.

optimization and allocation of resources have to be evaluated according to diverse criteria than minimization, the boundary might be expanded to the local/regional scale in order to include the chain of processes or the market mechanisms. Embodied energy analysis, economic analysis, LCAs and other exergy-based approaches perform very well in this context. Finally, other approaches, such as the emergy accounting, address concerns that go beyond the process and regional scales and try to assess the dynamics of the environmental support to the system considering the larger scale of the biosphere (e.g. generation and supply of resources and uptake of pollutants).

The different, clearly stated or implicit, assumptions at the basis of the different approaches make them capable to perform different tasks and answer to different kinds of questions related to the goals of the analyst. These assumptions are described in the reference papers indicated above for each method. Some of these specific aspects have also been addressed in a companion paper [6], while others are presented below.

Policy and industrial decision-makers at all levels may need to know a system performance and sustainability under many complementary points of view. In so doing, short time and long time, small scale and large scale consequences of policy decisions can be fully assessed, trade-offs evaluated and strategy choices be taken accordingly.

3. Details of the ‘3E’s’ (energetic, economic, environmental) approach

In order to have a proper comparison between plants or any other kind of conversion systems, an important step is the correct identification of the boundary conditions and the elements included in the system. This allows a careful accounting of matter and energy flows, over a time window previously selected to make sure that the process is correctly described and all significant flows have been taken into account, no matter they are recognized useful or not by the user. This means looking at input and output flows of matter and energy, under the point of view of the general laws of conservation.

Once flows to and from the system are carefully described, their energetic, economic and environmental quality can be described by means of suitable intensity indicators (cost, efficiency, transformities, etc.) capable of addressing the goals of each approach and the concerns of the investigator, as explained further.

Energy evaluations shed light on the interactions among the system and the flows interacting with the system; the proposed indicators provide an overall picture of how resources are exploited, taking also into account specific properties of these flows (e.g. *quality* to the user, by means of the exergy content, and *nature*, renewable and non-renewable).

The economic assessment provides information on how the economic resources (investments, fuels, human resources, etc.) are used in generating (i) profits for the plant shareholders and (ii) benefits for the overall society. The first assessment investigates the plant operation with respect to the market context by means of a microeconomic evaluation, in particular using methods based on the analysis of the net present worth (NPW). The second assessment looks at the benefits for the overall society involved by the products and might be performed through a macroeconomic evaluation [6]. However, the latter approach is not addressed in this paper.

Similarly, the environmental aspects should be investigated considering the environment both as a source of resources or a sink for the polluting by-products associated with the production process. The investigation of the first aspect was very often limited to the current availability of raw materials and energy, with no attention for the dynamics of resource generation and quality. Though, the emergy approach proposed in this paper is intended to explore the convergence of natural support into resource creation and storage, in order to provide a more comprehensive picture than the simple availability of resources. The second aspect, environment as a sink, looks at the environmental performance of a system by taking into account the emissions of by-products (mainly in air and water[2]) required to provide the main products. The latter is strictly linked to the process configuration and the plant arrangement and has historically been given huge attention by both industry and policy makers.

Within the described framework, several key indicators have been selected or developed in order to account for relevant performances in a quantitative way. They are shortly described in the following paragraphs, while equations are given in Table 1:

- *First Law efficiency* η (Table 1, eq. (1)), which evaluates how the energy content of input resources (both renewable and non-renewable) is exploited using first law balances.
- *Raw energy conversion coefficient*, $\varepsilon_{\mathrm{raw}}$ (Table 1, eq. (2)), which quantifies the level of utilization of raw resources (non-renewable resources, fossil fuels). Its numerical value can range between η (no renewable energy used) and $+\infty$ (best use, no raw energy used at all). In comparison with η, $\varepsilon_{\mathrm{raw}}$ highlights how much raw energy can potentially be saved if renewables are substituted for fossil fuels to get the same products.
- *Second Law efficiency*, η_{ex} (Table 1, eq. (3)), which evaluates system performance in converting input exergy (‘fuel’ exergy) into exergy associated with the delivered products.
- *Potential second law efficiency*, η_{pot}, (Table 1, eq. (4)), which assesses the potential additional exergy efficiency deriving from exploiting the outlet flows that exist as streams but are not considered as useful products and effectively used. These products are normally useful only if particular conditions

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[2] Energy conversion plants are typically characterized by relevant environmental emissions to the atmosphere and to water bodies and in some cases impact to soil and groundwater. Also production of waste might be relevant in some cases (nuclear power plant, coal power plant, for example). In this paper only the most typical aspects are dealt with (emission into atmosphere and discharges in water bodies).

Table 1
Formulae for the calculation of indicators

$\eta = \frac{\sum_{j=1}^{t} E_j}{E_{\text{in}}}$	(1)	$c = \frac{Z + c_{\text{F}} \cdot B_{\text{F}}}{\sum_{j=1}^{t} B_j}$	(7)
$\varepsilon_{\text{raw}} \frac{\sum_{j=1}^{t} E_j}{E_{\text{raw}}}$	(2)	$f = \frac{Z}{Z + c_{\text{f}} \cdot I}$	(8)
$\eta_{\text{ex}} = \frac{\sum_{j=1}^{t} B_j}{B_{\text{F}}}$	(3)	$s_{\text{air}} = \max\left(\frac{S_j}{L_j}\right) \quad j \in$ (air polluting substances)	(9)
$\eta_{\text{pot}} = \frac{\sum_{j=1}^{t+w} B_j}{B_{\text{F}}}$	(4)	$s_{\text{water}} = \max\left(\frac{S_j}{L_j}\right) \quad j \in$ (water polluting substances)	(10)
$\text{PI} = 1 + \frac{\text{NPW}}{\text{Inv}} = \frac{\sum_{j=1}^{n} \text{DCF}_j}{\text{Inv}}$	(5)	$\text{Tr} = \frac{\text{Em}_{\text{Y}}}{\sum_{j=1}^{t} B_j}$	(11)
$\text{IRR} = i : (\text{NPW} = 0)$	(6)	$\text{EIS} = \frac{\text{EYR}}{\text{ELR}}$	(12)

occur (consider, for example, the heat released with flue gases when low temperature heat is not needed nearby).

- *Profit index (PI)* (Table 1, eq. (5)), which provides a direct measure of the investment performance by measuring the profit associated with the plant operation at the end of the economic life (NPW) referred to the initial investment.
- *Internal rate of return (IRR)* (Table 1, eq. (6)), which assesses the ability to report profits. It expresses the value of the discount rate at which the investment involves no economic benefit. The greater this value, the more competitive the investment.
- *Cost of products*, c (Table 1, eq. (7)), which determines the efficiency in using the economic resources to get the products. In order to compare different products (heat and electricity for example), the cost is expressed on exergy basis.
- *Exergo-economic factor*, f (Table 1, eq. (8)), which compares the plant capital cost against the cost of the irreversibilities linked with the process. In fact, the latter involves increased amounts of energy and material (and thus increased costs) in order to get the same products, if compared with ideal processes. In principle, the exergo-economic factor f may vary between 0 and 1.
- *Environmental impact factor for air*, s_{air}, (Table 1, eq. (9)) *and for water*, s_{water} (Table 1, eq. (10)), which provide a measure of the environmental performance of the process in releasing polluting substances to get the products [15]. It compares the emission of selected substances or waste flow with an appropriate threshold value (directly referred to the legal limit for emission).
- *Transformity (Tr)*, (Table 1, eq. (11)), which provides a measure of both environmental quality of the product and efficiency of the generation process on the scale of the biosphere, according to the emergy accounting method [11]. It is defined as the ratio of the total emergy input to the total exergy of the outputs.
- *Emergy index of sustainability (EIS)*, (Table 1, eq. (12)), which measures the potential ability of the system in providing the highest benefit (emergy yield ratio (EYR)) to the economy versus the lowest environmental loading (environmental loading ratio (ELR)). It is therefore an aggregate measure of yield and environmental loading, i.e. a sustainability function for a given process (or economy), expressed in emergy terms. Definition, meaning and variability of EYR, ELR and EIS are extensively explained in Brown and Ulgiati [2].

The above set of indicators, based on the combined or integrated use of complementary approaches, may support decision-making on energy conversion and use, providing a transparent assessment of the energy system under consideration and help understanding hidden aspects, relationships and constraints across different spatial and time scales.

3.1. Use of the indicators for the overall evaluation of system performance

For practical evaluations, it is worth comparing system performance with a reference benchmark. Comparisons are done by considering the deviation of each performance indicator from its benchmark value. A global and proper investigation [10] of these deviations, assessed quantitatively, provide the analyst with useful hints to reach a comprehensive judgement on the plant.

To ease the comparison, deviations of all the indicators have been normalized by means of a correspondence scale based upon a set of mathematical equations, that reduce the range of each indicator to a standard one $[-1,+1]$ and associate the number 0 to the benchmark value (see Fig. 2). Correspondence scales are properly defined in such a way that deviations close to benchmark values are emphasized. Different benchmark values can be considered, according to the goals of the investigation.

The choice of the benchmark values can be made according to different criteria: if a specific process configuration is under investigation, an average-in-class plant can be considered as benchmark and it might be possible to identify positive and negative features and infer their influence, even in an empiric way. Additionally, an option is to consider as benchmark the recognized ‘best available techniques’ for a given category of energy conversion systems, in order to assess the global ‘distance’ of the investigated plants from the future requirements and to help prioritize the options to be selected in a short-term future.

To help the analyst interpret the results, a graphic representation is proposed (see Fig. 3), with a radial axis having fixed range devoted to each indicator: the position of the line connecting all the ‘performance points’ provides an assessment of the global behaviour of the system and a rough, even if approximate, integrated picture of it. Indicators are placed on the plot in relation with the three main aspects (energy, economy and environment). The reference system (benchmark) is indicated on the plot by the mid circle. When the system under investigation has a performance similar to that of the reference system, calculated indicators fall near the benchmark circle. External circles mean better behaviour; conversely, internal circles indicate worse performance. One may argue that the sum of the transposed indicators can be a global index on plant performance. Indeed, it might be useful to adopt a weighted sum with an appropriate set of coefficients to emphasize one or more aspects, as requested.

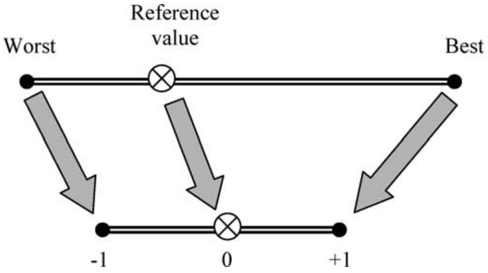

Fig. 2. Construction of the normalized scale.

4. Case studies

Selected case studies have been investigated in order to show how the suggested method can be applied. Their main characteristics are summarized in Table 2. Mass and energy flows to and from each system have been carefully accounted for, their upstream and downstream characteristics and quality factors assessed, and finally the performance indicators listed above have been calculated. In so doing, case studies can be compared on the basis of a set of consistent indicators (Table 3).

The first two plants in Table 2 are very similar except for their power capacity: both are thermoelectric plants, have been built in the late 70s, use seawater for cooling and did not have NO_x and SO_2 abatement systems installed at the time of investigation. The hydroelectric plant started operating in the first 70s after a long period of construction due to technical problems; additional facilities (basin, piping, turbine and buildings) have been considered in the analysis. The ethanol production plant is based on a well-established conversion technology and data are available from the preliminary feasibility study performed prior construction [7]. The evaluation accounts for the industrial conversion of corn to ethanol, with corn production data from Ulgiati [17].

The examples have been conveniently selected in order to discuss the different approaches. The goal of these approaches is to compare plant performances in an integrated way, so that all aspects (efficiency in the use of resources, reduction of environmental impact, etc.) are properly taken into account.

4.1. Comparison of different configurations of plants of the same class

This is the case of the two thermoelectric power plants investigated. When the technologies and the products are the same, (i.e. a choice between competing alternatives is not the main focus of the investigation), local-scale performance can be directly compared and differences pointed out. Specific emissions are also related to the process ability in exploiting the fuel energy. The exergies of the products allow comparison among processes (for instance, pollution levels and production costs per exergy unit of product). Focus is first addressed to the process dynamics within the system boundaries rather than to the relations with the outside. On this scale of the process, theories focussing on larger scales, such as the emergy analysis and the microeconomic evaluation, do not add any significant insight

Table 2
Description of the case studies

Type	Location	Main features
Thermoelectric	Porto Tolle, Italy	4×660 MW power groups, fuelled with fuel oil, super-critical steam cycle. Condenser cooled with seawater. NO_x and SO_2 removal system not yet installed at the time of the investigation
Thermoelectric	Piombino, Italy	4×320 MW power groups, fuelled with fuel oil, sub-critical steam cycle. Condenser cooled with seawater. NO_x and SO_2 removal system not yet installed at the time of the investigation
Hydroelectric	Castrocucco, Italy	Two Pelton turbines on vertical axis (45 MW each). The related water basin system holds a natural productiveness of 140 GW on a yearly basis
Ethanol production plant	Michigan, USA	196×10^6 l/yr of ethanol produced from corn. Dry milling type. Basic fermentation–distillation cycle with final addition of denaturant. Distillers dried grains with soluble (DDGS) is recovered and sold as it is

Table 3
Numerical results from case studies

Indicator	Reference value	Thermo 1	Thermo 2	Hydro	Biomass
η	0.38[a]	0.41	0.38	0.85	0.72
η_{ex}	0.38[a]	0.41	0.38	0.85	0.63
η_{raw}	0.38[a]	0.41	0.38	∞	2.86
η_{pot}	0.38[a]	0.45	0.42	0.85	0.64
Tr	1.50×10^5—electrical energy 5.40×10^4—fossil fuel	1.42×10^5	1.50×10^5	6.68×10^4	1.32×10^5
EIS	1[b]	0.04	0.05	9.48	0.17
s_{water}	1[c]	2.35	2.00	0	6.50
s_{air}	1[c]	3.71	4.42	0	0.97
IRR	0.06[d]	0.09	0.08	0.04	0.11
IP	1[e]	1.54	1.46	0.81	1.61
c	1.43×10^{-8} €/J—electrical energy[f] 3.01×10^{-9} €/J—fossil fuel[f]	1.19×10^{-8}	1.25×10^{-8}	1.50×10^{-8}	5.06×10^{-9}
f	–[g]	0.48	0.49	1	0.45

[a] Average values of the efficiencies for base load power plants.
[b] Value when economic return equates the load on the environment.
[c] Emissions in compliance with in-force regulations.
[d] Average value in financial market.
[e] No economic benefit obtained.
[f] 1998 average Italian prices.
[g] Best value is assumed 0.5 for all plants but hydroelectric, that is 1.Worst value are 0 and 1 (only 0 for the hydroelectric).

and suggestions for process improvement. However, they provide absolute position against the benchmark values and help to understand the position of the system under investigation within the larger frame of the environment and the economy in which the system functions, in order to allow comparison with alternative designs and solutions providing the same product.

4.2. Comparison of different classes of plants or processes

When different classes of plants or processes are compared, new criteria in addition to efficiency in getting the products gain importance and so different indicators are required process-scale indicators (exergy efficiency, exergy based cost, emission factors, etc.) are still be used for comparison of processes that provide different products (electricity and bioethanol) or different processes that provide the same product (hydro and thermoelectric plants), but a deeper understanding of costs and effectiveness requires that support from outside the system is investigated by means of emergy and microeconomic evaluations. In particular, emergy analysis quantifies the environmental support provided to the system and emergy-based indicators take into account the large-scale relationship with the environment as a source of resources and services. According to this, the larger the convergence of environmental services through the system, the larger the environmental support required (i.e. the amount of ecosystem services that are assigned to the process). A product requiring a large environmental support should also have a high intrinsic value and ability to contribute accordingly to the dynamics of the system or economy in which it occurs. Otherwise the product (and the associated process) is very likely to be discontinued.

Therefore, in order to address the choices between competing or alternative energy strategies, large-scale assessments should be the starting point of the decision-making process, while local-scale optimization procedures come later for further improvement of the chosen option.[3]

5. Results

The four industrial plants described in Table 2 (two thermoelectric oil fuelled plants, one hydroelectric plant and one ethanol production plant) have been investigated by means of the methods presented here. Performance indicators have been calculated and results compared to a benchmark (reference values and indicators are reported in Table 3).

For the case studies, benchmark values for energy and exergy indicators are typical of a base load thermal power plant; by using these values, differences between thermoelectric, hydroelectric and biomass classes are stressed. Economic benchmark values are average in economic context while environmental emission factors stand for compliance with regulations.[4] Reference values for transformities are average literature values for the two outputs of the plants under investigation (electricity and fuel). In particular, electricity is referred to different electricity production studies, while the reference value for biomass is that of fossil fuels. Furthermore, it seems reasonable to assume as a reference for the EIS a value equal to 1, i.e. the value where the potential contribution to the surrounding economic system, measured in emergy terms, equates the load on the surrounding environment. Normalized values are plotted in Fig. 3.

6. Discussion

Table 3 offers a synoptic picture of each system performance. Within the conceptual framework adopted in this paper, the individual performance is not very significant itself. Instead, a comparison among systems based on a multiplicity of combined and integrated indicators seems to provide a much more interesting contribution to the understanding of energy conversion and use problems.

6.1. The hydroelectric plant

Based on results (Table 3), small or medium size[5] hydroelectric power plant are generally speaking well-performing systems with high energy and exergy efficiencies (in a broad sense) since they are

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[3] A similar approach was also applied by some of the authors of the present paper in order to develop a method for power plant design improvement [6].

[4] Limits considered for the air emission are EU limits for newly built plants, according to Directive 88/609/EC for the large combustion plants, while water discharge limits are taken from Italian Legislation (Law 152/99). Transposition to the limits set by new and future directives will only cause a shift of the reference value and will not affect the meaning of comparison between plants.

[5] Large hydroelectric plants involving the construction of big dams and the conversion of large areas into water reservoirs are not dealt with in this paper. They involve much bigger problems, among which significant land use change, water diversion from previous economic activities, displacement of local population, and finally water cycle and microclimate alteration. Calculation of their performance parameters requires a special attention to the relationship of the plant with the surrounding environment and results would be very different than those presented by small and medium size hydroplants.

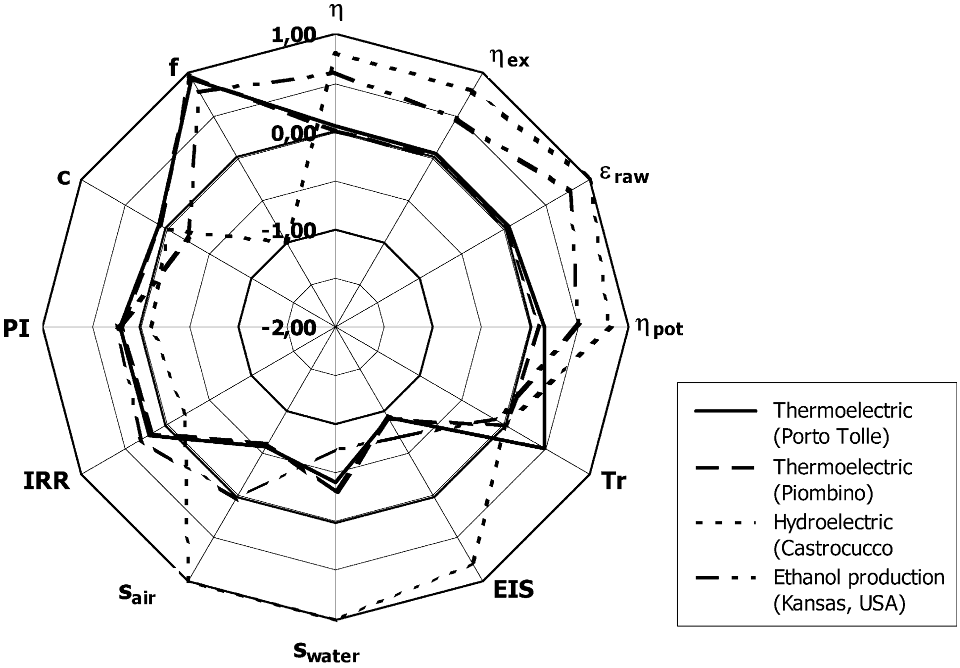

Fig. 3. Amoeba plot of results.

conversion processes where input and output energy have the same quality in exergy terms. During the operating life they do not involve noteworthy emission of pollutants in the atmosphere and quality of discharged waters does not vary significantly, if a careful water management is adopted, required in order not to alter the flow of sediments through the watershed. The exergoeconomic factor is not very meaningful for this class of plants, and in general for all plants involving an almost zero economic cost of the fuel.

The economic analysis of the hydroplant under investigation is not favourable because the real construction time for the plant was much longer than estimated and so were the costs. Even if generalization about investment costs is almost impossible, since every site involves different and specific civil and hydraulic works, usually these plants involves high investment and so they need longer time to be economically competitive, since they show little operating cost.

Finally, the emergy analysis gives a very low transformity for the electricity (6.68×10^4 seJ/J) and a high value of the EIS = 9.5. The EIS of the investigated hydroplant is really good, indicating that this process can provide a large contribution to the surrounding economy and the final user, without generating any significant excess load on the environment.

6.2. The thermoelectric plants

The two thermoelectric plants have similar behaviour and the plotted lines in Fig. 3 overlap significantly. Anyhow, the choice of a super-critical steam cycle (Porto Tolle plant) has several benefits which cannot be appreciated on the plot but can be verified in Table 3. First of all, a more efficient use of energy, expressed by the first law, exergetic and raw energy efficiencies, involves non-negligible energy saving and results also in lower fuel costs and less pollution to get the same amount of products. Since auxiliary structures and personnel mainly depend upon the number of power groups, scale factor further supports this kind of plants.

Though, all the energetic parameters (efficiencies) for the thermoelectric plants investigated are lower than those of the hydroelectric power plant, because of the different type of conversion process (chemical to electrical energy). In addition, they have significantly larger emissions of pollutants per unit product, since their driving force is the combustion of relatively low quality fossil fuels, very often containing significant amounts of sulphur. The Porto Tolle plant shows lower air emissions but greater discharges on the water (s_{water}).

As far as the economic point of view is concerned, thermoelectric plants are by no means viable options. The exergoeconomic factors of both the plants are very close to the best value which is intended to be 0.5, thus showing a fair compromise between capital and costs associated with irreversibilities. Well-designed plants will have f higher than 0 and lower than 1, approximately close to the average value of the interval (0,5): in the first case (f close to 0), expensive irreversibilities might suggest the use of more efficient components or different plant arrangements, in the second (f close to 1), cheaper plants might be convenient despite the reduced efficiency, because the cost of irreversibilities is not very relevant. A careful study of f may be useful to infer which political initiative is recommended. If f is close to 1 (high investment associated), financial incentives or fiscal allowances on the capital costs are suggested, whereas, when f approaches 0, penalization on fuels should be given, thus forcing for more efficient plants. In the authors' opinion, the comparison of the values of f for plants of the same class supplies effective information.

The economic implication of better first Law and second Law efficiencies in the Porto Tolle plant is expressed by the lower production cost while the slight difference of the exergoeconomic factor shows that Piombino is affected by higher irreversibility associated cost than Porto Tolle.

Emergy data show a substantially similar performance of the two thermal plants, as expressed by the transformities of the electricity produced as well as by their EIS. These indicators show that thermoelectric plants have global-scale conversion efficiency lower than that of the hydroplant (the higher the transformity, the lower the efficiency of the conversion of environmental resources into the final product). Similarly, the index of sustainability (EIS) of thermoelectric plants is very low, not only because they rely on non-renewable resources, but also because these are not locally available and must be imported.

6.3. The corn-to-bioethanol conversion

With regard to the biomass conversion process, the difference between first Law and exergetic efficiencies can be ascribed to the divergence between the calorific value and the exergy content of biomass. The value of $\varepsilon_{\mathrm{raw}}$ is lower than it could be expected by considering the fact that corn, a 'renewable' substrate, is the main input; indeed, corn is no longer a renewable input, as most of the energy in corn is being supported by non-renewable goods, fuels, and services. The low efficiency also depends upon the relatively large amount of fossil fuels (in terms of input energy) required in the cooking phase of the process (25% of the input energy which is supplied by fossil fuels).

When comparing ethanol production plant with other plants, it must be underlined that ethanol itself is an intermediate product for the production of highly valuable forms of energy (e.g. power in car engines) and in particular it is different from the energy form provided by thermoelectric and hydroelectric plants. For example, it could be used in a combustion process to produce electricity and results would change substantially. For this reason the process parameters for this plant are more properly compared to those typical of a fossil fuel.

Water and air emissions of the plant producing ethanol are relatively low. However, it should be pointed out that related activities (corn production and biofuel combustion in combustion engines) usually release additional and non-negligible pollutants. The transformity of ethanol (1.32×10^5 seJ/J) is quite high if compared to that of a fossil fuel (5.4×10^4 seJ/J). This result is not surprising if we consider that bioethanol production is driven by a large amount of non-renewable inputs (fertilizers, fuel, machinery). The transformity thus suggests that bioethanol is not a renewable resource. As a consequence, the EIS of bioethanol production is only slightly higher than that of thermal electricity. In fact, this indicator is in general higher when local or renewable inputs are used (e.g. hydroelectricity) and decreases with increasing use of imported or non-renewable flows (e.g. oil to thermal plants as well as fossil-based fertilizers and fuels to industrialized agriculture and bioethanol conversion). Conversion of biomass to ethanol in order to burn it as a substitute of fossil fuels clearly appears to be a misuse. Finally, the low values of the economic parameters for this process suggest that the plant should be improved either by reducing inefficiencies or by reducing fuel costs.

7. Additional considerations

The information provided by the proposed procedure is not only useful to assess a plant or process performance, but also to shed light on the complex interactions among thermodynamic parameters, economic costs, and environmental emissions, that, in many cases, are almost impossible to be determined analytically. By evaluating the performances of the plant (as monitored by indicators) in different selected scenarios, some empirical correlations can be drawn. If, for example, different alternatives for controlling air emission are evaluated, the resulting environmental benefits are judged against the additional cost of production, the investments required, the reduction of energetic efficiencies, etc. Evaluation of several scenarios will provide enough data for establishing correlations between the parameters.

Additionally the method can be used to carry out sensitivity analyses, in order to investigate how much the performance indicators (which track the overall behaviour of the plant) change as a result of variations of some internal parameters within an appropriate range, under sensitivity criteria. In fact one of the main concerns for policy makers is to evaluate how their choices will be effective considering the future behaviour of some parameters (in light of the expected variations). For example, variations of fuel cost might be so important as to determine a transition of technology of power plants aiming at a decreased use of such expensive commodity.

Time window is crucial in this kind of analysis. Evaluation should consider manufacturing of equipment, production process and decommissioning (i.e. the complete life cycle of the plant). Many studies have been conducted about the influence of manufacturing and decommissioning on the global process. When fossil fuels are used, Riva and Trebeschi [12] noted that, in economic terms, environmental pollution during operation process is far greater than pollution generated during decommissioning. On the other hand, Brown and Ulgiati [3] came to analogous conclusion using the emergy analysis: by accounting for all the energy directly and indirectly used in supporting commodities, the conclusion was stated even stronger. Results showed that the operating phase heavily affects the sustainability of power plants running on fossil fuels. The same approach applied to plants powered by renewable sources like wind, hydro and solar photovoltaics showed the importance of the construction emergy input (i.e. the solar emergy supporting machinery and services) to be inversely proportional to the concentration of solar emergy in the supporting emergy flow. This clearly indicates that the higher the transformity of energy flows driving the process, the higher the advantage provided by strategies aimed at optimizing their use, as compared with construction flows. These strategies might well be implemented by the use of exergetic and exergoeconomic tools at process scale.

8. Conclusions

The approach presented in this paper, based upon integration of several methods for the analysis of energy conversion processes, leads to a better understanding of the thermodynamic, economic and environmental performance of energy conversion process. Its use for energy and resource use planning may support strategies for resource conservation and better matching of use versus resource quality.

The approach allows for evaluating different process aspects and examining distinct scenarios. In so doing a more comprehensive and global view is achieved on the larger scale, even without losing track of process details on the plant scale.

The value of the integrated approach does not only rely on the fact that it offers a comparison among results of several methods, but more on its ability of providing further ‘added value’ such as the possibility of drawing scenarios of future changes of the set of indicators, following changes in some of the environmental or process conditions. In the absence of analytical relationship among performance parameters, the empirical view offered by the integrated set of these parameters is a step towards reliable assumptions about the future behaviour of the system.

Space and time scales are of crucial importance in the evaluation of complex and dynamic interactions like those involved in the equilibrium between human made systems and the environment. It is therefore also very important to build decision-making tools capable of supporting multi-scale policies and strategies for resource use.

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