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Methods

The Four-Sector Diagram of Benefits (FSDOB) as a method for evaluating strategic interactions between humans and the environment
The case study of hydrogen fuel cell buses

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ABSTRACT

In this paper we propose to adopt a new multi-criteria methodology, termed as the Four Sector Diagram of Benefits (FSDOB), to evaluate potential benefits generated by new energy options. This method allows us to account for a multiplicity of economic, social and environmental indicators, but especially for a particular form of benefits, termed as Ordinal Benefits. These Benefits can never be reduced to a monetary value, nonetheless they can be estimated in Emergy terms, albeit such estimations only represent simple "ciphers" of their real values. On the basis of the FSDOB Method we evaluate all the various forms of benefits provided by the introduction of hydrogen fuel cell buses.

The case-study shows that our benefit-oriented approach tends to favor the adoption of environment-friendly technologies, as a consequence of the huge amount of social and environmental benefits they provide. The same solutions would result as non profitable from a traditional financial point of view. In such a perspective, they would never be realized, by loosing, in actual fact, the opportunity of taking advantage of all the associated benefits.

1. Introduction

Strategic choices concerning investments in new technologies are traditionally made by mainly considering their financial return. This only offer a partial contribution to the analysis of potential benefits provided by the introduction of environment-friendly technologies. Interactions between human activities and the environment are usually neglected, partly because estimating external effects (created by a project or program) is not a clear-cut issue. The main methodological difficulties are related to the need of a precise quantification of damages to the environment and their corresponding economic values, which are not reflected by market prices (EEA, 2008).

The design and operation of new energetic sources require the evaluation of several complex aspects involving also their ecological and social performance. Recent developments have pointed out the need for new investment decisions of "comprehensively considering" ecological, societal, technical and economic factors simultaneously (Bardouille and Koubsky, 2000). This suggests a multi-criteria analysis combining indicators from different disciplines. Such an approach seems to be the most appropriate framework to account for a multiplicity of elements and a variety of stakeholders (Pohekar and Ramachandran, 2004; Polatidis and Haralambopoulos, 2005). In this respect an accurate inclusion of environmental and social impact indicators, along with other relevant aspects of energy schemes (namely their economic profitability, the availability of the resource used, etc.) can help in supporting the introduction of new energy solutions and their acceptability.

This paper adopts a multi-criteria approach and proposes a new methodology, termed as the Four Sector Diagram of Benefits (hereafter FSDOB), allowing us to simultaneously account for a variety of indicators developed in several disciplines. The basic advantage of this method is related to the possibility of decomposing the overall impact of a new investment on the four main actors involved. At the same time, it offers the opportunity of accounting for *Ordinal Benefits*, i.e. those Benefits which are never reducible to a monetary value (and thus, from now on, they will be referred to with a capital B). Nonetheless they can always be estimated, still in economic terms, by means of values understood as "a cipher". Through a simulation tool, the Code POLIDEMACO,[1] the FSDOB Method is implemented in order to summarize the information provided by several indicators and to graphically display the results.

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Table 1
List of the adopted indicators (I_{ij}) divided by Sectors.

Sector 1	$I_{11}=$ Plant cost per unit power (€/kW)	$I_{21}=$ Energy efficiency (%)
Benefits for the firm	$I_{12}=$ Fuel cost per unit product (€/kWhex)	$I_{22}=$ Exergy efficiency (%)
	$I_{13}=$ Labor cost per unit product (€/kWhex)	$I_{23}=$ Raw energy conversion coefficient (%)
	$I_{14}=$ Maintenance cost per unit product (€/kWhex)	$I_{24}=$ Transformity of the product (seJ/(J kg))
	$I_{15}=$ Cost of NO_x uptake device (€/kWhex)	$I_{25}=$ Profit index (%)
Sector 2	$I_{31}=$ Total heat supplied release (kg/MWh)	$I_{41}=$ Global warming (CO_2 release) (kg/MWh)
Benefits for the environment as a “sink”	$I_{32}=$ Cost of CO_2 sequestration and storage (€/ton)	$I_{42}=$ CO_2 emission costs at local level (€/kWh)
	$I_{33}=$ Cost of NO_x uptake (€/ton)	$I_{43}=$ CO_2 emission costs at global level (€/kWh)
	$I_{34}=$ Reuse of uptaken materials (%)	$I_{44}=$ NO_x emission costs (acidification) (€/kWh)
	$I_{35}=$ Fraction of recycle after decommissioning (%)	$I_{45}=$ NO_x emission costs (via ozone) (€/kWh)
Sector 3	$I_{51}=\sum_{k=1}^{4}()_k$ (economic benefit per unit invest.)	$I_{61}=\pi_4/\pi_2$ (benefit to economy/product cost)
Benefits for the society	$I_{52}=$ EYR* (process economic amplification)	$I_{62}=\pi_5/\pi_2$ (feedback benefits/product cost)
	$I_{53}=Tr_{pd}/Tr_{pc}$ (product benefit per type of process)	$I_{63}=\pi_6/\pi_2$ (I_{62} at net of local damages)
	$I_{54}=(F'\cdot EYR_f-Inv)/Inv$	$I_{64}=\pi_8/\pi_2$ (I_{63} at net of global damages)
	$I_{55}=\pi_1/\pi_2$ (firm/citizen financial sustainability)	$I_{65}=\pi_8/\pi_2$(I_{64} at net of resource consumption)
Sector 4	$I_{71}=$ ELR (Environmental Loading Ratio)	$I_{81}=$ Emergy density (seJ/m^2)
Benefits for the environment as a “source”	$I_{72}=$ EIS (Emergy Index of Sustainability)	$I_{82}=$ Non-renewable emergy/total emergy
	$I_{73}=$ Decrease of biodiversity (%)	$I_{83}=$ Material intensity, water factor (g/kWh)
	$I_{74}=$ Area supporting the process (m^2/MW)	$I_{84}=$ Material intensity, abiotic factor (g/kWh)
	$I_{75}=$ Actual NO_x emission/law emission limit	$I_{85}=$ Fraction of imported fuel (%)

Note: for each indicator, i represents the generic axis of the diagram, for $i=1$ to 8; j indicates the sequential order of the indicator on a given axis (i), for $j=1$ to 5.

As a case study, the potential introduction of hydrogen fuel cell buses in the public transport system of Rome is evaluated.

The low profitability of investments during the early stages of hydrogen buses introduction tends to discourage their adoption (as for other environment-friendly technologies). The costs of currently used alternative fuels are significantly lower also because they do not reflect either their environmental impact or the thermodynamic value of natural resources for their generation. At the same time, environmental benefits of clean technologies cannot be captured as income by investors.

The competitiveness of hydrogen buses could clearly be increased by considering a financial support by the State. Point is that monetary incentives needed in order to decrease the financial burden for firms and consumers are very high and can only be justified by the wide range of benefits the investment provides. This paper aims at showing that hydrogen technologies can be considered as immediately competitive with respect to conventional solutions, if an adequate policy action is taken in order to financially support their economic costs. Financial incentives are widely compensated by additional (Ordinal) Benefits, generally not accounted by traditional analyses.

2. The Four Sector Diagram of Benefits

When alternative technologies are compared, financial evaluations related to capital profitability and operational costs tend to prevail. Consequently traditional energetic systems continue to be preferred despite their environmental impact. The methodology here proposed is able to quantify both economic performance and social and environmental advantages provided by new technological options.

The method considers the main four actors (identified as “Sectors”) usually involved in any productive process. These are synthetically termed as the Firm, the Society and the Environment, where the latter is seen both as a Source of material inputs and a Sink for by-products of the production process. The method also accounts for the different kinds of benefits produced by the interactions between each sector and the others.

Benefits and costs pertaining to each actor are graphically represented on a diagram. The sectors are symmetrically set with respect to the center (see Figs. 2 and 3), which ideally corresponds to a Decision Maker evaluating the new technology. The Decision Maker compares the net benefits gained by each actor and balances different needs and interests, often in an irreducible contrast between each other. Each sector is identified by two axes which represent its fundamental input/output properties respectively.

Each axis can be characterized by a variable number of indicators,[2] whose appropriate choice depends on the analyst's goals and the characteristics of the investigated system. In this simulation we consider five indicators per axis (listed in Table 1 and defined in Appendix A), specific for each sector.[3] To allow comparisons between heterogeneous indexes, indicators are normalized to specific reference values, determined on the basis of the best available technology for the typology of the system analyzed. This implies that each indicator expresses its best value when equals 1. In this way the positioning of the new technology is made in terms of the relative values representing the “distance” between the innovative and the reference case.

Normalized indicators are also appropriately weighted[4] in order to obtain “performance indexes” which summarize different economic, social and environmental criteria for sustainability assessment. The only condition the specific weights ($w_{ij}^{(k)}$) have to satisfy is that

$$\sum_{j=1}^{n} w_{ij}^{(k)} = 1 \text{ for } i = 1,2,\ldots 8 \text{ and } k = 1,2,\ldots m \tag{1}$$

where $i=$ axis, $n=$ number of selected Indicators, $j=$ sequential order of their corresponding weights, $k=$ sequential order of the system considered. The weighted average of each axis ($\bar{w}_i^{(k)}$) is preliminarily evaluated by assuming that all normalized indicators have the same weights (namely $w_{ij}^{(k)}=1/5=0.20$) as a basic reference level. Since the Decision Maker can adopt a differentiated distribution of weights, the method foresees the evaluation of the maximum (positive and negative) variations ($\Delta\bar{w}_i^{(k)}$) with respect to the previous values, within a predefined margin of confidence.[5] On the basis of the values obtained, performance indexes for each sector can be plotted on the diagram in the form of two concentric circles (see, for instance, Fig. 2). The barycenter of the “circles” represents the average values $\bar{w}_i^{(k)}$, which are assumed to be a fundamental starting

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[2] The simulation code enables us to consider up to fifteen indicators for each axis.

[3] Indicators are derived from a multi-criteria analysis, based on Material Flow Accounting (Hinterberger and Stiller, 1998), Energy analysis, Exergy analysis (Szargut et al., 1988), Thermoeconomic analysis (Valero, 1998), microeconomic evaluations (Giannantoni et al., 2005), environmental impact assessment (environment as a sink) (ib.), Emergy accounting (environment as a source of information and resources) (Odum, 1996), macroeconomic and externality evaluation (Giannantoni et al., 2005).

[4] Such a weighting procedure allows analysts and policy makers to choose the weighting coefficients according to their specific needs or preferences, depending on assumed priorities.

[5] The margin of confidence is defined as the ratio between the maximum and minimum modified weights and it usually equals 500%.

point for evaluating different kind of benefits according to the Method of Barycenters[6] (see Section 6). The inner radius ($\bar{r}_g$), defined as

$$\bar{r}_g = \max\left(\left(\sum_{i=1}^{8} \bar{w}_i^{(k)} / 8\right) \cdot \left(\sum_{i=1}^{8} \Delta \bar{w}_i^{(k)} / 8\right)\right) \ \text{for } k = 1, 2 \tag{2}$$

corresponds to the maximum variation evaluated at a global level, whereas the outer radius ($\bar{r}_l$)

$$\bar{r}_l = \max\left(\bar{w}_i^{(k)} \cdot |\Delta \bar{w}_i^{(k)}|\right) \ (i = 1, 2, ..8;\ k = 1, 2) \tag{3}$$

represents (in the same scale) the maximum variation evaluated at a local level.

3. Typology of Benefits: Cardinal Benefits and Ordinal Benefits

The benefits considered by the method can be distinguished in economic benefits, traditional externalities and Ordinal Benefits.

The first two kinds of benefits are well-known in economic literature. Economic benefits arise from the investment financial return to the firm and the society as a whole. The second typology of benefits corresponds to the traditional concept of externality.[7] Such externalities remain outside the market and thus uncompensated for since, by definition, they are not included in the transaction price. They can be expressed in monetary terms, albeit as proxies. Both economic benefits and externalities can then be evaluated as *cardinal* benefits.

The third typology of benefits is characterized by their intrinsic impossibility of being captured by the traditional economic analysis. These benefits are directly related to those physical processes whose outputs show an unexpected excess with respect to their corresponding inputs. Such processes can then be defined as Generative Processes because, according to the Maximum Emergy Power Principle,[8] they cannot be reduced to mere mechanisms. Co-productions, Inter-actions and Feed-backs are the most important processes. The "unexpected excess" can be termed as Quality (with a capital Q) in order to distinguish it from the traditional concept of quality (with a small q), that is a simple characteristic of a given phenomenon. Quality, vice versa, is any property *emerging* from the considered process never reducible to its phenomenological premises or to our traditional mental categories. Ordinal Benefits[9] are proportional to this high level of Quality, which can be accounted for by means of a completely different physical concept (see Transformity, later on).

While Ordinal Benefits result from Generative Processes, cardinal benefits result from "necessary" (both natural and economic) processes. The main difference between them is that the latter can always be described by physical–economic laws. Like cardinal externalities, Ordinal Benefits remain outside the market but, differently from the former, they can never be reduced to economic values, not even as proxies, precisely because of their intrinsic Ordinal meaning. Any adopted value has accordingly to be understood as a simple "cipher".[10] Ordinal Benefits can be estimated in Emergy terms, since the higher level of Quality of any output can be accounted for by the concept of Transformity.[11] This physical quantity, which is defined on the basis of a non-conservative Algebra termed as Emergy Algebra (Brown and Herendeen, 1996), leads to the definition of the total Emergy of a process as:

$$\text{Emergy} = \text{Energy Quality (Transformity) multiplied by Energy quantity (Exergy)} \tag{4}$$

Transformity (Tr), in turn, can be articulated in two distinct factors:

$$Tr = Tr_{\phi} \cdot Tr_{\text{ex}} \tag{5}$$

where Tr_{ex} (dissipative Transformity) accounts for the (usual) losses of Exergy used up during the production process of a given good or service, whereas Tr_{ϕ} (generative Transformity) accounts for the ever-increasing content of Ordinal Information due to the three fundamental Generative Processes previously mentioned (Giannantoni, 2006a,b). This is why Transformity is always understood in an Ordinal sense, although represented as an algebraic cardinal factor.

Since Ordinal Benefits (induced to the surrounding habitat) are proportional to the Ordinal Information content of any natural product or human artifact, Generative Transformities can be interpreted as a "cipher" of such Benefits.[12]

Ordinal Benefits emerge, in particular, in all the transactions between humans and the environment. To provide an example, let us consider the concept of transaction analyzed by Odum (Odum, 1994: p. 8 and Chapter 23) (see Fig. 1).

Money and goods (exchanged in counter current), when analyzed in Emergy terms, do not reduce their meaning to mere physical–economic concepts. The Emergy associated to any product/service (i) can be written as

$$Em_i = Tr_{\phi,i} \cdot Tr_{ex,i} \cdot Ex_i \tag{6}$$

where $Tr_{\phi,i}$ (generative Transformity) is understood as a cipher of the Ordinality vehicled by a given product/service (see also Eq. (5)).

Consequently any transaction (see Fig. 1b) represents an exchange of different Emergies, both in terms of cardinality and Ordinality. As a consequence of the ever-present disequilibrium between the exchanged Emergies and related Ordinalities, any transaction becomes a true *transactive* interaction only when the two subjects of the transaction operate in consonance with the Maximum Em-Power Principle. In such a case the transaction realizes a reciprocal increase in Ordinality. Ordinal Benefits can then be defined as the excess of Ordinality emerging from a *real* transaction relationship.

In this paper we do not consider either the generative Transformity ($Tr_{\phi,2}$) associated to money (such as, for instance, that pertaining

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[6] The method of Barycenters is an original method of evaluation, first developed in Giannantoni (2009) and here synthetically recalled and applied in Section 6.

[7] According to a basic definition, an externality is present when two conditions hold: "1. whenever some individual's (say A's) utility or production relationships include real (that is, nonmonetary) variables, whose values are chosen by others (persons, corporations, governments) without particular attention to the effects on A's welfare; 2. the decision-maker, whose activity affects other's utility levels or enters their production functions, does not receive (pay) in compensation for this activity an amount equal in value to the resulting benefits (or costs) to others" (Baumol and Oates, 1988; pp. 17–18).

[8] Proposed by H. T. Odum (1994) as the Fourth Thermodynamic Principle, it states that "every system reaches its optimum working conditions when it maximizes the total processed Emergy (including that of its *surrounding habitat*)", (Giannantoni, 2002, p. 40). This Principle refers to those processes mentioned in the text, whose outputs show an unexpected excess. It suggests we can think about a different form of "causality" (at least as a "work hypothesis"), which may be referred to as "generative" since it gives rise to something "extra" with respect to what it is usually foreseen (and expected) by the traditional approach. In this sense we may consequently speak about Generative Processes.

[9] Ordinal Benefits are also capitalized to highlight their direct relationship with this new concept of Quality.

[10] The term "cipher " is here understood (in a gnoseological sense) as any symbol, of a given nature, adopted to represent another entity of a completely different nature.

[11] Transformity is a conversion factor which can be used to "transform" all the units of materials and energy needed to produce a service or commodity into units of solar energy required in its production. Formally, it corresponds to the "ratio of the total emergy used to the energy produced" (Brown and Herendeen, 1996; p. 221).

[12] While the dissipative Transformity Tr_{ex} is defined as $Tr_{\text{ex}} = 1/\theta$, where θ is the generalized Carnot coefficient of the considered process, the generative Transformity Tr_{ϕ} translates, for each process, the corresponding rules of Emergy Algebra. For instance, in a Co-production process, Tr_{ϕ} equals the number of by-products. This simply expresses that the generative activity of the process equals $(n-1)$ times the input Emergy (Giannantoni, 2002, p. 25. Eq. (3.8)).

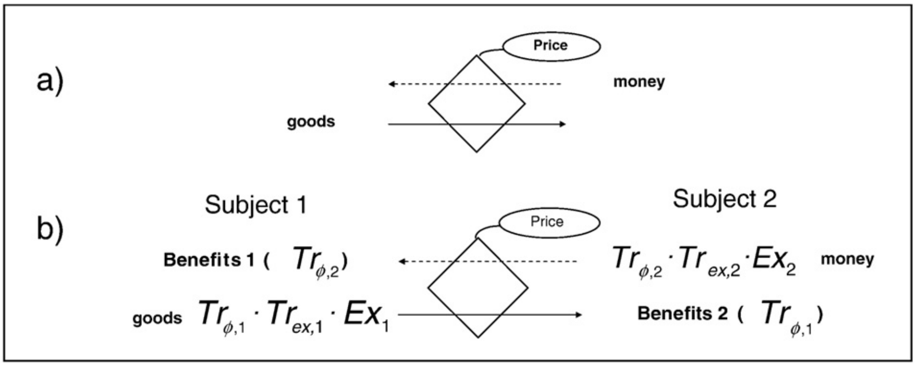

Fig. 1. Ordinal externality understood as an "excess of Ordinality".

to state incentives), or the total energy spent to produce it (represented by $Tr_{ex,2}$ Ex_2). This is because we aim at showing the advantages of the FSDOB method with respect to intrinsic limitations of traditional investment criteria, which systematically neglect not only the thermodynamic value ($Tr_{ex,1}$ Ex_1) of natural resources but especially all Benefits proportional to the generative Transformity $Tr_{\phi,1}$. The FSDOB Method simultaneously accounts for different kinds of cardinal and Ordinal Benefits (hereafter jointly labeled benefits/ Benefits).

4. Ordinal Benefits and Cardinal Benefits in the FSDOB

In the FSDOB the four sectors are strictly related to each other, representing different sub-systems of a whole characterized by a "circulation of benefits" between adjacent sectors. Such an aspect can be highlighted by considering, for instance, the axis termed as "Environmental Impact". This axis offers a double possibility of reading: in terms of damages when it is oriented toward the outside of the diagram and in terms of benefits in the opposite versus. In the latter case, benefits do not only correspond to the mere complementary value of the former.

Damages estimations only call for the minimum investment required to avoid them, since avoiding a damage leaves the system as it is, without any evolution or improvement. Induced benefits on the environment and the society, on the contrary, can be much higher because generating benefits might start a chain of amplifying feedback loops as well as of downstream improvements to other systems or processes, the extent of which cannot be fully anticipated.

The adoption of a "benefit oriented approach" then is much more rewarding. This "positive" interpretation is reflected by a coherent orientation of the axis termed as "Social–economic benefits".

Sector One evaluates the benefits/Benefits that any productive process provides to the firm. The performance indices on the axes reflect the economic assessment of the system, highlighting how the economic resources (investments, fuels, human resources,...) are used in generating profits for the shareholders (see Table 1). All indicators on the horizontal axis refer to operation costs (e.g. the system cost per unit power or the fuel cost per unit product), whereas indicators on the vertical axis account for the efficiency of the system (see Appendix A). Three of them (Energy efficiency, Exergy efficiency, Profit Index) are well-known. The Raw Energy conversion coefficient quantifies the utilization level of non-renewable resources and is related to the amount of raw energy that can potentially be saved if renewable resources replace fossil fuels to produce the same output (Tonon et al., 2006). The indicator termed as Transformity of the product is particularly relevant, providing a measure of both the efficiency of the generation process and the environmental Quality of the product (see the definition of Transformity).

The environmental impact is firstly assessed by considering the environment as a sink for the polluting by-products associated with the production process (Sector Two of the diagram). Indicators in axis three measure the compatibility between the process and the environment from the early phase of design. Indicators of axis four account for traditional negative externalities that are evaluated as proxies of the overall damages created by an economic activity to the environment. Methods that estimate the value of environmental services on the basis of the costs of avoiding damages (due to lost services or the cost of replacing ecosystem services) implicitly assume that expenditures for repairing damages are valid indicators of the benefits provided by the environment. Such costs however usually underestimate the benefits generated by interventions aimed at protecting natural resources (as previously noted).

The majority of the indicators pertaining to Sectors Three and Four are based on Emergy and thus on the concept of Transformity. Such indicators, through the cardinal component of Transformity (Tr_{ex}), account for the rate of natural resources use, their optimum exploitation, the carrying capacity of the environment and the production of wastes and pollutants, all factors which determine the global sustainability of a system. The same indicators, through the Ordinal component of Transformity (Tr_{Φ}), also account for both ecological and economic contribution of different inputs and outputs, explicitly considering the interaction between the system and its environmental habitat. This interaction can be expressed in terms of Ordinal Benefits because it cannot be reduced to traditional externalities. Since such Benefits do not correspond to the simple sum of the initial inputs, they represent an extra-contribution that the environment, as a Donor, gives to human beings.

Sector Three summarizes the benefits/Benefits the system generates for the overall societal assets involved in the process. The first indicator (I_{51}) on the horizontal axis accounts for economic benefits to society (per unit product/investment), whereas the next three indicators express Ordinal Benefits. I_{52}, the Emergy Yield Ratio (i.e. the ratio between emergy output and emergy inputs of the economic system), measures the ability of the process to contribute to economy, by better exploiting local resources for each unit of input used (Brown and Ulgiati, 1997). I_{53} is an indicator of the environmental Quality of the product (generated by the considered process) compared to that of the same product generated by the best production process currently available on the market. In addition, I_{54} points out the economic value of the effects induced by the product through the "feedback chains" of the productive system of the country. The last indicator (I_{55}) calculates the financial sustainability of the system for the society, expressing the repartition of costs between citizens and firm.

All Indicators of axis six have the same structure, i.e. a ratio between economic (either proxies or Ordinal) benefits generated by the process and the specific production cost of the product (π_2). I_{61}

represents the contribution of the product to the GDP of the country (per unit product cost); I_{62} accounts for Ordinal Benefits associated to the Emergy Yield Ratio of the process (net of the initial investment) per unit product cost. I_{63} expresses previous Ordinal Benefits (I_{62}), net of local damages, always evaluated per unit product cost. I_{64} accounts for Ordinal Benefits (I_{63}) net of global damages (per unit product cost), whereas Ordinal Benefits (I_{64}) net of resource consumption (per unit product cost) are measured by I_{65}.

Ordinal Benefits are particularly relevant when assessing the impact of a production process on the environment as a source of resources (Sector Four of the diagram). This aspect is generally investigated by simply looking at the current availability of raw materials and energy, without paying any attention to the dynamics of resource generation and the Quality vehicled and diffused by the same. A more comprehensive picture is provided by indicators I_{71}, I_{72}, I_{81}, I_{82}, which measure the environmental sustainability of an energetic source. The Environmental Loading Ratio (ELR — corresponding to I_{71}) remarks the pressure of an economic activity on natural resources, being the ratio of the emergy provided by the economic system divided by the renewable component of total emergy. I_{72}, the Emergy Index of Sustainability (EIS), provides a measure of the relation between the yield and the environmental loading of the system, whereas the Emergy Density (I_{81}) expresses the emergy investment (flow) per unit of area involved in the process. Finally, I_{82} (the ratio of Non-renewable Emergy divided by Total Emergy) explicitly considers the environmental burden generated by the use of exhaustible resources in the production process. The remaining indicators in Sector Four account for external effects created during the process and evaluated in the traditional sense (see, for instance, the decrease of biodiversity or the material intensity of the system).

On the basis of this structure of benefits/Benefits, the introduction of hydrogen fuel cell city buses is evaluated.

5. A Case-study: The Introduction of Fuel Cell City Buses for Public Transportation

In this Section we explicitly consider all benefits/Benefits potentially generated by the adoption of hydrogen fuel cell buses in the public transport sector of Rome.[13] Since hydrogen technologies are currently not competitive with fossil fuel solutions, we consider the possibility that their introduction is temporarily supported by public financial incentives. To this purpose we firstly analyze the case of buses without public incentives and secondly we model the effects due to an environmentally concerned financial support.

The transport sector has been chosen as a matter of investigation mainly because of the relevance of environmental problems associated with this sector. The introduction of hydrogen fuel cells in vehicles has not only the potential to abate local emissions from fossil fuels use, but also to achieve a drastic reduction of transport-related greenhouse gas emissions. Hydrogen is also a relevant option to be considered in the shift from a transport system based on exhaustible resources to a system relying on renewable energy sources (RES). The public transport sector, in particular, has been considered as a strategic niche to promote the adoption of hydrogen vehicles, especially because high initial costs of fuel cells are less problematic for buses. The transit market in fact is generally subsidized by the State and the amount of financial incentives can be increased if there are considerable societal benefits (Karlstrom, 2005).

The costs of hydrogen vehicles mainly depend on the way hydrogen is used. Hydrogen internal combustion engines imply lower costs, which are expected to rapidly approach those of conventional petrol engines. Fuel cell systems are more expensive, albeit they are more desirable from an efficiency point of view (Report of the Alternative Fuels Contact Group, 2003; ENEA, 2006). Nonetheless considerable cost reductions are expected to be achieved through technological progress and large scale economies. In our simulations we have considered the cost of a prototype fuel cell bus, because the cost of a mass-produced fuel cell bus is currently unavailable. Such a cost is assumed to be 1,200,000 €[14] (ENEA, 2006), corresponding to a unit investment cost equal to 7500 €/kW (see Table 2, which provides the values adopted for all indicators).

As far as the lifetime of fuel cell buses is concerned, we can refer only to results from pilot projects, which have tested their vehicles for a short time. On the basis of the stacks' average lifetime of about 3000 h (European, USA and Japanese strategy documents, 2004–2006; ENEA, 2006) we have assumed 2 years' operation.[15]

Variable costs mainly depend on the source of hydrogen. We have supposed that hydrogen is produced through water electrolysis,[16] which entails lower emissions compared to natural gas steam reforming. This implies a working cost equal to 1.35 €/(bus km) (calculated on the basis of data provided by ENEA, 2006), compared to 0.35 €/(bus km) for gasoline buses and 0.30 €/(bus km) for CNG buses.

Finally, other costs associated to a decentralized hydrogen production plant (storage, maintenance, infrastructure costs, etc.) have also been included by taking a comprehensive cost of about 2 million € (equivalent to 20,000 €/bus).

In our first simulation, by considering overall costs and a 3% discount rate over the considered bus lifetime, variable costs of hydrogen fuel cell buses are estimated to be 36.9 €/kWh (see Table 3), which is structurally based in energy terms. In order to make such costs sustainable for the Public Transport Company, financial incentives are needed. These incentives can be justified by all kind of benefits/Benefits provided, far wider than the increased sustainability of the public transport system (in terms of reduction of fossil fuel and other exhaustible resources, low emissions, both at the point of use and along all the productive chain, etc.).

The benefits/Benefits provided by fuel cell buses are displayed in Fig. 2. The diagram clearly shows that capital and variable costs of hydrogen buses tend to discourage their adoption, without an environment-friendly policy sustaining their introduction. From the Firm's point of view (in our case the Public Transport Company), fuel cell buses are not profitable. Investment costs are too high compared to the benefits for the Firm, due to the large amount of economic inputs required and the relative low level of the system efficiency. This is represented by the circles in Sector One, whose barycenter belongs to the “Medium” interval of both axes. Under the same hypotheses, hydrogen buses produce low benefits for the Society too, as revealed by the positioning of the circle on the third sector. Such an unsatisfactory performance is explained by the low values of indicators representing the ratio between the benefits to the Society and the production costs (indicators from I_{61} to I_{65} in Table 1), and the financial sustainability indicator (I_{55}) (see also Table 2, upper values, and Table 3).

On the other hand, hydrogen buses produce wide benefits for the Environment, both as Sink and Source (Sectors Two and Four). The corresponding good positioning in these sectors reflects the low levels of harmful emissions, the reduced use of non-renewable resources and energy resource depletion induced by hydrogen vehicles. It also

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[13] The case study was conceived as an ENEA (Italian Agency for New Technology, Energy and the Environment) potential proposal to ATAC (the Public Transportation Agency of Rome) for the introduction of one hundred fuel cell buses. The project was realized in collaboration with Luiss University of Rome (2004–2006).

[14] Costs of hydrogen buses are hardly competitive with other buses. The cost of a diesel bus, for instance, is around 250,000 €.

[15] It is equivalent to assume that each bus works only 8 h a day. Even though the lifetime of fuel cell buses is expected to rapidly increase up to 15,000 h, their performance is obviously lower compared to other buses, whose average lifetime can reach 10/15 years (corresponding to 40,000 h of working).

[16] Electrolysis is assumed to be obtained from wind electricity, because Emergy Analysis shows that such source presents the highest advantages among the renewable energies from an environmental point of view.

Table 2
Characteristic Parameters of HYDROGEN BUS (160 kW).

Sector	Axis	I_{i1}	I_{i2}	I_{i3}	I_{i4}	I_{i5}	$\bar{w}_i$
1	1	7500 (1000)	1.200 (0.30)	1.34 (1.0E−4)	1.20 (0.25)	1.01E−3 (1.0E−3)	0.494
		1000 (1000)	0.364 (0.30)	1.34 (1.0E−4)	1.20 (0.25)	1.01E−3 (1.0E−3)	0.321
1	2	79.5 (85.0)	41.0 (75.0)	79.5 (85.0)	1.95E5 (1.0E5)	1.00 (2.00)	0.593
		79.5 (85.0)	41.0 (75.0)	79.5 (85.0)	1.95E5 (1.0E5)	1.10 (2.00)	0.603
2	3	0.372 (0.40)	Not available	Not applicable	Not applicable	0.70 (0.80)	0.918
		0.372 (0.40)	Not available	Not applicable	Not applicable	0.70 (0.80)	0.918
2	4	558 (300)	0.604 (0.015)	0.164 (0.054)	1.01E−3 (1.0E−3)	1.01E−3 (1.0E−3)	0.377
		558 (300)	0.604 (0.015)	0.164 (0.054)	1.01E−3 (1.0E−3)	1.01E−3 (1.0E−3)	0.377
3	5	1.08 (3.50)	104 (158)	2.17 (2.50)	1.45 (2.70)	0.723 (1.0)	0.491
		1.08 (3.50)	104 (158)	2.17 (2.50)	23.5 (30.0)	7.32 (10.0)	0.542
3	6	0.778 (2.0)	1.83 (3.0)	1.77 (3.0)	1.52 (3.0)	1.37 (5.0)	0.474
		7.89 (10.0)	180 (200)	174 (180)	149 (180)	134 (180)	0.845
4	7	625 (9.02)	0.023 (0.0125)	Not available	1000 (500)	0.256 (0.90)	0.699
		625 (9.02)	0.023 (0.0125)	Not available	1000 (500)	0.256 (0.90)	0.699
4	8	4.92E17 (1.56E15)	0.90 (0.51)	4480 (4500)	972 (1050)	0.85 (0.80)	0.683
		4.92E17 (1.56E15)	0.90 (0.51)	4480 (4500)	972 (1050)	0.85 (0.80)	0.683

Note: Upper values in each cell refer to a no-financial incentive hypothesis, while lower values include governmental support to system implementation.

The weighted average ($\bar{w}_i$) is given by $\bar{w}_i = \sum_{j=1}^{5} w_{ij} \cdot F[(I_{ij} / I_{ij,r})^{\alpha}]$, where $\alpha = 1$ if $(I_{ij}/I_{ij,r}) \leq 1$, and $\alpha = -1$if $(I_{ij}/I_{ij,r}) \geq 1$.

Normalized indicators are dimensionless; values are expressed in the same units as in Table 1.

Table 3
Macro-economic indicators (fuel cell bus without incentives).

GDP*		GDP (€)				ΔK_n (€)		
Items	Inv	Con	Exp	Imp	$F^* \cdot EYR_f \cdot EP - Inv$	$\Delta K_{n,p,l}$	$\Delta K_{n,p,g}$	$\Delta K_{n,r}$
	6.00E+05	2.30E+05	0.00E+00	−1.84E+05	8.72E+05	−5.16E+04	−2.06E+05	−1.22E+05
Σ_i	6.00E+05	8.30E+05	8.30E+05	6.46E+05	1.52E+06	1.47E+06	1.26E+06	1.14E+06
$\Sigma_i(\ )_i$/Inv	1.00E+00	1.38E+00	1.38E+00	1.08E+00	2.53E+00	2.44E+00	2.10E+00	1.90E+00
π_i [c€/kWh]	2.67E+03	3.69E+03	3.69E+03	2.87E+03	6.74E+03	6.52E+03	5.60E+03	5.06E+03
π_i/π_2	7.23E−01	1.00E+00	1.00E+00	7.78E−01	1.83E+00	1.77E+00	1.52E+00	1.37E+00

reflects the corresponding Ordinal Benefits, such as those represented, for instance, by the Emergy Index of Sustainability (I_{72}). The circles display an overall mean value of the indicators much closer to the best result, particularly in Sector Two.

Fig. 3 shows that hydrogen buses can become an attractive option also for the Society and the Firm if a system of financial incentives is applied. Our second simulation assumes that the Firm can receive public incentives to compensate capital and variable costs of hydrogen buses. More specifically, with reference to a single bus (including the fraction of hydrogen production plant) we have assumed that (see also Tables 3 and 4):

i) State financial incentives cover 90% of the initial investment (1,080,000 €);
ii) the Firm can benefit from the exemption of any form of taxes on the electricity production and all other inputs;
iii) residual investment costs are covered either by specific tax on a pre-defined class of polluting fuels or directly financed by the

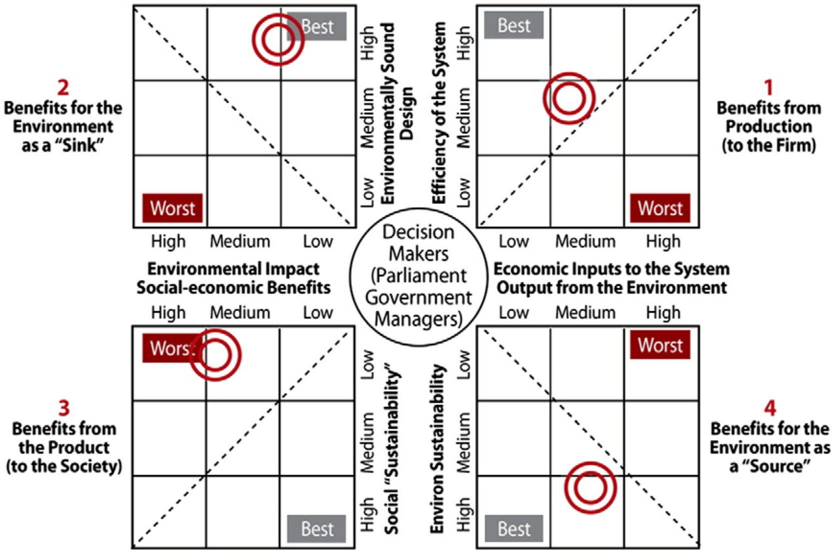

Fig. 2. Fuel cell buses without incentives. The axes in each Cartesian plan range from 0 to 1. Each axis is divided in three equal intervals [(0, 1/3), (1/3, 2/3), (2/3, 1)], corresponding to the "low", "medium" and "high" value the barycenter of the considered axis can assume.

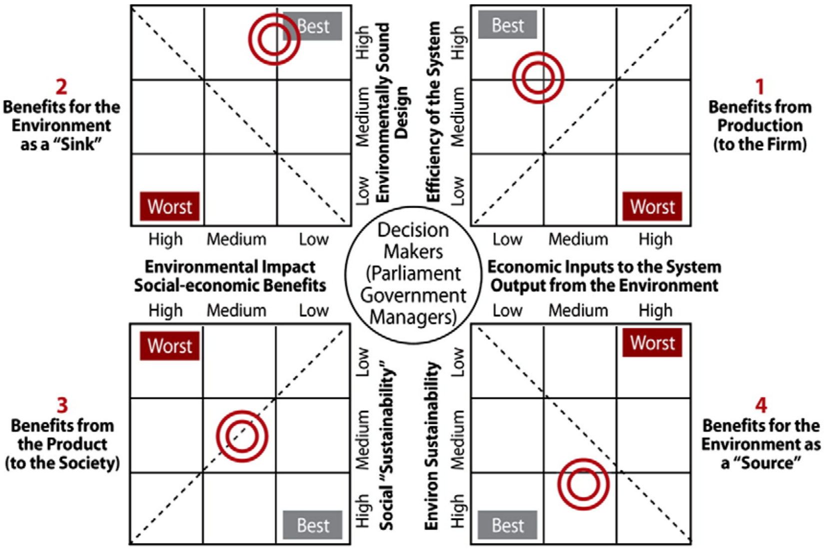

Fig. 3. Fuel cell buses with incentives. Best and worst refer to the highest and the lowest values the composite "performance indexes" can reach (1 and 0 respectively). The inner and outer radius of the circles are calculated as explained in Section 2.

State. In this respect, it should also be considered that more than 50% of the initial investment can be recuperated by the State, generally within the first year, in terms of VAT and income taxes on the induced economic activities. This is because all economic activities related to the buses production process (the use of labor force, inputs and fuels, for instance) are subjected to some form of (direct or indirect) taxation, which represents an additional revenue (with respect to those considered by the method) allowing the State to partially recover initial expenses for financial incentives.

Incentives here assumed are only an example of how an environment friendly policy intervention can support the introduction of hydrogen buses for public transport. We only want to show that such (or other) incentives can be justified by considering that induced benefits/Benefits provided by fuel cell buses are much higher than the initial investment. Accordingly, financial incentives can be broadly justified by a social welfare point of view (see also the next Section). Other forms of financial subsidies can also be taken into account. Additional contributions, for instance, could be provided by specifically finalized UE Programs (examples are the project CIVITAS and the MIRACLE Program).

By providing financial incentives, the State can immediately improve the performance of buses in Sector 1. This clearly implies that new buses can be realized and operate. Their adoption induces benefits/Benefits to the Society (see Sector Three), particularly because incentives improve the financial burden distribution between the State and the consumers, as explained by the high values of sustainability indicators (see Table 2, lower values and Table 4). In addition, the operation of hydrogen buses also induces several forms of benefit to the Environment, both as a Source and as a Sink. Incentives not only convert potential benefits into real benefits but, at the same time, drive additional investments on the considered productive processes. This is because, by providing an immediate return, incentives attract further investments that are needed to increase the competitiveness of buses. Thus, in a dynamic perspective, incentives can be interpreted as a form of anticipated remuneration for all benefits/Benefits that the investment produces in favor of the Society and the Environment in a non-zero sum circular process.

6. Comparison Between Incentives and Induced Benefits

As noted above, a comparison between the required incentives and all kinds of benefits/Benefits reveals that the former are widely compensated by the global advantages of fuel cell buses.

The induced benefits/Benefits due to an initial investment I_0 (within its life time n) can be estimated on the basis of the Method of Barycenters. Annual Economic Benefits (AEB) can be expressed as

$$AEB = \frac{I_0}{n} \cdot [I_{51,0} \cdot \sum_{i=1}^{8} \lambda_i \cdot \xi_i \cdot \bar{w}_i (1 \pm \Delta \bar{w}_i)] \tag{6}$$

where λ_i is "scale coefficient" referred to axis five (Social-economic Benefits; $\lambda_5 = 1$), whereas ξ_i accounts for the specific orientation of each axis. If we consider that incentives (ΔI_0) are always a fraction (χ) of the Investment I_0, we obtain

$$AEB = [I_{51,0} \sum_{i=1}^{8} \lambda_i \cdot \xi_i \cdot \bar{w}_i (1 \pm \Delta \bar{w}_i)] \cdot \frac{\Delta I_0}{n\chi} \tag{7}$$

Table 4
Macro−economic Indicators (Fuel Cell Bus with incentives).

GDP*		GDP (€)				ΔK_n (€)		
Items	Inv	Con	Exp	Imp	$F^* \cdot EYR_f \cdot EP - Inv$	$\Delta K_{n,p,l}$	$\Delta K_{n,P,g}$	$\Delta K_{n,r}$
	6.00E+04	−3.38E+04	1.12E+05	−7.36E+04	1.41E+06	−5.16E+04	−2.06E+05	−1.22E+05
Σ_i	6.00E+04	2.62E+04	1.38E+05	6.46E+04	1.48E+06	1.42E+06	1.22E+06	1.10E+06
Σ_i ( )$_i$/Inv	1.00E+00	4.37E−01	2.30E+00	1.08E+00	2.46E+01	2.37E+01	2.03E+01	1.83E+01
π_i [c€/kWh]	2.67E+02	1.16E+02	6.14E+02	2.87E+02	6.56E+03	6.33E+03	5.41E+03	4.87E+03
π_i/π_2	2.29E+00	1.00E+00	5.28E+00	2.47E+00	5.64E+01	5.44E+01	4.65E+01	4.19E+01

In our case study (for $\chi = 0.9, I_{51,0} = 3.5, n = 2$, and for $\lambda_j = 1$) we have that

$$AEB \cong (5.1 \div 9.9) \cdot \Delta I_0 \tag{8}$$

that is, induced benefits/Benefits provided by hydrogen buses are much higher than the amount of incentives needed to support their introduction. This evaluation represents one of the main reasons for the adoption of a decision making process based on the estimated benefits/Benefits through the FSDOB.

The possibility of evaluating all the different forms of benefits/Benefits induced by the process to each actor of the system enables us to provide a justification for public incentives to the Firm. In such a perspective, incentives cannot simply be viewed as a "gift" to the Firm, but as a sort of remuneration for benefits/Benefits produced in favor of the Society and the Environment. This implies that innovative activities should be promoted and sustained in proportion to their positive impact on the whole natural and social system.

The methodology so far adopted might be considered as being too subjective since correlation coefficients λ_i $(i \neq 5)$ are defined by the Decision Maker. Such coefficients however can be obtained by evaluating the AEB corresponding to the optimum Ordinal configuration of the system under dynamic conditions (Giannantoni and Zoli, 2008).

In a dynamic perspective the concept of Transformity is replaced by the more general concept of Ordinality. In this case, the rules of Emergy Algebra (which are already expression of the process *a-functional* characteristics under steady-state conditions) transform into Ordinal Differential Equations, expressed through the incipient derivatives (see Giannantoni, 2002). The Incipient Differential Calculus has been specifically conceived for giving a very general mathematical formulation of the Maximum Em-Power Principle under variable conditions (ib.). It allows us to account for the *generative activity* of the processes, under dynamic conditions, by means of its output cardinality and associated Ordinality[17] (Giannantoni, 2006a,b, 2009; Giannantoni and Zoli, 2008).

The corresponding generalization of the Method of Barycenters to dynamic conditions accounts for all the benefits/Benefits which arise from the multiple Sector interactions. The optimal value of the coefficients λ_i can be obtained on the basis of those relations which maximize the Ordinal level of the System, understood as a whole, consistently with the associated re-formulation of Maximum Em-Power Principle in terms of Ordinality.[18] The research for the optimal working conditions is also favored by the fact that a dynamic Ordinal model of any complex system always presents an explicit solution in a closed form when it is formulated in terms of incipient derivatives (Giannantoni, 2006a).

On the basis of the properties of the Incipient Differential Calculus, the Ordinal optimization method is independent from the number of sectors involved in the analysis. The method is applicable, in principle, to any energetic–economic–environmental system, however complex it might be.

7. Conclusions

In this article we propose a new framework for assessing all the various forms of benefits potentially provided by new energy solutions. The FSDOB Method offers the opportunity of simultaneously considering a multiplicity of indicators developed by different disciplines. The overall effect induced by the introduction of a new technology can be evaluated either by considering the specific benefits pertaining to each of the four main actors involved in the production process (such as the Firm, for instance) or, much better, by considering the global circulation of benefits among them. Most of all, the methodology here proposed enables us to account for a particular form of benefits, termed as Ordinal Benefits, systematically ignored by traditional economic analyses since they cannot be measured in monetary terms. These Benefits emerge in all the transactions between humans and the environment and are related to the unexpected higher Quality shown by output of some physical processes. This explains why Ordinal Benefits can be evaluated in Emergy terms, albeit any adopted value can only be intended as a simple cipher of their real values.

By accounting for these forms of benefits, the FSDOB Method allows us to capture all potential advantages of solutions generally deemed non-profitable from a strictly economic point of view.

This article applies such a methodology to the introduction of hydrogen fuel cell buses in the public transport system of Rome. The novelty of the present case study consists in the fact that all forms of social and environmental benefits provided suggest the opportunity to support the introduction of hydrogen buses, despite their extremely high fixed and variable costs (see Section 5). Differently from the current state of the art focused on financial aspects and favoring traditional fossil-fuels solutions, our benefit-oriented framework tends to privilege hydrogen buses. This is exactly because the method is able to justify relevant State financial incentives compensating initial investment costs, in view of the huge amount of benefits that fuel cell buses produce to the Society and the Environment. This also shows that in this perspective hydrogen technologies are already "competitive". The associated public intervention cannot be considered as a simple gift in favor of the new technology (or even to the Firm), but becomes a sort of anticipated remuneration for the benefits/Benefits provided.

Traditional evaluation methods, on the contrary, consider hydrogen technologies (or equivalent alternatives) as being non-profitable. Consequently, they would never be realized. By missing, in actual fact, the opportunity of taking advantage of all the benefits associated to their realization.

Appendix A. Nomenclature for Indicators used for Sector 1

The majority of indicators do not require to be defined because well-known in energetic–economic analyses, except for Transformity of the product and Raw Energy conversion coefficient. Transformity has been illustrated in detail in Sections 3 and 4. The Raw Energy conversion coefficient quantifies the amount of raw (non-renewable) energy resources used as fuels during operation to supply the final products. This indicator can be used to highlight the amount of raw energy potentially saved if renewable are substituted for fossil fuels to get the same products (Giannantoni et al., 2005; p. 1994).

Nomenclature for Indicators used for Sector 2

The majority of indicators are also self-explaining. What it is worth noting, however, is that all indicators are conceived for traditional plants. In the case of hydrogen based technologies some of them are "not applicable". Others, on the contrary, such as I_{42} and I_{43}, show the advantage of such technologies because there are no CO_2 emission costs. In such a case they give the maximum

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[17] Given a process modeled by a differential equation of any order, written in terms of incipient derivatives, its solution can always be represented as $[f(t)]^{l,(\frac{m}{n}\cdot)}$ where: the *cardinality* is given by $[f(t)]^l$, that is the instantaneous value $f(t)$ raised to the power l (if present), whereas its *Ordinality* is expressed by the ratio (m/n), which is defined as the order of the basic fractional derivative $(1/n)$ multiplied by the non-linearity degree (m) of the considered generating equation.

[18] Enunciation in note 8 now correspondently becomes: "Every system tends to the maximum Ordinality, including that of its surrounding systems (understood as *habitat*)".

advantage, which is represented by a specific incidence equal to 1 (see Table 2).

Nomenclature for Macro-Economic Indicators used for Sector 3

Inv	Annual fraction of the initial Investment.
Con	Net annual marginal receipts. Given Inv, Exp, Imp, n (Investment lifetime) and A.F. (annuity factor), they are estimated as Con = (n/A.F. − 1) Inv − Exp + Imp.
Exp, Imp	Economic values of the pertinent annual import (Imp) and export (Exp) quantities. The associated Emergetic values are also considered for more general strategic evaluations related to the international exchange of Natural Resources (namely $\Delta K_{n,r}$).
EYR	The ratio of the emergy of the output divided by the emergy of those inputs that are fed back from outside the system under study. At the scale of the biosphere, EYR is an indicator of the yield compared to inputs other than local and gives a measure of the ability of the process to exploit local resources (Brown and Ulgiati, 1997; p.56).
$F' \cdot \mathrm{EYR}_f - \mathrm{Inv}$	Economic value of the effects induced on Economy (by the generated product) through the "feedback chains" of the Productive System of the Country. Note that F (total Emergy amount of physical resources coming from the Economic System, external to the Process) generally differs from the physical–economic Investment F'. This in fact is evaluated by considering that the Emergy associated to the fuel is now replaced by the Emergy of money spent to buy the same fuel on the international market.
$\Delta K_{n,p,l}$, $\Delta K_{n,p,g}$	Effects due to both pollution (air, water, soil, etc.) at a local level and climate change at a global level. As a mean value, a comprehensive cost of 0.32 €/kg CO_2 has been assumed (subdivided into 20% and 80% respectively). These costs, generally considered as "internalized costs", are here accounted for in terms of "social benefits". This is why they underestimate such "social benefits", that are always much greater than "avoided costs".
$\Delta K_{n,r}$	Costs due to the consumption of natural resources. An ideal Carnot coefficient equal to 2/3 has been assumed in order to make such an estimation conceptually homogeneous with the other final costs listed in the table.

$\sum_{i=1}^{4} ()_i / Inv$ (sum of items in upper cells of columns 1 to 4, divided by the investment term) represents the traditional concept of ROI (Return on Investment, referred to the annual fraction of the initial Investment).

The ratios $\sum_{i=1}^{j} ()_i / Inv$ (defined as above, for $j = 5,6,7,8$) represent an "extended" concept of ROI because they progressively account for additional contributions illustrated above. This ratio, when evaluated for $i = 8$, can be termed as "global" ROI, because it includes all the terms considered in the table.

The terms π_i, defined as $\sum_{K=1}^{i} ()_k / Inv$/Exergy Output, represent the various mean "costs" per unit product. As a consequence, the term π_2 represents the traditional mean production cost (the repartition of costs between heat and electricity is performed by means of thermoeconomic analyses).

While the ratios referred to the Investment (Inv) represent the Firm perspective, the ratios π_i/π_2 substantially represent the Citizen's perspective because, by paying for those products, the latter sustains the profitable activity of the Firm.

Nomenclature for Macro-Economic Indicators used for Sector 4

Indicators that require a specific definition are only those usually adopted in Emergy Analysis. In particular, the Environmental Loading Ratio (ELR) is defined as the ratio between the resources invested from outside and the renewable energy that is locally available (Giannantoni et al., 2005; p. 1998). The Emergy Index of Sustainability (EIS) measures the ability of the system in getting the highest benefit versus the lowest environmental loading. It is therefore an aggregate measure of yield and environmental loading, i.e. a sustainability function for a given process under study (ib.). The Empower Density (ED) measures the relation between the emergy investment and the area involved in the process (where empower stands for "emergy per unit time") (ib.).

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