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Journal of Cleaner Production 15 (2007) 63–74
Journal of Cleaner Production
www.elsevier.com/locate/jclepro

Emergetic ternary diagrams: five examples for application in environmental accounting for decision-making

C.M.V.B. Almeida, F.A. Barrella, B.F. Giannetti*

LaFTA – Laboratório de Físico-Química Teórica e Aplicada, Instituto de Ciências Exatas e Tecnologia da Universidade Paulista,
R. Dr. Bacelar 1212, Cep 04026-002 São Paulo, Brazil

Received 17 February 2005; accepted 6 July 2005
Available online 19 September 2005

Abstract

In a recent paper, "A combined tool for environmental scientists and decision makers: ternary diagrams and emergy accounting." [Giannetti BF, Barrella FA, Almeida CMVB. A combined tool for environmental scientists and decision makers: ternary diagrams and emergy accounting. J Clean Prod, in press http://dx.doi.org/10.1016/j.jclepro.2004.09.002] Ternary diagrams were proposed as a graphical tool to assist emergy analysis. The graphical representation of the emergy accounting data makes it possible to compare processes and systems with and without ecosystem services, to evaluate improvements and to follow the system performance over time. The graphic tool is versatile and adaptable to represent products, processes, systems, countries, and different periods of time.

The use and the versatility of ternary diagrams for assisting in performing emergy analyses are illustrated by means of five examples taken from the literature, which are presented and discussed. It is shown that emergetic ternary diagram's properties assist the assessment of the system efficiency, its dependence upon renewable and non-renewable inputs and the environmental support for dilution and abatement of process emissions. With the aid of ternary diagrams, details such as the interaction between systems and between systems and the environment are recognized and evaluated. Such a tool for graphical analysis allows a transparent presentation of the results and can serve as an interface between emergy scientists and decision makers, provided the meaning of each line in the diagram is carefully explained and understood.

Keywords: Emergy analysis; Emergetic ternary diagram; Graphical tool; Sustainability; Environmental indicators; Environmental accounting

1. Introduction

Dealing with anthropogenic systems within the environment involves consideration of many complex aspects, ranging from economic concerns, energy production/consumption and environmental benefits/damages. Different methods have been developed to analyze each cited aspect, but there is no agreement on the possibility of an evaluation procedure that can unify these aspects. For these reasons, there is also a huge difficulty to represent graphically, the results of such analyses.

The analyses of most systems, especially those concerning environmental issues, require an understanding of the relationship between multiple dependent and independent variables. Indeed, if numerical simulation is required, one faces the problem of gaining understanding over a potentially large number of variables and their ranges. The use of graphical representation is a powerful technique in gaining understanding, because it permits the visualization of the relationships between and among variables. The most commonly used graphic is 2-D plotting of data. However, for most systems there are many more variables than two that must be

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* Corresponding author.
E-mail address: biafgian@unip.br (B.F. Giannetti).

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doi:10.1016/j.jclepro.2005.07.002

compared and many more possible graphical representations that can be employed.

Several authors proposed graphical representations for environmental issues [1–9]. As the relationships between the environment and the anthropogenic systems depend upon several variables, the most commonly used plot is the multi-objective representation, which can have as many axes as needed or desired. The axes may represent a variety of parameters, which are not necessarily accounted with the same unit. Most parameters related to environmental topics are derived from different theoretical approaches depending on different scales of time and space. For this reason, most multi-objective plots show a normalized comparison between different systems or between a given system and an ideal one (Fig. 1).

Emergy accounting is a methodology that analyses the relationships among components of anthropogenic systems and the resources needed to maintain these systems, while permitting the calculation of environmental indices [10,11]. These indices are subjected to three main variables: the fractions of renewable (R), non-renewable (N) and purchased inputs (F). The accounting of these three fractions permits one to credit the carrying capacity of the environment, and provides valuable information about the development and functioning of economic systems within the environment. Hence, the graphical representation for emergy accounting requires three axes. Few works that have accomplished this are present in the literature. Bastianoni [12] considers emergy and exergy as complementary aspects of a system, the ratio of exergy to the emergy flow being indicative of the efficiency of an ecosystem in producing or maintaining its organization. Pollution is defined as an emergy flow, the increase of which corresponds to a loss in the exergy content of the system. The results are shown in a two dimensional diagram where the variation in exergy is plotted as a function of the emergy changes. Ulgiati and Brown [13] have plotted the ratios $N/F = \upsilon$ and $R/F = \eta$ to the economic investment F. Three-dimensional plots representing the indices ELR (environmental loading ratio), EYR (environmental yield ratio) and SI (sustainability index, or EIS environmental index of sustainability) against υ and η, called exploit functions, were used to evaluate the amount of investment required to exploit a local renewable or non-renewable resource. The resulting surfaces allow simulations where the amount of inputs can be changed.

Tonon et al. [14] used multi-objective representations to compare the results of energetic, exergetic, economic and emergetic evaluations. Twelve variables were normalized and represented in order to compare economic and environmental viewpoints (represented by the sustainability index), the thermodynamic viewpoint at the processes scale (represented by energy and exergy) and the sink side, corresponding to the emissions of the systems studied. The results are compared with those of a hypothetical process with "average performance".

Giannantoni et al. [15] proposed a four-sector diagram of benefits including emergy accounting in the sector, "Benefits for the environment as a source." In this sector the indicators adopted include the ELR (environmental loading ratio), the EIS (or SI) and the emergy density (seJ/m^2), among others. The resulting graphic representation of each sector contains 9 squares, which show the combination between low, medium or high environmental sustainability with low, medium or high output from the environment.

The purpose of this paper is to explore the use of ternary diagrams as graphic tools to assist environmental accounting and environmental decision-making based on emergy analysis, which is based on three main

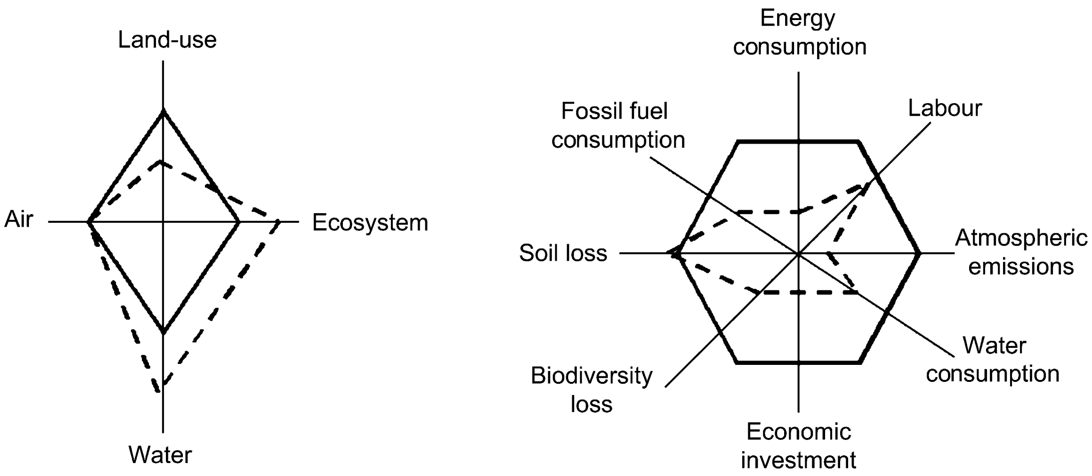


Fig. 1. Examples of multi-objective representation, where the straight lines represent normalized ideal systems and the dashed lines represent the hypothetical results of systems under a supposed investigation.

variables. Ternary diagrams are called tools instead of graphic representations because they offer not only possibilities for data interpretation, but also permit data treatment [16]. The use of the properties of triangular diagrams brings additional information about the dependence of the system upon renewable and non-renewable inputs, the system efficiency and the environmental support for dilution and abatement of process emissions. The graphic representation of the emergy accounting data makes it possible to compare processes and systems with and without ecosystem services, to evaluate improvements and to follow the system performance over time. With the aid of ternary diagrams, aspects such as the interaction between systems and the interactions between systems and the environment can be recognized and evaluated. To illustrate the use and the flexibility of this graphical tool, five examples taken from the literature are presented and discussed.

Table 1
Emergy-based indices

Symbol	Description	Equation[a]
EYR	The emergy yield ratio (EYR) is the ratio of the emergy of the output (Y), divided by the emergy of those inputs (F) to the processes that are fed back from outside the system	$\mathrm{EYR}=\frac{Y}{F}=\frac{R+N+F}{F}$
EIR	The investment ratio is the ratio of purchased inputs (F) to all emergies derived from local sources	$\mathrm{EIR}=\frac{F}{N+R}$
ELR	This index of environmental loading is the ratio of non-renewable emergy to renewable emergy	$\mathrm{ELR}=\frac{N+F}{R}$
SI or EIS	This index aggregates the measure of yield and environmental loading. The objective function for sustainability is to obtain highest yield ratio at the lowest environmental loading	$\mathrm{SI}=\frac{\mathrm{EYR}}{\mathrm{ELR}}=\frac{\frac{Y}{F}}{\frac{N+F}{R}}$

[a] The equations presented are a particular case of Eqs. (1)–(4), shown in the text, in the specific case where $R_2 = 0$, being R_2 the emergy corresponding to the contribution of environment to dilute and abate process emissions.

2. Methodology

2.1. Emergy indices

A complete inventory of emergy analysis and emergy-based indices cannot be provided here, but complete information can be found in Refs. [10] and [11]. The emergy flows represent three categories of resources: R as renewable resources, N as non-renewable resources and the inputs from the economy, F. All the three categories are fundamental for the emergy accounting and for the understanding of the system interactions with the environment. The R and N flows are provided by the environment and are economically free, while the renewable resources can be replaced at least at the same rate as they are consumed, the non-renewable resources are depleted faster than their ability of recuperation. The economic inputs, F, are provided by the market and are related to fluxes that are accounted for by the economy. The outputs, Y, may include products, services and also emissions that are released to the environment. In this paper four indicators are employed to assist the discussion: the environmental loading ratio (ELR), the emergy yield ratio (EYR), the emergy investment ratio (EIR) and the emergy index of sustainability (EIS or SI) (Table 1).

2.2. Emergetic ternary diagrams

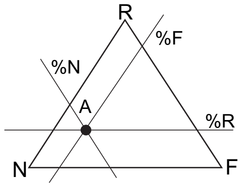
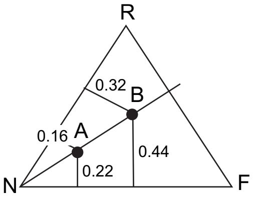
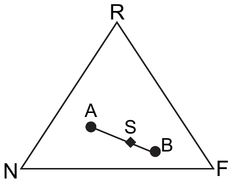
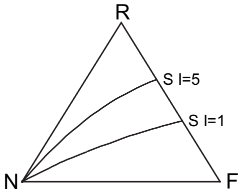
The graphic tool produces a triangular plot of three variables with constant sum [16]. Most commonly, three percentages add to 100 or three fractions or proportions add to 1. The constant sum constraint means that there are just two independent pieces of information. Hence, it is possible to plot observations in two dimensions within a triangle. Emergetic triangular plots may be named with various names, including emergetic triaxials, emergy three-element maps, emergy percentage triangles and emergy mixing triangles.

The emergetic ternary diagram has three components, R, N and F. These fluxes are represented by an equilateral triangle; each corner represents a flux, and each side a binary system; ternary combinations are represented by points within the triangle, the relative proportions of the elements are represented by the lengths of the perpendiculars from the given point to the side of the triangle opposite the appropriate element. Hence, the "composition" of any point plotted on a ternary diagram can be determined by reading from zero along the basal line (axis) at the bottom of the diagram to 100% at the vertex of the triangle.

Ternary diagrams show important properties that are summarized in Table 2. A complete description of the graphic tool is published in Ref. [16].

Before presenting the applications of ternary diagrams, it is important to emphasize that the discussions that support the chosen examples use the sustainability index and sustainability lines to compare and/or to classify systems. The sustainability concept is centered in human society where industrial and agricultural systems operate. On the other hand, humans tend to adjust the attention to different scales, as it is easy to manage and understand small parts of the global system defining boundaries and limits. However, this anthropocentric view sometimes hinders the understanding that the concept of a sustainable subsystem in an un-sustainable global system is fundamentally defective. Labels such as sustainable communities or sustainable products must

Table 2
Properties of emergetic ternary diagrams functioning as auxiliary tools for emergy analyses

Properties	Description	Illustration
Resource flow lines	Ternary combinations are represented by points within the triangle, the relative proportions of the elements being given by the lengths of the perpendiculars from the given point to the side of the triangle opposite the appropriate element. These lines are parallel to the triangle sides and are very useful for comparing the use of resources by-products or processes.	
Sensitivity lines	Any point along the straight line joining an apex to a point represents a change in the quantity of the flux associated to the apex. Any point along the line represents a condition in which the other two fluxes maintain in the same initial proportion. For example, the system illustrated on the right is progressively poorer in *N*, as it passes from A to B, but *R* and *F* maintain at the same initial proportion.	
Symergy point	When two different ternary compositions, represented by points A and B within the triangle, are mixed, the resulting composition will be represented by a point *S* called here "symergy" point, which lies at some point on the segment AB.	
Sustainability lines	The graphic tool permits one to draw lines indicating constant values of the sustainability index. The sustainability lines depart from the *N* apex in the direction of the RF side allowing the division of the triangle into sustainability areas, which are very useful to identify and compare the sustainability of products and processes.	

be seen as indications of benefit contributions to the global system. By definition the SI index indicates a high environmental yield combined with a low environmental load. This index graphically represented by the sustainability lines indicates the contribution of each system, product or sector to the global sustainability and may, therefore, be used as an important guide to conceptual progress.

3. Examples of applications of the emergetic ternary diagram

The following examples were taken from the literature and were selected in order to provide an overview of the graphical tool applications. With the use of emergy analyses assisted by emergetic ternary diagrams, different types of investigations can be easily assessed. The choices were performed considering several aspects such as economic/environment interfaces (from agriculture to electricity production), different space and time scales and different approaches (comparative or tendency analysis) (Table 3).

3.1. Example #1: emergy evaluation of electricity production systems

The first example selected to illustrate the use of ternary diagrams applied to emergy accounting is based upon a case study, which evaluates six electricity production systems in Italy [17,18]. The authors divided this case study into two papers. The first compares six different production systems using renewable energy sources (geothermal, hydroelectric, and wind plants) and non-renewable energy sources (natural gas, oil, and

Table 3
Criteria for the selection of the examples

Example	Sector studied	Location	Time/years	Type of analysis	Ref.
#1	Electricity production	Italy	1	Comparative	[17,18]
#2	Agriculture	U.S.A	10	Tendency	[13]
#3	Agriculture	Italy	1	Tendency	[20]
#4	Economic development	Taiwan	4	Tendency	[23]
#5	Agriculture	Australia	1	Comparative	[25]

Table 4
Summary of the results from [17], the study of six electricity production systems[a] without considering environmental services

	Eolic	Geothermal	Hydroelectric	Thermoelectric		
				Methane	Oil	Coal
Emergy inputs (10^{18} seJ)						
Renewable	0.728	33.6	16.9	27.2	312	368
Non-renewable	0.000	4.61	4.45	268	3320	3050
Purchased	0.113	10	3.21	52.8	1130	763
Total emergy	0.841	48.2	24.6	348	4760	4180
Emergy indices						
EYR	7.44	4.82	7.65	6.59	4.21	5.48
EIR	0.16	0.26	0.15	0.18	0.31	0.22
ELR	0.16	0.43	0.45	11.79	14.26	10.36
SI	47.95	11.09	16.88	0.56	0.30	0.53

[a] The production scale of each plant is shown in Table 6.

coal thermal plants). The output/input energy ratio as well as the emergy-based emergy yield ratio (EYR) and environmental loading ratio (ELR) were used to explore and compare system performances. Generation of CO_2 was accounted in order to evaluate a ratio of CO_2 released to CO_2 avoided, according to the fact that renewable power plants do not require a direct combustion and therefore, release a lower amount of CO_2 than a thermal plant for the same electricity output. The second paper quantifies the environmental support for dilution and abatement of process emissions, accounting for the environmental services required to dilute CO_2 emissions of each process. In this paper the role of environmental services in disposing of chemicals that are released after electricity has been produced is explored and a method of quantitatively determining the carrying capacity is presented. Under this approach, emergy-based yield indicators may decrease drastically coupled to a parallel increase in a loading indicator, when the environmental services required for the dilution of pollutants are accounted for. As a consequence of including environmental services, a lower sustainability is calculated for each investigated process when compared to evaluations that do not include them. Accounting for environmental services also provides a way to evaluate the carrying capacity of the environment in relation to human dominated processes. Tables 4 and 5 summarize the results of both papers.

Fig. 2a presents the ternary diagram for six electricity production systems. It is easy to note that two distinct groups are shown in the diagram. The first group, at the top of the diagram, is composed of systems using renewable energy sources (geothermal, hydroelectric, and eolic plants). The second, at the bottom of the diagram, includes the systems using non-renewable energy sources (natural gas, oil, and coal thermal plants). The diagram also shows resource use lines. It can be observed that systems 4, 5 and 6 (natural gas, coal and oil) are practically located on the line $R = 0.08$, which indicates the use of 8% of renewable resources. As ELR may be estimated by the quantity of renewable resources employed, it can be inferred that these three systems have similar characteristics concerning the environmental impacts that they produce. The diagram also shows that all six systems are located close to the line $F = 0.16$. In this way, it is useful to note that for both types of energy generation, using either renewable (geothermal, hydroelectric, and eolic plants) or non-renewable resources (thermoelectric plants), the economic investment is similar. In fact, the value of EYR is strongly tied to the quantity of purchased inputs, and all energy production systems have these indices between 4.21 and 7.47 [17]. In the same way, it can also be readily observed that hydroelectric and geothermal plants have similar environmental loading, despite the difference in their EYR values. The use of non-renewable resources by the plants that use natural gas, coal and oil is higher than 70% of the total emergy to produce energy.

Fig. 2b shows the sustainability lines for the values 1 and 5, along with the representation of the energy production systems. The systems using non-renewable

Table 5
Summary of the results from [18], the study of four energy production systems[a] considering environmental services

	Geothermal	Thermoelectric		
		Methane	Oil	Coal
Emergy inputs (10^{18} seJ)				
Renewable	33.6	27.2	312	368
Non-renewable	4.61	268	3320	3050
Purchased inputs	25.7	85.7	2160	1920
Total emergy	63.9	381	5790	5340
Emergy indices				
EYR	2.49	4.44	2.68	2.78
EIR	0.67	0.29	0.59	0.59
ELR	0.90	13.00	17.56	13.50
SI	2.76	0.34	0.15	0.20

[a] The production scale of each plant is shown in Table 6.

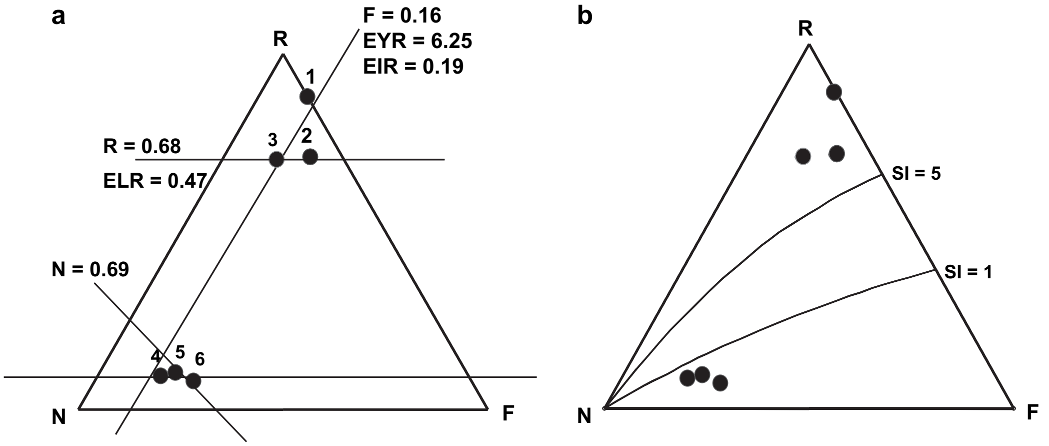


Fig. 2. Representation of six electricity production systems with the goal of presenting emergetic ternary diagrams. (a) The use of resource flow lines and (b) the use of sustainability lines. Plants: (1) eolic, (2) geothermal, (3) hydroelectric, and thermoelectric supplied by (4) methane, (5) oil and (6) coal.

resources are located below the line SI = 1, while the systems using renewable resources are located above the line SI = 5. As pointed out by Brown and Ulgiati [17], SI indices of less than 1 appear to be indicative of processes that are un-sustainable, in the long run, while processes with long range sustainability have SI indices greater than 5. As the eolic plant, located closer to the *R* apex, offers very high SI value (SI ≅ 48), the diagram makes clear that even in comparison with the hydroelectric and geothermal plants, the eolic plant has longer term sustainability.

When the requirement for environmental services to effectively recycle emissions is considered, a careful analysis of the environmental area that is required to absorb, dilute and process the undesired by-products is needed [18]. This area contains environmental systems and the storage of chemical and heat by-products from the production system. Environmental services required (R_2) for the dilution and abatement of emissions are assumed as the interaction of environmental systems and these emissions. The environmental services required were quantified as the renewable emergy necessary to drive the dilution process and environmental services were accounted for the amount of air that is required to dilute the emissions. The emergy value of required environmental services, R_2, was determined and included in the index calculations, as shown in Eqs. (1)–(4),

$$\mathrm{EYR}=\frac{R_1+R_2+N+F}{F+R_2} \tag{1}$$

$$\mathrm{EIR}=\frac{F+R_2}{N+R_1} \tag{2}$$

$$\mathrm{ELR}=\frac{N+F+R_2}{R_1} \tag{3}$$

$$\mathrm{SI}=\frac{\dfrac{Y}{F+R_2}}{\dfrac{N+F+R_2}{R_1}} \tag{4}$$

where R_1 represents renewable resources and R_2, gives a measure of the environmental services for the dilution and abatement of emissions, in units of emergy.

Ternary diagrams representing the systems under this approach are shown in Fig. 3, for the geothermal and the thermoelectric plants. All diagrams illustrate that, as a consequence of including environmental services, a lower sustainability is obtained for each investigated process when compared to evaluations that do not include them.

The requirement for environmental services to effectively recycle emissions translates into the need for

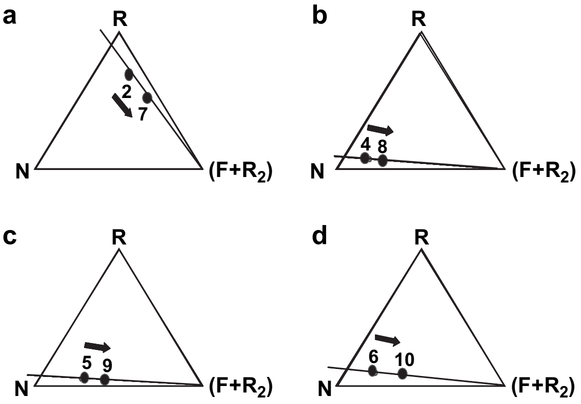


Fig. 3. Representation of four electricity production systems with the goal of producing ternary diagrams, and the use of sensitivity lines, where (a) represents the geothermal plant and (b), (c) and (d) represent the thermoelectric plants, supplied by methane, oil and coal, respectively. Points (2), (4), (5), and (6) do not include R_2. Points (7–10) include the environmental services to dilute and abate process emissions.

a suitable support area for each process. The shift of the points that represent each system on the sensitivity lines is in agreement with the equations proposed by the authors [18]. Accordingly, the shift towards the bottom of the diagrams clearly indicates an increase in the environmental loading of all four systems.

Ternary diagrams offer an additional possibility for emergy analysis (Figs. 4 and 5). Fig. 4 shows the symergy point, which represents the composition of all six electricity production systems, as they are presented in the papers studied [17,18]. The ternary diagram shown in Fig. 5 includes a weighting factor considering the Italian electricity production matrix; each system was associated to a weighting factor equivalent to the production of electricity by each type of electricity production system in Italy in 2003 [19]. The production capacity of each plant and the percentage of each type of production in Italy are shown in Table 6.

As it can be observed with the use of the ternary diagram (Fig. 4), the resulting system, based upon the six electricity production systems, presents an SI = 1.5, indicating that this set of systems is characterized with medium run sustainability, but makes sustainable contributions to the economy [17]. The location of this point in the diagram also supplies information about the environmental loading of the sector (ELR = 2.9) and of the fractions invested from renewable (%R = 25), non-renewable (%N = 20) and economic sources (%F = 55).

As it can be observed, the resulting system (Fig. 5), associated to the six energy production systems, presents an SI = 0.5, indicating that this set of systems is not sustainable in the long run [11]. The location of this point in the diagram also supplies information about the environmental loading of the sector (ELR = 11.3) and of the fractions invested from renewable (%R = 8.0), non-renewable (%N = 71.0) and economic sources (%F = 21.0).

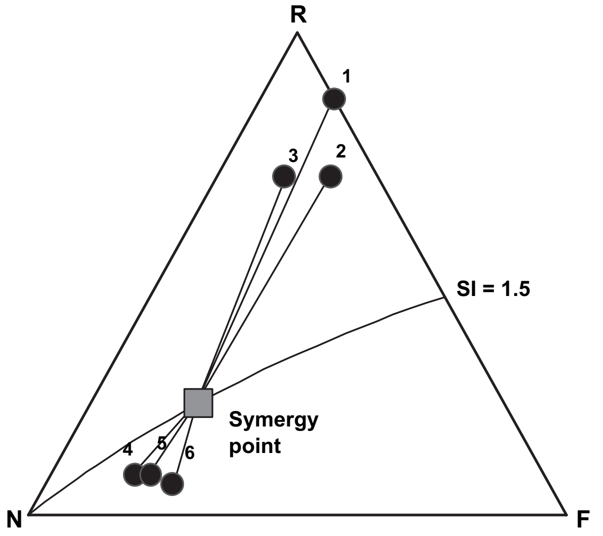


Fig. 4. Representation of the symergic point weighted by megawatt of electricity produced: (1) eolic, (2) geothermal, (3) hydroelectric and thermoelectric, (4) methane, (5) oil, and (6) coal.

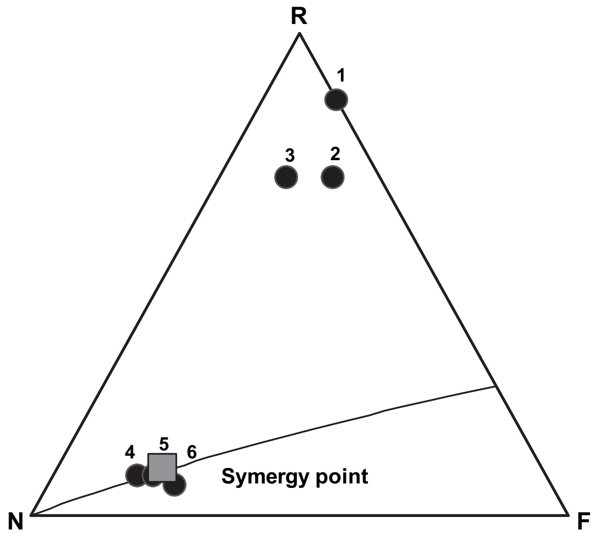


Fig. 5. Representation of the symergic point weighted by Italian electricity production matrix: (1) eolic, (2) geothermal, (3) hydroelectric and thermoelectric plants supplied by (4) methane, (5) oil, and (6) coal.

3.2. Example #2: monitoring patterns of sustainability in natural and man-made ecosystems

The chosen paper [13] emphasizes that emergy-based indices can be usefully applied to monitor the system's oscillations, to forecast the system's behavior and to adopt suitable policy measures to drive it onto a more sustainable path, since monitoring past trends should help to plan future development. For this, the authors [13] introduce exploit functions, $\upsilon = N/F$ and $\eta = R/F$ plotted against the indices ELR, EYR and SI in order to monitor or simulate conditions where the amount of inputs is changed. The resulting three-dimensional plots were used to evaluate the amount of investment required to exploit a local renewable or non-renewable resource, providing additional information about the indices.

Table 6
Electricity production of each plant and their contribution to the Italian production

	Electricity production (MW) [17]	Italian production matrix (%) [19]
Eolic	2.5	0.3
Geothermic	20.0	0.8
Hydroelectric	85.0	27.7
Thermoelectric		
Methane	171.0	4.5
Oil	1280.0	33.4
Coal	1280.0	33.4

Among the examples presented in the paper, the trend of emergy indices in U.S.A corn production since 1945–1994 was selected. The exploit function η as well as the SI followed over this period reveal that corn production had a very steep decrease until the end of the 1980s, then it slowed to a nearly stable level, with SI at about 0.37–0.34. The N/F ratio increased until the end of the 1980s and stabilized at about 0.3.

To introduce the data on the ternary diagram, the values of N, R and F, were calculated from the values of υ, η and $\%R$, defined as the fraction of renewable to total emergy use (Table 7).

The ternary diagram that represents the U.S.A corn production between 1945 and 1994 is shown in Fig. 6.

The decrease in the SI index can be readily noticed, as well as its stabilization after 1980. The observation of the diagram brings also additional information. The resource line $F = 0.6$ evidences that the economic investment did not change substantially over the years. The emergy yield ratio and the emergy investment were maintained at about 1.6 and 1.5, respectively. Despite economic investments of approximately 60% during the whole period, the environmental loading increased more than 20% and the fraction of the renewable resources decreased from 0.40 to 0.18, reducing the SI value approximately three times.

The use of ternary diagrams allows monitoring systems over time. Unfortunately, a decreasing trend was observed in the present example, which clearly shows that the technological changes to increase productivity not always lead to the sustainability of the process. However, assessing sustainability with the use of ternary diagrams permits one to anticipate or simulate the system's behavior according to changes in its driving forces.

3.3. Example #3: importance of the *Bradhyrizobium japonicum* symbiosis for the sustainability of soybean cultivation

This paper evaluates how sustainability of a soybean crop in south Tuscany (Italy) is increased using the specific bacterial inoculation to satisfy, through fixation, the nitrogen requirements of the crop used [20]. The study of this agricultural activity and its interaction with the environment requires emergy indicators to assess not only productive and economic factors, but also environmental impact and ecological effects. Soybean cultivation was studied with two options: (1) utilization of chemical fertilizers to supply nitrogen needs as was often done in the past, and as a viable present alternative and (2) the symbiotic activity of *Bradyrhizobium* bacteria, given as inocula, to cover all nitrogen needs. The results of this work are compared with literature data [21,22]. The values of EYR, EIR and SI shown in Table 8 were taken from Ref. [20] and the values of $\%R$, $\%N$, and $\%F$ were then calculated.

Table 7
Exploit functions, SI index, $\%R$ and relative values of N and F for U.S.A corn production (1945–1994) [13]

	N/F	R/F	SI	$\%R$	$\%N$	$\%F$
1945	0.04	0.68	1.12	0.40	0.024	0.588
1950	0.14	0.65	1.02	0.36	0.078	0.554
1954	0.18	0.56	0.83	0.32	0.103	0.571
1959	0.24	0.50	0.70	0.29	0.139	0.580
1964	0.28	0.45	0.61	0.26	0.162	0.578
1970	0.29	0.37	0.48	0.22	0.172	0.595
1975	0.37	0.39	0.50	0.22	0.209	0.564
1980	0.32	0.29	0.35	0.18	0.199	0.621
1989	0.30	0.28	0.34	0.18	0.193	0.643
1994	0.23	0.28	0.34	0.19	0.156	0.679

Fig. 7a shows the representation of the soybean cultivation with chemical fertilizers (1), which presents an SI = 1.6 and with bacteria inoculation (2), SI = 2.5. The SI index for both soybean management scenarios is greater than 1 and is higher than those of all the other crops, except that of forage (Tuscany) (Fig. 7b).

The sensitivity line (S_F) that passes through points 1 and 2 shows that the main difference between both the types of soybean cultivation is due to the contribution of purchased inputs. Approximately 5% of renewable and 3% of non-renewable resources composes the resources used to cultivate soybean, for both production processes. The increase in the sustainability index is due to the economic investment or the substitution of chemical fertilizer by the inoculums.

Both the types of soybean cultivation have a quite low environmental impact in comparison with other Tuscan and Italian crops, which is readily noted by the location of points (1) and (2) in relation to the R apex.

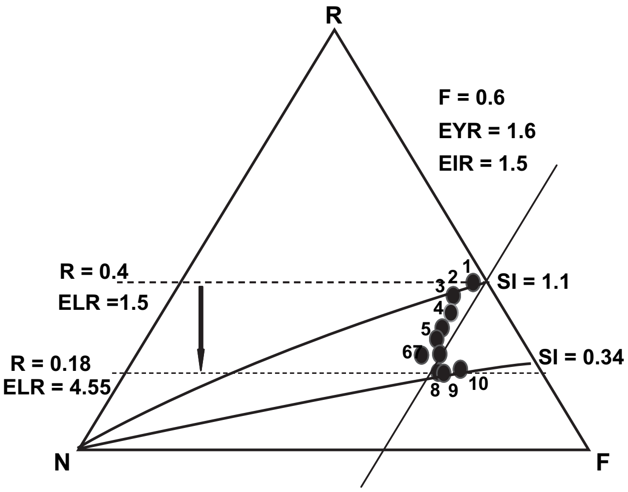


Fig. 6. Ternary diagram representing U.S.A corn production (1945–1995), where (1) 1945, (2) 1950, (3) 1954, (4) 1959, (5) 1964, (6) 1970, (7) 1975, (8) 1980, (9) 1989, and (10) 1994.

Table 8
Emergy indices for soybean crop under different cultivation methods and for other agricultural products [20–22]

	ELR	EYR	SI	%R	%N	%F
Non inoculated soybean	1.22	1.98	1.62	0.450	0.044	0.505
Inoculated soybean	0.93	2.32	2.49	0.518	0.051	0.431
Corn (Italy)	5.63	1.19	0.21	0.151	0.009	0.840
Corn (Tuscany)	2.47	1.53	0.62	0.288	0.058	0.654
Sunflower (Italy)	27.88	1.04	0.04	0.035	0.004	0.962
Sunflower (Tuscany)	1.89	1.64	0.87	0.346	0.044	0.610
Cereal (Tuscany)	3.02	1.33	0.44	0.249	0.001	0.750
Forage (Italy)	1.45	1.76	1.21	0.408	0.024	0.568
Forage (Tuscany)	0.64	2.57	4.02	0.610	0.001	0.389

The environmental loading is lower than that of corn, sunflower, cereals, and forage (Italy) and the ELR for forage cultivated in Tuscany is 30% lower than that for the inoculated crop. The value of the EYR, around 2, suggests a reasonably good exploitation of the local resources for both systems. The ternary diagram offers additional information to complete the analysis. All 9 systems studied use similar quantities of non-renewable resources, from 0.1% to 5.8% (Fig. 7b). Thus, the main difference between systems lies on the use of renewable (3.5%–51.8%) and purchased resources (39%–96%).

The sustainability index also varies substantially from 0.04 (sunflower) to 4.02 for forage (Tuscany). As the contribution of non-renewable resources is about the same, the variation in the SI values is due to the balance between renewable and purchased inputs. In this way, the systems that better work with the environment, that is, have higher EYR, and will have a higher SI index.

3.4. Example #4: urban ecosystems, energetic hierarchies, and ecological economics of Taipei metropolis

Emergy analysis was applied to evaluate resource flows to and from the urban and economic systems in order to classify urban ecosystems within Taiwan [23]. The overall purpose of this work was to extend the results of the Taipei urban system analysis to generate insights on how to plan for an ecologically sustainable urban development. The study presents revised data from 1960, 1970, 1980, and 1990 used to gain a perspective on the evolving pattern of emergy uses in Taiwan. Table 9 summarizes the resource inflows of Taiwan [24] and the respective index for each year calculated by the authors [24].

Fig. 8 presents the ternary diagram constructed with Taiwan's inputs. As the total emergy of the country has increased over the four decades, the size of the points was adjusted to represent this increase, that is, points' sizes are proportional to the value of the total emergy (Y) relative to each year. Subscripts used below correspond to the respective year, for example $\%R_{60}$ refers to the percentage of renewable inputs of 1960.

The fraction of renewable inputs decreased four times along the decades ($\%R_{60} = 43.2\%$, $\%R_{70} = 29.4\%$, $\%R_{80} = 12.4\%$ and $\%R_{90} = 10.0\%$), the fraction of non-renewable resources decreased in a low rate ($\%N_{60} = 41.7\%$, $\%N_{70} = 32.0\%$, $\%N_{80} = 16.7\%$, and $\%N_{90} = 18.8\%$), but the fraction of purchased inputs increased substantially ($\%F_{60} = 15.1\%$, $\%F_{70} = 38.6\%$, $\%F_{80} = 70.9\%$, and $\%F_{90} = 71.2\%$).

The location of the points in the diagram shows the evolution of the country and is in agreement with the history of its economic system. In 1960, Taiwan was a less developed country; its economic development was carried out mainly through U.S.A aid. The contribution of renewable emergy (R) to the entire ecological economic system was equivalent to 43% of the total emergy. On the other hand, the percentage of the imported emergy was only 15% of the total emergy. The sustainability index $\mathrm{SI}_{60} = 5.03$ showed a good exploitation of the local resources against a low environmental load ratio. During the 1970s, in order to

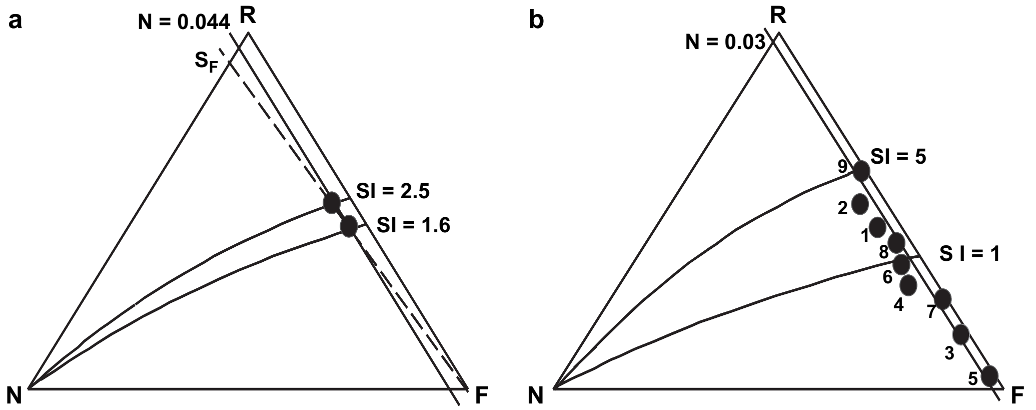


Fig. 7. Ternary diagram representing (a) soybean production with chemical fertilizer (1) and with bacteria inoculation (2) and (b) other agricultural products (3) corn (Italy), (4) corn (Tuscany), (5) sunflower (Italy), (6) sunflower (Tuscany), (7) cereal (Tuscany), (8) forage (Italy), and (9) forage (Tuscany).

Table 9
Resource inflows of Taiwan from 1960, 1970, 1980, and 1990 [24] and the respective calculated index for each year considered

	1960	1970	1980	1990
Emergy inputs (10^{22} seJ)				
Renewable	2.13	2.13	2.13	2.13
Non-renewable	1.05	2.32	2.86	4.02
Purchased	0.745	2.79	12.2	15.2
Total emergy	4.93	7.24	17.2	21.4
Emergy indices				
EYR	6.61	2.59	1.41	1.40
EIR	0.18	0.63	2.44	2.48
ELR	1.32	2.40	7.06	9.04
SI	5.03	1.08	0.20	0.16

expand the foreign trade, Taiwan increased the quantities of imported and exported flows to a level three times greater than in 1960. The sustainability index decreased to $SI_{70} = 1.08$, indicating that the development policy led the country to a condition in which sustainability, in a long term, was not more possible. In 1980 and 1990, the country was classified as a highly industrialized country, with SI index equal to 0.20 and 0.16, respectively.

The ternary diagram shows that the transition of Taiwan from a less developed condition to a highly industrialized country in 1980 occurred by means of a huge economic investment, while the proportion between renewable and non-renewable inputs remained practically the same. From 1980 to 1990, the fraction of purchased inputs remained at about 71%, but there was a decrease in renewable inputs and an increase in non-renewable inputs causing a small decrease in the sustainability index.

Since the country area is the same, the increase in the total emergy represented by the size of the points also shows a greater activity between 1960 and 1990, that is, an increase in the EmPower density, indicative of the system's auto organization process.

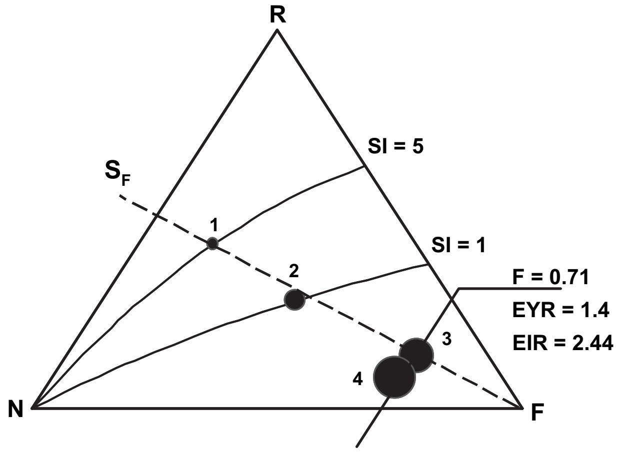


Fig. 8. Ternary diagram representing Taiwan from 1960 (1), 1970 (2), 1980 (3), and 1990 (4).

3.5. Example #5: emergy evaluation of three cropping systems in southwestern Australia

In this study [25], an annual cropping system was compared with two novel systems designed to address the threats to the ecological sustainability of annual plant-based farming systems in southwestern Australia, in terms of their use of renewable indigenous resources, their use of non-renewable indigenous resources, their purchased inputs of energy and materials, and their profitability. The farming systems were an annual lupin/wheat crop rotation, a plantation of the fodder tree tagasaste and an alley cropping system in which the lupin/wheat rotation was grown between spaced rows of tagasaste trees. Flows of energy and materials between the environment and the economy were identified for each farming system and the natural and human activity involved in generating inputs as goods or services was then valued in terms of the equivalent amount of solar energy required for their production.

The results showed that the two largest energy flows in the conventional lupin/wheat cropping system were wind erosion and purchased inputs of phosphate ($\%R = 0.15$ and $ELR = 5.5$). The renewable component of production was 15% of total flows in the lupin/wheat system, 30% in the alley cropping system ($\%R = 0.3$ and $ELR = 2.3$) and 53% in the tagasaste plantation ($\%R = 0.53$ and $ELR = 0.7$). The annual net income from the plantation system was nearly four times higher, and from alley cropping 45% higher, than from the lupin/wheat rotation. This analysis suggested that once the two agro forestry systems were fully established, the tagasaste plantation was the most efficient at transforming natural resources into goods and services and the most profitable, while the lupin/wheat system was the least energy efficient and the least profitable. Table 10 summarizes the resource inflows of the three systems calculated from the indices presented in Ref. [25].

The ternary diagram shows the three farming systems studied (Fig. 9). Among them, the annual lupin/wheat crop rotation presents the lowest sustainability index ($SI = 0.58$) and the lowest fraction of renewable inputs ($\%R = 15.5\%$), while the highest sustainability index is associated to the plantation of the fodder tree tagasaste ($SI = 3.1$) with a fraction of renewable inputs greater than 50%. The alley cropping system lies in an intermediary position with $SI = 0.99$ and $\%R = 30.2\%$ (Fig. 9a).

Despite of the higher sustainability index obtained for the tagasaste plantation, it is worthy to note that the change from the simple lupin/wheat rotation to the alley cropping system is beneficial, since the second has a sustainability index practically equal to 1, which means that this alternative form to obtain lupin and wheat has the possibility to sustain itself for longer

Table 10
Emergy indices and the calculated resource inflows of the farming systems: annual lupin/wheat crop rotation, plantation of the fodder tree tagasaste and alley cropping system in which the lupin/wheat rotation was grown between spaced rows of tagasaste trees [25]

	Lupin/wheat	Tagasaste	Alley cropping
Emergy inputs (10^{14} seJ)			
Renewable	2.88	6.26	3.81
Non-renewable	9.88	1.24	3.25
Purchased	5.84	4.27	5.55
Total emergy	18.6	11.8	12.6
Emergy indices			
EYR	3.18	2.76	2.27
EIR	0.46	0.57	0.79
ELR	5.46	0.88	2.31
SI	0.58	3.14	0.99

periods than the simple rotation. On the other hand, the need for purchased inputs to operate the alley system is about 15% higher than that needed for lupin/wheat rotation (Fig. 9b). The higher need of purchased inputs reflects on the value of the environmental yield ratio, which indicates that the alley cropping system, despite a higher sustainability index, uses local resources less efficiently than the lupin/wheat rotation system in relation to the economic investments that they need.

4. Discussion and concluding remarks

Adopting emergy-based ternary diagrams expands the understanding of the actual contribution of given inputs and the global sustainability of production processes and especially industrial sectors. Ternary diagrams allow one to rank and to assess significant differences that can be immediately evaluated. The use of the triangle based on emergy accounting and emergy indices to assess production processes and industrial sectors permits one, not only to evaluate the actual situation of a given process, but also to identify critical parameters that may be changed to improve the environmental performance of the whole system. For example, the location of the six energy production plants in the diagram makes it clear that the group formed by the plants that use fossil fuels is non-sustainable and that the Italian policy for energy should support the other three forms of electricity. It is also evident that the economic investment (F) needed by both groups of plants, based upon fossil and non-fossil energy, is similar.

The emergetic triangle properties, especially the sensitivity lines and the symergic point, complement the emergy-based analysis and permit monitoring the present state of a system by means of well-defined sustainability indicators and forecasting the system's behavior according to changes in its driving forces. The prompt characterization of products, processes or regions in the diagrams, as was observed by means of the example concerning the resource inflows of Taiwan, shows how the change in a single parameter (in this case the fraction of purchased inputs) can influence the condition of the system being studied.

With the use of sensitivity lines, one can assess a process, identify the main driving force to enhance its sustainability, diminish the environmental loading and evaluate the need of economic investment or change of inputs. It is possible to follow the effects of any economic or technological change and to determine the real consequences of these actions. For example, if emergy is invested in removing emissions using technology, this emergy can be accounted and the position of the point will change in the interior of the triangle. The analysis of the introduction of *B. japonicum* into soybean crops in Tuscany illustrates this point. Analogously, if environmental services are needed to absorb and dispose of the emissions, performance of a production process becomes more time and location dependent. When the free services of the environment are accounted for [18], a shift of the point in the diagram

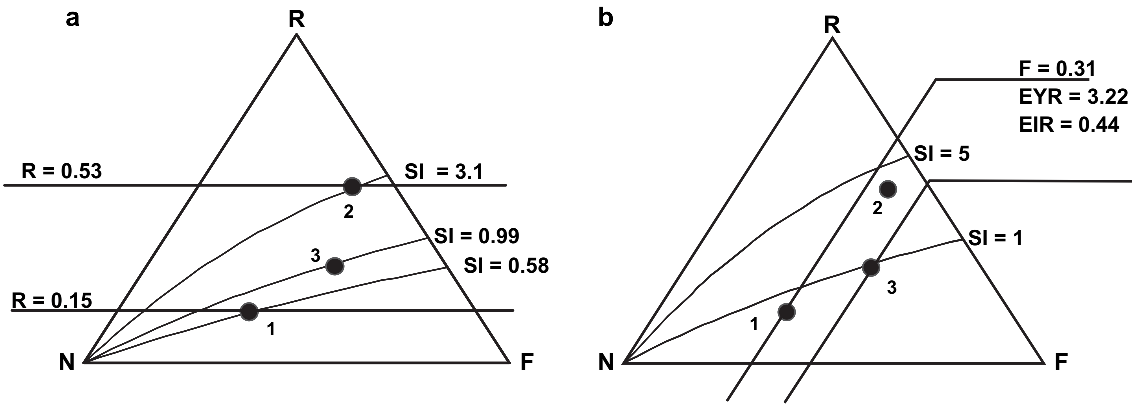


Fig. 9. Ternary diagram representing the farming systems: (1) annual lupin/wheat crop rotation, (2) alley cropping system in which the lupin/wheat rotation was grown between spaced rows of tagasaste trees, and (3) plantation of the fodder tree tagasaste.

is also noticed, showing the actual condition of the system under evaluation (see Section 3.1).

The introduction of the symergic point permits one to go further. The calculation of the symergic point, taking into account the production capacity of each component of an industrial sector, permits one to evaluate not only the sector as a whole, but also to identify the processes with inferior environmental performance and the areas where investment is necessary for making improvements. The best alternatives can be simulated and analyzed. This is clearly shown in the case of the six electricity production plants, in which it was possible to consider the Italian matrix of electricity production and how it may be changed to a more sustainable system.

Emergy-based ternary diagrams may be seen as progress compared to methods that result in a list of interventions or an impact score profile. Such a tool for graphical analysis allows a transparent presentation of the results and may serve as an interface between emergy scientists and decision makers, provided the meaning of each line in the diagram is carefully explained and understood. In the decision-making process regarding sustainability of economic development, governments and society will have a powerful tool to establish policies and to choose alternatives concerning the environment.

Acknowledgements

Financial support from Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP and from Vice-Reitoria de Pós Graduação e Pesquisa – UNIP, are gratefully recognized. Special thanks are addressed to Dr. Corrado Giannantoni (ENEA, Italian Agency for New Technology, Energy and Environment) for his valuable comments and to Dr. Silvia H. Bonilla (UNIP, Universidade Paulista) for important contributions.

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