

GRAPHICAL TOOL FOR EMERGY ANALYSIS: CONCEPTS AND AN EXAMPLE OF APPLICATION

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ABSTRACT

Emergy analysis is commonly performed through a sequence that includes drawing energy flow diagrams and the construction of emergy tables. In view of the quantity and of the diversity of data in emergy tables, the interpretation of the results may be not always clear or easy. This work presents a graphical tool that allows clear and uniform representation of emergy based indicators with the aid of ternary diagrams. Ternary diagrams make possible the immediate visualization of the results of emergy analysis and the comparison between different systems or different moments of the same system. Besides exploring the intrinsic information of emergy accounting, the graphical tool allows the use of two additional approaches to assist and complement emergy analysis: (i) sensitivity and (ii) synergy of emergy (called herein symergy; meaning synergy of emergy) denominated, in this work, tool's functionalities. It is also possible to define areas in the diagram that characterize any product or process in relation to the sustainability index: (i) region of long term sustainability, (ii) region of short term sustainability and (iii) region of non sustainability. To illustrate the use of the graphical tool, a case study found in the literature (Brown, M.T.; Ulgiati, S. Emergy Evaluations and Environmental Loading of Electricity Production Systems. Journal of Cleaner Production, v.10, p.321-334, 2002) is employed.

1. INTRODUCTION

The use of conventional economic analysis for decision-making including environmental issues, in spite of being usually accepted, doesn't contemplate intangible benefits and costs. The evaluation of environmental aspects is quite complex and must consider a great number of factors, some of which cannot be appraised by traditional economic analysis, since it is very difficult to establish monetary values to intangible costs and benefits, such as the value of natural resources or the cost for the environment to absorb pollutants. Therefore, it is at least inconsistent to establish economic analysis as a tool to evaluate environmental issues. The environmental evaluation based on emergy analysis takes into account the exploitation rate of natural resources, the efficient use of these resources and the environmental support capacity [1]. The indicators that result from emergy analysis reflect the contribution of the economic system as well as the contributions of the environment [2-3]. These indicators can be used to assess the relationships between components of productive systems and the resources used for obtaining a given product, as they depend on the fraction of renewable and non-renewable inputs and consider the locally available inputs and those imported from outside the system. In this way, valuable information is obtained about the development and the operation of anthropogenic systems, taking into account the carrying capacity of the environment. Assuming there are no co-products, which will violate input-output balance conventions, emergy analysis can also evaluate the thermodynamic efficiency of the system, the quality of the input flows and yield of any production system and especially the interaction between the system and the surrounding environment.

Several complementary studies have been accomplished [4-15], which consolidate the

importance of energy analysis and its indicators [16]. New indices and approaches have been proposed for different processes [17, 10-14, 18-20] expanding the importance of energy analysis, but at the same time generating more analytic complexity. In this work, the use of a graphic tool [21-22] is proposed to represent energy-based indices obtained from the assessment of ecological and man-made systems. The tool, developed in Visual Basic for applications, is based on phase diagrams or three components diagrams, widely used to describe equilibrium situations in which two or more phases of matter exist together in pure substances or in solutions [23], especially in the fields of metallurgy, materials science, geology, and physical chemistry. The clear and uniform representation of energy data with the aid of phase diagrams allows visualization of the results of energy analysis and comparison of different systems or time series evaluations of the same system. Moreover, the use of ternary diagrams allows users to explore their intrinsic properties [23] and to add two new approaches to energy analysis: the sensitivity and the synergy (synergy of energy, discussed below in the text). It is demonstrated that the interpretation of the results is facilitated with the use of the graphic tool, assisting decision-making.

2. METHOD

Ternary diagrams offer a very efficient graphical representation for the characterization of systems, which can be described with three variables [23]. This method, extensively used in physical sciences, is based on the geometric properties of equilateral triangles. Most commonly, three fractions or proportions add to 1 (corresponding to the height of the triangle), or three percents add to 100 as presented in the figure 1a. 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 the diagram. The main properties of these diagrams are the **sum of the coordinates**; the **composition of mixtures** and the **proportionality**, as shown in Figures 1b, 1c and 1d.

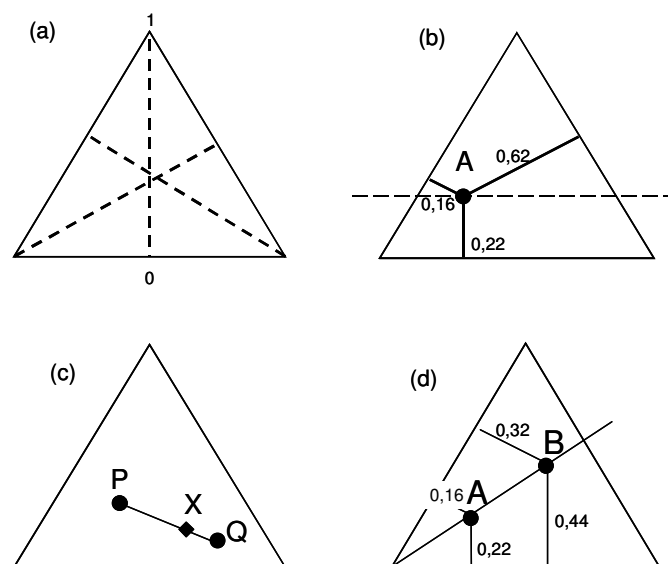


Figure 1. Geometric properties of emergent triangular diagrams: (a) dashed lines indicate the unitary heights; (b) the sum of perpendicular lines joining each side of the triangle to point A equal 1.0, the height of the triangle. These perpendicular lines define the point A coordinates. The dashed line, parallel to the side of the triangle, shows all points that have the same coordinate value of point A (0.22); (c) the combination between points P and Q would be represented in a point laying at any point of segment PQ. Point X shows one of the possibilities of combination. (d) any point on the line that passes through an apex would maintain the proportionality between the perpendicular joining the point to the sides of this apex. Points A and B show the proportionality ($0.16/0.22 = 0.32/0.44$)

A graphical tool that allies the properties of the equilateral triangle and the emergy concepts was developed in Microsoft Excel 2002 (10.2614.3501) SP-1, using the graphic capacities of Visual Basic for Applications 6.3–version 9108–VBA: Retail 6.3.0863 Forms3: 2.01. The tool is composed by two modules: (i) Data Input and (ii) Configuration and Triangular Diagram. Both modules are presented in the figure 2.

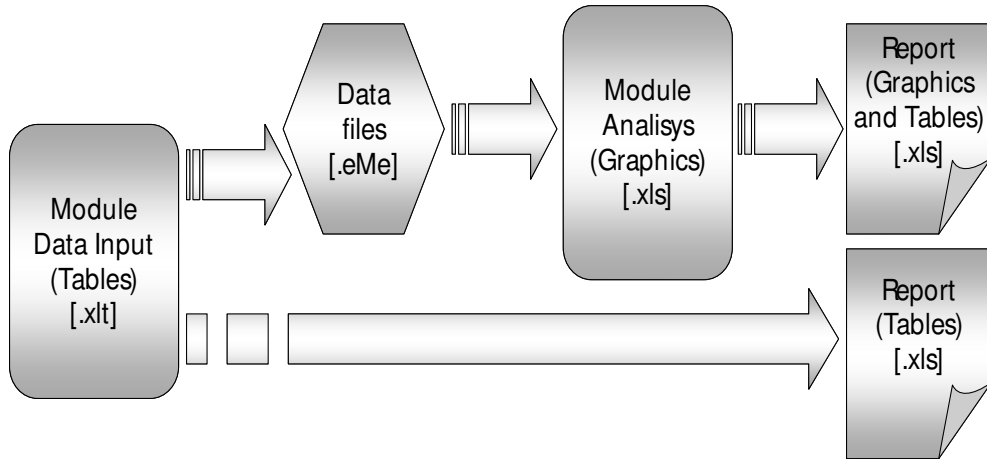


Figure 2. Software modules

The emergy values of renewable (R), non-renewable (N) and economic (F) resources were defined with their relative values in relation to the output of the system (Y), according to Eqs. 1.

$$(a) \bar{R} = \frac{R}{Y} \quad (b) \bar{N} = \frac{N}{Y} \quad (c) \bar{F} = \frac{F}{Y} \quad (d) \bar{Y} = \frac{Y}{Y} = 1 \quad (1)$$

The values of EYR, EIR, ELR and SI don't change with this procedure and can be calculated according to Eqs. 2.

$$(a) EYR = \frac{1}{\bar{F}} \quad (b) EIR = \frac{\bar{F}}{\bar{F}(1-\bar{F})} \quad (c) ELR = \frac{1-\bar{R}}{\bar{R}} \quad (d) SI = \frac{EYR}{ELR} = \frac{\bar{R}}{\bar{F}(1-\bar{R})} \quad (2)$$

Some functionalities of the tool are presented as follows: (i) Lines of constant values of \bar{R} , \bar{N} and \bar{F} , (ii) lines of the sustainability, (iii) lines of sensitivity and (iv) synergy of emergy point (synergic point) (Fig. 3).

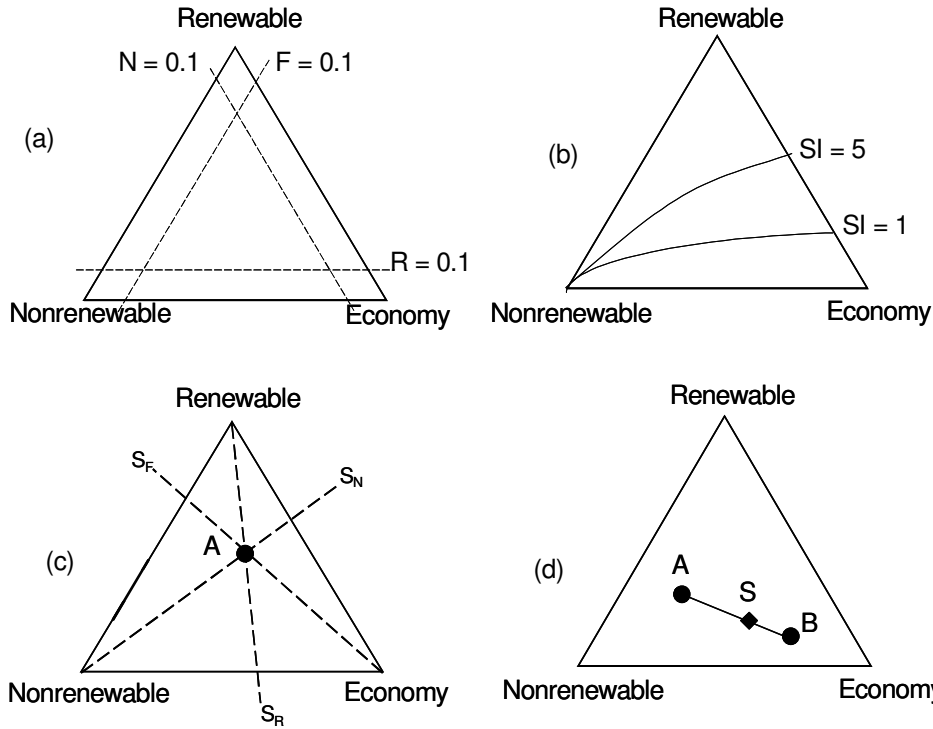


Figure 3. Emergetic triangular diagram properties: (a) Resources, where the line $N = 0.1$ shows the points in the diagram where the percentage of non-renewable resources equals 10% of the total energy. The same reasoning is applied to R and F , regarding renewable resources and purchased inputs, respectively. (b) Sustainability, where the lines SI represent the points in the diagram associated to sustainability indices of 1, 2 and 5 (c) Sensitivity, where point A represent a system composed by R , N and F flows. The line S_F , passing through A , show the points in the diagram where varying the F flow, the proportion between R and N flows remains constant. The same reasoning can be applied to S_R and S_N , which are the sensitivity lines for renewable and non-renewable inputs, respectively. (d) Synergy, where, points A and B represent two systems with their respective fluxes R , N and F . Point S , represent the composition of both systems, that is, if systems A and B were joint, the resulting system would be represented by system S , which can be located at any point of the segment AB . This diagram property can be only applied if the fluxes composing systems A and B are independent

For each line \bar{R} , \bar{N} and \bar{F} there is a selection key to activate or to disable the line. The new functionalities, which were implemented in the analysis tool, are the lines of sustainability. For the synergic point there is a selection key to activate or to disable each one of the inputs. This point represents a “composition / combination” of two or more products or processes. It uses the composition property, Figure 3d and it summarizes the behavior of a system composed by different products or processes. Two calculation methods are possible: the sum of the inputs (Eqn. 3) or a weighted average (Eqn. 4).

$$(a) R_s = \sum_{i=1}^n R_i \quad (b) N_s = \sum_{i=1}^n N_i \quad (c) F_s = \sum_{i=1}^n F_i \quad (3)$$

where R , N and F are the input fluxes associated to point i

$$(a) R_s = \sum_{i=1}^n R_i \times k_i \quad (b) N_s = \sum_{i=1}^n N_i \times k_i \quad (c) F_s = \sum_{i=1}^n F_i \times k_i \quad (4)$$

where R, N and F are the input fluxes associated to point i and k is the weight factor

It is important to clarify that three-component systems thermodynamics use the expression “composition of mixtures” to define the composition of a system composed by the mixture of two or more systems, each of them an independent three-component system. The designation “composition of mixture” does not denote the significance of that is obtained by the combination of two systems accounted by emergy synthesis (constituted each of them of three emergy fluxes). The term synergic seems to be more appropriate as it may denote cooperative, co-acting, coactive and conjoint. Moreover, the same term also can be defined as the combined power of a group of things when they are working together, which is greater than the total power achieved by each working separately. For instance, synergic or synergetic points should represent the result of a combination of two or more industries (supplied by R, N and F fluxes) to compose an industrial sector (supplied by all its industries’ inputs). It is worthy to attention that activities that compose a sector interact forming a network, where each component should be connected with one or more components improving the network efficiency, and promoting competition for a long term empower transformation (observing the Maximum Empower principle). The same reasoning could be applied to environmental systems. In this way, the use of this property of the tool should be limited to the cases in which there is a network formation, and for these reasons, this text employs the terms synergy and synergic denoting the synergy of emergy.

Figure 4 shows the screen for data input. For the graphic presentation, analysis and simulation, the tool operates with two screens.

1	2	A	B	C	D	E	F	G	H	I	J	K
		Ponto	Nome	Item	Descrição	Unidade	Classe	Valor	Transf.	Emergia	Gravar Dados	Resumo
							R/N/F	[XX]	[XX/seJ]	[seJ]	Ler Dados	Tabelas
1	1			1	Renewable energy sources (R)					0.00E+00		
2	1			2	Sunlight		J	5.66E+13	1.00E+00	5.66E+13		
3	1			3	Wind, kinetic energy		J	2.72E+10	1.50E+03	4.08E+13		
4	1			4	Rain, chemical energy		J R	1.88E+10	1.82E+04	2.88E+14		
5	1			5	Rain, geopotential energy		J	9.02E+08	1.05E+04	9.47E+12		
6	1			6						0.00E+00		
7	1			7	Non-renewable sources (internal) (N)					0.00E+00		
8	1			8	Net topsoil loss		J N	1.88E+10	6.25E+04	9.88E+14		
9	1			9						0.00E+00		
10	1			10	Purchased fuels and goods (M)					0.00E+00		
11	1			11	Diesel, gasoline and lubricants		J F	3.05E+08	5.61E+04	1.71E+13		
12	1			12	Electricity		J F	3.60E+06	1.74E+05	6.25E+11		
13	1			13	Phosphate		Kg F	1.29E+01	1.70E+13	2.19E+14		
14	1			14	Pesticides		Kg F	2.72E+08	5.61E+04	1.53E+13		
15	1			15	Seed		J F	1.10E+09	3.48E+04	3.83E+13		
16	1			16	Machinery and buildings		Kg F	1.17E+00	3.00E+12	3.51E+12		
17	1			17						0.00E+00		
18	1			18	Labor and Services (S)					0.00E+00		
19	1			19	Labor		\$ F	1.34E+01	2.40E+12	3.22E+13		
20	1			20	Diesel, gasoline and lubricants		\$ F	2.98E+00	2.40E+12	7.19E+12		
21	1			21	Electricity		\$ F	5.00E-01	2.40E+12	1.20E+12		

Figure 4. Screen for data input

The options offered in the main screen are: visualization of the basic concepts, definitions and the navigation to the triangular diagram screen (Fig 5a). In this screen, dialogue boxes, menus and selective buttons allow one to choose points and lines to be presented in the triangular diagram, to load data, to print reports, to export data and graphics, to visualize information of specific points and to configure the general aspect of the diagram (Fig. 5b).

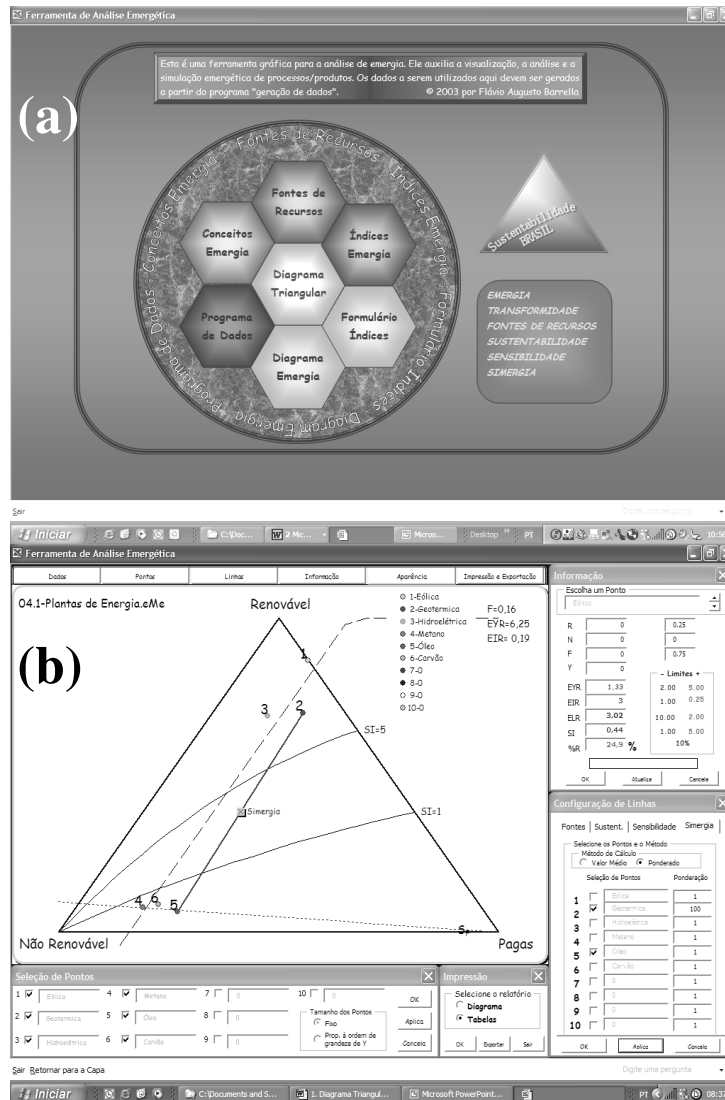


Figure 5. Analysis module screens: (a) Main (b) Diagram

3. THE CASE STUDY

As a first example to illustrate the use of ternary diagrams applied to energy accounting a case study, which evaluates six electricity production systems in Italy, we selected a case study that evaluated six electricity production systems in Italy [1]. The authors divided this case study in two papers. The first compares six different production systems using renewable energy sources (geothermal, hydroelectric, and wind plants) and nonrenewable energy sources (natural gas, oil, and coal thermal plants). The output/input energy ratio as well as the energy-based energy yield ratio (EYR) and environmental loading ratio (ELR) have been used to explore and compare system performances. Generation of CO₂ has also been accounted in order to evaluate a ratio of CO₂ released to CO₂ avoided, according to the fact that renewable power plants do not

require a direct combustion and therefore release a lower amount of CO₂ 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 emissions of each process [2]. 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 carrying capacity is presented. Under this approach, energy based yield indicators may decrease by 40–70% coupled to a parallel increase of a loading indicator, when the environmental services required for the dilution of pollutants are accounted for. As a consequence of including environmental services for waste assimilation, 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.

4. RESULTS

The Figure 6 presents the triangular diagram for the six electric power plants [1]. In this diagram, the plants of electric power that use different sources of energy (Eolic, Geothermal, Hydroelectric, Methane, Coal and Oil) were identified. It is clear that they form two different groups, the first formed by the electric power plants using eolic, geothermal and hydroelectric resources, which use non-fossil energy. The second group is formed by the electric power plants that use fossil fuels (methane, oil and coal).

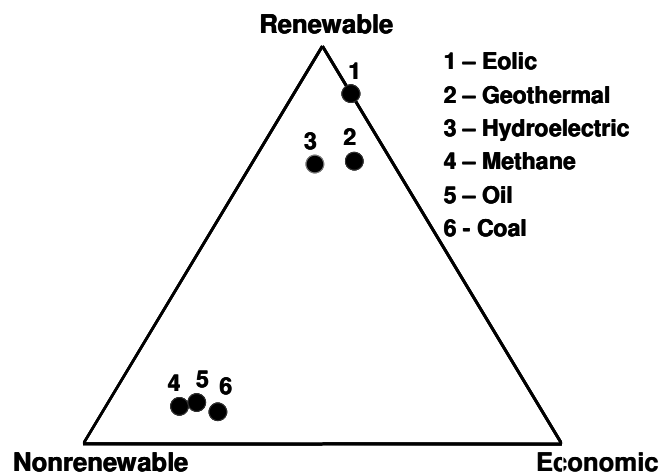


Figure 6. Representation of six electricity production systems with the aim of emergetic ternary diagrams

The complementary article analyzed [2] accounts for the environmental services required to absorb and to dilute the by-products of the electric power plants. The mitigation strategies to suppress the by-products consider that as the economic investment in treatment processes for elimination of undesirable emissions increases, the service of the environment to dilute or to absorb these emissions will decrease. In this way, this service should be accounted together with the economic resources [2]. The indices EYR, EIR, ELR and SI under this point of view are calculated by Eqs. 5, where the renewable resources are represented by R_1 and the necessary resources to absorb and to dilute the undesirable co-products are represented by R_2 .

$$(a) \text{ EYR} = \frac{R_1 + R_2 + N + F}{F + R_2} \quad (b) \text{ EIR} = \frac{F + R_2}{N + R_1} \quad (c) \text{ ELR} = \frac{N + F + R_2}{R_1} \quad (d) \text{ SI} = \frac{\frac{Y}{F + R_2}}{\frac{N + F + R_2}{R_1}} \quad (5)$$

The triangular diagram, considering the services of the environment is presented in the Figure 7, where the shift of the points can be observed when the environmental services are considered for absorption and dilution of the co-product.

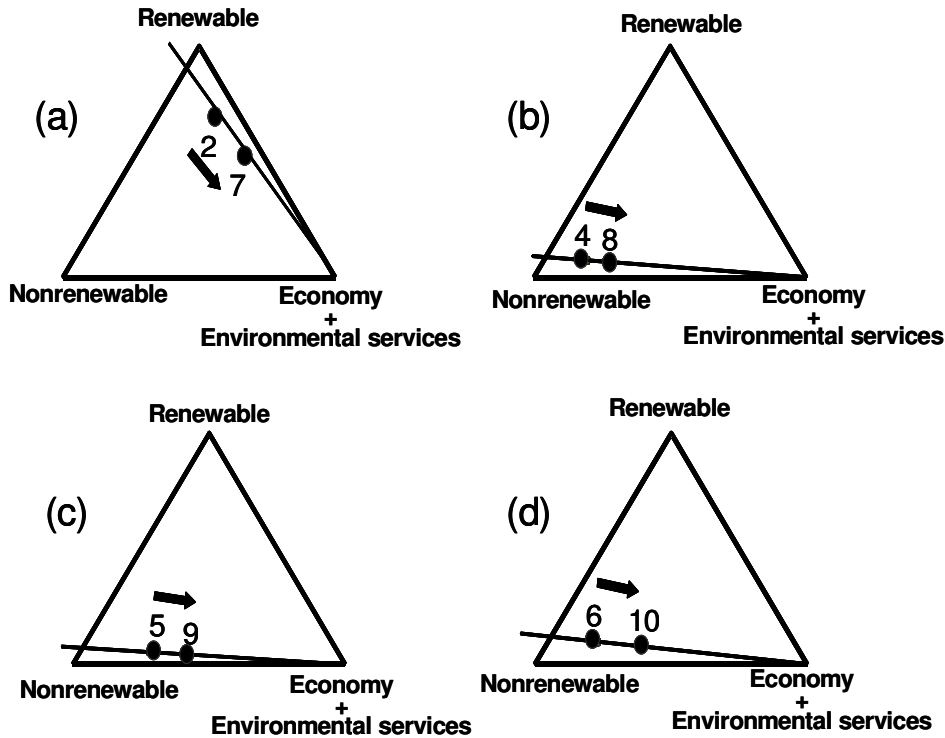


Figure 7. Representation of four electricity production systems with the aim of ternary diagrams, and the use of sensitivity lines, where (a) represents the geothermal plant (point 2) and (b), (c) and (d) represent the thermoelectric plants, supplied by methane (point 4), oil (point 5) and coal (point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

Another possibility of analysis offered by triangular diagram is presented in the Figure 8. Figure 8a represents the synergic point for the production of electric power of each plant per MW (column 2, table 1), that is, the energetic density per unit of energy production. As can be observed with the ternary diagram, the resulting system, composed by the six energy production systems, presents an $\text{SI} = 1.5$, indicating that this set of systems is characterized with medium run sustainability, but has sustainable contribution to the economy [1]. In figure 8b, the Italian matrix for energy production [24] (column 3, table 1) was considered. As it can be observed, the resulting system, associated to the six energy production systems, presents an $\text{SI} = 0.5$, indicating that this set of systems is not sustainable in the long run [1].

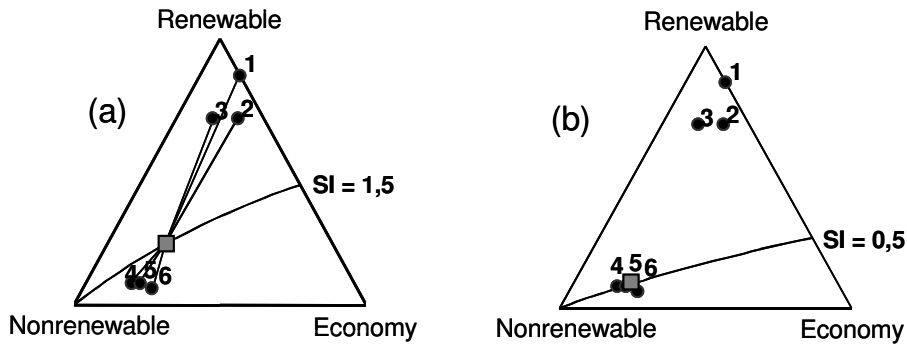


Figure 8. Synergic point (a) Weight by MW. (b) Weight by Italian energetic matrix

Table 1. Weight factors for electric production units

Type of power plant	Production / (MW)	% Electricity production (Italian matrix)	Weighting factor / (MW^{-1})
Eolic	2.5	0.3	0.400000
Geothermic	20.0	0.8	0.050000
Hydroelectric	85.0	27.7	0.011765
Fossil fuels		71.2	
Methane	171.0	4.5	0.005848
Oil	1,280.0	33.4	0.000781
Coal	1,280.0	33.4	0.000781

5. DISCUSSION

Figure 9 presents the sustainability lines for the values 1 and 5, along with the representation of the energy production systems. The systems using nonrenewable resources are located below the line $S = 1$, while the systems using renewable resources are located above the line $SI = 5$. As pointed out by Brown and Ulgiati [1], SI indexes of less than 1 appear to be indicative of processes that are not sustainable in the long run, while processes with long range sustainability have SI indexes greater than 5. As the wind 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 wind plant has longer term sustainability.

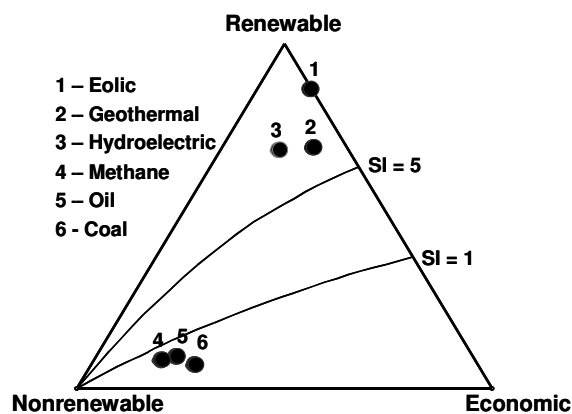


Figure 9. Six power plants with the lines $SI = 1$ and $SI = 5$

The diagram shows also the use of the resource lines (Fig 10). 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 impact that they produce. The diagram shows also that all six systems are located close to the line $F = 0,16$. In this way, it is worthy noting that for both types of energy generation, using either renewable (geothermal, hydroelectric, and wind plants) or nonrenewable resources (natural gas, coal and oil 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 this index between 4,21 and 7,47, indicative of secondary or primary energy sources [1, 2]. 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.

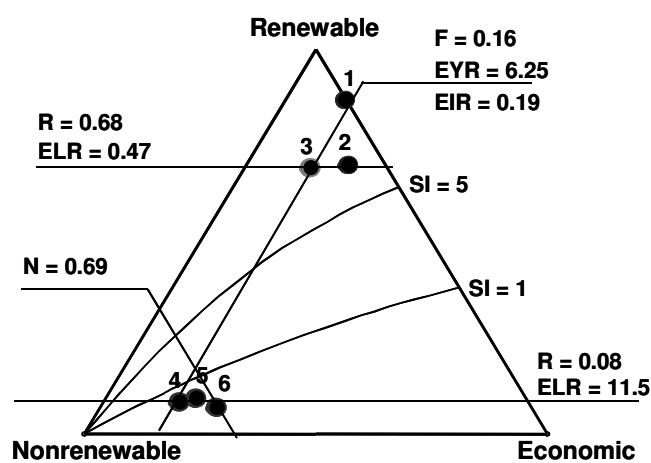


Figure 10. Six power plants with lines R, N e F

The requirement for environmental services to effectively recycle emissions translates into the need for 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 [2]. Accordingly, the shift in direction to the bottom of the diagrams indicates clearly an increase in the environmental loading of all four systems.

The points of synergy, when the unit of electric power production (MW) is considered, is positioned in a point with sustainability index is equal to 1.5 (Fig. 8). It is worth pointing out that the calculations of the sustainability index for the synergic point are only valid when the absolute values of the energy of each resource are used. In the case were the current matrix of energy production of Italy was used, the synergic point has a sustainability index 0.5 in the non-sustainability area. Then, the current Italian system has a simergy point that equates to a sustainability index of 0.5 and should they employ alternative sources of production in the future, the change in simergy point could help to interpreted progress toward sustainability.

6. CONCLUSIONS

Adopting energy based ternary diagrams provides a better visualization 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 energy accounting and energy indices to assess production processes and industrial

sectors permits, 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.

The triangle properties, especially the sensitivity lines and the synergetic point, complement 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. With the use of sensitivity lines, one can assess a process; identify the main driving force that will enhance its sustainability, to diminish the environmental loading and to evaluate the need for economic investment or change of inputs. It is possible to visualize 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 technological solutions, this emergy can be accounted and the position of the point will change in the interior of the triangle. Analogously, if environmental services are needed to absorb and dispose the same emissions, performance of a production process becomes more time and location dependent. When the free services of the environment are accounted [2], a shift of the point in the diagram will be also noticed, showing the actual condition of the system under evaluation. The introduction of the synergetic point permits investigation. The calculation of the synergetic point, taking into account the production capacity of each component of an industrial sector, allows one to evaluate not only the sector as a whole, but principally to identify the processes with inferior environmental performance and areas where investment is necessary. The best alternatives can be simulated and analyzed. 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. Emergy based ternary diagrams may well 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.

ACKNOWLEDGEMENTS

The authors thank the support from Vice Reitoria de Pós Graduação e Pesquisa da Universidade Paulista. The presented tool, still in its initial phase of development, needs to be tested, revised and altered. The tool is available by request to the authors. Any collaboration and criticisms that may help to improve it are welcomed. Special thanks are addressed to Dr. Corrado Giannantoni, Dr. Mark T. Brown and Dr Matt Cohen for their valuable comments.

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