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Sustainable expansion of electricity sector: Sustainability indicators as an instrument to support decision making

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A B S T R A C T

The aim of this paper is to put forward a proposal for a methodology to analyze the sustainability of the expansion of electricity generation. To do so, an approach is needed that takes into account, in an integrated perspective, the technical, socioeconomic, environmental and technological factors of the various alternatives for sector expansion. In this regard, multicriteria analysis (MCA) is proposed as an evaluation tool. It will be applied to a situation that involves the selection of the following expansion alternatives: small hydropowers, wind energy, generation from sugarcane bagasse, biodiesel, urban solid wastes, natural gas and nuclear energy. The methodology involved the development of indicators encompassing technological, environmental social and economic dimensions, for each of the aforementioned expansion alternatives, and the results were very interesting, from a multicriteria point of view, in their capacity to internalize socioenvironmental, technological and economic aspects in the decision making process for electricity generation expansion. It may well prove to be a useful tool for supporting this decision, although efforts are required to standardize the methodology with regard to its evaluation procedures.

Contents

1. Introduction

Energy is an essential vector for the social and economic development of a country and, in addition to the availability and

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reliability of competitive energy supply, it is essential that two other factors are present at the same time to ensure that economic growth is sustainable: afford energy access for the people as well as promote efficient use of natural resources.

In the global scenario, Brazil stands out for its large share of renewable energies in its energy supply mix, which, in 2007, was approximately 44% of the total [1]. Maintaining this profile is a solution of convergence from socioeconomic, environmental and strategic perspectives:

- From the *socioeconomic* standpoint, the exploration of renewable energy sources is related to making the best use of local energy characteristics, which may result in income gains for the local population.
- From an *environmental* perspective, as a rule, the use of renewable energy sources generates less environmental impacts when compared to those generated by fossil based thermopower generation.
- From a *strategic* point of view, when combined with a policy to support scientific and technological development, it leads to industrial capacity building, generating goods and services that have a multiplying effect on the economy. Furthermore, the use of renewable energy sources available in the country contributes to reducing Brazil's level of foreign dependence on energy.

In order to internalize these aspects in the analysis of the expansion of the electricity system, this paper will initially set out a set of indicators addressing various dimensions of energy planning: technological, economic, environmental and social. This aims to provide inputs for the actual process of formulating public policies that will guide the expansion of the Brazilian energy system within appropriate sustainability guidelines.

With this in mind, the structure of this paper, in addition to an introduction providing the background of the problem, has another three sections. In Section 2, the methodological issues that involve the definition of the multicriteria methodology limits for the problem of expanding electricity generation, as well as the logical premises used to establish indices per dimension (technical, environmental, economic and social) for applying the methodology. Section 3 presents a case study in which the proposed methodological tool is applied. Finally, Section 4 presents the conclusions and recommendations of this study.

2. Methodology for assessing the expansion of energy production systems

2.1. Introduction

The assessment of the expansion of energy supply is usually a multivariable problem encompassing aspects related to the costs of this expansion and the socioenvironmental aspects arising from the choice of the alternatives. These costs relate both to the opportunity of having energy available and being able to make use of the social structure derived from its use as well as to the loss of well being as a result of environmental impacts ensuing from these choices. There is no such thing as energy production without impacts, so society is left with the task of how to minimize those impacts.

These many aspects must be analyzed from an integrated standpoint, thereby reducing the risk of biased analyses. Ideally, the integrating element of these various dimensions should be government guidelines for energy and environmental policies, which provide elements for consideration in the final decision on the path to be taken for expanding energy supply.

Nevertheless, this consideration is a complex problem insofar as these various interests are often conflicting. Furthermore, the various ways of producing energy have impacts that are not always comparable, which increases the degree of subjectivity built into these choices.

Thus, for example, traditional economic feasibility analysis provides an economic value criterion: the more competitive a particular way of producing energy is, the better its insertion. This approach does not always correspond to the option with the fewest environmental impacts and highest social well being. The combination of traditional technical/economic criteria with exogenous socioenvironmental ones is a strategy that has been adopted to address this problem.

Another alternative for internalizing these impacts is through the economic valuation of the associated environmental impacts, although these methods also have a certain degree of subjectivity built-in, which can lead to controversial conclusions in certain cases. Such is the case of the application of a dose–response function to a population affected by pollution: lower local income would tend to encourage pollution in that area, since the opportunity cost of disposing of human beings in this case could be interpreted as "acceptable", when compared to the alternative of the socioenvironmental impacts in richer areas, for example.

The proposal put forward here seeks to create a standardization criterion for the various dimensions/interests involved in the decision on the expansion of energy production systems. It, thus, seeks to encompass the following aspects:

- *Technical*: related to the technological feasibility of the use of an alternative, bearing in mind the availability of the resources both in absolute terms and in terms of their associated yield.
- *Socioeconomic*: related to the cost of supply and the possible benefits that energy supply may bring society as a whole.
- *Environmental*: stressing the most relevant impacts on the biota and seeking to find a common comparative basis for quite different phenomena.
- *Strategic*: related to the choices that society must make to have energy, taking into account factors such as energy security, which is not always convergent with less cost criteria.[1]

Below is an overview of the methodology used, based on multicriteria analysis, as well as of the process for formulating the selected indicators. As mentioned, the assessment carried out here encompasses the expansion of electricity production systems and the indicators are applied to the Brazilian case.

2.2. Multicriteria analysis (MCA)

Data envelopment analysis (DEA) is a multicriteria methodology that allows alternatives to be assessed through their quantitative aspects. Its main virtue is to consider the statistical outlier (which would be discarded in adjusting the trend) as a "*benchmark*" (the best among those evaluated, the one to be pursued) in establishing an efficiency frontier taking into account inputs and outputs. Its limitation is the same as that of similar methodologies, that is, the difficulty in proving itself to be better than others when faced with multicriteria problems, thus it always remains the choice of the analyst.

To calculate the efficiency of organizational units has been an important topic in administration, but a difficult one to solve, particularly when considering multiple inputs and multiple outputs associated to these units. Among the proposals to address this problem is the derivation of an empirical frontier for the

[1] For example, it might be said that the existence of stocks act as a regulator of domestic market prices, but the structure required to effect these stocks need investments, which add costs to the final product that would not exist if this mechanism were not used; but this mechanism makes the final consumer less vulnerable to price and availability fluctuations.

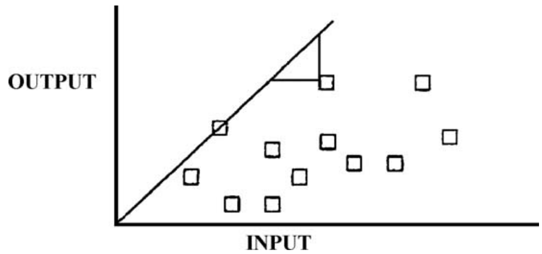

Fig. 1. Input/output graph. Source: [3].

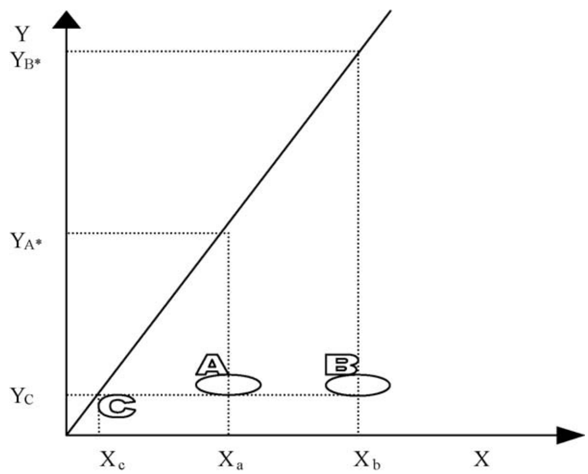

Fig. 2. Input/output graph with projections.

relative efficiency instead of a theoretical production function, to be used as a basis for measuring the relative efficiency of the units. Based on this derivation, previous works [2] created a technique based on linear programming to calculate the relative efficiency of the units and determined a reference point on the frontier for each inefficient unit. They called their new approach to measuring efficiency data envelopment analysis (DEA) and the evaluated units were called decision making units (DMUs).

According to [3], data envelopment analysis (DEA) is a methodology for comparing performances of decision making units (DMUs) operating in similar contexts, using the same resources and generating the same outputs[2]. The best possible performance is identified from the set of production units, allowing the relative efficiency of each of the other production units to be measured, which can be done according to various criteria.

To illustrate these orientations, we are using the diagram used by [3] which can be seen in Fig. 1, showing twelve units producing a single output and using a single input. The input volume is measured on the *x*-axis and the output volume on the *y*-axis. The output/input ratio is the slope of the line that goes through the origin and the representative point of the unit. In this way, the most efficient unit is the one for which this line is closest to the *y*-axis. The efficiency frontier is given in the figure by the ray going through the origin and the most efficient unit.

In order to better understand the difference between the orientation for input and for output, Fig. 2 only shows two production units (A and B) with the same projection on the *y*-axis, the efficiency frontier, and the horizontal projection of DMUs in the efficiency frontier (C). In this graph, the *x*-axis represents the inputs while the *y*-axis represents the outputs. Y_{b^*} and Y_{a^*} represent the *y*-coordinates of the vertical projections of the DMUs in the efficiency frontier, while Y_c represents the *y*-coordinate of projection C. X_a, X_b and X_c represent the *x*-coordinates of the two DMUs and of projection C.

With respect to inputs, the production unit that consumes fewer inputs will be most efficient. Comparison is made through proportionality, for which standards must be set. Using the virtual unit projected on the efficiency frontier, represented by C, we can see that the ratio X_a/X_c is smaller than the ratio X_b/X_c. But in the case of outputs, the DMU that produces most will be the most efficient one. In this case the comparison will be made with the *y*-coordinates of the projections of the DMUs and the virtual unit C, which shows that the ratio Y_c/Y_a is greater than the ratio Y_c/Y_b. It is clear that the DMU that is most to the left will be the most efficient one, but the measurement may be different because of the orientation chosen.

The weights used to maximize the efficiency, that is, minimize the use of inputs or maximize the supply of outputs, should be evaluated by the analyst. In this case, the methodology allows for two options: exogenous determination or the use of a means to identify the values that represent the intrinsic importance of the variables within the context. In fact, this tool allows the comparison between the effects of the two alternatives.

However, if the problem has a single input and several outputs, the orientation will be geared to inputs, likewise if the problem only has one output and several inputs, its direction will be geared to the output. If it is one with several inputs and several outputs, the comparison will be carried out through a combination of outputs using a combination of inputs.

In order for the results to encompass the concept of sustainable development (that is, for them to adopt the premise of equilibrium among the dimensions), the chosen inputs and outputs were related to the five dimensions of this concept, but they had to meet the premise of being able to be expressed numerically in absolute values. To do so, the economic and environmental dimensions – in fact a negative output, for which a small supply is desired – were considered to be inputs, for which the least consumption is desired. Likewise, the technological dimension—which is normally measured with respect to optimization, highest value, but in order to meet the criterion of being considered an input, underwent a differentiated numerical treatment. The chosen expected outputs, for which highest results are sought, were the social dimension and the operational/strategic dimension—represented by the supply potential. The rationale behind these indicators is shown below.

2.3. Formulation of indicators

An essential part of energy and environmental planning is the identification of the driving forces of the use/supply of energy to provide inputs for decision making [4]. The use of indicators is a tool that allows viewing, in a synthetic manner, the complexity of this decision making process. Indicators are considered to be measurements of the condition, processes, reaction or behavior, providing a summary of the various parameters of a complex system [5].

Basically, the advantage in using indicators resides in: (i) synthesizing a set of diverse data, indicating the general condition of a particular aspect, its progress or even trends (when analyzed from a retrospective and/or prospective viewpoint, by using historical series or scenarios for the expansion of the energy sector); (ii) when data is thus synthesized, they indicate the key issues to be addressed through incentives, public policies or attitudes of the involved agents (Fig. 3).

When some specific information acquires importance for decision making, then it can be classified as an indicator. Thus, the qualitative knowledge jump provided by the aggregation of knowledge in the form of indicators is very clear. Indicators allow enhancing the comprehension of reality by establishing cause and effect relationships built on basic statistics. Thus, when analyzed

[2] DEA may be applied even if the DMUs use multiple inputs to generate various outputs and the productivity of each output and input can vary.

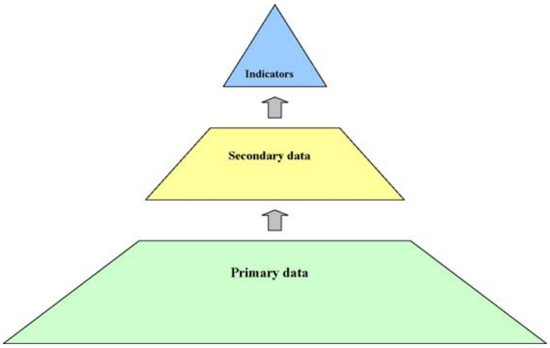

Fig. 3. Diagram of the evolution of primary data up to acquisition of indicators. Source: [6].

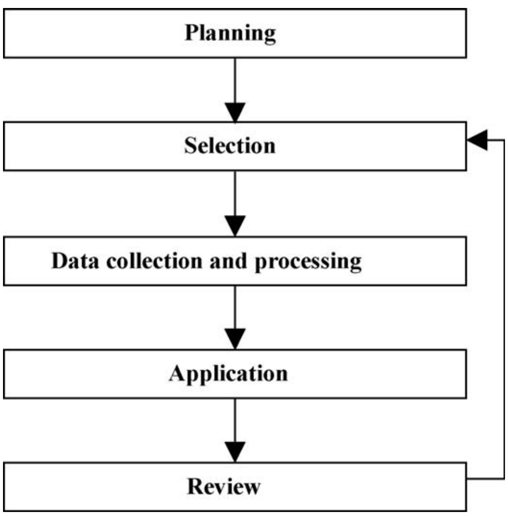

Fig. 4. Stages in the development of indicators. Source: [6].

together, indicators provide a clear view of the system as a whole, including the interrelations among the various dimensions [7].

2.3.1. Criteria for indicator selection

Establishment of the indicators used in this study corresponds to an adaptation of the analysis undertaken in [6] for environmental indicators for oil and gas E&P activities. According to that study, the first consideration refers to the stages of development and application of indicators, which include the following stages: (i) planning; (ii) selection of indicators; (iii) data collection and processing; (iv) application of indicators; (v) review and improvement of indicators system. This process is shown in Fig. 4.

In all the stages, establishing criteria for these indicators is essential for them to be useful for decision making and, for this study, the criteria chosen in [6] were adopted, resulting in a total of 15 attributes, grouped under three major topics: conception, application and consistency. The summary of this grouping can be seen in Fig. 5. The concept of each attribute is shown in Table 1.

Table 1
Attributes considered in indicator selection.

Topic	Attribute	Aspects comprised
Conception	Adhesion	Direct relation to the analyzed aspect
	Feasibility	Technical/economic feasibility of acquisition
	Validity	Acquisition through standardized and robust methodology
	Clarity	Adequate detailing of the desired information
	Simplicity	Ease of understanding by decision makers
Application	Sensitivity	Capacity for allowing trend analysis
	Spatiality	Satisfactory coverage of the evaluated aspect
	Temporality	Possibility of temporal analysis of behavior
	Reliability	Unbiased and apt to capture both positive and negative issues
	Ease	Ease of practical application
Consistency	Relevance	Information suitable for decision making
	Discernment	Capacity to discern noise in the information
	Equilibrium	Balanced integration with set of indicators
	Verifiability	Capacity for reproducing data
	Comparability	Allows temporal analysis

The selection of indicators was based on quali-quantitative criteria using the following set of premises:

- Each indicator is assigned a value for the attributes contained in Table 1, as follows: (i) 0.0: does not meet the criterion; (ii) 0.5: partially meets it; (iii) 1.0: fully meets it.
- The proposed indicator is then selected if for topic "i" and attribute "j", the following statements hold true simultaneously: $\Sigma A_{i,j} \geq 3.5$ and $A_{i,j} \geq 0$;
- In each topic, one of the attributes is considered to be essential for the value of the information made available by the indicator, and the following "topic/attribute" pairs are selected: (1) conception/clarity; (2) application/reliability; (3) consistency/relevance. if $A_{i,j} \neq 1.0$ for the attributes that are considered essential for this topic, then the proposed indicator is eliminated.

2.3.2. Overall conception of the indicators for the expansion of electricity generation

The initial formulation of the indicators sought to cover five dimensions of energy planning: technological, environmental, social, economic and strategic [8]. Although important, the strategic dimension was re-evaluated because of the difficulty in establishing indicators in an objective fashion for this dimension. Therefore, the strategic dimension was replaced by an absolute indicator that reflected the potential and the availability of an energy source for electricity generation.

The indicators established per dimension are, whenever possible, segmented by the phases of an electricity generation project. This segmentation is shown in Fig. 6. Furthermore, for each evaluated dimension, a set of cumulative indicators was established, taking into account the various stages of the energy chain,

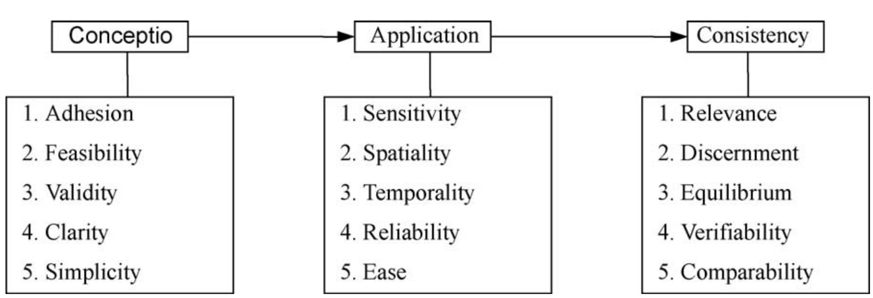

Fig. 5. Attributes adopted in the selection of indicators for the study. Source: [6].

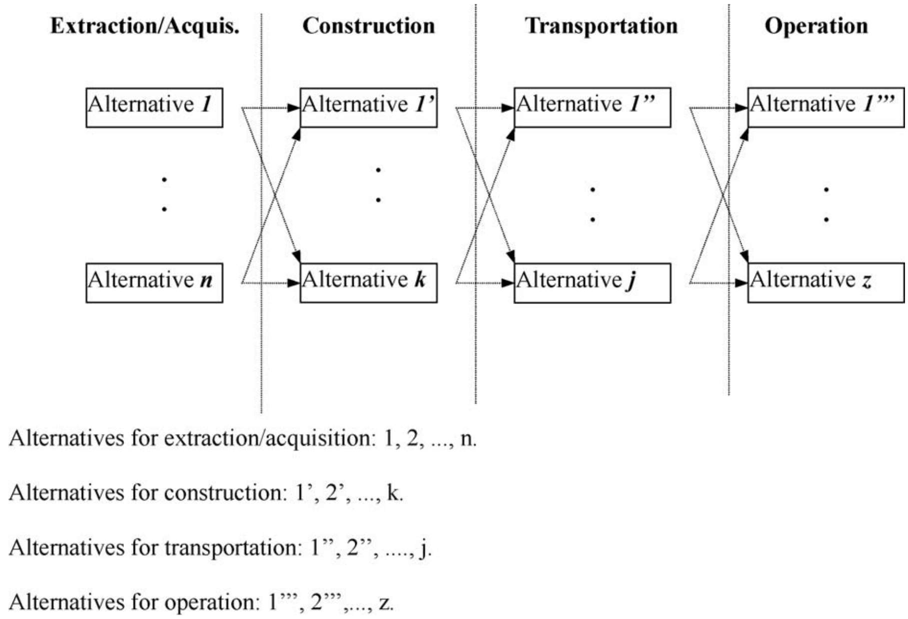

Fig. 6. Diagram of the segmentation per stage of the electricity generation chain per source per dimension. Source: [8]. Alternatives for extraction/acquisition: 1, 2, . . ., *n*. Alternatives for construction: 1′, 2′, . . ., *k*. Alternatives for transportation: 1″, 2″, . . ., *j*. Alternatives for operation: 1‴, 2‴, . . ., *z*.

wherever data was available. In some cases, values were estimated. New generation projects have also been differentiated from those that involve technological modernization of existing facilities (ex.: upgrading of SHPs), since the additional environmental impacts differ in each case.

The phases represented in this figure do not necessarily apply equally to all energy sources evaluated in this study, for example, the case of wind energy, where the "acquisition" phase does not apply. In another example, the "acquisition" phase of water of SHPs depends on the building of dams and facilities to make use of the energy contained in the head.

The selected indicators, after tests with the quali-quantitative criteria defined in section 2.3.1 were as follows:

- *Environmental*: water consumption, specific CO_2 emissions, occupied area, non-CO_2 emissions, percentage of effective land use.
- *Social*: number of direct jobs created, average level of job income, job seasonality.
- *Economic*: specific investment, cost–benefit index, percentage of imported inputs.
- *Technological*: net generation efficiency, average annual availability, construction period and electricity generation potential.

The types of indicators used include both "relative indicators", which translate efficiency ratios between inputs and outputs (for example, the cost of capital, in US$/kW), and "absolute indicators", which refer to the total extension of a variable, as is the case of the potential of the source for generation (technological dimension) or the total number of jobs created (social dimension).

2.4. Set of selected indicators

2.4.1. Environmental dimension

- *Water consumption* [m^3/*MWh*]: consumed water demand per unit of generated energy.
- *Specific CO_2 emissions* [*tonnes of CO_2/MWh*]: corresponds to the specific emission of CO_2 per unit of energy generated.
- *Occupied area* [m^2/*kW*]: includes the area used exclusively for the electricity generation undertaking. It is necessary to carry out the qualitative analysis of the occupied area as a function of the economic or environmental potential of the region.
- *Percentage effective land use* [*%*]: refers to the area effectively made unavailable by the generation undertaking.
- *Specific emissions of non-CO_2 gases* [*tonnes of non-CO_2 gas/MWh*]: refer to the emission of local pollutants such as: SO_X, NO_X and particulate material.

2.4.2. Social dimension

- *Number of direct jobs created* [*jobs/kW or jobs/MWh*]: The specific indicator to be used depends on the phase of the energy chain being considered. During the construction phase, for example, an indicator related to the installed capacity is more appropriate. But during the operational phase, an indicator based on the activity, that is on MWh, is used.
- *Average job income level* [*R$/employee*]: also indicates, in addition to the level of income, differences in the skills required for the generated job.
- *Job seasonality* [*months/year*]: indicates the level of continuity of the job over time.

2.4.3. Economic dimension

- *Specific investment* [*US$/kW*]: refers to the unit cost of the installed capital for each electricity generation alternative.
- *Cost–benefit index—CBI* [*R$/MWh*]: corresponds to the even cost of an undertaking, which translates the effect of parameters such as: investment costs, fuel, O&M, capacity factor, construction period, generation efficiency, capital cost and useful life of the undertaking.
- *Percentage of imported inputs* [*%*]: measures the percentage of costs from external acquisitions for equipment, materials and services.

2.4.4. Technological dimension

- *Net generation efficiency* [*%*]: refers to the thermodynamic efficiency of the first law—that is, evaluation of the ratio "amount of energy leaving/amount of energy entering". Each generation technology has different generation yields;

Table 2
Indicators selected per electricity generation alternative: environmental and social.

Alternative	ENVIRONMENTAL					SOCIAL	
	Water consumption [m^3/MWh]	Specific CO_2 emissions [t CO_2/MWh]	Occupied area [m^2/kW]	Non-CO_2 emissions [kg/MWh]	Percentage of effective land use (%)	Number of direct jobs created [jobs/MWh]	Average job income level [R$/employee]
Natural gas	0.94–39.6	0.484	0.222	0.5	100	0.0375–0.075	750
New SHPs	0	0.005	100	0	100	15	750
SHP updating	0	0	100	0	0	3.75	750
Nuclear[a]	4.1	0	1.74 (3.5 km^2)	0	100	0.0002	6.992
Wind	0	0.007	50	0	0.2–3	20–45	100–2000
Biodiesel-wastes	0	−1.17	0.04	0	100	30	350
Biodiesel-vegetables	3500000.00	−0.78	25.069	0	97.78	98.6	579.17
Biodiesel-perennials	1200000.00	−0.78	4200	0	83.33	9.76	579.17
MSW-landfill gases	0	−3.45	40	0	100	7.23	750
MSW-optimized CC	7.14	−0.29	15	0	100	24.2	600
Modified traditional bagasse CEST	50–250	12–27	2.73	0	100	83.1	232.7
Low bagasse CEST	33.8–168.8	7–10	2.73	0	100	56.1	157.07
High bagasse CEST	18.5–92.4	29	2.73	0	100	30.7	85.97

Source: [8].
[a] *Notes*: relative to the power stations operating in Brazil; availability of wastes = % area not burnt times efficiency of waste recovery.

- *Average annual availability* [%]: measures the average annual time that the undertaking supplies electricity, taking into account interruptions, planned or otherwise, and the characteristics of the electrical system as a whole;
- *Construction period* [*years*]: measures the time in which the generation undertaking will be made available;
- *Electrical generation potential* [*GWh/year*]: refers to the potential electricity supply available for each analyzed source.

The information sources used to estimate the proposed indicators include journals in the technical–scientific literature, contacts with market agents (equipment manufacturers, professional organizations, representatives of the Ministry of Mines and Energy, consultants and power industry specialists), in addition to researching documents from scientific institutions available on their internet sites. The indicators per alternative generation source are shown in Tables 2 and 3. It is expected that in some cases there will be great dispersion along the mean values, both because of the different technologies and operational conditions and because of local specificities, particularly in the case of local energy use.

2.5. Building the indices per dimension

Formulation of indicators resulted in a set of 15 data for each of the technologies and since the mathematical model used only had the capacity to use five parameters, aggregate indices were established per dimension, based on the initial indicators, in the following manner:

- *Social index* (I_S): expressed by: $I_S = eps$, captures the effect of job generation (e), payment attributed to these generated jobs (p), as well as their seasonality (s). This is obtained by the expression: $s = t/12$, where "t" is the number of months in the year in which there is employment in the activity. The higher this index, so better is the result for the energy chain in this dimension.
- *Economic index* (I_E): brings together aspects such as the cost–benefit ratio of a generation project (moderate tariffs), the percentage of technology produced domestically and the cost of expansion of generation with respect to a reference scenario. The economic index is determined by the product: $I_E = \mathrm{CBI}(1+\gamma)N$, where "CBI" is the cost–benefit index, "γ" is the percentage of inputs imported for the technology and "N" is the relative cost of expansion. The latter uses as reference the marginal cost of expansion, for which the adopted "proxy" was the average composition of the last few electrical energy auctions, from December/2005 to December/2007. It is given by: $N = i_n/i_t$, where i_n is the investment cost of the analyzed technology and i_t is the typical investment cost observed in these auctions. The smaller the economic index, the better it is.

Table 3
Indicators selected per electricity generation alternative: environmental and social.

Alternative	Economic			Technological			
	Specific investment [US$/kW]	CBI [R$/MWh]	Percentage of imported inputs (%)	Net generation efficiency (%)	Average annual availability (%)	Construction period (years)	Electrical generation potential (GWh/year)
Natural gas[a]	400–800	139	50	45	90	2	78454.88
New SHPs	880	108	0	70–85	95	2	71619.57
SHP Updating	200–600	108	0	85	95	1	963.6
Nuclear	2800	120.3	37	30	90	5–6	7971[1]
Wind	3061.20	236	0–39	95	97	5–6	42591–55117
Biodiesel-wastes	1459.69	554.9	0	33	80	0.2	1533
Biodiesel-vegetable	1348.13	756.3	0	33	80	1	68300
Biodiesel-perennials	1348.13	867.4	0	33	80	4	166600
MSW-landfill gases	2500	94.1	0	25	80	0.5	47600
MSW Optimized CC	4165	168.2	1.5	40	80	2	52312
Bagasse CEST	500	59.1	0	7	36	0.5	4770
Low bagasse CEST	600	68.1	0	7.5	69	0.5	7155
High bagasse CEST	1550	105.3	0	12.7	69	0.5	13475

Source: [8].
[a] *Note*: capacity factor = 70%.

- *Absolute index* (I_{ABS}): refers to the electrical generation potential available for each alternative and seeks to incorporate local energy characteristics. The larger the absolute index, the better it is.
- *Environmental index* (I_E): involves the conversion of all available data to the same electrical base (MWh) and the sum of indicators, according to the following formula: $I_E = W + G + (S/7)(1 + P) + H$, where W = water consumption, G = specific CO_2 emission, S = occupied area, H = emission of non-CO_2 gases and P = percentage of effective use of land.[3] The smaller the environmental index, the better it is.
- *Technological index* (I_T): corresponds to the product of net conversion efficiency (η) and the average annual availability (CF)[4] of this source, divided by the construction period (P_c), that is: $I_T = \eta CF/P_c$. This index expresses a direct ratio between efficiency and availability (that is, it maximizes generation and use of resources) and is inversely proportional to the construction period, meaning that options with longer maturation periods prolong impacts over time, or, are not expedite responses to the expansion of the system. The higher the technological index, the better it is.

3. Application of the proposed methodology: case study

3.1. Application of the methodology

For the purposes of the data envelopment analysis, the indices obtained in the previous section generated three inputs and two outputs, due to the constraints of the mathematical model previously available, with the aim of minimizing inputs and maximizing outputs. Thus, the absolute and social indices are outputs and the others, inputs. The technological dimension, in turn, was captured by the inverse of the technological index, adapting the methodology to the computing tool available for simulating data envelopment analysis.

In order to cover the dispersion of the indices arising from the propagation of uncertainties in the indicator scores and to avoid the formulation of multiple scenarios, given the large number of variables, the limit situations were considered: a scenario in which all the variables used the lowest scores for each of the indicators that make up the aforementioned indices and another scenario in which the upper values were used.

Applying this solution to the concept of using lower and upper limits, two simulations were formulated, one for the lower limits and one for the upper limits.

Note that the environmental dimension is an undesirable "*output*". The undesirable "*outputs*" can be incorporated into DEA models according to four main approaches, as discussed in [5], and in this study we opted to consider the environmental dimension as an undesirable output, as a "*proxy*" for a finite environmental resource, representing it as an input.

As to the technological dimension, even though it is an input, the rationale of its construction shows that the best technology is the one that obtains the highest score, which is different from the orientation for inputs (the less consumed, the better). This led to changes in the rationale used to build the index, which came to be the multiplicative inverse of the original construction, which made it possible to meet the orientation requirement for inputs without altering the hierarchy found originally. The rationale of the model is to prioritize the least input and the most output. Table 4 shows the results of the formulated scenarios.

Table 4
Results of the formulated scenarios—setting priorities for expansion alternatives.

Energy alternative	Lower	Upper
Natural gas-combined cycle	7	7
SHPs-new projects	8	8
SHPs-updating of existing plants	3	3
Bagasse-manual harvest-back-pressure[a]	1	1
Bagasse-manual harvest-CEST[b]	9	9
Bagasse-mechanized harvest-CEST[c]	10	10
Nuclear	5	5
Wind	11	12
Biodiesel-wastes[d]	6	6
Biodiesel-immediate vegetables[e]	12	13
Biodiesel-perennials[d]	13	11
MSW-landfill gases[f]	2	2
MSW-optimized CC[g]	4	4

Produced from palm oil grown in 7% of the available area in the country (140 million hectares) or 20% of the deforested area of the Amazon (50 million hectares).
[a] Corresponds to manual harvest with traditional system.
[b] Corresponds to manual harvest with the BIG/GT system.
[c] Corresponds to mechanical harvest with BIG/GT system.
[d] Produced from used oils, industrial wastes and sanitary sewage.
[e] Produced from vegetable oils grown in 25% of the idle arable land in the country (90 million hectares).
[f] Produced from biogas from all existing landfills.
[g] Produced from all the Brazilian garbage applied to this alternative.

4. Final considerations

Growing environmental concerns about the sustainability of economic development together with the complexity of the aspects that must be taken into account in this decision result, essentially, in a multivariable problem, where many aspects must be evaluated. This challenge includes the internalization of the traditional economic-financial approach, whose results do not take into account those aspects that must need to be considered when undertaking from an integrated assessment, that is, the environmental, social, strategic and technological aspects. Establishing a hierarchy of alternative energy sources according to multiple concurrent criteria is an international trend. This approach assimilates the importance of socioenvironmental dimensions and, consequently, reduces the economic predominance traditionally used in this type of assessment.

In this regard, the methodological proposal put forward here aims to contribute to this discussion, incorporating socioenvironmental aspects in its calculation tools. This approach was based on the use of indices per dimension, which were integrated using multicriteria analysis. Obviously, neither the list of indicators nor that of the dimensions are exhaustive lists and certainly improvements can be made with further studies. Possible improvements include consideration of the distribution of each variable, from a statistical point of view. Another application is in expansion projects geared specifically to a geographic region.

Although there are several groups of methodologies for this purpose, data envelopment analysis (DEA) was selected, a linear programming tool that allows establishment of the relative efficiency of production units and of their hierarchy. The coherence of the results suggests that this methodology should be applied in a broader manner, using mathematical models developed specifically for the problems of this sector.

It was also seen that the use of sugar cane bagasse obtained from manual harvest and using back-pressure technology proved to have the best performance within a multicriteria assessment approach, where aspects other than economic ones were also evaluated. In its favor lie items such as the number of jobs

[3] The use of this factor refers to the possibility of adding other uses to the area. But since it is necessary to use the entire extension for the undertaking, even though some technologies are more concentrated than others in spatial terms, it was decided to add the usage percentage to the total amount required.

[4] This variable refers to the capacity factor of the source, that is, the average time that the supply is available. This parameter is quite relevant in the case of some renewable energy sources, where there is intermittence, as in the case of wind energy.

generated and the reduced environmental impact, from the point of view of greenhouse gas emissions. The environmental issue also drove the energetic use of municipal solid wastes and the modernization of small hydropowers to the top positions. Nuclear energy can also be included among these. At the other end of the list is biodiesel, which includes the traditional high cost inherent to the diesel cycle in comparison to the other electricity generation technologies.

Nevertheless, the ranking of generating sources may vary according to the indicators of each project portfolio, and the order established above could change due to parameter dispersion and also to specific regional aspects. The choice of indicators also influences the results and it is important to endeavor to achieve standardization of these criteria, as has been very successfully done when dealing with economic criteria for decision making on the expansion of electricity generation. In spite of these limitations, it is important to stress that the proposed methodology allows for the internalization of socioeconomic aspects in the decision making process of implementing generation projects, aspects which will be increasingly present in the sector.

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