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Evaluation of the total systemic cost of wind power generation in face of the replacement of hydroelectric and thermoelectric sources considering socioeconomic and environmental externalities

Avaliação do custo sistêmico total da geração de energia eólica em face da substituição das fontes hidrelétrica e termoelétrica considerando as externalidades socioeconômicas e ambientais

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Abstract: The power generation market has been under constant expansion in Brazil. This market consists of different sources of power generation, which carry different socioeconomic and environmental impacts linked to their operations. These impacts generate externalities in the form of damage to society, and their compensation is not of common consensus among stakeholders. In this sense, through the application of the systems thinking method, this article aims to create a computer model of system dynamics that enables the evaluation of the total systemic cost, considering the externalities of power generation. To this end, an adaptation of the STSP – Systems Thinking and Scenario Planning method was applied. In the first phase, a greater understanding of the subject was raised. Subsequently, there was the construction of the computational model. Finally, the model was applied to three real plants in order to assess of the integration of wind power in face of the replacement of hydroelectric and thermal (coal) sources. The results show an evolution in the understanding on the comparison of the actual cost of energy to society due to the learning provided by the use of systems thinking in conjunction with the dynamic modeling of systems. The findings also indicate a change in the decisions about the energy matrix, if a systemic cost for evaluating new projects is adopted.

Keywords: Systems thinking; Total systemic cost; Power generation externalities; System dynamics modeling; Decision-making.

Resumo: *O mercado de geração de energia está em contínua expansão no Brasil. Este mercado é formado por diferentes fontes de geração de energia, as quais acarretam diferentes impactos socioeconômicos e ambientais atrelados às suas operações. Estes impactos geram externalidades na forma de dano para a sociedade e a compensação destes não é de consenso comum entre os atores envolvidos. Neste sentido, o presente artigo busca, com a aplicação do método do pensamento sistêmico, criar um modelo computacional de dinâmica de sistemas que possibilite a avaliação do custo sistêmico total, considerando as externalidades, da geração de energia. Para este fim, foi aplicada uma adaptação do método do PSPC – Pensamento Sistêmico e Planejamento por Cenários. Na primeira fase, gerou-se um entendimento maior sobre a temática. Em seguida, realizou-se a construção do modelo computacional e, por fim, o modelo foi aplicado a três usinas reais a fim de se fazer uma avaliação da inserção da energia eólica em face da substituição das fontes hidroelétrica e termoelétrica a carvão. Os resultados obtidos apresentaram uma evolução no entendimento na comparação do real custo da energia para a sociedade, devido ao aprendizado proporcionado pela utilização do pensamento sistêmico em conjunto com a modelagem dinâmica de sistemas. Os dados encontrados também apontaram para uma mudança nas decisões sobre a matriz energética, se adotado um custo sistêmico para avaliação de novos projetos.*

Palavras-chave: *Pensamento sistêmico; Custo sistêmico total; Externalidades da geração de energia; Modelagem dinâmica de sistemas; Tomada de decisão.*

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1 Introduction

Energy, water and air are essential elements to human survival. The global dynamics brought constant evolution of industry and technology; this evolution is fostered largely by the economic disputes between companies and nations. Hence, the energy is presented as one of the key factors for this scenario to be achieved and as the society advances, the amount of energy needed also advances.

In view of this, there is a continuous and consequent increase in power generation parks. According to Rafaj & Kypreos (2007), a power generation project has negative impacts on the environment, generating a cost that is often not fully accounted in the total cost of the power generation. The total systemic cost consists of the internal and external costs, the latter being not accounted and regarding the impacts that are generated and not compensated.

The total systemic cost is adopted to compare intervention strategies, envolving the assessment of the monetary costs relative to the results that are expressed in a currency distinct from money, which has its value calculated by a mathematical function particularly developed for each case, reaching, this way, an economic value (Jensen et al., 2015). This value corresponds to what would be paid in shares to offset the impacts generated. Therefore, the concept of total systemic cost is formed by summing the traditional cost with the monetary value corresponding to all effects, positive or negative, generated by the organization and its operations.

In their research, Klaassen & Riahi (2007) state that the greatest impacts that generate external cost are related to the emissions of particulate matter in the air, which is also considered by Zhang et al. (2007) as a generator of external costs related to human health damage, with respect to the emission of pollutants, and the climate change damage. In general, the internal costs are those that are accounted and considered. Externality is the cost (or benefit) generated to a third party, resulting from an activity in which the third party is not involved, and it is not adequately compensated (or charged) by this (Puma, 2011), therefore, the total systemic cost is the sum of these, and is presented in a monetary value.

According to Pereira et al. (2012), the world continues to consume, mostly, energy from fossil fuels and, when it comes to the final consumption of energy, this represents 79% of the global energy matrix. Although this model presents numerous economic and technological advances, if there is not a change and society continues to follow the same strategies for energy supply, possibly there may be changes in the climatic, ecological and social structures, with catastrophic effects for humans (Allen & Varga, 2013).

Renewable energy projects are usually taken as sustainable and "environmentally friendly" (Davidsson et al., 2012). Notwithstanding, all activities that men perform in the design of a new product (goods and services) generate impact to the environment, and this also occurs when a new power generation enterprise is built (Varun et al., 2009). However, the lack of accounting of the impacts generated - for a comparison across the different sources of energy – can bring distortion in decisions regarding the impact-benefit assessment (Mahapatra et al., 2012).

From the academic point of view, Davidsson et al. (2012) concluded in their studies that there are many controversies about the assessment of the impacts generated by wind power. This impasse influences the accounting of the systemic cost. Also according to these authors, there are many studies on the same subject using different methodologies, and the best way to approach this issue is not yet known. The study concludes, in addition, that the most important topics to study the wind energy chain are the use of resources, energy and materials.

Moreover, the modeling of impacts on power generation systems is endowed with limitations and uncertainties, which are linked (among other reasons) to income distribution, technological changes and regional differences (Rafaj & Kypreos, 2007). Addressing the future of research in the energy area, Jansson & Fülöp (2013) conclude that research evaluating the sustainable use of natural resources should be a high priority for the government, for universities and for the industry.

In this academic context, and targeting a future where greater accuracy is necessary in decisions on energy sources to meet the growing energy demand, assessments establishing the best cost-benefit ratio in the choice of a particular energy source are needed. These assessments should consider the total systemic cost, analyzing not only the socioeconomic and environmental aspects but also their impacts on organizations. All these topics show to be relevant in the extent of their discussion, however, when unified, there is a gap for which the present study aims to contribute.

Given the above, the aim of this study is to create an artifact that enables the evaluation of the total systemic cost, considering the externalities of power generation. Thus, it serves as a support to the decision-making on investments in energy matrices.

2 Referencial

2.1 Principles of systems thinking

The Systems Thinking is a way of conceptualizing the way one perceives the complexity of the world, or, in this case, a specific situation. Through this technique, it is possible – through logical relationships – to describe a complex world coherently. The Systems Thinking unites the individual and collective vision in the pursuit of learning about complex situations, in order to create strategies that lead towards the targeted results. The use of systems thinking develops skills that bring new levels of perception, sensitivity and awareness (Sterman, 2002).

Its use is in line with the search for a better human perception of reality, this reality being structured in layers, which require different levels of perception. One can see this reality with a superficial view or, adopting the iceberg metaphor, just the tip of the iceberg can be seen. As more elaborate instruments of perception are adopted, such as models that represent reality (Pidd, 2003), there is an advancement in the levels of knowledge and the iceberg starts to be better viewed. These levels of perception are illustrated below. Figure 1 shows the iceberg metaphor for the perception of reality according to Andrade et al. (2006).

In the first level, there are the **events** that occur and are perceived by the people involved. The perception of events is characteristic of the human nature, and through this, people explain situations and react to them (Andrade et al., 2006; Morandi et al., 2013).

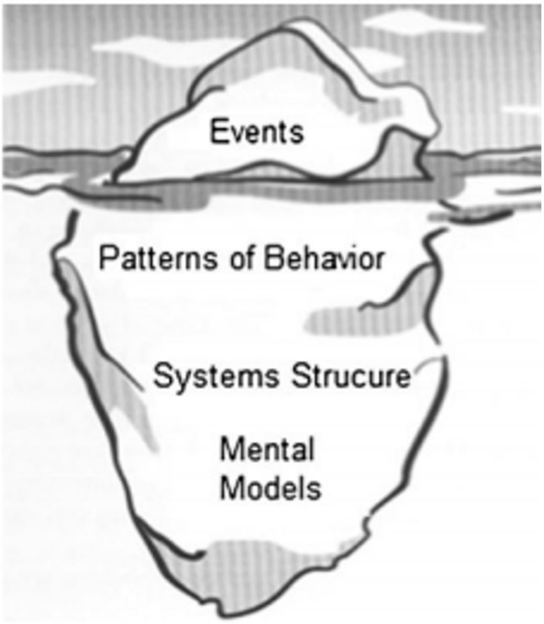

Figure 1. Levels of reality illustrated by the iceberg metaphor. Source: (Andrade et al., 2006).

Notwithstanding, these events are evidence of the variation of the **patterns of behavior** of the reality described, and to advance the perception, it is necessary to analyze trends over time and to check their implications.

The next level seeks to explain what causes the observed behaviors, and refers to the understanding of the **systemic structure** of reality. By showing how the variables are influenced, this is the richest level, and brings understanding of what can be altered to change undesirable behaviors, i.e., to lead to a desirable behavior.

According to Andrade et al. (2006), any system can be explained by these levels, but in the systems that involve the society, there is one more level of complexity that refers to what people carry in their minds. **Mental models** are responsible for decision-making in several areas, and due to their strong influence on the structures, it is necessary to identify these models and understand them so as to modify them (Sterman, 2002).

Hence, the Systems Thinking brings a learning that leads to effective changes on a given situation. Says Senge (2004) apud Morandi (2008, p. 41), "Systems thinking is a discipline to see the whole. It is a frame of reference to see interrelationships instead of events: to see changing patterns instead of snapshots."

2.2 System dynamics

System Dynamics is a technique focused on the use of dynamic computational models to simulate a certain reality and its behavior over time. Among the main applications, energy and environment are related (Forrester, 2007).

One of its features is to elucidate what is not intuitive. Since the human mind has certain limitations, when faced with situations of greater complexity, it tends to complete responses based on intuition. In most simulated dynamic models, the findings are surprising because they show completely different results than previously thought (Andrade et al., 2006).

System Dynamics – SD has been used in several studies in the areas of energy, socioeconomic and environmental impacts, and externalities. Cepeda & Finon (2013) make a proposal for compensation of the externalities generated by wind parks. Yet Shih & Tseng (2014) use the System Dynamics Modeling – SDM to make an assessment of the social benefit of a sustainable energy policy involving renewable energies and energy efficiency, among others, following the example of the studies done by (Ansari & Seifi, 2012; Arbault et al., 2014; Elliott et al., 2010; Liu & Burns, 2011; Liuguo et al., 2012; Movilla et al., 2013; Stasinopoulos et al., 2011; Wu et al., 2011). The SD is also considered an important tool that helps us understand the complexity of policy decisions and their effects (Sterman, 2002), for this reason, Dynamics brings important contributions to this research, as in the study of Streimikiene & Alisauskaite-Seskiene (2014), which uses the SDM to evaluate the external costs of the different options of power generation for their country.

2.3 Generation costs and externalities

Energy is generated for society, and its total systemic cost for this consists of internal costs (direct and indirect) and externalities. Sometimes it is difficult to understand these costs isolatedly, like in the Brazilian system of power generation, which, when in a regulated environment, has an auction-based market. These costs are accompanied by investors and do not consider externalities (Custódio, 2013).

Although there is a tendency for adopting the systemic cost in the future - starting with the internalization of environmental damage -, externalities are surrounded by many uncertainties, and their accounting in monetary values is not yet endowed with a universally accepted method (PRI, 2011). Thus, comparisons between different energy sources are not made based on their total costs, i.e., do not take into account externalities.

2.4 External cost

The external cost is made up of the externalities generated for the society. The externalities can be perceived generating a cost or revenue. Cost, when the activity has an impact on the environment, and revenue, when the activity generates a benefit. These externalities are manifested in various ways, such as environmental degradation, air pollution, human health, visual impacts, noise, changes in fauna, economic impacts and social changes (Georgakellos, 2010; Rentizelas & Georgakellos, 2014; Puma, 2011).

The electricity comes from different sources, and each of these sources has different socioeconomic and environmental impacts, thus, their externalities are also different (Larkin, 2013). Several researchers have studied the monetary value of these externalities for different energy sources (Carlson, 2002; Costs, 2011; Kosugi et al., 2009; Rafaj & Kypreos, 2007; Shindell, 2013). Nonetheless, these figures are endowed with uncertainties and do not take into account local aspects, referring to the southern region of Brazil. One way to estimate this impact is the methodology of Life Cycle Analysis (LCA).

2.5 Incorporation of externalities in the energy cost

In energy projects, the cost at which energy is produced is often calculated based on the implementation of the projects. In the case of the regulated energy market in Brazil, the price is a key indicator for decision-making in the composition of the energy matrix, since it works through auctions.

Current models of calculation of the electricity cost do not consider all the externalities generated by the impacts caused by the generation of this energy (Elliott et al., 2010). Appropriate models of energy cost should include the environmental debts caused, and the socioeconomic debits and credits caused by the enterprises. It is believed that when considering these costs (and benefits), they can be gradually incorporated into the final price of energy. This attitude brings a better understanding of the real cost of energy to society. Consequently, better decisions can be taken on energy policies (Elliott et al., 2010).

In order to get a comprehensive analysis of the balance of energy systems, one should use an approach that addresses the impacts of the internalisation of the external costs originated in the energy production. This approach should impose additional fees on electricity generation, these fees are a reflection of the local damage generated to the environment, health, climate changes, risk of accidents, waste, noise, and other impacts (Rafaj & Kypreos, 2007).

In an analytical study of the internalisation of external costs, Georgakellos (2010) reports that the external costs amount to a value that is equal to 70% of the average cost of energy production in the case of coal-fired thermal plants (cost only associated with CO_2 emissions). Therefore, the author concludes that there is a major impact of the external costs generated by the production of energy on the decisions of energy matrices.

The incorporation of externalities was the subject studied in the research of Streimikiene & Alisauskaite-Seskiene (2014), being stated that this is the most important environmental criterion for decision-making in electrical systems. It was also made an estimate of the external costs generated by each source and a comparison between them. According to the survey data, renewable sources are the least likely to cause externalities. In this regard, by adopting the total systemic cost for power generation, one can obtain a comparative evaluation of the benefits of the power source. Through this tool, the Brazilian energy market may undergo some changes.

3 Methods

In order to organize the research in a logical order of reasoning and meeting the objectives proposed without limiting to an explanatory and descriptive research, this study adopted the Design Science Research (DSR) method. This method involves the construction of knowledge by creating an artifact that can be used to design solutions (Lacerda et al., 2013; Van Aken, 2004).

The situation of interest is an assessment of the accounting of external costs resulting from the choice of a particular energy matrix. The knowledge obtained about the external costs aims to enable an understanding of the real cost of electricity generation, considering the external costs, and thus a better stance on the decisions on energy issues. This study was directed to the wind energy source, replacing the hydroelectric and thermoelectric sources.

It was chosen to use, for the development of this survey, an adaptation of the method of Systems Thinking and Scenario Planning (STSP), as proposed by Andrade et al. (2006). This choice was made because the method brings a better understanding of reality, through the principle of leverage, which may generate strategies for addressing the learning; in this case, decisions on the energy matrix and its externalities.

It was decided to use, in addition to the STSP, the System Dynamics approach. This approach has been used in several complex situations since its inception, and its scope is being expanded as science advances. Among its applications are the subjects of energy systems and environment, sustainable development, strategic planning and dynamic decision-making, all of these being present in this study (Andrade et al., 2006; Forrester, 2007). The combined use of these approaches has proven successful to achieve the objectives proposed in the study by Morandi et al. (2013), who studied the dynamics of ore pricing.

This study aims to create an artifact to be used in a real environment of power generation and to identify the real cost of decisions on energy matrix, this logic of thinking follows that presented by Van Aken (2004). The resulting artifact of this research is a model for calculating the cost of energy generated by wind power, considering also the externalities linked to this type of enterprise.

In order to achieve the proposed objectives, it was adopted a multi-step method of working during the development and analysis of this research (Figure 2). The steps are divided into three main phases: I - Understanding the situation; II - Building the systemic cost; III - Assessing the systemic cost in different scenarios. The working method design aimed to organize the sequence of activities in this research.

The description of the phases of the working method is detailed below:

Phase I: In this phase, there is the structuring of data and information that will serve as a support for the construction of the System Dynamics Model.

Step 1 – Literature review: A bibliographic review was made, which aimed to put the researcher in direct contact with what is written on the subject

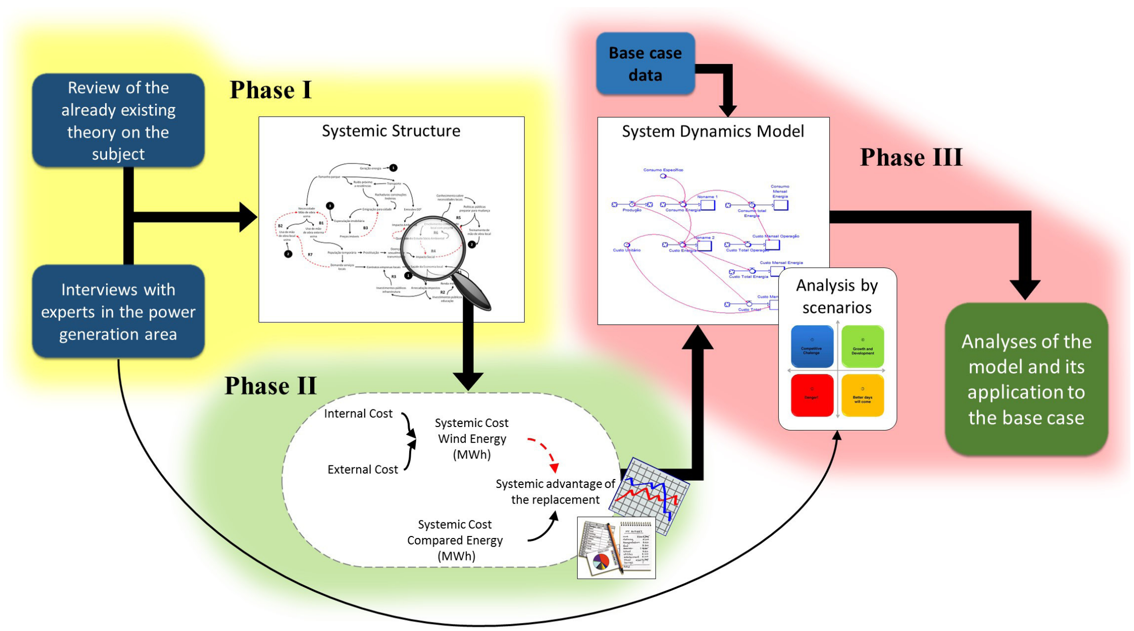

Figure 2. Macro-Phases of the working method. Source: Elaborated by the author.

studied, seeking to verify the possible and different interpretations surrounding the theme (Marconi & Lakatos, 2005).

Step 2 – Semi-structured interview preparation: In this research, a semi-structured focal interview was applied, which resembles an informal conversation and is guided by a set of questions. The script of the interview was developed after analysis of the selected literature, in order to obtain information related to the socioeconomic impacts of a project of power generation.

Step 3 – Selection of respondents: Based on the study areas that the research would include, it were defined the profiles of the experts who should be interviewed. The Group of selected experts was composed of 11 professionals, among them: field engineers, project managers, researchers and professionals in the field of environmental energy generation who work directly with the implementation of power generation projects.

Step 4 – Application of the interviews: The interview is focused on the subject of socioeconomic and environmental impacts during the life cycle of the project and all the perceived costs surrounding these projects. Each interview lasted approximately 50 minutes. The interviews were recorded, analyzed and, after, were heard again, in order to achieve a deeper understanding of the content through inference and interpretation. As a result of each of the interviews, it was obtained a list of events related to the situation of interest of the variables that explain these events and of the factors that have correlation in their behavior.

Step 5 – Construction of the systemic structure: Once elaborated the list of events of the interviews, it was built a map of causal relationships between the factors identified, which were pointed by the experts. In a second moment, each interview was transcribed into a Systemic Structure - SS, to represent the real relationships between the factors. From this, a unique structure was elaborated, which was initially built with relationships based on the theory learned during the literature review, and supplemented by the addition of each of the structures that had been transcribed from the interviews. The SS was presented for validation to a Systems Thinking expert, with experience in Management and Manufacturing for over 20 years, acting mainly in the areas of Strategic Management, Systems Thinking and Scenario Planning, Operations Research, Theory of Constraints (TOC) and Synchronization of Production, and Theory of Constraints and Systems Thinking. Upon completion of the validation, corrections were made in the SS and, thus, Phase I was completed.

Phase II: At this stage, there is the structuring of data and information that will serve as a support for the construction of the System Dynamics Model.

Step 6 – Identification of key variables and data collection: At this stage, the objective was to extract from the systemic map the key relationships that explain the systemic cost of a power generation project, analyzing the map elements one by one. Hence, the relationships and links that make up the systemic cost of the energy have been identified. The variables were selected when considered relevant for the assessment proposed, based on the learning of literature and interviews. Subsequently, it was initiated the data collection to compose the historical series of these variables, and to generate a better understanding of these, analyzing their long-term behavior. The selected variables and the data obtained were used to build the computational model.

Step 7 – Construction of the System Dynamics Model: Having the variables and the data, and following an evaluation of the SS, the elements of this structure that better explain the systemic cost of the energy were defined. Hence, it was built the mathematical function, being analyzed how the variables are related, and the influence one has on the other. This process was done by mathematical modeling based on research in the literature and in the data collected for each specific variable. Later, these functions were used in the system dynamics model for the computational simulation. For this step, concepts of the Life Cycle Analysis (LCA) were used in order to identify the environmental impacts in the energy generation and then estimate its cost to society. The relationships between the variables and still the monetization of non-financial events were made based on the relationships shown in other studies and by the specialists during interviews. This way, it was built the system dynamics model, where efforts were applied in the computational modeling of the systemic structure. The system dynamics modeling used flows and stocks to represent the system behavior. It was necessary to identify which variables are stocks and flows, and to apply the mathematical relationships between the variables and the supporting links identified in the SS, built in Phase I, wherein, using the data and the raised hypotheses, the relationships were established and formalized.

Step 8 – SDM Verification: Upon completion of the system dynamics modeling process, we have the simulation model in which each round generates learning about the situation of interest. It was first made a pilot test of the model, so that hypothetical data were imputed, and relations were checked one by one. The parts of the model that behaved very differently from the expected were analyzed from the consistency of their mathematical relationships. Thus, after all inconsistencies were corrected, the pilot test was completed. Then, data of a reference case for the plants were selected, and these were imputed to the model, in order to verify whether this could represent reality. The results generated by the model were compared with actual data from existing plants. The results were subjected to statistical tests to prove the representation of reality. Still, the model was presented to two specialists, and to one professional who did not participate in the round of interviews, with higher education in energy engineering, which works with teaching and development of projects of electric power generation systems. The specialists interacted with the model, initially applying data from the reference plants. Then, they simulated extreme situations for the data. Finalizing these tests, the two experts issued their opinion regarding the results generated by the model.

Phase III: In the final phase, the future scenarios to which the model would be submitted to have been defined. Subsequently, the model was evaluated and the simulations of the planned scenarios were carried out. Finally, it was made an analysis of the model, of the results and of the research as a whole.

Step 9 – Construction of the scenarios: At this point, the hypotheses to build a scenario planning are defined, in addition to the driving forces, which are based on reality and have great impact on the dynamics of the situation of interest. These forces are usually external. Then, the critical uncertainties were selected and the possible future scenarios were created, to see how the model will behave in the near future. The scenario planning followed the proposal of Van Der Heijden (1996). In this process, the hypotheses and scenarios are based on suggestions from experts and literature.

Step 10 – SDM Application: In this step, different simulation rounds are made to each projected scenario. Behavior patterns are observed for each of the scenarios, and thus an understanding of the situation of interest is raised. Database information were imputed to the model, and this has performed the simulations. The simulation period was 20 years. The parameters have been changed according to each scenario, and simulation rounds were performed and recorded.

Step 11 – Evaluation of the model and its results: The simulation in various scenarios is used to assess the implications and limitations of the model. Tests of the structural behavior of the model are also made, with respect to the suitability of the model boundaries, the structure, the dimensional consistency of the mathematical relationships, the parameters used and the behavior under extreme conditions, which follows the proposed by Qudrat-Ullah & Seong (2010). After the test, being identified the inconsistencies, the attention returns to the artifact's development phase and, with this knowledge, the necessary changes are made in the model.

3.1 Building the Systemic Structure (SS) of the total systemic cost of power generation

At first, to understand the problem to be addressed, articles related to the topic of the externalities of energy generation were analyzed, as presented in the previous chapters. It were also sought subsidies to understand the impacts identified in the locations where the energy generation plants are installed, these being wind, water or fossil thermal plants. Thus, it was selected a range of variables that best explain the situation, meeting those of the research. The SS was built gradually, and after its construction, it was divided into sectors according to the main theme addressed by the grouped variables. The sectors into which the SS has been divided are: Power generation business; Economic impacts; Social impacts; Environmental impacts; Impacts to the local human health; Impacts to the national interconnected system.

The relationships presented in the systemic structure were verified from the theoretical point of view, being evaluated the knowledge gained through interviews and primarily from the perspective of systems thinking. This verification was carried out by a specialist in Systems Thinking, which has extensive experience in research in the mining and energy sector. Full and revised SS, showing all sectors and the way they relate, is shown in Figure 3. This SS served as a subsidy for the construction of the System Dynamics Model - SDM.

3.2 Setting the key variables

The SDM objectives focus on identifying the internal and external variables to energy production, resulting in the calculation of the Total Systemic Cost of the Energy Generated. It is noteworthy that the SS developed and the model itself are generic, i.e., can be analyzed by different sources of power generation. However, in this study, the variables considered were thought regarding the generation of wind energy taking into account the comparison with thermal (coal) and water energy.

The Model should represent the reality and its trends as accurately as possible. Hence, it were identified the most relevant variables for the situation of interest, analyzing the sectors of the SS and comparing with the literature and the information obtained in the phase of interviews. The Total Systemic Cost being the central variable of greatest importance, as this is what we intend to measure.

As seen above, the Total Systemic Cost consists of the internal and external costs, and from there the main variables that influence these were selected. For example, the variable Public Revenue, regarding the

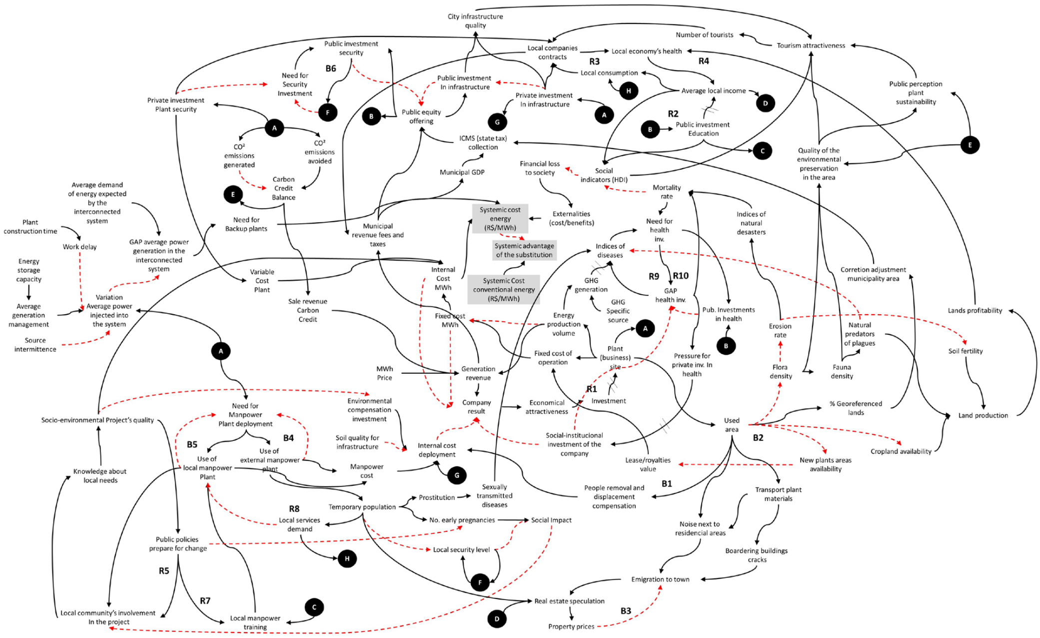

Figure 3. Complete systemic structure of the studied situation. Source: Elaborated by the author.

collection of fees and taxes, is aimed at understanding the importance of the amount collected and reversed to mitigate the impacts generated. Following this logic, the other key variables that were selected are: Balance of Avoided Emissions; Cost of Greenhouse Gas Emissions; Cost of the Damage of the Temporary Population; Cost of the Need of Backup Plants in the Interconnected System; Revenue of the Power Generation; Volume of Energy Generated; Cost of Use of the Plant Area; Operating Cost of the Pant.

3.3 Construction of the system dynamics model

The SS was analyzed and its relationships were written for the model created by using the System Dynamics Modeling – SDM – software iThink, version 10.0.3. The mathematical modeling of the model was based on statistical data and relationships found in literature. The model was built entirely in three dimensions, one for each source of energy; this way, it was assured that the comparison between the sources was made under the same aspects. In general, it is as if we had three distinct models that run simultaneously and generate different results for each of the sources evaluated for later comparison.

The simulation period was defined with annual sensitivity, since the renewable generation is seasonal, of annual cycle pattern (ANEEL, 2008; EPE, 2013; Marreco, 2007; Pereira et al., 2013). In addition, the simulation time was set to 20 years, which is the supply deadline stipulated in the auctions for power generation in Brazil. The final system dynamics model that was used for the estimates of this study – and for the simulations in the different scenarios – is shown in Figure 4.

The assumptions and the data used in the construction of the model are shown in Table 1. This table shows, in the first line, the sources of energy, and in the first column, the SDM block name and the measure unit.

3.4 Development and evaluation of scenarios

During the interviews stage, one of the applied questions was: “What would be, in your opinion, the critical uncertainties on future scenarios in the treatment of the internalisation of external costs?”. The answers obtained at this stage of the interview were used for the construction of scenarios facing possible future realities. This construction began with the identification of the driving forces, whose behavior in the future is not clear, being then defined as critical uncertainties, according to the concept presented by Schwartz (2006) apud (Rudibert, 2009). Eleven critical uncertainties have been identified; some examples are: Carbon credit price; National Gross Domestic Product – GDP; Energy supply; Change in energy regulation; among others.

An analysis of these critical uncertainties was carried out and two of them were selected (Figure 5). Following the objectives of this research, it was selected the uncertainty “Internalisation of Externalities”. This is the uncertainty that comprises the total systemic cost, which was intended for evaluation. For the second

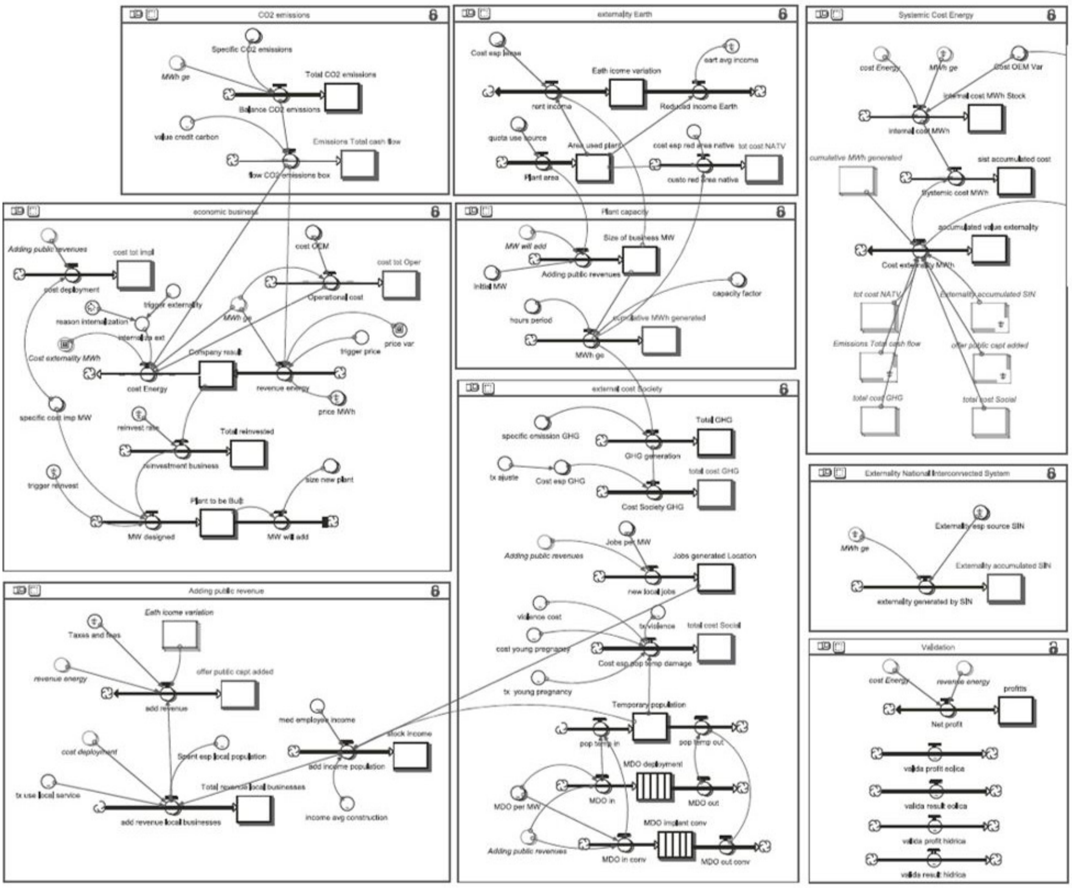

Figure 4. Computational model of system dynamics. Source: Elaborated by the author.

Table 1. Data used for the relationships during the SDM.

Relations used in the SDM				
Relation	**Measure unit**	**Wind**	**Water**	**Thermal**
Area not used by the plant	MW/km^2	50	8.65	406
Cost associated with intermittency	R$/MWh	6.00	-	-
Cost associated with native area reduction	R$/km^2/year	166456.38		
Jobs generated O&M	person/MW	0.4	0.22	1.725
Early Pregnancies Statistics	pregnancies/100,000 inhabitants	321.29		
Deaths from violence Statistics	deaths/100,000 inhabitants	80.9		
Income spent locally	%	56%		
City tax	%	2%		
Financial loss of early pregnancy	R$/pregnant/year	15124.76		
Financial loss of a death	R$/death/year	162635.46		
Cropland income	R$/km^2/year	130000		
Average income O&M	R$/year/ person	27124.76		11136
Average income temporary population	R$/year/ person	11136		
Jobs plant construction	person/MW	15.4	11.3	14.4
Land lease/royalties value	R$/km^2/year	7200	15061.14	-

Obs.: 1- The currency values were adjusted annually by 5.4%, related to the average value of the WCPI for the period of 2005-2014; 2- When there is only one value, this is the same for all sources. Source: (CDM, 2006, 2012; CES-FGV, 2013; CGTEE, 2014; EPE, 2014; Georgakellos, 2010; Marreco, 2007; Shih & Tseng, 2014; Simas, 2012; Streimikiene & Alisauskaite-Seskiene, 2014; Tancredi & Abbud, 2013).

uncertainty, it was listed the one that could have the greatest impact on the power generation market in the opinion of the researcher. This option was also discussed with an expert who has experience with scenario planning, and that considered this second uncertainty as appropriate: energy price.

For setting the scenarios (Figure 5), two extreme levels were considered, and for the simulation, the uncertainties were altered between these levels. Thus, it is possible to verify the impact of these uncertainties on the business result, and the consequences for the company in the future. For internalization of the external cost, it were defined the levels for non-application of this policy, or 0%, and for partial application of this policy, or 50%, which was considered as internalizing 50% of the total systemic cost. This value was adopted because a policy of this magnitude is thought to be implemented gradually. For the price uncertainty, the continuation of current prices, readjusted only to the WCPI, annually, was set to the low level. For the high level, it has been set a 20% increase over the current price adjusted by the WCPI. This value was set based on the trends identified by experts.

Placing the critical uncertainties on two perpendicular axes, four quadrants were formed (Figure 5). Each of these quadrants generates a scenario with values of uncertainties according to the axes, for example, scenario 2 has a low level of price, and low level of internalization of the external cost. Mnemonic names are also assigned, which is a practice commonly adopted to facilitate the identification of the scenario with its content (Andrade et al., 2006; Van Der Heijden, 1996). The scenarios were designed to visualize 20 years in the future.

The values used in the critical uncertainty of the energy price were applied to the base value of the

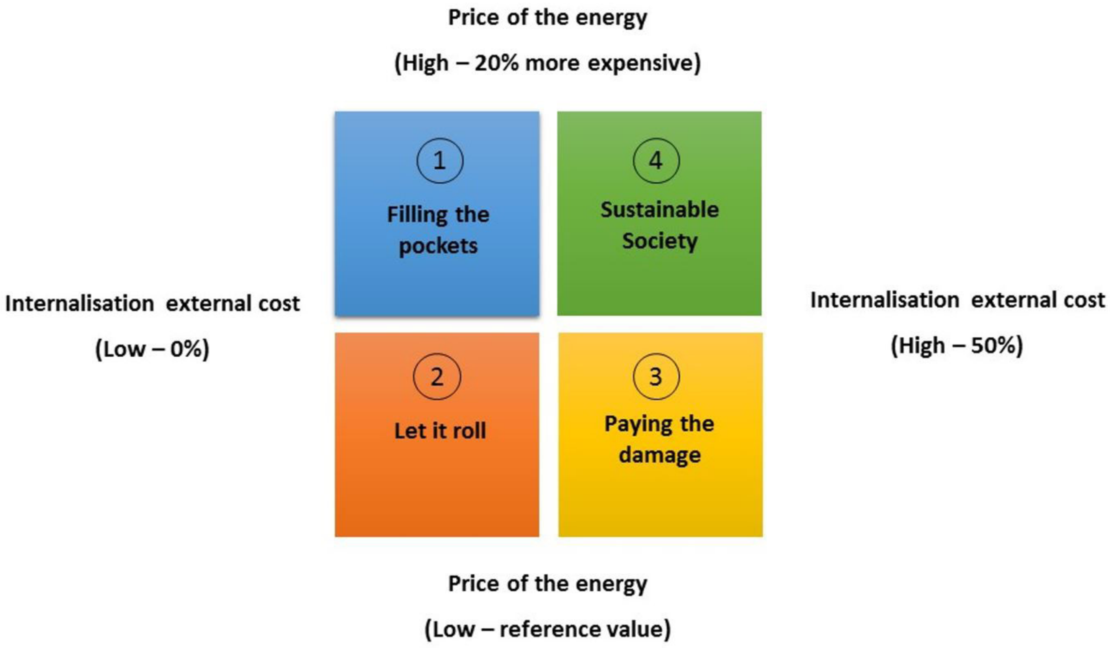

Figure 5. Construction of the scenarios. Source: Elaborated by the author.

Table 2. Data of the plants, used for the creation of the scenarios.

Plant input databank				
Input datum	**Unit**	**Wind**	**Water**	**Thermal**
Size of the Plant	MW	100	100	350
Capacity Factor	%	39.8%	50.0%	83.0%
O&M Value* **	R$/MWh	99.8	129.2	167.9
Energy Price Contract*	R$/MWh	136.08	161.97	201.98
Deployment Cost	Million R$/MW	4.497	1.995	2.940
Financing Amortization Time	years	10	10	10
Considered Life Cycle	years	20	20	20

* Initial reference values, readjusted to 5.4% per year. ** This value was multiplied by a correction factor to simulate the financing amortization. Source: (CDM, 2006, 2012; CES-FGV, 2013; CGTEE, 2014; EPE, 2014; Marreco, 2007; Tancredi & Abbud, 2013).

energy price, adjusted to the rate of 5.4% per annum over the years.

After the creation of the scenarios, these were implemented in the SDM, applying the data of actual plants for comparison of the impact of the use of the total systemic cost to the business. The data used are presented in Table 2.

4 Evaluation of the results of the scenarios' application

The results obtained in the scenarios are valid for the assumptions (data, relationships and critical uncertainties) adopted in this study, especially the accounting of external costs, representing the view of the future in this context. The fact that the model was not validated quantitatively shows that these results represent a visualization of trends, and can not be assumed to be completely accurate. Yet, it is remarkable that there is a tendency for the viability of the adoption of the total systemic cost to make up the cost of energy generation in future scenarios, but only for the renewable sources discussed in this study, as can be seen in Table 3, which shows the economic result of the enterprises at the end of each scenario.

For each of the sources, the externalities generated by the SDM in each scenario were calculated. The externality of the added Public revenue is a benefit that the generation of energy brings to society, being greater for thermal (coal) energy, especially because this has a higher price, which causes a higher tax collection.

Analyzing these externalities, to the power options, it is noted that each of the three sources has its main external costs distributed in distinct impacts. The wind power has a relevant externality accounted with the costs generated to the National Interconnected System – NIS, in virtue of its intermittency and also for the energy storage incapacity, being thus unfeasible to make a management of the generation according to the load curve of the system, which brings the need to insert backup plants in the NIS, not being, therefore, at the mercy of the intermittency of winds. As for the water plant, there is a more significant cost in relation to the damage caused by the native area reduction due to the flooding of the reservoir. Finally, the thermal plants have their externalities almost entirely concentrated in emissions and these showed a high cost to society, corroborating other studies that address the issue of emissions (Kudelko, 2006; Rentizelas & Georgakellos, 2014; Streimikiene & Alisauskaite-Seskiene, 2014).

These different impacts also affect the systemic cost of the energy in different ways. In this way, given the base conditions of each source and the conditions in each scenario, it were obtained quite different systemic cost figures (Table 4). The results show an advantage for wind energy in all scenarios, as it had the lowest systemic cost.

It was also observed that the wind power showed no externality of damage to the native area. This is due to the features of Rio Grande do Sul, where the wind farms are located mostly in farming areas. Therefore, the plants reduce the croplands and, in turn, the rent of the land and the public revenue, which is one of the reasons why wind power causes a minor benefit due to the tax collection.

One can see that the social damage caused has low values for both sources. This value is slightly higher for the water source due to the greatest labor requirement in its construction.

Table 3. Comparison of the business result in the different scenarios.

SOURCE	Accumulated Result for the business (million R$/MW)*/**			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Wind	6.80	3.90	3.43	6.36
Hydroelectric	8.91	4.58	4.01	8.38
Thermal (coal)	15.95	6.97	(–7.08)	1.97

*Result at the end of the 20-year period for each MW of capacity installed. ** Values represent the average of 20 years considering the annual readjustments.Source: Elaborated by the author.

Table 4. Comparison of the systemic cost in the different scenarios.

SOURCE	Average systemic cost (R$/MWh)*/**			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Wind	153.81	153.81	160.72	160.37
Hydroelectric	205.11	205.11	211.94	211.53
Thermal (coal)	258.77	258.77	358.30	357.79

*Result at the end of the 20-year period for each MW of capacity installed. ** Values represent the average of 20 years considering the annual readjustments. Source: Elaborated by the author.

In this context, this model showed, in its responses, GHG emissions as the externality of greatest impact on the total systemic cost. Even with the lack of historical data to quantitatively compare and verify the model on the issues of externalities, it is still possible to infer that the conclusions from the analyses of the scenarios tend to represent a future view. The process of construction and application of the model has brought a better understanding of the factors that influence the external cost of power generation, such as the fact that there are GHG emissions in the wind and hydroelectric generation. Superficially, the emissions are associated with the burning of fuel and, in this light, the wind and water sources could not generate emissions. Nonetheless, emissions occur during the design and from their components, by the decomposition of organic matter, especially in the reservoirs, in the case of hydroelectric plants.

It is worth noting again that these findings refer specifically to the context of this research, wherein the adoption of the total systemic cost was simulated, and can not be considered for other situation than that described by this research.

Still, it was found that for each of the scenarios there is a tendency for the decision-making - about the investments in the power generation sector - to be different, i.e., each scenario will require a different approach because of its implications.

Although the model has shown an expected behavior, it is believed that a more detailed modeling, regarding the composition of the operational and financial costs of power generation, could bring greater richness in the evaluation of scenarios. In this regard, it could have been used the prospect of energy supply and demand in the country, making it thus possible to evaluate the market as a whole, considering future energy options. The model was designed to represent the growth of each business, but with this also being linked to supply, demand and other dynamics, it was decided not to use this functionality, leaving the model static with respect to its generation capacity.

It is believed that this model can be transfered from the academic world to the corporate world, since, being adapted to a real evaluation, where there would be availability of data, it would be possible to estimate the total systemic cost and to promote decision-making on it.

5 Conclusion

The procedures of this research led to the construction of a system dynamics model, with its relationships and externalities. Although there are several studies addressing this subject, studies deal mostly with environmental issues. Even with this aspect being the most eminent, through this research, it was found that there are other factors, also important, to be considered as knowledge advances.

The built model permitted the evaluation of three distinct energy sources and their behavior when considering the external costs. For the assumptions of this study, assessing the total systemic cost, wind power had the lowest generation of external costs among the sources analyzed. It was also possible to verify that the thermal (coal) source tends to not be feasible, considering the accounting of externalities.

The application of the computational model created as an evaluation tool of the total systemic cost showed that, possibly, decisions are taken in the energy field based on distorted information of the real cost to society. Hence, an insertion of the total systemic cost in energy policy tends to change the pattern of decisions in the energy sector.

Even if the model has not been validated mathematically as the systems thinking proposes, trends and patterns of behavior for future conditions were observed. In this sense, it is likely that the adoption of the concept of total systemic cost would not derail all energy businesses, but with the revelation of a great difference in the external impacts between renewable and fossil sources, it is possible that one starts to be more used than the other.

Given the complexity of the decisions and policies of the energy market, combined with a need to adapt to new forms of interaction among the organizations, the environment and the society, this research has proved relevant to generate learning and build a tool that will allow a better assessment of future decisions of organizations, aiming at sustainable growth.

The main limitation of this study refers to the modeling, since the model was not mathematically validated, and thus could not represent reality. However, this model is not final and definitive, remaining open to improvements. Even though the research was limited to the data available for evaluation, the creation of the model brought an ease in importing data from other plants.

The conclusions of this research are still limited to the view of the expert group, since this was not composed of representatives of all classes. Finally, it is important to expose that the model was applied to three distinct plants and their conditions. Therefore, the results are bound to them.

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