ENGENHARIA DE PRODUÇÃO:

Além dos Produtos e Sistemas Produtivos

Elói Martins Senhoras
(Organizador)

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APRESENTAÇÃO

A evolução do campo técnico-científico da Engenharia da Produção está diretamente relacionada com a construção histórica das 4 Revoluções Industriais materializadas desde o século XVIII, o que influenciou de modo recíproco, tanto, na consolidação de novas ideias, técnicas e métodos, quanto, na emergência de novos desenvolvimentos das estruturas organizacionais e dos sistemas produtivos.

Contextualizado pela difusão de uma história de 4 séculos dos contemporâneos conhecimentos científicos do campo da Engenharia de Produção, o presente livro traz uma abordagem empírica nacional por meio de um conjunto de estudos que valorizam a produção científica brasileira em uma área de estudos que somente se desenvolveu com robustez a partir da segunda metade do século XX.

Partindo da centralidade que a Engenharia de Produção possui no desenvolvimento organizacional e produtivo, esta obra intitulada "Engenharia de Produção: Além dos Produtos e Sistemas Produtivos 1" combina uma série de conhecimentos, métodos e técnicas consolidadas internacionalmente por este campo científico ao longo do tempo com uma análise empírica fundamentada em estudos de caso da realidade brasileira.

O objetivo do presente livro é apresentar uma coletânea diversificada de estudos teóricos-empíricos sobre a realidade dos sistemas organizacionais e produtivos à luz de um olhar multidisciplinar próprio do campo de Engenharia de Produção que se manifesta pelas influências de diferentes conhecimentos de *soft* e *hard science*.

Os 20 capítulos apresentados neste livro foram construídos por um conjunto diversificado de profissionais, oriundos de diferentes estados das macrorregiões Sul, Sudeste, Centro-Oeste e Norte do Brasil, os quais colaboram direta e indiretamente para a construção multidisciplinar do campo científico da Engenharia de Produção no país por meio de uma série de estudos sobre a realidade empírica da área.

A proposta implícita nesta obra tem no paradigma eclético o fundamento para a valorização da pluralidade teórica e metodológica, sendo este livro construído por meio de um trabalho coletivo de pesquisadoras e pesquisadores de distintas formações acadêmicas e expertises, o que repercutiu em uma rica oportunidade para explorar as fronteiras das discussões no campo da Engenharia de Produção.

A indicação deste livro é recomendada para um extenso número de leitores, uma vez que foi escrito por meio de uma linguagem fluída e de uma abordagem didática que valoriza o poder de comunicação e da transmissão de informações e conhecimentos, tanto para um público leigo não afeito a tecnicismos, quanto para um público especializado de acadêmicos interessados pelos estudos de Engenharia de Produção.

Excelente leitura!

Elói Martins Senhoras

SUMÁRIO

CAPÍTULO 7

THE EVOLUTION OF THE BRAZILIAN SUPPLYING ELECTRIC ENERGY MATRIX CONSIDERING THE INCLUSION OF RENEWABLE SOURCES IN A HYDROTHERMAL SYSTEM

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ABSTRACT: The PRISMA method, widely used in medicine, relates the literature on a particular topic, as well as the researcher’s analysis of the phenomenon, eliminating biases in the research. By using PRISMA approach, this paper presents an analysis of the evolution of the diversification of the Brazilian electric matrix and its tendency for the coming years. The method consists of determining the publications on power-producing sources and the investigation of documents provided by the regulatory agencies of the Brazilian Electrical System (BES) such as the Operator of the National Electricity System (ONS) and the Brazilian Electricity Regulatory Agency (ANEEL)**.** The results indicate that the BES is supplied by hydroelectric generation, complemented by thermoelectric generation, with a tendency to invest in biomass generation. In many regions of the country, wind and solar generation are also developed. However, it is possible to notice a tendency towards the use of a margin of the reservoirs, mainly by risk aversion systems (RAS) implemented in the software of hydrothermal dispatch, NEWAVE, and using other sources for variations in the demanded load. This way, the new function of the reservoirs would be “the system battery”, storing energy without being depleted as the main source of generation.

KEYWORDS: Planning and operation of the Brazilian Electrical System (BES), diversification of the energy matrix, Risk Aversion System (RAS).

1 I INTRODUCTION

As in other countries, the Brazilian electric sector is the most importance for socio-economic development. The expansion of the power offer is a problem of diversification of the electric power matrix, assessed under the light of the use of non-polluting energy (Campos et al., 2017). In the case of Brazil, a considerable amount of the energy offer is supplied by hydroelectric generation (Campos et al., 2017; Gomes et al., 2018).

The Brazilian power generation sector is facing a paradigm shift driven, on the one hand, by the shift of a hydroelectric energy-based generation mix to a diversified one and, on the other hand, by international targets aiming at the reduction in the emission of greenhouse gases (Santos et al., 2017). The supply solely using hydroelectric plants presents risks of shortages due to periods of low affluence and the fact that the reservoirs have multi-year regulations, the distance from generation plants to the load centers and the government policy in the process of concession and construction of reservoirs and hydroelectric plants, which delay the operations of hydroelectric plants (Lima et al., 2017).

The search for new power generation sources for the Brazilian electric sector emerges as a solution to the problem of meeting the energy demand. The Decennial Plan for Energy Expansion, prepared by the Energy Research Company between 2006 and 2015, predicted that hydroelectric plants would continue to participate in the matrix ranging about 73% in the period. In 2015, the Brazilian Electricity Regulatory Agency (ANEEL) admitted that these plants represented just 63% of the capacity, 10% less than the target at the time. As a result of this new condition, the reservoirs of the plants that previously had the potential to supply 6.2 months of load in 2001, fell to 5.63 months in 2005 and 4.82 months in 2013 (ONS, 2016).

Several authors agree that the problem of the Brazilian electric matrix diversification consists of the following fundamental questions (Ferreira et al., 2015; Kileber and Parente, 2015; Bradshaw, 2017; Brannstrom et al., 2017; Dantas et al., 2017):

- How is the process of diversifying the Brazilian Energy generation matrix being carried out?
- What power generation alternative sources could be used in Brazil?
- What are the variables that have an influence on the planning and operation of the Brazilian Electric System that assures the demands of the market, so that several energy generation sources will be used?

This paper aims at analyzing the diversification process of the Brazilan energy generation matrix, as well as point out possible variables that may help the planning and the operation of BES, considering the introduction of other energy generating sources the will help reservoir management and BES operation, reducing the dependence on hydropower generation. This will be carried out by using the combination of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). This paper is divided into five sections. The second section presents BES's planning and operation problem, which is a problem of hydrothermal coordination. The research method is presented in the third section. The fourth shows the result analysis, The conclusion and suggestions for future researches are presented in the fifth section.

2 I BRAZILIAN ELECTRICAL SYSTEM: CHARACTERISTICS AND CHALLENGES

The Brazilian electrical system is mostly supplied by hydropower generation. The advantage of hydroelectricity over other sources includes high efficiency, water storage capacity for future power generation and low operation and maintenance costs. Also, hydropower generation is considered to have the lowest cost among renewable generation sources, although the design and implementation of a hydropower plant require high investments. The hydropower generation system in Brazil comprises large reservoirs with multi-year regulation, arranged in a complex cascade system, considering rivers and basins (Dranca and Ferreira, 2018). Figure 1 presents the problem regarding planning and operation of the Brazilian electrical system, whose solution, in a preliminary approach, lies on the balance between fuel consumption (thermoelectric) in relation to the amount of water accumulated in the reservoir (hydroelectric), which provides the lowest cost at a future time.

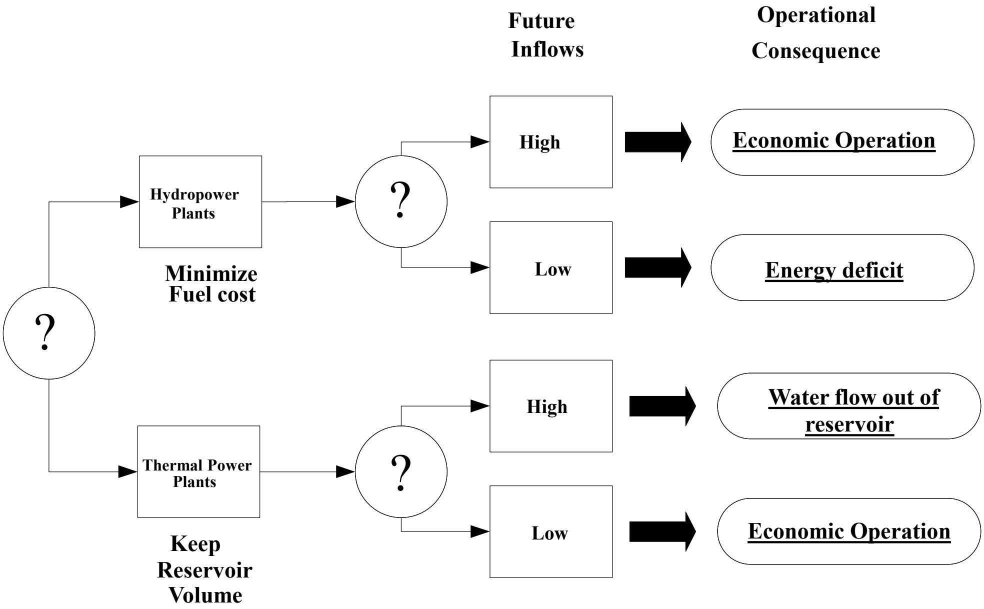


Fig. 1 The problem of hydrothermal coordination.

Source: Adapted from Ferreira et al., 2015.

Hydrothermal planning and operation or coordination consist of identifying an operating strategy, whereby the resources available for power generation are used reasonably, resulting in meeting the demand of electric power at lower and lower electric system operating costs. The characteristics of the hydrothermal coordination problem are: Time-coupled, an operating strategy adopted in the present that brings consequences in future strategic decisions; irregularity in the inflows to the reservoirs or hydrological uncertainty; Coupled in space, *i.e.*, hydropower plants are interdependent, for the amount of water released in one plant affects the operation of another and the value of the power generated by a hydropower plant can be measured based on the resulting savings in the thermal generation costs or on the avoided deficits one located downstream (ONS, 2016).

The objectives of operation savings and service reliability are antagonistic and conflicting: the maximum use of hydropower energy available at each stage is the most economical policy, given that it minimizes the cost with the fuel. However, this policy is the least reliable, once it results in higher future deficit risks in a predominantly hydropower-based matrix. The maximum supply reliability is accomplished by keeping the level of the reservoirs as high as possible. However, this means using more thermoelectric generation, incurring an immediate cost. This way, the total operation cost, given by the sum of the future cost and immediate cost installments, increases. The balance between operating cost and reliability is obtained through the deficit cost, which represents the economic impact associated with the interruption of the energy supply. The determination of the deficit cost is a highly complex problem, but it is fundamental towards the determination of the most appropriate operation policy for the system. When the deficit cost is significantly low, the result is excessive use of the reservoirs and, therefore, greater rationing risks in the future. If the deficit cost is high, the result is an overuse of the thermoelectric resources of the system at high operating costs (Marzano et al., 2014; Aragão et al., 2017; Rego et al., 2017).

The operation planning consists of finding an operation strategy that, for each stage of the planning period, given the condition of the system at the beginning of the operation, provides generation goals for each plant of the system. Such a strategy must minimize the operation cost expected value along the period, which consists of the fuel cost plus the fines due to eventual faults in the service. Assuming the inflows are known at the beginning of stage *t*, the resulting control problem may be solved by the recursion of stochastic dynamic programming (SDP) of the type chance-decision, according to equation 1.

$$\boldsymbol{\alpha_t(X_t)} = \underset{\boldsymbol{A_t|X_t}}{\boldsymbol{E}} \left\{ \min_{\boldsymbol{U_t}} \left[\boldsymbol{C_t(U_t)} + \frac{\mathbf{1}}{\mathbf{1}+\boldsymbol{\beta}} \boldsymbol{\alpha_{t+1}(X_{t+1})} \right] \right\} \tag{1}$$

$$\begin{aligned}
&s.a.\\
&\boldsymbol{X_{t+1} = f_t(X_t, A_t, U_t)}\\
&\boldsymbol{g_{t+1}(X_{t+1}) \geq 0}\\
&\boldsymbol{h_t(U_t) \geq 0}
\end{aligned}$$

where t = T, T-1, ...; for every $\boldsymbol{X_t}$

Equation 1 is performed for each stage t of the study period. The study horizon is represented by T and ß is the discount rate or capital cost for the electric sector. The length of each stage and the horizon depend on the characteristics of the system. Condition variables $\boldsymbol{X_t}$ include the characteristics of the problem that affect the operation decision. In the case of hydrothermal systems, there are usually two classes of condition variables: volumes stored in the reservoirs at the beginning of stage t, $\boldsymbol{V_t}$, and some information about the hydrological tendency. This information can be given, for example, by the rising inflows to the reservoirs in the previous stages. The number of past stages that are represented is directly associated with the order of the stochastic model and varies for each system. $\boldsymbol{A_t}$ $\boldsymbol{|X_t}$ represents the probability distribution of inflow $\boldsymbol{A_t}$ related to the condition of system $\boldsymbol{X_t}$.

The decision variables of the problem at each stage t, U_t include the water that passes through the turbines, Q_t, and the outflow, S_t, in the reservoir. $C_t(U_t)$ is the immediate cost associated with decision U_t, and $a_t(X_t)$ represents the expected value of the operation cost from stage t to the end of the planning period under the optimum operation hypothesis. The condition transition equation, $X_{t+1} = f_t(X_t, A_t, U_t)$ corresponds to the continuity equation of the equation, given by equation 2:

$$V_{t+1} = V_t + A_t + M(Q_t + S_t) \tag{2}$$

Where M is the incidence matrix of the hydropower plants ($m_{i.i} = -1$, $m_{i.j} = 1$ if i is immediately upstream of j and $m_{i.j} = 0$ in the other cases). The restrictions associated with the condition of the system, $g_{t+1}(X_{t+1}) \geq 0$ correspond to limits of the volumes stored in the plants, given by equation 3:

$$V^{i}_{-t+1} \leq V^{i}_{t-1} \leq V^{-i}_{t+1} \tag{3}$$

Where V^{i}_{-t+1} and V^{-i}_{t+1} are, respectively, the lower and upper limits of storage of reservoir i. The restrictions associated with the decision variables, $\mathbf{h}_t(\mathbf{U}_t) \geq \mathbf{0}$, corresponds to the upper limits of the water that passes through the turbines, given by equation 4; and the lower limits of the total outflow of the plant are given by equation 5.

$$Q^{i}_{t} \leq Q^{-i}_{t} \tag{4}$$

$$Q^{i}_{t} + S^{i}_{t} \leq Q^{i}_{-t} \tag{5}$$

Thermoelectric plants are represented by thermal plant groups with similar costs, called thermal classes. The energy supply deficit is represented by a fictitious thermopower plant with infinite generation capacity and a differentiated operation cost for each percentage of market non-compliance at each load level. Thermoelectric generations and the exchange are indirectly represented by the *immediate cost function* $C_t(U_t)$. This function represents the thermal generation cost required to complete the demand in stage t (the service is ensured by the inclusion of a fictitious thermal plant). This complement is the difference between the demand and the hydroelectric energy produced by the volume of the water that passes through the turbines Q_t, given by equations 6.

$$GH(U_t) = \sum_{t=1}^{NH} \rho_i Q_t^i \tag{6}$$

Where p_i is the productivity of the hydropower plant i. It is important to notice that the productivity is, in fact, a function of the total outflow and the initial and final volumes of reservoir i, *i.e.*, $p_i = p(V^{i}_{t}, V^{i}_{t+1}, Q^{i}_{t}, S^{i}_{t})$. This way, the calculation of the operation immediate cost at each stage can be attained by solving the linear programming problem:

$$C_t(U_t) = min \sum_{j=1}^{NT} c_j\left(G_t^j\right) \tag{7}$$

$$s.a.$$

$$\sum_{t=1}^{NH_K} \boldsymbol{\rho_i Q_t^i} + \sum_{j=1}^{NT_k} \boldsymbol{G_t^j} + \sum_{r\in\Omega_k} \left(\boldsymbol{f_t(r,i)} - \boldsymbol{f_t(i,r)}\right) = \boldsymbol{N_t^K}$$

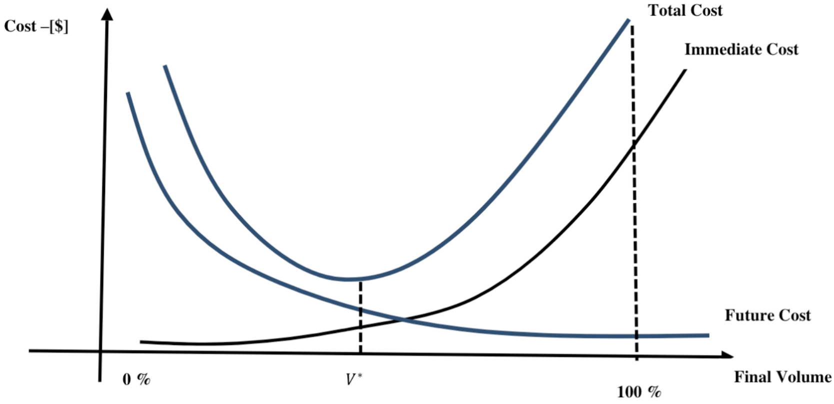
$$G_{-t}^{j} \leq G_t^j \leq G_t^{-j}$$

$$f_t(i,r) \leq \overline{f_t}(i,r)$$

For values of k=1,2,3,...., NS, where:

NS	Total number of subsystems;
$\boldsymbol{NH_k}$	Total number of hydropower plants of subsystem k;
NT	Total number of thermal plants;
$\boldsymbol{NT_k}$	Total number of thermal plants of the subsystem k;
k	Considers the number of the used subsystem, com $k=1, 2,..., NS;$
j	Represents thermoelectric plants, with $j=1,2,..., J$;
$\boldsymbol{G^{i}_{t}}$	Thermoelectric generation j at stage t (MWh);
$\boldsymbol{G^{i}_{-t}}$ e $\boldsymbol{G_t^{-j}}$	Minimum and maximum generation limits of j at stage t (MWh);
$\boldsymbol{C_j}$	Thermopower generation cost j (R\$/MWh);
$\boldsymbol{N^k_t}$	Power need of subsystem k at stage t (MWh);
$\boldsymbol{f_t (i,r)}$	Energy exchange from subsystem i to subsystem r (MWh) at stage t;
$\boldsymbol{\overline{f}_t (i,r)}$	Power Exchange limit from subsystem i to subsystem r (MWh) at stage t;
$\boldsymbol{\Omega_k}$	Set of subsystems directly connected to subsystem k.

For a graphical analysis of the hydrothermal coordination problem, it is enough to consider that function $\boldsymbol{a_{t+1} (X_{t+1})}$ represents the expected value of the operation cost form stage $t+1$ to horizon T, starting at condition X_{t+1}, *i.e.*, the future cost considering the use of hydroelectricity and the uncertainties concerning the inflow. The immediate cost related to thermoelectric generation is $\boldsymbol{C_t (U_t)}$. This way, the total operation cost that is comprised by two parts at each strategy to meet the demand must be minimized, which is the minimization of the objective function, given by equation (1). Graphic 1 presents future and immediate costs in relation to the reservoir use, considering the uncertainties related to the inflow for the development of the future cost function.



Grap.1 Cost Dynamics in relation to the final volume of reservoirs

Source: (ONS, 2016).

The approach used to solve the planning and operation problem of the Brazilian electrical system, given by the stochastic dual dynamic programming, considers that all the reservoirs of the subsystems can be grouped in a single equivalent reservoir. This way, each subsystem presents one single equivalent reservoir subject to the rainfall regime, considering a series of two thousand values generated by a Box-Jenkis periodic autoregression model based on the precipitation at the plant sites from rains at the stations of the mills form 1931 to 2001. In this stage of solving the planning problem, a period of five years is considered. This computational module is called NEWAVE. The second stage is to split the equivalent reservoir and obtain the generation per plant and the water values that remained in the reservoir. The DECOMP module is responsible for this stage. The discretization or time period of the DECOMP is weekly-based. In case an hourly-based discretizations is necessary, the module *DESSEM* must be used.

3 I RESEARCH METHODOLOGY

This research can be classified as applied research, once its results can be used to solve problems that occur in real life, mainly related to the planning and operation of the Brazilian Electrical System (BES). As for its goal, it can be classified as exploratory research, given that it aims at being familiar with the issue of energy diversification, considering the several sources of energy. Thus, this research consists of a systematic review of the literature, focusing on alternative sources of energy and the diversification of the electric matrix (Campos et al., 2017). The case study approach is used by carrying out an analysis of the documents regarding the BES, published by the Operator of the National Electricity System (ONS) and the Brazilian Electricity Regulatory Agency (ANEEL).

The systematic review of the literature was performed by using the Preferred Report Items for Systematic Review and Meta-Analyses, PRISMA, developed at a meeting of researchers in Ottawa, Canada. The goal of using PRISMA is to favor systematic reviews of the literature and Meta-Analysis, avoiding bias in the research (Moher et al., 2009; Haddaway et al., 2015). PRISMA consists of four phases: Identification, Screening, Eligibility and Included. The Identification phase consists of extensive research on all papers published from two 2014 to 2017 in the most important databases, such as Web of Science, Scopus and Google Scholar. The research in the papers and abstracts was made using these keywords: Electrical matrix diversification, energetic sources, renewable energy. The result was 404 papers. The Screening phase consists of the reading of the abstracts. The complete text must also be read if it is necessary to filter the relevant papers, following criteria below:

1. The paper must address problems regarding planning, expansion and operation of the electric system;

2. The paper must address the research issue, *e.g.*: the necessary natural resources to favor the use of a certain alternative source;

3. Presenting the empirical study of the impact of several sources of electric power generation in the electric matrix of other countries.

4. The last criterion consists in dividing the papers into three groups: (i) first group: papers with studies about the planning and operation of BES, focusing on the use of alternative sources, and their modeling in hydrothermal dispatch software, Newave ; (ii) second group: the papers that address alternative sources of energy: solar and photovoltaic, wind and biomass (mainly solid waste); and (iii) third group: papers that relate the sector variables such as deficit risk or low electricity offer; amount of power supplied by each type of generation source and operation cost of the electric system.

The Eligibility phase consists of reading the papers, highlighting the research method that was used, the main results and suggestions for future researches, which indicate the gaps that must be investigated. The Included phase consists of a joint analysis of documents and reports provided by the Ministry of Mines and Energy (MME), the Operator of the National Electricity System (ONS) and the Brazilian Electricity Regulatory Agency (ANEEL) and the papers obtained by the systematic review of the literature. Figure 2 presents the research method, relating the results of each step.

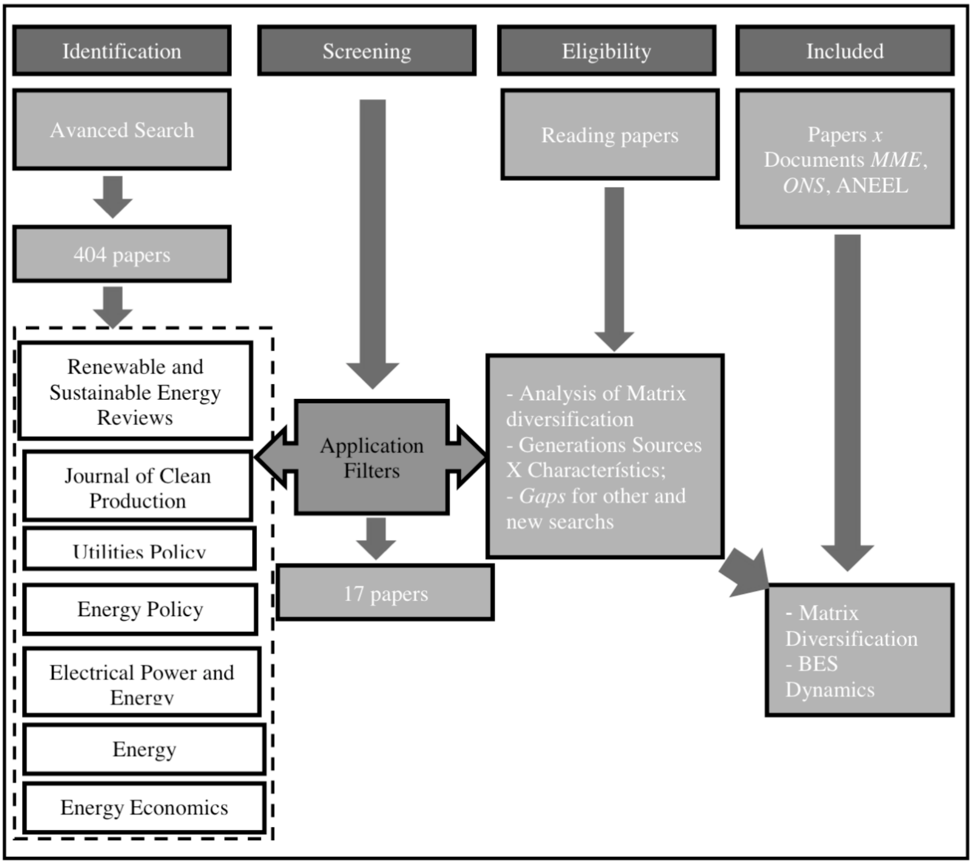
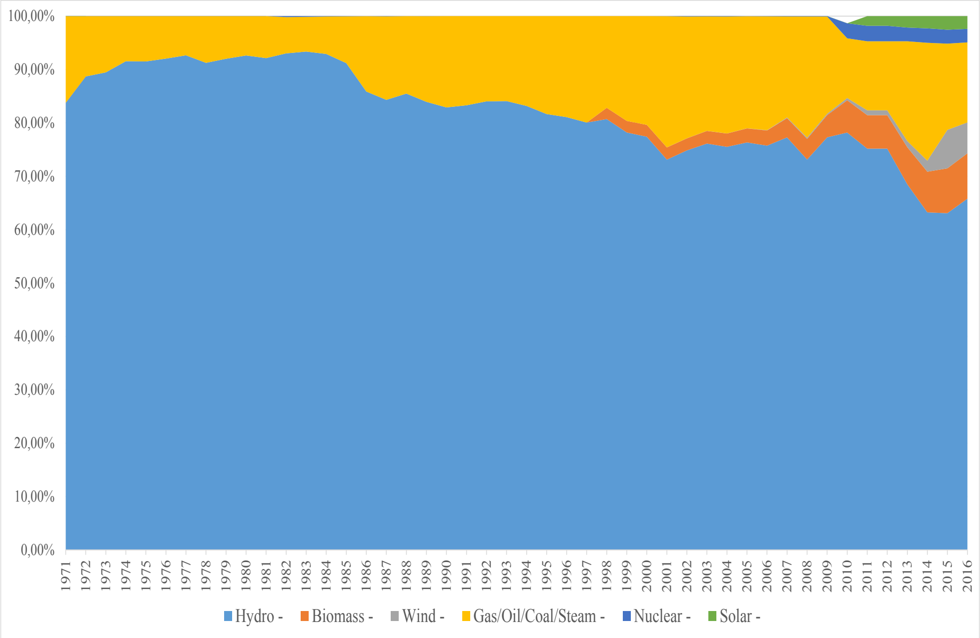


Fig. 2 Research Method.

4 | PRESENTATIONS AND ANALYSIS OF RESULTS

One of the concepts mentioned in the study of matrix diversification is the endowment effect. Such concept reinforces that the presence of natural resources in the country makes the development of new technologies for the production of electric energy difficult, for it is estimated that such investments are high compared to the use of technologies that already use the existing and traditional resources for electric power generation (Kileber and Parente, 2015). As far as Brazil is concerned, as it has been pointed, the power offer comes mostly from hydropower generation. Graphic 2 shows the evolution of the electric power load supply in Brazil from 1971 to 2016, considering the inclusion of other sources of electric power production.



Grap. 2 Evolution of the load supply for each power source.

The expansion of the electric power offer in Brazil must also consider the premises of economic growth that is safe and respects the environmental regulations. Brazil has a significant power potential, where renewable sources such as hydraulic, wind, solar and biomass must be highlighted (ANEEL, 2019). When it comes to the definition of the diversified matrix, a problem that must be taken into account is to provide the necessary flexibility power supply at any given time and in response to instantaneous variations in load and short-term demand. For these situations, a possible policy, adopted in PDE 2026 (MME,2019), consists of:

- Repowering or installing additional generating units at existing hydroelectric power plants;
- Fast start-up thermoelectric plants;
- Reversible hydroelectric plants;
- Chemical power storage (batteries);

The repowering and use of motors at existing hydroelectric plants pose as an alternative for situations where it is possible to obtain power benefits due to the reduction of eventual outflow, resulting in gains related to the physical guarantee of the plant. However, it is necessary to verify the water availability and whether the expansion does not violate operating restrictions. Fast start-up thermoelectric plants operate in simple cycles by using internal combustion engines, gas turbines or even industrial turbines (heavy duty). The most important characteristic of such plants is the high flexibility, allowing their generation to increase or decrease in a few minutes, thus following the curve of the load that must be supplied. For natural gas plants, the availability of the fuel and the respective pipelines are so important that the fuel supply is guaranteed even if the plant does not operate for long periods, increasing fixed costs. However, when the flexibility of sources of energy is considered, it is possible that thermoelectric plants can operate with other fuels besides natural gas. Reversible hydroelectric plants are characterized by the possibility of pumping water from a lower reservoir to an upper one, during periods of lower demand and providing power to the system throughout more significant demand. Nevertheless, the power balance of such plants is negative, for the generated power corresponds to eighty percent of the power consumed to pump. The desired number of hours of generation cycle, the difference in the level of the upper and the lower reservoirs, available water storage volume, as well as the topographic conditions are important variables for the planning of reversible hydroelectric plants. It is noteworthy that there are studies carried out in the 1970s indicating the southeastern region of Brazil as a potentially good location for reversible hydroelectric plants. The storage of electric power, on the other hand, by using batteries, aims at acting as a load or immediate dispatch generators. In California, there are 30MW/120 MWh battery systems, predominantly lithium-ion technology, operating at nominal power for up to four hours. The storage of electric power by batteries emerges a promising alternative in Brazil, as long as the cost of this technology and the additional services decrease over time. In addition to the batteries, there are two other promising technologies to keep the power up for a few load levels: hydrogen cells and compressed air energy storage (Compressed Air Energy Storage).

Table 1 shows the 2019 arrangement of the Brazilian energy matrix, where it is possible to notice the predominance of hydroelectric generation. It is also possible to observe investments in other sources of generation, such as wind, biomass and fossil fuel and natural gas thermal plants. The objective of investing in such plants is to minimize the hydrological risk present in a predominantly hydropower matrix and balance the supply to the load, which presents periods of peak and is more unstable than the average demand.

Source			**Installed Capacity**		
Origin	**Level 1**	**Level 2**	**Number of power Plants**	**kW**	**%**
Biomass	**Agro Industrial**	Sugarcane Bagasse	407	11.352.402	6,5977%
		Biogas AGR	3	7.951	0,0046%
		Elephant Grass	2	31.700	0,0184%
		Rice Husk	13	53.333	0,0310%
	Liquid Biofuel	Ethanol	1	320	0,0002%
		Vegetable Oils	12	4.350	0,0025%
	Forest	Charcoal	8	48.197	0,0280%
		Blast Furnace Gas - Biomass	12	127.705	0,0742%
		Firewood	5	36.7185	0,0213%
		Black Liquor	18	2.542.616	1,4777%
		Forest Residues	58	434.117	0,253%
	Animal Residues	Biogass Animal Residues	14	4.481	0,0026%
	Urban Residues	Biogas – Urban Residues	21	137.735	0,080%
		Coal Urban Residues	2	5.250	0,0031%
Wind Power	**Wind Kinetics**	Wind Kinetics	610	14.958.393	8,6934%
Fossil	**Mineral Coal**	Process Heat – Mineral coal	2	28.400	0,0165%
		Mineral Coal	12	2.857.740	1,6608%
		Blast Furnace Gas – Mineral Coal	8	365.960	0,2127%
	Natural Gas	Process Heat – Natural Gas	1	40.000	0,0232%
		Natural Gas	166	13.314.419	7,7380%
	Others Fossils	Process Heat – Obter Fossil	3	157.950	0,0918%
	Oil	Blast Furnace Gas - Oil	1	1.200	0,0007%
		Refinery Gas	6	319.530	0,1857%
		Fuel Oil	77	3.344.179	1,9435%
		Diesel Oil	2.147	4.162.451	2,4191%
		Other Oil Energy	17	1.023.328	0,5947%
Hydraulic	**Hydraulic Potential**	Hydraulic Potential	1.341	104.471.516	60,7160%
Nuclear	**Uranium**	Uranium	2	1.990.000	1,1565%
Solar	**Solar Radiation**	Solar Radiation	2.469	2.074.002	1,2054%
Wave Power Plant	**Kinetics or Water**	Kinetics or Water	1	50	0,0000%

Import	**Paraguay**			5.650.000	3,2836%
	Argentina			2.250.000	1,3076%
	Venezuela			200.000	0,1162%
	Uruguay			70.000	0,0407%
TOTAL			**7.429**	**172.065.990**	**100%**

Table 1. Brazilian energy matrix arrangement

Source: ANEEL (2019)

Figure 3 shows the study plan for calculating the diversification of the Brazilian matrix, defining the variables that influence the decision of the offer expansion policy and the policies that several researchers approach (Maceira et al., 2015; Guerra et al., 2015; Bradshaw, 2017; Dantas et al., 2017; Gomes et al., 2018; Lamas et al., 2013).

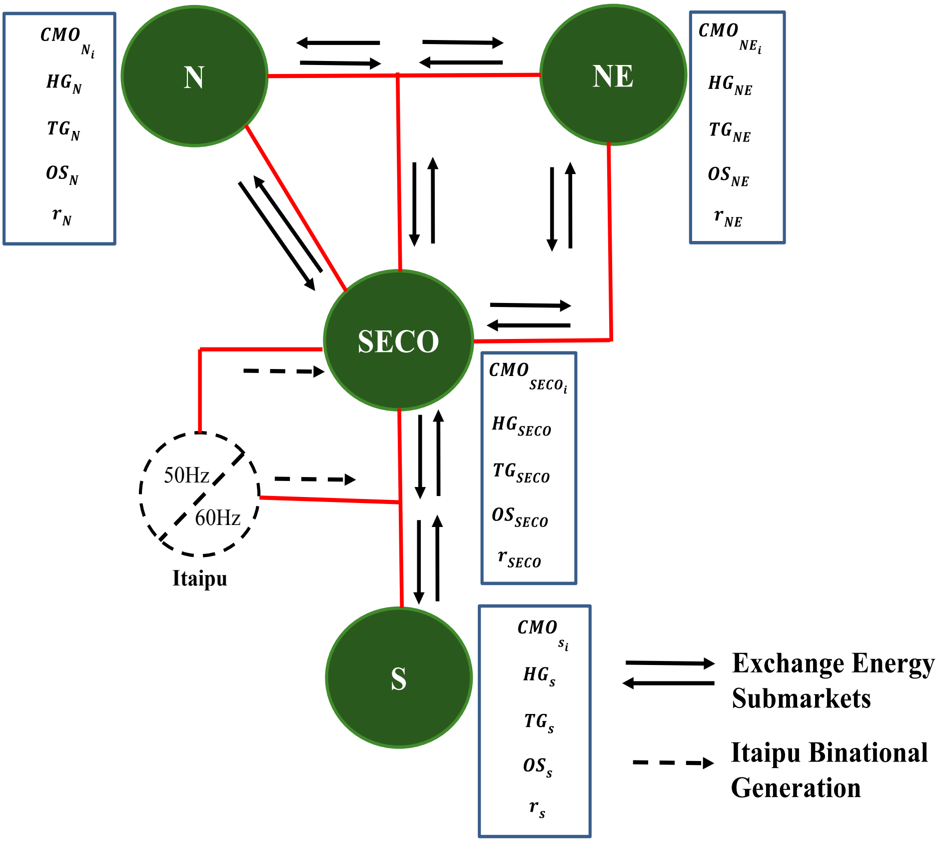


Fig. 3 BES, considering condition variables

The BES variables are provided at the end of the simulation with Newave. These variables provide the configuration of the system and are used for planning and operation studies. They are:

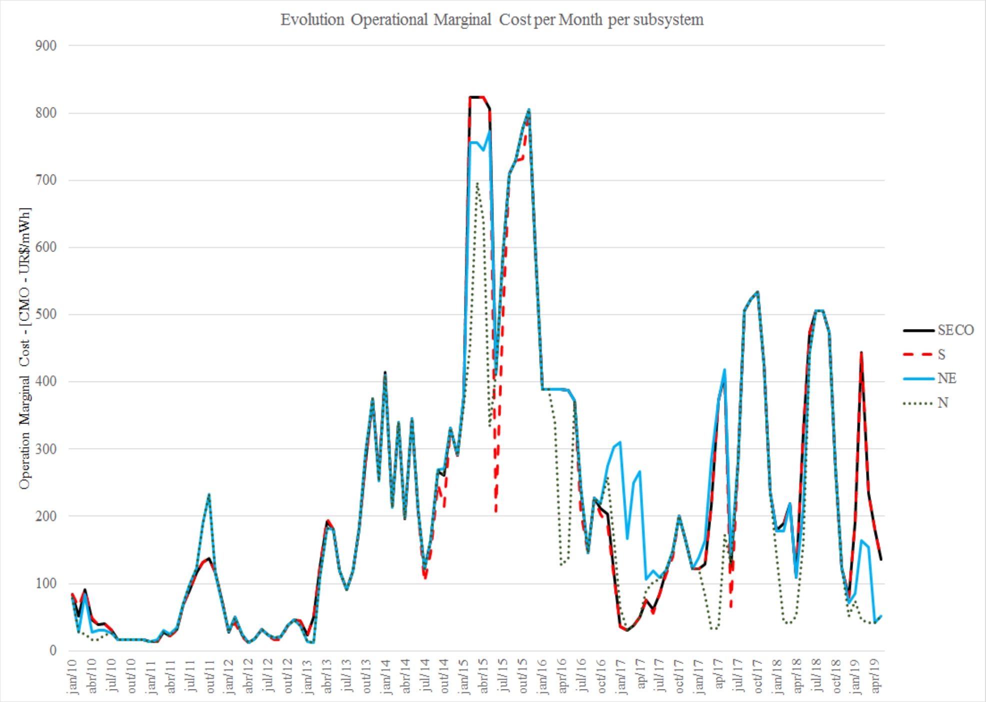
- Marginal cost operation per load level i ($i = 1$ - heavy, 2 - average or 3 - light): The marginal cost reflects the cost to meet a demand variation of one mWh, given in US$/mWh. The marginal cost operation is calculated for each load level, as shown in Table 2, and for each submarket. Thus, for example, CMO_{S_1} refers to the marginal cost operation of the South submarket at the heavy level. As the dispatch model is hydrothermal, the marginal cost is very sensitive to the inflow (Maceira et al., 2015).

Load level	**Monday to Saturday**	**Sunday/holiday**
Heavy	6 pm – 9 pm	
Average	7 am – 6 pm	5 pm – 10 pm
Light	12 am – 7 am	12 am – 5 pm 10 pm – 12 am

Table 2. Periods of energy load level.

Source: MME (2018).

Graphic 3 shows the marginal cost operation for each subsystem over the past ten years; monthly-based data.



Grap. 3 Evolution of the marginal cost operation for each subsystem over the last at a monthly basis

- Hydropower generation, thermal generation and generation using other sources per submarket (respectively represented by HG, TG and OS) consist of the amount of energy supplied by each type of generation within BES for each subsystem (Maceira et al., 2015; Hunt et al., 2018; Pereira et al., 2012; Pottmaier et al., 2012; Schimdt et al., 2016).
- Deficit risk consists of the probability of a load cut in the market demand. In the hydrothermal dispatch model, Newave, the deficit is associated to the cost, which measures the value of the lack of electric energy by taking into account the impact of the restrictions on the electric energy supply in the economic production of the country (Paim *et al.*, 2019). The cost of the deficit is a key parameter for the planning and operation of the BES, for under unfavorable hydrological conditions, it is one of the determinants in the formation of the CMO and the price in the spot market, given that it is an indicator of thermal plants dispatch. The calculation of the deficit cost was developed by the Research Center in Electrical Energy (CEPEL), based on the National Energy Policy Council (CNPE) resolutions No. 1/2004 and No. 9/2008. The maximum limit of probable energy deficits occurrence is 5% of the hydrological horizons. The planning, then, must seek equality between CMO and Marginal Cost of Expansion (CME), establishing power and economic security criteria. Thus, the cost of the deficit is the value

for which the CMO and CME equalize considering a non-market criterion of 5% for each subsystem. This strategy for valuing the cost of the deficit presents a high computational cost, given that several simulations of the Newave model are necessary to reach the equality between CMO and CME (Campos et al., 2017).

The CMO_{it} and r_i variables stimulated the creation of risk aversion systems (RAS), introduced in the problem of minimization of total operation cost, automated by Newave. The first approach consists of inserting a constraint in the stochastic dual dynamic programming, called Risk Aversion Curve. The second approach is to introduce a Risk Aversion Surface in the objective function of the hydrothermal dispatch problem. In the latter, the simulation with Newave presents a subroutine that determines the deficit risk, considering not only the final stored energy in the reservoirs of each subsystem, but also the total energy of the system. The other method within the RAS approach is the Conditional Value at Risk (CVaR), which allows more focus on the most critical hydrological horizons in the calculation of the operation policy. This approach is given by altering the objective function, so that not only the total operation cost with a given weight (1-λ) is minimized, but also an additional part related to the cost of the most critical hydrological horizons with weight λ. The most critical set of hydrological horizons is identified by an α parameter related to the protection level and that indicates the percentage of the total horizons of the period that will be considered with additional cost in the objective function. The values of parameters λ and α are associated with the level of risk aversion that was adopted (Maceira et al., 2015).

5 | CONCLUSIONS AND POLICY IMPLICATIONS

The diversification of the electric energy matrix, considering renewable and non-polluting sources, is a challenge for several countries. As for Brazil, its geographic extent divided into regions with different climatic characteristics and energy consumption profiles, the problem of using other sources for electric power generation is facilitated by the existing abundance of natural resources. Throughout the systematic literature review, it was observed that mainly after the 1970s, a period when the country invested in industrial growth, the need for electric power was mostly met by hydroelectric plants. This characteristic made the supply of the demand susceptible to hydrological risks due to the inflow regime.

The evolution of the electric energy matrix must be able to meet not only the consumption, but also the loads (composition of the system load curve), which have different behaviors according to the period of the day. Thus, the management of BES's electrical matrix considers the use of reservoirs up to a point. Thus, BES must implement the risk aversion systems, in case part of the power supply must come from other sources, mainly gas thermal plants, in such a way that part of the energy of the system is stored in the reservoirs, which start to work as batteries of the system.

This study points out the variables that can be used for planning the matrix diversification. They are marginal cost of operation (CMO), power generation (supplied by several sources: hydropower, wind, solar) and the deficit risk. For the Brazilian market until the 1940s, power generation was close to the load centers and the amount of energy supplied was the main variable of the Brazilian electrical system. However, from 1940 on, the construction of large plants with reservoirs for future generation became a more economical alternative, given that doubling the inputs, energy production increased more than twice (increasing scale economy).This way, the system operation cost was added to the analysis. As BES was predominatly hydropower-based, the risk of low inflow and the issue regarding the load behavior stimulated the inclusion of other sources, especially thermoelectric plants. However, it was necessary to associate the cost of the water stored in the reservoirs with the decision to dispatch the thermal plants, mainly those using gas. The CMO variable incorporated this information and the risk of deficit completed the diagnosis of the system, for it emphases the risk of power shortage.

Over the last two decades, the BES trend has been to bring generation closer to consumers or to a load centers. This policy is known in Brazil as distributed generation and it uses several sources energy, mainly solar. However, the accounting for the power generated in this modality consists of calculating the difference between the energy supplied by the system and the energy supplied by the producer, who is a consumer at the same time. This new player is called prosumer. As at BES the planning and operation are centralized, the variables are manipulated according to the hydrothermal dispatch model, NEWAVE, which is the BES official planning and operation software.

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