Natural Gas in the Long-Term Energy Planning for Power Sources Diversification within Brazilian Power System

Eduardo M. Viana, Miguel E. M. Udaeta, Luiz Claudio R. Galvão, and André Luiz V. Gimenes

Abstract—**This paper discuss the energy sources for hydroelectric complementation considering diversification in the long-term energy planning. Among these sources, natural gas thermoelectricity appears as adequate for use on the scale required by the Brazilian electric system. This result justifies the necessary changes for both electricity and natural gas sectors to ensure energy supply in long-term horizon. Thus, we discuss some of required measures and propose a conceptual model for integrated gas-electricity planning.**

Index Terms—**Electricity, energy planning, natural gas, renewable energy.**

I. Introduction

Brazilian hydroelectric potential summed 261 GW in 2014 with only 32% of this potential being explored [1]. Most of hydroelectric power plants in the Brazilian electric system are of regularization type, that is, they have reservoirs for water storage for later use, thus having a fundamental role in optimizing the generation and security of supply of Brazilian National Interconnected Power System (SIN).

Even with a great share of unexplored potential, some factors questions the expansion of hydroelectricity in Brazil. The first factor refers to the increasing of environmental restrictions related to the construction of power plants with large reservoirs. In fact, the hydroelectric plants licensed since 2003, were mostly run-of-river type, therefore, without storage capacity. In this scenario, Brazilian National System Operator (ONS) has been warning about the risks of reducing the regularization capacity of SIN [2]. The second factor raises an energy security issue: how safe is to depend on a single source for energy supply? Some authors such as Li [3] and Bishop [4] establish that an energy system can only be sustainable in the long-term by diversifying energy sources.

Energy diversification implies in adding new sources to the energy matrix to ensure supply and reliability in the medium and long term horizon. In addition, the concept of energy diversification is related to the inclusion of cleaner sources in the energy matrix. In Brazil, this aspect appears in background, since the country already has one of the cleanest electric matrices in the world, and diversification is more related to energy security to ensure long-term supply, with diversification of the type and location of sources. Although holding a clean matrix, Brazil is going through a process of insertion of Variable Renewable Energy (VRE) in the electric matrix, most notably solar and wind energy. Brazilian official energy plan considers for the next ten years, an installed capacity of 31 GW of VRE sources [5].

The insertion of VRE sources in the electric matrix is welcome from the point of view of diversification, but does not mitigate energy security problem caused by the storage capacity reduction, which has intensified in the last decade. Therefore, diversification will also have to move towards the insertion of ensured energy sources in the Brazilian electric matrix. That is, Brazilian Electric Sector (SEB) needs to replace the loss of regularization by ensured energy from other sources. Facing this scenario is the question: which source has the potential for long-term ensure supply?

In Brazil, the diversification to replace regularization is moving towards the direction of thermoelectric power plants usage. As we will show later, Brazilian thermoelectricity park was originally designed for complementary dispatch, but since 2012 assumed an almost base load profile, being dispatched continuously since then, costing near 500 million dollars per month. This fact indicates that SIN requires a change on its operation philosophy to include competitive thermoelectric power plants in base load dispatch. In addition, a new operation philosophy should be able also to deal with the intermittent aspects of VRE sources, which requires that the residual power plants, i.e., the power plants that supply the remaining load not supplied by VRE's, have the flexibility to assume the variability of VRE sources.

In this sense, this work aims first to discuss SIN operation philosophy addressing the issue of loss of regularization capacity. The change in operation philosophy demands competitive thermoelectric sources on base load dispatch and, therefore, it is necessary to analyze the primary sources for diversification in the long term, searching for sources that have potential to cover the new thermoelectric profile. Among the options, natural gas (NG) appears in a promising position, considering the long-term prospects of NG in the Brazilian energy matrix. This scenario indicates the need for planning the NG sector to supply Brazilian thermoelectric power plants. The network characteristic of both electricity and natural gas shows that an integrated gas-electricity planning is the most adequate for the optimized expansion of these sectors in Brazil. Therefore, another objective of this work is to propose conceptually an integrated planning model, discussing the assumptions of this model, and showing the possible gains in relation to the Brazilian energy planning today.

The remaining of this paper is structured as follows: Section II presents a characterization of the Brazilian

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hydrothermal system. Section III discusses the new paradigms of the electric sector addressing the operation philosophy and primary thermoelectric sources. Section IV addresses the issue of gas-electricity energy planning, showing the importance of integrated energy planning. Section V presents the proposed energy planning model and Section VI concludes the work.

II. Brazilian Hydrothermal Power System

Brazilian National Interconnected System is characterized by the predominance of the hydroelectricity that accounts for 65% of installed capacity [1]. A system with these characteristics has strong dependence on rainfall, resulting in uncertainties such that is not possible to predict the affluent natural energy (ENA). This way, over the years, SIN was constructed to minimize the impacts of the uncertainties, with the construction of large reservoirs for energy storage. Due to this feature, hydroelectric power plants supply the major part of electricity and flexible thermoelectric power plants complements the required energy.

Brazilian power system passed through significant changes in recent years, and environmental restrictions started to affect the generation expansion planning. In general, the hydroelectric power plants constructed the last decade, are run-of-river type and Small Hydroelectric Plants (PCH's). This is largely because the main alternative for hydroelectricity expansion is in the Brazilian Amazon region where, for geographic reasons, the rule is the construction of run-of-river power plants. In addition, the electric matrix has also expanded through the VRE sources, such as solar and wind power, increasing the intermittent characteristic of generation. This seems to be a path with no return in the expansion of the Brazilian electric matrix.

In this scenario, since 2001, SIN is losing capacity to store the ENA, which leads to a reduction in the ratio of Stored Energy (EAR) to the load. According [6], the relationship between EAR and SIN load dropped from 6.3 in 2000 to 4.5 in 2012, as shown in Fig. 1.

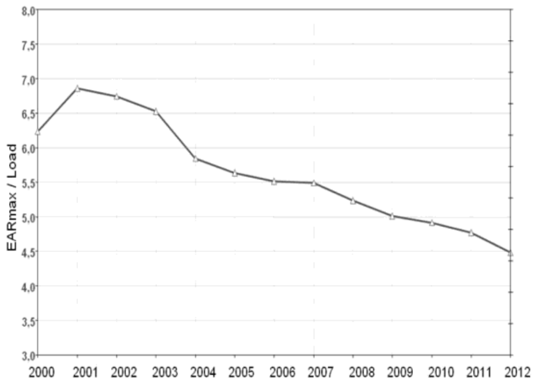


Fig. 1. Brazilian hydroelectric storage level [6].

SIN will experience a gradual reduction of EAR / load in the coming years. By 2024 the storage capacity will expand only 2.6 averages GW, which corresponds to approximately 1% of the total existing in 2015, while demand will grow 45% [5].

In extreme scenarios, where the generation of non controllable sources, as VRE's, begins to be representative, it is necessary to have controllable sources to guarantee demand supply, that is, the storage capacity need to be replaced by ensured energy from other sources. In this way, it will be necessary to diversify the resources of firm generation and SEB must be prepared for this change. The new generation resources should be able to overcome the uncertainties related to the inflows, replacing the necessary regularization by ensured energy from other sources.

As EAR reduces related to the load, the operational strategy for yearly regularization of reservoirs may not be feasible, implying an increase in the exposure of SIN to the inflows uncertainties, resulting in an increasingly frequent and long use of thermoelectric sources. In fact, in last five years, Brazilian thermoelectric power plants assumed a continuous dispatch profile, while reservoirs levels were in reduction. Fig. 2 shows the participation of thermal generation and the level of the reservoirs of the Southeast and Midwest regions of Brazil. Since 2012, the continuous use of thermoelectric power plants with a reduction of the reservoirs level left SIN in a more vulnerable situation than the rationing occurred in 2001.

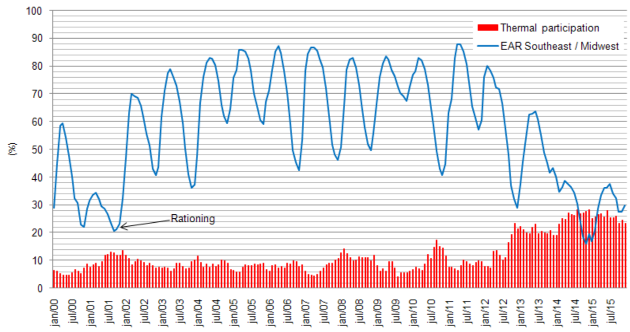


Fig. 2. Storage level x thermoelectric participation.

Brazilian thermoelectric power plants were designed for complementary dispatch, having, therefore, low fixed cost and high variable cost. However, when moving to a frequent dispatch profile, the total costs become high, evidencing the inefficiency of the Brazilian thermoelectric power plants to the new operational profile required by SIN. Thus, two paradigms need to be issued in SEB: (i) change of the operation philosophy, considering the thermoelectric power plants on a base load dispatch. This has already been pointed by ONS [2] and; (ii) selection of competitive primary sources for these thermoelectric plants for base load dispatch.

III. Paradigms of Brazilian Electric Sector

A. Operation Philosophy

Brazilian power system was designed to take advantage of the vast hydroelectric potential of the country, so that the hydroelectric plants would mostly supply the demand for electricity and the thermoelectric power plant would be flexible, complementing the missing energy, in moments of low affluence. Therefore, to reach the optimal operation cost, the dispatch is done centrally by ONS, which defines the ratio between hydroelectricity and thermoelectricity in the load supply, observing predicted hydrology scenarios. ONS chooses to use or store water over the time and complements the missing energy with thermoelectric power plants that are dispatched in merit order.

However, SIN goes through a transformation where the importance of the reservoirs is decreasing in relation to other sources that have been assuming a larger portion of the load. Although thermoelectric power plants are at the forefront of this change, other sources are also assuming the role of diversification of SIN sources. This is the case of VRE's, whose insertion in the SIN adds even more variability on the offer side. The official study of Energy Research Company (EPE) plans an increase of 24 GW and 7 GW of wind and solar sources respectively in its 10-year expansion plan compared to 2014, representing 15% of all installed capacity in the country [5]. These sources have high unpredictability of supply, which translates into new operational and commercial challenges [7]. As VRE increases their participation in the electric system, the remaining sources must be ready to respond to the operational variability of VRE source, that is, to guarantee the supply when the oscillations occur. As pointed out in [8], as soon as VRE generation starts to respond to an expressive proportion of load, other sources that compose the generation park are displaced, facing high variability in their dispatches. In this new context, the intermittent VRE imposes a high degree of flexibility to the residual generation, responsible for meeting the residual demand not supplied by VRE's.

The problem for SIN is, on one hand, the necessary increase of firm energy for base load operation and on the other hand the need of higher flexibility to accommodate the intermittent aspect of the VRE sources. Therefore, a change in the operation philosophy of SIN should be able to accommodate firm energy sources in place of hydroelectric regularization, intermittent VRE's, and other flexible sources that can handle with the variability of VRE's.

The solution to the operation problem pass through evaluation of sources types and their role in the dispatch: base load, mid-merit, or peak-loads. Historically, SIN was conceived in a way that the hydroelectric plants constituted the base of the electric system, due to the hydraulic availability and because these plants have virtually no marginal operation cost. However, as indicated by [7], hydroelectric plants have a natural characteristic of flexibility that can be very useful to the electric system when VRE's are dispatched. On the other hand, thermoelectric power plants presents technical limitations such as load pick up rate, shutdown time, start time, ramp restrictions, causing thermoelectric plants better to accommodate continuous dispatch characteristic without large variations, such as base load profile dispatch.

In this sense, with the increasing of VRE participation, it seems natural that hydroelectric power plants play the role of flexibility, while thermoelectric plants deliver a fixed base load dispatch, mitigating part of the problem of SIN regularization. As will be discussed later, for NG fueled thermoelectric power plants, this change would have a positive impact on the Brazilian NG sector, which depends on firm demand to anchor its development.

For SIN, an operation philosophy with base load thermoelectric power plants depends, however, on changes in the way of contracting thermoelectric power plants in energy auctions. Currently, the Cost Benefit Index (ICB) methodology favors power plants with low fixed cost and high variable cost, which privileges power plants for complementary dispatch [9], [10]. Therefore, it is necessary to change ICB methodology in order to attract investments in low costs thermoelectric power plants, placing them in a competitive position related to the hydroelectric power plants. This way, the thermoelectric power plants would begin to gradually take a base load position without abrupt changes to SIN.

In order to this change in operation philosophy be possible, the flexibility aspect of the residual generation required by VRE's also needs to be assessed. At the same time that the ICB calculation must be changed, the flexibility needs to be remunerated so that naturally flexible sources would migrate to a mid-load dispatch position, leaving base-load condition, and dealing with VRE variability. The remuneration of the flexibility needs to be done in a way that does not result in revenue losses for such power plants, considering that these units are currently remunerated by the amount of generated energy. In the Brazilian generation park, the hydroelectric power plants have the flexibility characteristic, being more appropriate to the interface with the VRE sources.

In this sense, the SEB needs a reorganization in the function of each electric source in the generation park, inserting more thermoelectric power plants in base load dispatch while moves some hydroelectric to the mid-load function, as shown in Fig. 3. Additionally, some high cost thermoelectric power plants, as those fueled by coal or Liquefied Natural Gas (LNG) can still do the peak-load function.

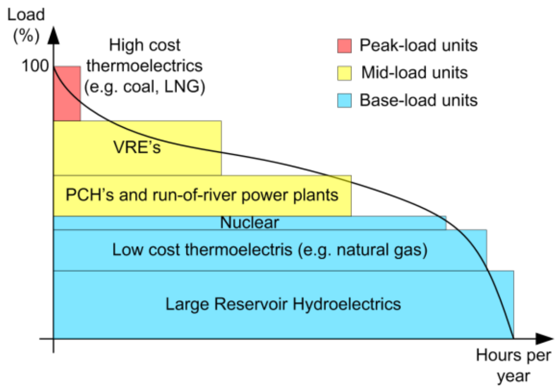


Fig. 3. Load duration curve.

The described change has the capacity to mitigate the EAR reduction effects of the SIN, and to accommodate the variability aspect of VRE sources, with potential to improve the efficiency of SIN in long term planning.

B. Electricity Expansion Options

The generation expansion in SIN has two aspects, the replacement of regularization capacity and the insertion of VRE sources, that is, the need of a firm energy source to mitigate the decrease of EAR and on the other side the need of flexible sources capable of dealing with the variability required by VRE's.

From the point of view of generation expansion, the increase of VRE supply is natural, considering the possibility of decentralized use, directly by the final consumer in the form of distributed generation. Technological evolution and government interest have encouraged this type of use in Brazil. There is also the portion of greater capacity, which is foreseen in the Brazilian energy auctions. The insertion of VRE sources brings the challenge of supply variability while not adding firm energy to SIN. Thus, it becomes impossible to dispatch as base load these sources and this limit their usage.

The most appropriate source for mitigating the regularization capacity reduction is the thermoelectric source, which has been assuming a continuous dispatching role in the past few years due to the reduction of the level of the reservoirs, as shown in Fig. 1.

The participation of thermoelectric source in SIN is even clearer if the evolution of installed capacity of the thermoelectric sources is observed, compared with hydroelectric source, as shown in Fig. 4.

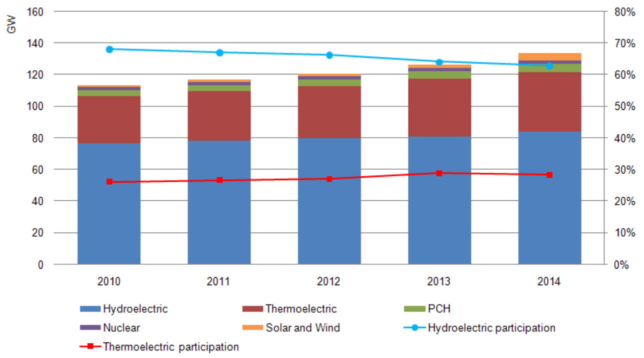


Fig. 4. Evolution of installed capacity.

The increasing thermoelectric participation in installed capacity and in power generation indicates that this is the natural source for base load generation in SIN. At the limit, in an extreme scenario where there is no hydroelectric expansion, the existing thermoelectric plants would be dispatched continuously, being transformed from the original function of energy reserve (complementarity) to the firm energy source (base load) [11]. In addition, thermoelectricity has the necessary scale for energy supply in SIN, what make them suitable for generation expansion.

As stated earlier, diversification assumes two directions in SIN, the first to guarantee firm energy and the second to the insertion of the VRE in the electric matrix. In this work, we are interested in the diversification of base load generation resources, so it is necessary to define which type of thermoelectric has the capacity to play this role in SIN.

Among the options for thermal sources expansion are the coal-fired thermoelectric. According to [12] Brazilian coal is of low quality what makes its use feasible only for thermoelectric power plants near coal mines. Although EPE considers in the National Energy Plan 2030 the possibility of importing coal for this type of power plant, its use as a primary source is subjected to strong environmental restrictions.

Another source that appears as an option is the sugarcane biomass, which has an exact complementary potential to SIN seasonality. The usage of this source has been increasing and in 2016, seven biomass-fueled thermals were contracted in the Brazilian New Energy Auction (A-5 auction) summing 81.5 averages MW [13], as shown in TABLE. Although biomass preserves the renewable electric matrix profile, this source has a low capacity factor throughout the year and is feasible only for use in complementary in the dry period.

A third thermal option is nuclear energy. This source has a low CO_2 emission in ton / MWh with low marginal cost, having potential for use in base load dispatch as shown in [12]. In Brazil, Angra III nuclear power plant was expected to start operation in 2014, increasing installed nuclear power capacity to 3.3 GW, what not happened. The Fukushima accident in 2011 slowed down the interest in nuclear power over the world.

The option that appears as the most promising for thermoelectric expansion is the usage of natural gas in view of mid-term prospect of this fuel for Brazil. Currently, these power plants have contributed significantly to guarantee supply of SIN demand, responding by almost 15 averages GW in 2015 [1]. The most effective insertion of NG thermoelectric power plants in SIN depends, however, on factors related to both operation model of SIN and the Brazilian NG sector. As we will discuss ahead, there is a regulatory "vacuum" in these two sectors that inhibit NG thermoelectric participation in New Energy Auctions in recent years.

For example, in 2016, the A-5 auction, 36 NG-fired thermoelectric projects were presented, and only one was contracted [13], predominating hydroelectric usage, but by PCH power plants. Table I summarizes A-5 auction results.

TABLE I: 2016 A-5 AUCTION RESULTS

Type	Licensed	MW
PCH	20	82.9
Hydroelectric	1	34.1
Biomass	7	81.5
NG thermoelectric	1	3.4

What has being observed is that the requirement of fuel coverage for a long operation period, 15 years according to [14], has caused difficulties to these enterprises. In numerical terms of NG production perspective, this should not be a limitation, given that for the next few years, the projection is to quintuple NG production between 2005 and 2025 from 48.5 million m^3/day to 251.7 million m^3/day [15]. This increase in the domestic NG supply reduces external dependence and allows supply of the electric sector and the industrial sector, without deficits such as occurred in Brazil in 2009.

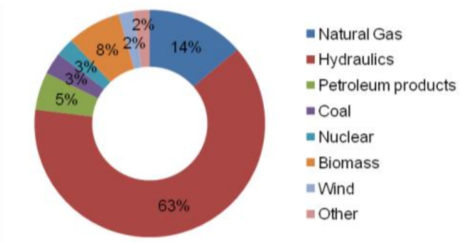
The main problem for NG thermoelectric expansion is an incompatibility of SIN operation philosophy with the type of supply contracts currently used in NG sector. Long-term NG supply contracts in Brazil have a *take-or-pay* clause, where the buyer undertakes to make a fixed payment to obtain the right to receive up to a certain amount of gas. This type of clause has a deep impact for thermoelectric power plants, due to the form of dispatch currently performed in SIN. As the dispatch occurs in a complementary and therefore uncertain manner, the revenues of the thermoelectric power plants may be compromised if the dispatch does not occur, but the owner remains obligated to remunerate the NG supplier due to the *take-or-pay* clause. Thus, there is a scenario where the dispatch is flexible and uncertain, as it depends on the inflows on hydroelectric power plants, and the fuel payment is fixed, which may unfeasible the operation of the thermoelectric power plants. As stated by [16], *take-or-pay* clauses are adequate to emerging and limited NG markets, where there is an interest in guaranteeing a minimum remuneration capable of feasible the construction of the NG transportation infrastructure. However, as the NG market begins to develop *take-or-pay* clause tends to block the negotiations.

In this sense, the current type of thermoelectric dispatch, impacts both electric and NG sector. Therefore, the uncertainty of the complementary thermal dispatch reflects in the NG sector. The thermoelectric power plants contracted as an energy reserve follow an unpredictable pattern dispatch throughout the year and may be non dispatched or be continuously dispatched in low inflow years. The contract by NG availability would be more appropriate but this type of contracting is not common for NG sector, where gas is traded by volume. Without existence of a strong guarantee of consumption by the thermoelectric power plants, gas producers will insert *take-or-pay* clauses in the contracts, in order to viable revenue for the construction of the necessary infrastructure for gas delivery.

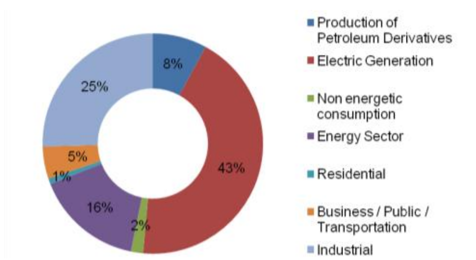
Therefore, these issues hinder the insertion of thermoelectric power plants as base load units in SIN. Thermoelectric power plants do not appear in energy auctions due to lack of gas coverage, and gas suppliers are not willing to invest due to lack of consumption guarantee. This way, the change in the SIN operation philosophy, including thermoelectric power plants on base load dispatch, would also contribute to the development of the NG sector, creating a demand capable of anchoring the development of the sector.

In this sense, integrated gas-electricity planning needs to be developed, aiming to reduce the risks for both electric and gas sector. This planning should also reduce the risk of supply deficit in SIN, in view of the new operation philosophy and the reduction of the regularization capacity of SIN.

IV. Measures for Natural Gas Sector



(a)



(b)

Fig. 5. (a) Generation by primary source; (b) NG use.

The prospect of NG supply in Brazil is promising, as shown in the EPE studies. However, the Brazilian NG market is still emerging and there are a number of challenges that need to be overcome in order to optimize the gas usage in the country.

The growing need for thermal generation in the SIN in recent years made the thermoelectric usage a significant part of the total gas consumption in Brazil. For year 2014, NG thermoelectricity represented 14% of electricity produced in Brazil Fig. 5a, while gas consumption for thermoelectricity represented 43% of total demand of NG sector, Fig. 5b. Therefore, uncertainties in thermoelectric NG demand have significant impacts on NG sector. Thus, NG sector needs to be thought of in an integrated manner with the electricity sector to reduce the impacts of these uncertainties.

In this sense, changes in electricity and in NG sector could conciliate the expectations of thermoelectric entrepreneurs, NG producers, contributing to the development of both sectors. Some measures could be applied to the NG sector so that gas-fired power generation can be competitive in the electricity sector.

A. NG Offer Expansion

The expansion of NG supply depends first of all on prospecting for new reserves. In regulatory terms, in Brazil, the supply expansion depends directly on the auctions of Exploration and Production areas promoted by the National Petroleum Agency (ANP), according to Law 9,478 / 1997. In these auctions, the physical characteristics of the exploration areas are defined, as well as the quantity of offered areas.

In the past auctions, the offered areas presented a low gas-oil ratio (RGO) and, therefore, oil production was more prominent. In these cases, the produced gas is usually injected into the reservoir to increase oil extraction and the construction of gas pipelines is not feasible. In cases of associated gas, oil production is prioritized, and the gas has a fixed ratio production to maximize oil production. This contributes to build an inflexible supply profile for Brazilian NG sector. The type of contracting of Bolivian gas also contributes to the inflexibilization of the national NG supply.

The inflexible profile of NG supply is incompatible with the Brazilian thermoelectric dispatch model. Thermoelectric power plants accommodate better base load dispatch with fixed generation without large variations. This applies to any type of thermoelectric, but is particularly important for Brazilian NG thermoelectric power plants, which need to accommodate the inflexible domestic supply profile. This ratifies the necessary change in the operation philosophy of SIN, which needs to match the flexibility required with by VRE sources, and needs to contemplate the growing use of thermoelectric plants. This change would have a positive impact on the Brazilian NG sector, which needs firm demand to anchor its development.

On the other hand, NG supply could contain a flexible portion from the moment in which non-associated gas fields are exploited, where this production is not limited by oil production. Such fields would still have the potential to make feasible the construction of exportation pipelines. This measure contributes to NG supply in the Brazilian market.

In addition, land-based production areas can be prioritized due to the lower cost and risk in relation to offshore areas. Another important point in relation to the offer increase is the realization of auctions with defined periodicity basis, in such a way that offer grows at a rate closed to market demand for the next years. In these auctions the participation of new private agents in the market should be encouraged through requirements compatible with the business profile of these agents.

B. NG Transportation Network Expansion

The supply expansion is insufficient to meet projected demand for the Brazilian NG market if the transport networks between producers and consumers were not expanded. In the past, constraints in NG transport network caused limitations of thermal dispatch as shown in [17]. This episode revealed the necessary coordination between the planning of NG and electricity sectors. Therefore, the construction of new pipelines should be a priority for NG sector, considering the increase in thermal participation in electricity sector.

EPE recognizes, in the 2022 Pipe Transport Network Expansion Plan (PEMAT), the need of expansion in Brazilian NG transportation networks, and the existence of potential future NG demand that can only be met by expanding network. However, network expansion only occurs if there is no uncertainty of demand, making the construction of the transportation network financially feasible.

The thermoelectric demand currently represents around 40% of the Brazilian natural gas consumption, but there is an uncertainty in this demand due to the complementary characteristic thermoelectric power plants. This uncertainty directly affects the NG sector, limiting the network expansion. In this sense, the change of operation philosophy in SIN could reduce the uncertainty of gas consumption, making possible to predict clearly the need for network expansion.

With the change in the operation profile of thermoelectric plants, from complementary to base load function, units with lower variable cost should be used, reducing the total cost of operation. One of the key factors in reducing this cost is the use of NG in detriment of LNG power plants, which is subjected to international spot market costs. However, the use of NG for thermoelectricity demands investments in the Brazilian natural gas infrastructure. The expansion of NG networks is anchored in certainty gas consumption, which only occurs with certainty of thermoelectric dispatch, which would occur if the thermoelectric has a base load function in SIN.

V. Proposed Gas-Electricity Planning

Electricity and natural gas have network characteristics, which mean that such markets are subjected to network congestion phenomenon, that is, the supply is subjected to transport restrictions. Brazil is moving towards a scenario of increased gas-electricity integration due to the pronounced use of NG thermoelectricity. In this scenario, constraints in one network can affect the other. This indicates that gas-electricity planning must be thought in an integrated manner, with a global requirement of reliability in the energy supply. This integration must cover both expansion, and operation planning.

In Brazil, energy system planning is carried out by EPE, through the Ten-Year Energy Expansion Plan (PDE), for the electricity expansion and through PEMAT for NG sector. For the electric generation PDE is indicative, pointing to a reference electric matrix, while for transmission, PDE is determinative aiming the interconnection of new sources. While hydroelectric expansion is subjected to feasibility studies, thermoelectric expansion within PDE does not define the location of the new projects, resulting in inefficiency, for both electric and NG sectors.

Unlike PDE, the PEMAT is determinative, but considers only the thermoelectric power plants contracted in the New Energy Auctions, as these guarantee ballast for the viability of gas pipelines. While PDE does not define the location for construction of thermoelectric power plants, PEMAT does not account all possible thermoelectric power plants, resulting in a disconnection between PDE and PEMAT. Thus, there is the risk of moving towards a scenario where the NG network is limited and does not have the capacity to supply all market consumers.

Considering the Brazilian reality, where energy planning is carried out in a centralized way, it would be interesting to establish an integrated planning that would be indicative for both NG and electricity. In this way, it would be possible to treat the locational question of thermoelectric power plants currently ignored by PDE, at the same time as the pipelines of interest for expansion are defined.

The influence of the locational factor in thermoelectric planning can be verified by considering the market behavior of an energy producer [18]. This producer wants to maximize its profit, which is given by the difference between revenue from energy sales, subtracted from production costs and investment costs. Consider (1):

$$\begin{aligned} &\max \pi = (p-c)X - c^{inv}CAP \\ &sa \\ &X \leq CAP \\ &CAP \geq 0 \\ &X \geq 0 \end{aligned} \quad (1)$$

where:

π : Profit of electricity producer (US$).
p : Energy price (US$/MWh).
c : Production cost (US$/MWh).
X : Produced energy (MWh).
c^{inv} : Investment cost (US$/MW).
CAP : Power plant capacity (MW).

The generator maximizes its profits by deciding on its generation output and installed capacity, given the electricity market price, its variable generation cost, and investment costs. The amount of energy sale is restricted by the generation capacity.

Note that the operation starts to be profitable only if, when the investment occurs. Therefore, the investment in operating capacity depends on the difference between the energy price and the operation cost, which reflects the fuel cost. The energy sale price depends on the location of the producer while the production cost depends on the production and the fuel cost. Thus, from the point of view of fuel and electricity, the construction site of the thermoelectric power plant is important and must be considered in the energy planning. In addition, the fuel cost and the electricity sales price are subjected to restrictions of the NG and electricity networks respectively, so that the expansion of such networks directly affects the optimal location of gas-fired thermoelectric power plants. Therefore, in a gas-electricity system, there is a commitment in choosing the investments in the network expansion. In this sense, investments in gas and electricity transportation and investment in gas-fired power plants affect both sectors. Therefore, an energy planning model more appropriated to the Brazilian case should have an indicative character and consider in an integrated manner at least gas and electricity networks, as well as thermoelectric power plants.

This planning, done in a centralized way, would indicate to the agents, only a reference trajectory for expansion, but would leave them free to make the investments. This type of planning is suited to the liberalized market profile where each agent is free to make his investments aiming to maximize his profit. Integrated gas-electricity planning also has the potential to minimize the total supply cost, considering investment and operating costs.

In terms of planning, the system must be expanded to meet a minimum level of reliability. Otherwise, NG would have to be prioritized between sectors. For example, if the interruption cost to the industrial sector is high, it is possible that the most economical option for society is to dispatch another source, not the gas-fired power plant. In this way, the cost of dispatch a gas-fired power plant should include the cost of the fuel plus the possible cost of an interruption in the gas sector. Similarly, the cost of gas supply to other sectors should include the risk of electric rationing due to non-activation of gas-fired thermoelectric plants. This joint analysis is important because, even if the economic losses of each sector are different, it is improbable that the optimal cost is to give total priority to one or another sector. In this sense, an expansion model should also consider operating restrictions, aiming to assess the issue of deficit cost. Integrated planning therefore involves a trade-off between investment costs and operating costs, for a desired level of reliability R*, as shown in Fig. 6.

The indicative planning proposed in this work could be synthesized in the form of the optimization problem shown in (2).

$$
\begin{aligned}
& Min \sum_{t\in T} \beta \left[IC(x_t) + OC(y_t) \right] \\
& sa \\
& ESR(x_t) \le a_t \qquad \forall t \in T \\
& OSR(x_t) + OSR(y_t) \le b_t \qquad \forall t \in T
\end{aligned} \tag{2}
$$

where:

t: Planning stage.

T: Set of planning stages.

β: Discount rate.

x_t: Vector of decision variables corresponding to network structures (electric lines, pipelines and thermal power plants) at stage t.

y_t: Vector of operation variables at stage t.

$IC(x_t)$: Investment cost.

$OC(y_t)$: Operation cost.

$ESR(x_t)$: Expansion specific restriction.

a_t: Resource limits for expansion

$OSR(\bullet)$: Operation specific restriction.

b_t: Resource limits for operation.

The decision variables x_t correspond to decisions on investments on network expansion. In the proposed model, the options are investments on NG thermoelectric power plants, NG pipelines and electric lines. The investments on these three options influence each other, so they need to be considered together.

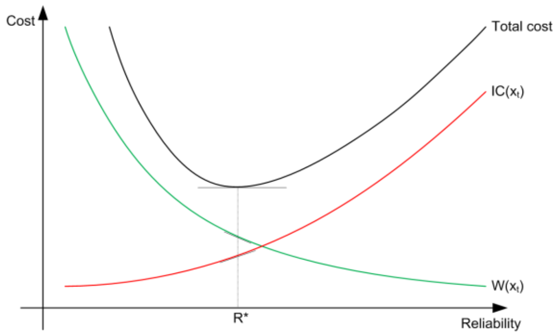


Fig. 6. Expansion decision.

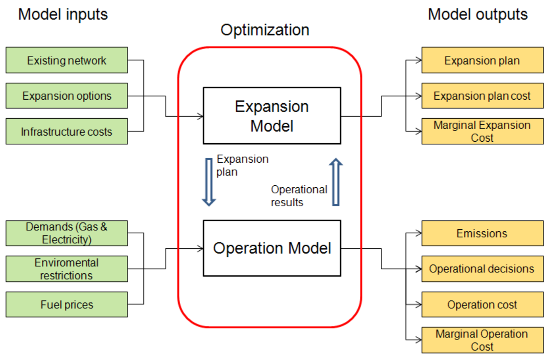


Fig. 7. Proposed model.

The model shown in (2) can be divided in investment and operational problem, making easier the solution of optimization model. Thus, for an given investment plan x_t^*, the operation problem becomes as in (3).

$$
\begin{aligned}
& W(x_t^*) = Min \sum_{t\in T} OC(y_t) \\
& sa \\
& OSR(y_t) \le b_t - OSR(x_t^*) \qquad \forall t \in T
\end{aligned} \tag{3}
$$

where:

x_t^*: Optimal expansion plan at stage t.

$W(x_t^*)$: Future operation cost for given x_t^*.

In the operation problem we consider the uncertainty of inflows on hydroelectric power plants, because this is what define the required amount of thermal generation in the power system and, at limit, this defines how much NG is needed for thermal generation. This gas consumption associated with the consumption of other sectors indicates where the NG pipelines need to be constructed. The operation problem (3) guides the investment problem (4), to find the optimal location of the networks structure.

$$\begin{aligned} &Min \sum_{t\in T}\beta\left[IC\ x_t + W\ x_t^*\right] \\ &sa \\ &ESR\ x_t \le a_t \qquad \forall t\in T \end{aligned} \tag{4}$$

In the proposed model, investment and operation problem, changes information to obtain a least cost expansion plan, under reliability criteria. The planning model schematic is shown in Fig. 7.

VI. Conclusion

This work discussed the issue of sources diversification in energy planning for the Brazilian electric system. Diversification of electric sources in Brazil will occur on two directions, the first with insertion of VRE's in the electric system and the second with the replacement of large reservoirs hydroelectric power plants by other sources of ensured energy that can be base load dispatched in SIN. Diversification in these two directions requires a change in operation philosophy of SIN, to insert ensured energy sources as base-load dispatch, as well to deal with the intermittent aspects of the VRE's.

Among the sources for base load operation, NG thermal generation is the only source that could ensure the necessary firm energy at scale required by SIN. In Brazil, the NG thermoelectricity has antagonistic objectives when considering gas and electricity sectors. For the gas sector, thermoelectric power plants were always considered elements to consolidate the sector, with the entire development of the sector being based on thermoelectricity. On the other hand, the electric sector always treated NG thermoelectric power plants as "simple" complementary sources, what causes uncertainty to their dispatches. This manner, changes in the operation philosophy of SIN has the potential to mitigate the effects of storage capacity reduction and allows establishing a firm NG demand for thermoelectric power plants, what would allow the development of the NG sector. This change reduces the uncertainty of the electricity sector reflected in the NG sector. As NG thermoelectric power plants enter in the base load dispatch, flexible power plants could be moved to mid load dispatch to deal with the flexibility required by VRE sources.

Therefore, integrated gas-electricity planning should be developed to the entire Brazilian energy sector. Thus, the planning of NG thermoelectric power plants reach the same scale of hydroelectricity, while at the same time, NG network for these thermoelectric power plants are planned, reducing the risks of supply deficit. Finally, this work proposed an indicative planning model that considers the NG thermoelectric power plants, gas pipelines, and electric lines what would have potential to contribute to the development of both sectors and could be used in a centralized energy planning environment, as in Brazil.

Future research is focused on the development and tests of the proposed model.

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