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Natural Gas Power Plants in the System Security Role—The Situation and Solutions in Brazil

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Abstract

This study aims to apply a methodology to analyze the regulatory obstacles for the development of thermal power plants in a country. The study uses Brazil as an application case, although mostly of the findings can be useful to other countries. It also discusses other policies and actions by the government that may contribute to the growth of natural gas-fired power plants. Using deductive and comparative research methods, the first part of this method focuses on the stage of thermoelectric power generation in Brazil. The subsequent sections present the role of the integration of gas and electricity sectors, the main obstacles to the expansion of natural-gas power generation, how the country has deal with the expansion of natural-gas power generation, as well as how other obstacles has been faced. In raising the research question, when comparing the research results of selected countries, it should be noticed the impact that the experience and lessons elsewhere have had on policies formulation on Brazil. Our conclusions pointed out that adequate policies for the natural gas-electricity Brazilian market integration make advisable the unification of electricity and natural gas agencies. We recommended developing a mathematical model to support decision-making on natural gas and electricity integration.

Keywords

Component, Formatting, Style, Styling, Insert

1. Introduction

In most countries, except Brazil and China, power generation using natural gas

primarily addresses the industrial sector [1] [2] [3] [4]. Natural gas accounts for approximately 20% of all electricity generated worldwide, resulting in a calculated consumption of 1.4 trillion m^3 of natural gas, moving from the fourth to the second position in the ranking of the most used sources for electricity generation [3] [5] [6] [7].

The United States, Russia, and Japan are leading the gas fired electricity generation field. Collectively, these three countries account for 41% of the electricity generated using natural gas as the primary source [3] [5] [8] [9]. The aforementioned three countries have already overcome their barriers in developing natural gas power plants to get electricity and other advantages from this source at a competitive cost [10] [11].

In Brazil, besides some economic advantages that natural gas thermoelectric systems bring to society, there are other reasons to promote natural gas power plants. For instance, there is a scenario of natural gas supply due to pre-salt exploration and structure for liquefied natural-gas (LNG) imports [12] [13] [14], added to the crisis of hydraulic generation, which is losing representativeness in the Brazilian energy matrix, particularly in the face of intermittent renewable energies, such as wind and solar energy [6] [12] [15].

Thus, thermoelectric power plants (TPP) powered by natural gas are strong candidates for complementing the generation of the Brazilian electricity network. The installed power of natural-gas-fired TPPs has increased in Brazil from 2,000 MW to 14,000 MW in the last two decades [12] [16]. However, it is still necessary to increase the representativeness of this power source in the coming years, and several regulatory and market barriers must be overcome [12] [17] [18].

In 2022, Brazil faced its worst hydrological crisis since 1931, particularly considering the rainfall between September 2020 and March 2021, a period that historically provides high levels of precipitation (called the 'humid period'), which is responsible for filling the reservoirs of the central hydroelectric plants [19] [20]. In such scenarios, the available thermal plants are activated, significantly increasing the energy price. It is estimated an amount around 2 billion US$ expended in 2021 for energy generation via thermal plants to preserve reservoir levels [21] [22]. Part of the price was because of the high cost of thermal plants, which were constructed immediately after a similar crisis faced by Brazil in 2000 and 2001 [22] [23].

Therefore, our main objective is the application of a methodology to improve natural gas and electricity integration in the Brazilian market. The methodology starts by explaining natural gas's role and energy integration in the energy transition context, clarifying how this integration can collaborate with energy security supply with sustainability (Section 2). After, we highlighted the importance of thermoelectric power plants in hydrothermal systems such as Brazil due to the importance of designing feasible solutions (Section 3).

After, the current situation of natural gas and electricity integration in Brazil is explained (Section 4). In sequence, the obstacles that should be overcome to

encourage the integration of energy sources not systematically dealt with by the government are focused (Section 5). These obstacles will be the main target to be solved by the proposed policies. In addition, a short comparison with specific countries which possess similar barriers are analyzed (Section 6). Finally, public energy policies for the integration of natural gas and electricity are suggested for Brazil (Section 7).

2. The Role of Natural Gas and Electricity Sectors Integration

In the energy transition context, power system flexibility is a crucial issue that needs to be addressed. One question that arises in this context is the role that thermoelectric power plants, as natural gas-fired generation, will play in the scenario of energy matrix expansion supported by non-dispatchable renewable energy sources, as wind and solar [24].

Although it can be argued that the financial attractiveness of renewables in relation to thermoelectric plants tends to lead to an increase in the share of the former to the detriment of the latter [25] [26], as thermal plants are dispatchable, they will continue to play an essential role in the energy markets, especially those with the need to system operational flexibility. In this rationale, in markets with both renewables and natural gas, combining these sources in the electrical matrix is beneficial in terms of system operation.

The expansion of wind and solar energy must be accompanied by an increase in electrical system flexibility to deal with the greater variability of electricity generation through (i) demand response, (ii) storage (batteries, heat storage, hydrogen, synthetic methane, or other chemicals), and (iii) gas-fired thermoelectric plants for generation in times of peak consumption [27].

As gas-fired thermoelectric power plants are dispatchable, their presence in the energy matrix can be used to provide either base energy supply or load peak shave, providing both inflexibility and flexibility when operated at base load mode, depending on the technology used [28]. In addition, it provides grid-balancing services, complementing the integration of intermittent renewable resources into regional electrical grids. Thus, natural gas power plants are used to provide the complementary generation required to balance renewables and load, including those with load-following or peaking capabilities [29].

Moreover, the existing natural gas system infrastructure can be used to store, transport, and distribute renewable gaseous fuels by adopting or blending low-methane gas, renewable gas, or even hydrogen to be used in industrial processes and energy generation [30] [31] [32].

In this context, initiatives observed in the PJM Interconnection, LLC (PJM) market, the largest wholesale electricity market in the US, among other markets, seeks to improve natural gas and electricity market coordination dispatch as a means to improve the efficiency between these sectors and the industries in which they belong [33].

Integrating natural gas and electricity is also a crucial topic within the pre-

cepts of energy transition, particularly in developing markets aligned with the energy justice concept [24]. The integration of the energy and natural gas sectors, known as the coupling sector, promotes the acceleration of the decarbonization of energy systems, beyond energy security and sustainability which could provide a clean source in comparison to coal or oil.

The coupling sector, as shown in general terms in **Figure 1**, involves different interconnected aspects of energy and gas sectors: (i) the electrification of transport, industry, and homes via transmission and distribution networks, (ii) the production of hydrogen and methane gases from renewable electricity, (iii) storage of energy in pumped hydro plants, batteries, and as hydrogen and methane gases, (iv) supply of renewable gases to final consumers, and (v) generation of electricity from hydrogen through fuel cells and from gas with thermal power plants [34]. It can be observed that modern gas turbines can operate using a mixture of hydrogen and natural gas. In contrast, hydrogen can be captured and transported in gas grids and re-electrified in gas turbines or fuel-cell power plants.

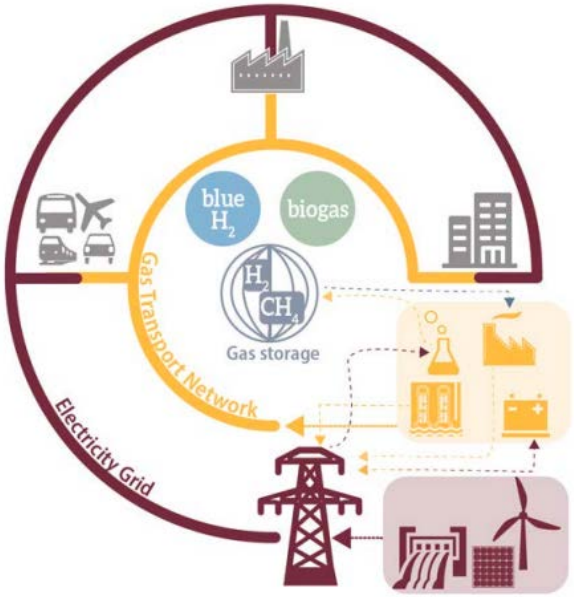

Figure 1. Illustrative scheme of sector coupling—electricity grid and gas transportation network.

3. Technical Investigation—The Importance of Natural Gas Power Plants in a Hydro-Thermal System

Although natural gas can complement the generation of intermittent renewable energy sources, such as wind and solar, this energy source is vital for the security of hydraulic-based systems [35]. Brazil is a global reference because it has a predominantly hydraulic energy matrix [36]. Although its representativeness is decreasing, the primary energy source still depends on rain in the country and on border countries [37].

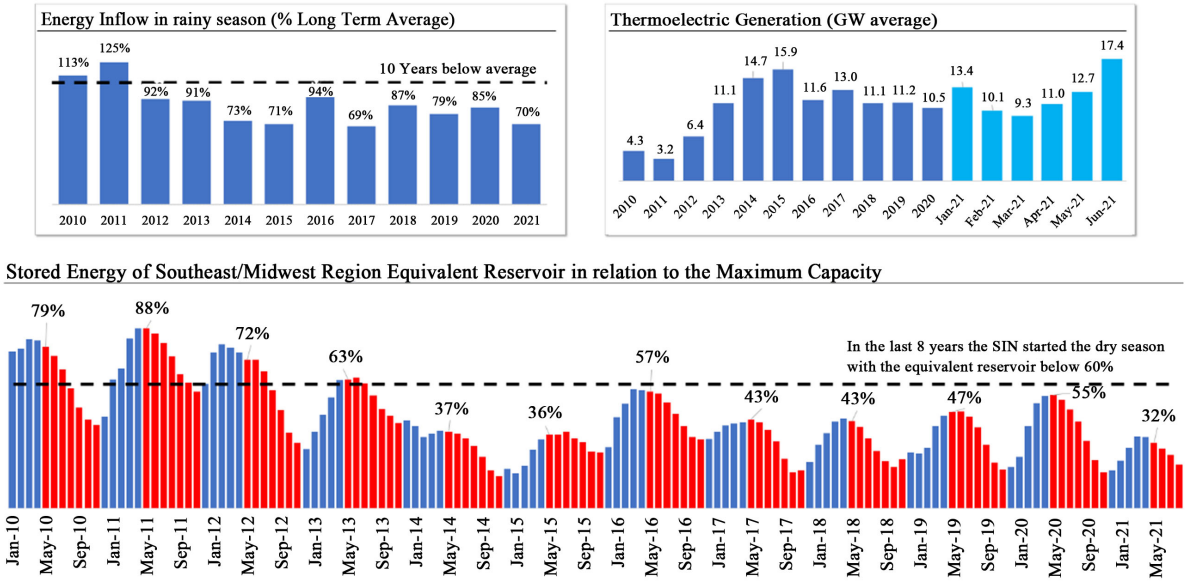

Figure 2. Behavior of strategic variables in the supply to the electricity market since 2010.

Hydraulic power generation has several advantages, and it is renewable and cost effective. However, it poses a risk to the system that must be managed, that is, the risk of a period with a short amount of rainfall, which can result in energy rationing [38] [39]. Energy rationing forces consumers to reduce their energy consumption; the cost of lack of energy is extremely high and must be avoided [40] [41].

The hydrological crisis Brazil faced in 2022 affected inflation and the population budget, and the damage could have been devastating if the dry season had lasted a little longer [42] [43]. The situation could have been predicted and contemplated in time in sectorial planning. More specifically, an early operation of thermoelectric plants ought to have been scheduled to preserve the storage status of the most relevant reservoirs to ensure the supply of energy to the Brazilian power network [44].

Figure 2 demonstrates that since 2012, the inflows from rain in the Brazilian system during the rainy season (from December to April) have been systematically below the historical average. As might be expected consequently, thermoelectric generation is growing on average in this period. The reservoirs levels did not recover during annual rainy seasons as it used to be before 2012. Therefore, since then, the Brazilian system has finished the rainy season with a lower reservoir storage level than that of the previous year. Thermoelectric plants were entirely activated in severe droughts to compensate the lack of hydroelectric generation, which have occurred more frequently in the last decade.

The benefits of the natural gas power plants in the Brazilian network materialize in the form of (i) improvement of the performance indicators of the Brazilian network, (ii) lower energy cost to consumers when compared with other thermoelectric options, and (iii) lower CO_2 emissions than other fossil fuels. For the entire system, the impact occurs in the reduction of total operation cost and

in the level of storage of the reservoirs, which directly affects the risk of restriction of supply or risk of rationing. An increase in the offer in the system always reduces the average cost of operation and contributes to the recovery of the hydroelectric reservoirs [45] [46] [47] [48] [49]. In turn, the benefits and costs of direct impact to consumers are perceived through (i) the reduction of dispatch costs of thermal plants out of order of merit that is allocated to the consumer through the system service charges, and (ii) the cost of exposure of the generation scalator factor (GSF) allocated to contracts with hydro plants and the cost of contracts with thermal plants (the costs of thermoelectric generation when hydro generation is incapable of satisfying the demand) [50] [51] [52] [53] [54].

4. Domestic Investigation—Status of Natural Gas in Brazil

Brazilian production of natural gas can be understood as the net production of natural gas in the Brazilian territory, which corresponds to the gross output, subtracting the portions of own consumption (amount consumed in the oil exploration and production process), re-injection for oil extraction, and burns or losses in operation [12] [55]. In Brazil, the net production of natural gas will grow significantly in the coming years, primarily owing to the availability of gas from pre-salt [12] [56].

Even with the tremendous economic attractiveness of using gas to be reinjected and thus optimize oil extraction in Brazilian pre-salt, there will still be an ample natural gas destinated to the Brazilian market [12] [57] [58]. The expectations of the introduction of a deregulated natural gas market in Brazil have aroused greater economic interest from majors consumers. For the companies that explores natural gas, this may increase the attractiveness to supply the gas to the market causing less natural gas to be reinjected for pre-salt extractions, and an even greater availability may be observed, as shown in **Figure 3**.

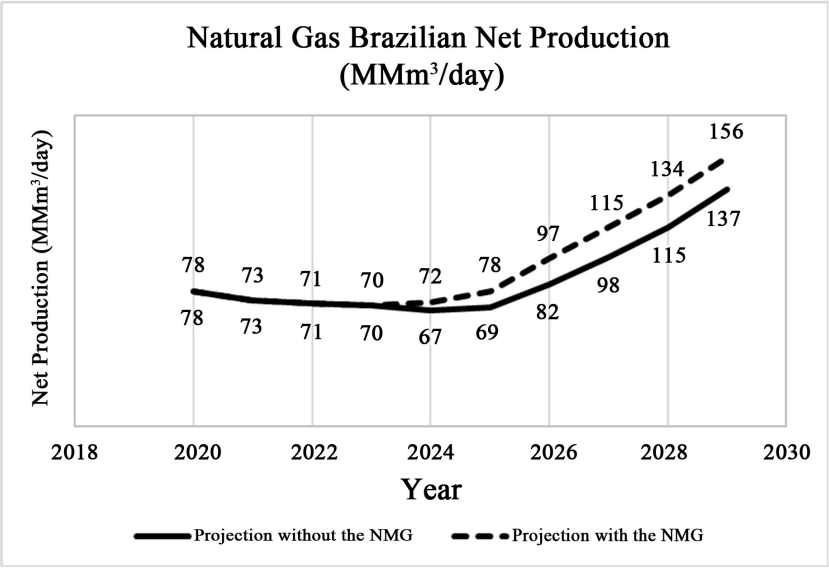

Figure 3. Brazilian pre-salt natural gas production forecast. (Source: EPE, 2020).

The existing gas pipeline structure for offloading natural gas produced offshore on Brazilian land, and considering the current routes (routes 1 and 2) and routes under construction (only route 3), the capacity to offload the expected production of natural gas will be sufficient by 2027, when it is above the 44 MMm^3/day capacity of routes 1, 2, and 3, respectively [12] [59] [60] [61]. To expand offshore flow capacity, 11 indicative gas pipeline projects have been mapped out by the government, seven of which are based on natural gas volumes from pre-salt books and four on post-salt books [60] [62]. The planned pipelines are approximately 2,100 km in length, and some of these projects provide different alternatives for the flow of offshore natural gas from the same sedimentary basins. Considering the construction of only one alternative pipeline for each bay, these projects may add more than 70 MMm^3/day of flow capacity to the offshore environment in Brazil, with respective gas processing units (GPUs) [60] [63].

In the case of imported natural gas, there is the possibility of LNG importation and exportation via terminals [64]. Imports from Bolivia reduced from 30 MMm^3/day to 20 MMm^3/day by 2021 [12] [14] [65] [66]. This reduction in volume imported from Bolivia is supposed to be supplied by imported LNG. Imports via LNG and imports via GASBOL will have their books strongly affected by consumers' demand flexibility (maximum and minimum take), the need for firm contracting by suppliers, and negotiated prices.

Thus, the production of associated natural gas, which can be understood as natural gas coming from pre-salt, will increase in the coming years, representing 67% of the national supply in 2024; however, its share is projected to reduce to 47% by 2029 [12] [67] [68]. The reason for the reduction in participation is not the reduction in total net production, but rather due to the increased representativity of imported gas in the national supply, primarily through LNG, which has been more competitive than the natural gas coming from Bolivia and even from pre-salt [69].

Independent of the origin, once natural gas is available in Brazil, its use depends on transportation and domestic distribution [70] [71]. To transport gas for industrial, commercial, and residential use, whether for energy purposes or not, a physical structure and regulatory framework are required, which is still under development in Brazil. The use of natural gas is lesser in the next decade for these segments [60] [72] [73].

The government signals poor grid expansion by 2029. Moreover, little activity is observed on the distributors' side, with the structures regionalized within their concession areas, as this is a natural monopoly [12] [71] [74].

Petrobras maintained a monopoly of natural gas operations in Brazil, generating distrust from other agents because Petrobras could benefit from the monopoly [75] [76] [77] [78]. Thus, aligned with the opening of the gas market, the signing of a commitment to practical assignment (TCPA) in 2019 between Petrobras and the Administrative Council for Economic Defense (CADE) was another action [78] [79].

In this agreement, Petrobras commits to selling operations and natural gas assets to increase competition within the sector [78] [79]. Thus, Petrobras renounced the exclusivity it had to contract the transportation capacity in its pipelines and indicated maximum withdrawal and injection volumes in the transportation pipelines. Another significant milestone was the resumption of the public call process, through which the Petroleum National Agency (ANP) would contract, at the appropriate time, the transport capacity was waived by Petrobras until December 2020 [78]. However, there are still assets to be privatized, and such assets must be sold as soon as possible to contribute to the free-market competition [80].

An additional possibility for natural gas usage is the use of plants that currently use fuel oil as an input. They can undergo a retrofitting process to work with natural gas, contributing to cleaner and cheaper energy security in Brazil [12] [81] [82] [83]. Thus, expanding the thermal generator park becomes essential to ensure the security of the energy system, particularly in times of hydrological crisis, with lower costs and tariff moderation for the consumer.

5. Barriers to Be Overcome—the Expansion of Natural Gas Power Plants in Brazil

In principle, there are three ways in which natural gas power plants can sell energy in the Brazilian market. Specifically, the first alternative is long-term sales through auctions that are controlled by the government, selling the energy to distributors in the regulated market. The second is bilateral sales in the deregulated market, where sellers and buyers can freely negotiate the commercial conditions, which can be extended or short-term. Finally, the third option, the plant can operate as a merchant, which sells all the energy generated in the spot market, delivering energy when the spot price is higher than the generation cost [64].

Several barriers remain concerning public policy for the expansion of these power plants in Brazil, which will be analyzed below. One includes an analysis of the Brazilian government's regulatory agenda to stimulate the development of natural gas thermal plants, which began in the Gas-to-Grow program in 2016 and is being continued by the Natural Gas Market Opening Monitoring Committee (CMGN).

5.1. The Barriers and Their Treatment from the Brazilian Government's Point of View

In 2016 the 'Gas to Grow' initiative was launched by the Brazilian government. The objective was to generate studies and proposals for the correct operation of the natural gas market because of the reduction in Petrobras' participation in this market, already anticipating the TCC that would be signed with CADE in 2019, and with estimates that the natural gas market could triple by 2030 [84]. Nine subcommittees were created to address each action front. One is the integration of the electricity and natural gas sectors (named S8GC) [84]. This subcommittee generated two reports in 2017 with a complete diagnosis of actions to

be evaluated to stimulate the market [84].

As for the new gas market (NMG) program, the natural gas market opening committee (CMGN) was set up to identify opportunities for regulatory improvement from the activities initiated by the S8GC, generating reports in 2019 and 2020 [78].

On the electricity sector side, a working group was established in April 2019 to deal with the sector's modernization. Following that, in October of the same year, the change integration committee (CIM) was created to create the work plan defined by the electricity sector modernization working group, which has created interactions with other working groups that also handled natural gas.

The measures that were diagnosed by the S8GC and disclosed in its two reports in 2017 were classified into three main groups [84]: (i) measures related to the correct allocation of costs and risks among agents; (ii) measures related to the regulation of the natural gas supply model for thermal plants; and (iii) measures related to the improvement of integrated planning between gas and energy.

Table 1 summarizes the status of each of these measures, listed as necessary for the development of Natural Gas Power Plants (NGPPs).

Table 1. Summary of the current situation of the measures to be addressed.

Current situation	Quantity of measurements in each situation		
	Cost and risk allocation	Natural gas supply model	Improvement of integrated planning between gas and electricity
Pending	2	0	2
Solved	2	4	1
Being handled	0	1	1
Overcome	0	2	0
Our of scope	0	0	2

Source: MME, 2019a.

In summary, the current situation of these measures is that five still have pending issues that need to be treated and will remain under the CMGN discussion and follow-up. Some have already been solved; however, two were considered outside the S8GC's scope, so they were concluded. They had similar treatments to those that have been solved without forwarding or even recommending this theme to another workgroup. Therefore, the need for the government to deal with such measures is emphasized, even if it is through other working groups. Two measures were forwarded to the respective regulatory agencies: ANP and Electricity National Agency (ANEEL). Four measures were considered surpassed, not requiring treatment, and two other recommendations were made for other NMG working groups (articulation between the natural gas grid manager and National System Operator—ONS, and establishment of short-term auctions for natural gas).

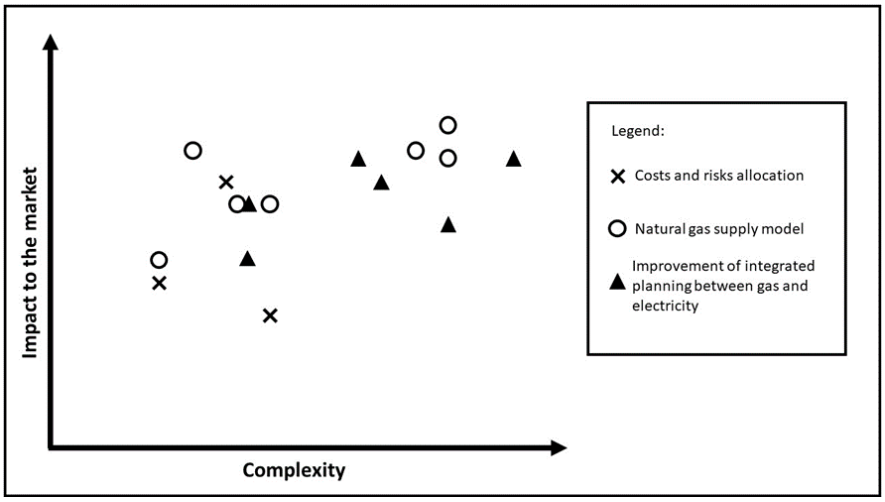

Figure 4. Classification for the measures to be treated. (Source: MME, 2019a).

Before arriving at the current situation in 2019, when the CMGN took over the activities that until then were being performed by the S8GC, a classification of the measures was carried out. It considers the impact of a given measure on the market and its level of complexity for implementation, as shown in **Figure 4**. In this graph, the further up and to the left, the greater the efficiency and effectiveness of the measure.

When analyzing **Figure 4**, it can be verified that the measures for the allocation of costs and risks present, in general, a relatively low complexity compared to the other two groups. However, on the other hand, they present low or medium impacts for the market. The measures related to the natural gas supply model and improvement of the integrated gas-energy planning present complexities that range from low to very high, and the impacts of the agents are medium/high. It is worth mentioning that the measures related to the supply model have a slightly more relevant impact on agents.

Accordingly, the S8GC classified each measure into five priority groups, ordering the themes to be treated [84].

5.2. Other Barriers to the Expansion of Natural Gas Thermal Plants

Regulation complexity

According to the Brazilian Federal Constitution (FC), natural gas distribution is under the regulatory responsibility of each state government. The federal government regulates other activities, such as production, commercialization, and transportation. Brazil has 26 states in total; therefore, it is complex for natural-gas-related companies to implement action in each state, primarily because it involves understanding and addressing 26 different regulations to consider and expand the use of this energy source when it is advantageous.

Furthermore, the business environment has become more complex, considering that each state has power in its regulation. In theory, a policy should be fixed to benefit the country itself; however, each state should have a weapon to fight

for its benefit. When state and federal government targets are not the same, there is a strong possibility of conflict and delays in the schedule. One way to solve this problem is to change the FC, which is a complex task that demands a strong federal executive influence under the Congress. In this regard, a political agreement that concentrates regulatory measures in federal level could benefit natural gas industry by promoting a rules standardization.

Moreover, there are tax issues and fiscal wars between the states. In October 2020, the Federal Supreme Court (STF) judged Petrobras' actions regarding collecting Tax on the Movement of Goods and Service (ICMS) imported from Bolivia. The dispute was whether the ICMS would be paid in the state of entry of natural gas (MS) or in the state of consumption (SP, SC, and RS). This resulted in a tax war between the states and left the industry more bureaucratic, slower, with more significant risks, and consequently higher costs [85].

Regardless of this isolated event, other examples are available in Brazil, where the tax war results in situations contrary to the public interest. For example, the winning TPP of the isolated auction of Rondônia, held in 2019, transports gas from AM to RO by truck because there are tax gains related to ICMS. Except for the gain generated by the ICMS, the best economic decision with less use of resources would be the transportation of the already converted electrical energy instead of gas.

Therefore, harmony in tax legislation is necessary to enable the rational use of natural gas by economic agents, instead of a tax war in which resources are used contrary to public interest. Because of those examples, such as issues related to FC and to tax legislation, one may say that changes in legal framework could bring benefits to promote natural gas industry development in Brazil.

Lack of information for decision making

In 2021, a law passed that was aimed at the privatization of the Brazilian electricity government company Eletrobras. This law enacted that 8 GW of thermoelectric power plants should be created in locations where natural gas is unavailable. This legislation should be evaluated in order to gain some insights [86].

The creation of power plants in locations where natural gas is unavailable aims to use these plants as anchor businesses to develop a natural gas network. If natural gas is not available in Brazil nationwide, and the best option is its direct use, determining the construction of these power plants will not contribute to the advantages already discussed but also lead to the expansion of the gas network in Brazil.

On the other hand, although it is advantageous to Brazil, only its impact on electricity can be evaluated. In this case, a cost increase in electricity of 52 billion is expected due to operational costs by 2031 and an additional 18 billion in investments [87]. However, there is no expectation of benefits from the natural gas side. The evaluations for these decisions should consider the energy cost to the consumer, not only on one side. There is no public information about the benefits to consumers looking at the gas side, and it is expected that even the private

side has such information.

Furthermore, a very important decision for Brazil's energy policy was introduced in the legislation that the focus was another, with a high impact on the market but different. There were no previous evaluations or studies on this consideration in the legislation, and it appeared as a surprise when the expected Eletrobras privatization law was released. A difficult decision should be made more cautiously in its treatment and be evaluated appropriately [86].

Brazil has a strong reputation for modelling the electricity sector due to the operation and optimization of its hydrothermal system, which is not commonly found in other countries, forcing Brazil to develop its own electricity decision-making models. These models are also available in the market, enabling all players to prepare projections for their decision-making. Moreover, it guides decisions in the expansion and operation of the electric sector, despite the expected human fine-tuning. The point is that, in the case of natural gas, there has not been a similar evaluation. This evaluation should be performed collectively once the final product to the consumer is provided as energy, and this should be the central concern, despite electricity or gas.

Cost competitiveness with other sources

In the last decade, renewable energy sources have become cheaper than conventional energy sources, including natural gas [88]. It has caused several companies to announce that they would only buy energy from renewable producers, as is the case for companies participating in the Renewable Energy Buyers Alliance (REBA). The great motivator for this strategic change is its lower cost compared to other energy sources. However, companies also use green marketing, reinforcing their commitment to society and the environment and maintaining the ESG conduct criteria. Thus, in addition to exploiting the low costs of renewable energy, companies are using marketing actions to reinforce their positions in the market.

In Brazil, there is also an aggravating factor: the discount on the use of the distribution system granted to solar, wind, small hydroelectric, and biomass thermal plants. As a means of fostering renewable energy in Brazil, since they are less competitive and strategic for the country, the government created a benefit in which it grants the buyer of the energy a discount on the tariff for the use of the distribution system. The discount can vary from 50 to 100% tariffs [89] [90]. Renewable energy was less competitive when this incentive policy was defined, requiring this subsidy to be competitive in the market and leveraging energy sources that were considered strategic by the government [91]. Currently, it is possible to verify that the renewable plants that receive this incentive are competitive in the market and no longer need to be subsidized. This subsidy made the natural gas thermoelectric plants even less competitive vis-à-vis renewable sources.

In March 2021, Law No. 14.120 was published, establishing a schedule for these discounts to be discontinued, with a two-year transition period; only SHP's will have a five-year transition period [92]. With the extinction of this incentive

for renewable sources, natural gas generation has become increasingly competitive. In the case of energy auctions held by the government, the amount purchased is divided into quotas for each primary energy source. Thus, the government could control the mix contracted in the auction. However, in the case of the free market, the energy generated by gas is, in fact, less attractive to the consumer and still lacks a green marketing appeal [91].

Part of the value of the TPP to society is, in moments of high energy demand, to attend to the consumption in situations where the other sources will not have the capability to increase the security of the system. Thus, the competitiveness of natural gas plants is harmed because, when selling only energy, the cost of R$/MWh is considerably higher. However, as soon as it starts to sell firm energy certifiers and capacity in a separate way, a given TPP can increase its revenue and billing by making it available in times of market shortage (times of high consumption). In any case, the new model is being prepared by the government and great care is required so that natural gas-fired plants can be rewarded for the value they offer to the electricity sector [93].

Electricity is a fundamental good to society and government, and the government must guarantee its supply. The bottleneck for energy production can be energy amount, for example, in markets with a predominance of hydraulic generation. The other possibility is a bottleneck of production capacity, having thermoelectric markets as a prominent example. The ballast is the warranty that the necessary energy will always be available to society so that both bottlenecks will not disturb the availability. Historically, Brazil's ballast was energy amount, but with intermittent renewable energy, the capacity ballast overpasses the energy amount requirements depending on the moment.

There is another issue related to the generator's rate of use in the transmission system. According to Brazilian legislation, certain plants from renewable sources have tariff discounts for distribution system use [89]. Renewable energy enterprises, primarily wind and solar, use this technology, which makes them more competitive. However, this benefit is about to be discontinued, similar to the discount granted to consumers who purchase this energy [92].

The different responsibilities of renewable and thermal gas sources within an energy system are worth highlighting. While renewable sources seek to generate energy sustainably, intermittently, and currently at low cost, one of the roles of thermal plants is to ensure service at peak times, thereby increasing the reliability and security of the system. To stimulate the competition of thermal plants for cheap energy, a law was published in December 2020 that enables natural gas thermal plants to participate in auctions, with 100% inflexibility, making them more competitive in terms of R$/MWh and with their generation entirely at the base of the system, which enables thermal plants to generate at the base, to relieve the demand on the reservoirs of hydroelectric plants [94].

Financing the power plants

Investments in the construction of thermal gas plants are significant, and for the most relevant plants, it is difficult to finance them with their resources be-

cause of the high investment level. Generally, agents resort to financial institutions to obtain financing. For this financing to be released, the institutions analyze the request. However, it is essential to present PPA's (Power Purchase Agreements), which also consider the credit rating of the buyer.

In the case of the regulated market, it is possible to qualify a plant for auction without the financing being granted so that the winner (s) of the auction, in possession of their PPA's with the participating distributors, obtain loans (usually granted because of the seriousness of the project) from financial institutions. These plants have already been granted by ANEEL, including environmental approval, and have buyers - in this case, the energy distributors - with robust financial health and government protection not to fail ("too big to fail") since electricity is a common good. Thus, there are no significant difficulties in obtaining financing for plants participating in auctions [95].

The difficulty for financing the project arises when power plants want to offer energy entirely in the deregulated market, as it is discussed as follows, considering a power plant that offers 100% of its generation in the free market. The investment return period is high, at approximately 20 to 30 years [96]. Generally, PPA's would be necessary for financial institutions to grant such loans, as in the case of the regulated market. However, in the free market, it is seldom for a consumer to buy energy for periods longer than five years; therefore, the plant would not be able to prove to the financial sector that it would have the income to pay the loan in the future [97]. Even if consumers would make 20 to 30-year energy purchase contracts, a small portion would have financial strength similar to that of energy distributors, making it more difficult to access credit. Additionally, these large consumers opted for renewable energies, which have a more competitive price, and still reinforce green marketing within the industry.

Another benefit resulting from capacity auctions and, subsequently, from the separation of capacity and firm energy certifiers, in order to make feasible a separate trading, that the government is now preparing, are the new rules that make this financing feasible [91]. Conceptually, the change planned by the government in the separation of capacity and firm energy certifiers, changing the form of energy contracting in Brazil, is that all consumers will pay for the new installed capacity (called ballast in Brazil), whether regulated or deregulated, through auctions [84]. The expectation is that, with the sale of the ballast, the entrepreneur can readily obtain the necessary financing, regardless of whether the energy will be sold in the free or regulated market. According to the most recent schedule, the separation of ballast and energy should be implemented as of 2022; however, it depends on the congress's approval [91].

However, to anticipate some of the benefits of the separation of capacity and energy as products to be traded, capacity auctions were also established in the same law that extinguished the incentive to renewable sources through discounts in the distribution system [92]. Accordingly, thermal plants will be able to sell their capacity in these auctions, and later, they will be able to sell energy in the regulated or deregulated market. A regulatory framework to make sizeable

thermal power plant financing feasible is now readily available. All that is required is for agents to know how to take advantage of this regulatory structure.

6. Lessons from Other Countries

Several measures have been taken to make natural gas thermal plants feasible, enabling this market to develop in the short and medium term. Simultaneously, the country lacks a structure to deliver gas directly to the consumer because this gas usage is more efficient for possible applications. It is possible to determine that all measures consider the current situation. However, there are no measures to ensure a continuous improvement in the integration of electricity and natural gas.

Although the schedule for oil exploration in the pre-salt has been known for a few years, little has been done to use natural gas in Brazil directly by consumers, which would be much more efficient. Companies were forced to construct thermal plants to convert gas and sell energy in a gas-to-wire format, and the population need to pay the inefficiency bill. It is unreasonable that the consumer could interfere negatively with the regulator's behavior and that, under no circumstances, the regulatory structure becomes negligent with the national energy policy.

Nigeria has faced regulatory challenges in expanding the natural gas market since 1979 through the Associated Gas Re-Injection Act (AGRA). However, the regulation was not sufficient to motivate agents, and the government made several adjustments in subsequent years to achieve the set target [98]. The challenges faced ranged from a lack of a market to attract investments (related to the lack of structure) to penalties that were considered payable by the agents and did not inhibit such activities [98].

The lack of regulation for the proper use of gas, even if it was to be sold as LNG, costs Nigeria approximately $2.5 billion per annum in opportunity cost, as well as causing several health problems to the population [99]. Similarly, suppose Brazil does not have an adequate regulatory structure for the use of natural gas. In this case, it will also be subject to significant losses, including economic losses of magnitude for the country, considering the scenario of an energy deficit.

It is known that public policy is not an exact science, and similar to Nigeria, Brazil may still face difficulties in defining policies related to the regulation of natural gas. In the case of Nigeria, despite the gas supply, no regulation allowed its use, which significantly penalized the country in financial and environmental aspects [98] [99] [100] [101] [102]. To avoid a similar situation in Brazil, the regulations created must be sufficient to motivate various agents to promote the use of natural gas and create penalties that inhibit behaviors harmful to the market.

The process of trial and error in defining an efficient public policy can be long, which increases the urgency of a rapid government initiative; however, if

designed consistently, it may achieve the desired objective, as Nigeria has done. Given domestic demand and reserves, much of its production is allocated to other markets via LNG. However, there were few international regulatory references when they began to face these challenges. The advantage of Brazil is that it can already reference many other cases of success and failure in other countries, shortening the process.

The USA is an excellent reference. The first legal act to regulate the natural gas market was passed in 1938, when the Natural Gas Act started regulating interstate gas sales. In 1978, the Natural Gas Policy Act (NGPA) initiated the deregulation of the gas market, which occurred slowly, with free access to natural gas distribution services only guaranteed in 1992 through FERC Order 636 - a change that was essential to create competition in the market [103].

Throughout the deregulation process, the Californian natural gas market experienced four incidents that shook it severely, making it more robust to future unplanned events [103]. Several lessons were learned during this period, and the following are those that can be applied to Brazil regarding the regulation of natural gas for thermoelectric plants [103]: (i) no political interest should influence decisions in a way that violates market principles; (ii) no regulation should pressurize a category of agents, particularly in financial aspects, as the market may not function properly; and (iii) there should be the possibility of trade options with the spot market in the short and long term, enabling participants to manage their risks.

Brazil needs to work on natural gas-related policies in a planned and anticipated way to avoid emergency decisions, as shown by the history of thermal plant construction in the 2000 s, which ended up paying for the cost of energy policy inefficiency [104]. Furthermore, despite the Brazilian culture of procrastination with its obligations, making an energy policy based on emergency decisions is inefficient for the country. With the hydrological crisis that Brazil is facing, and the eminence of energy policy decisions made without due planning, there is a risk of creating more problems for the future, in addition to not solving the present ones.

Brazil, due to its hydrothermal system, presents a constant risk, although controlled, of energy deficit, and a severe dry period is sufficient for start a new energy crisis. With the creation of thermal plants at the base in a planned approach and considering the realities of each agent group, contributions can be made to the energy security of Brazil and prevent the country facing an energy deficit, which was considered a value of R$ 7.643,82/MWh in 2022 [105], facing energy values from new gas thermal plants that vary from R$100 - 200/MWh (the exchange rate is around 5 R$/US$). If Brazil does not successfully improve these policies, in an extreme case of a hydrological crisis, it could be in a situation similar to Ghana, facing an economic depression for this reason [106].

In the case of Ghana, there was a power deficit due to the lack of a regulatory framework for power generation from natural gas, and gas was available, contrary to all principles of logic [106]. One of the reasons for the delay was the IOC

lobbies defending their interests (the root cause was also found in the US) and the lack of structure for natural gas operations, which did not attract investors.

Thus, to define public policies that do not necessarily have to be energetic, the government must listen to private agents' interests, limitations, and objectives. Decision-making must be focused on the public interest and cannot, under any circumstances, deteriorate due to private interests. Suppose that private interests capture public policies; in this case, Brazil may face a situation similar to that of Ghana, with the definition of its regulatory policy for natural gas delayed due to conflicts between public and private interests.

Similar to Ghana, Brazil is also a developing country, with public authorities being more susceptible to capture, and extreme care is needed to avoid it. The risk of capture is intensified in this case, considering that the IOC is strongly impacted by the decisions taken and influences in favor of its interests - behavior already predicted by agency theory [107]. In addition, the IOC has a long and extensive history of working with governments, particularly in underdeveloped and developing countries. In summary, the government needs to be close to the agents to understand the technical and operational challenges without diverting the focus and defending public interests.

As a consequence of the capture of public policy by private interests, there is also a possibility that the policy to be established will privilege private interests over public ones. This would be the worst result from a possible capture because it would not only delay the process of creating an efficient public policy; however, it would also consolidate itself as regulatory cancer through a policy that would privilege some agents, taking years or decades to be reviewed, and may be corrected.

It is necessary to make the gas business environment more straightforward and reliable, based on the entire picture. Once each state regulates the distribution activity, the 26 regulators are more susceptible to capture. With federal regulations, capture would be more challenging. Additionally, having only one regulation for natural gas in a country would attract more companies to the market. Companies with their core business related to gas supply would be attracted, as would companies that are energy consumers and can choose between electricity and gas. Several consumers are scared of the natural gas market because of regulation complexity.

Moreover, having only one regulator for the entire natural gas chain will harmonize regulation with the players and eliminate this risk to the market. The risk of a regulatory conflict highlights companies that are able to promote the use of natural gas.

Another advantage of changing natural gas regulation for federal competence is that the knowledge to improve and keep improving the regulation will be more prominent. Once the activity is split into states, each state's knowledge of improving the regulation is created independently with its budget for this purpose. A higher budget and more cases are expected to build more robust knowledge of this regulation in the case of a central regulator. Even when considering

the necessity of changing the federal constitution for this change, it should be done immediately.

The federal regulation of petroleum products in Brazil is ANP. Owing to its background, ANP has no experience with distribution regulation. On the other hand, ANEEL has a strong distribution regulation experience, as it has been executing this activity for more than two decades. Moreover, ANEEL has regulated the deregulated electricity market for the same period, and it is essential to remember the natural gas direction for the deregulated market. There are always necessary improvements in ANEEL regulations; however, they work well in the electricity market. The important aspect is the continuous improvement of regulation or adaptation to new circumstances.

Furthermore, we note that the actual product and good to the population is energy, whether it is electricity or gas. As natural gas transportation and distribution networks get territory in Brazil, the proximity between both worlds will become closer. For example, the availability of gas home equipment may increase, giving consumers more power to choose between gas and electricity. This means that more and each energy source will impact the others.

In conclusion, to change the distribution regulation to federal competence, it should be merged with the current ANEEL to create the Energy Agency in Brazil. The natural gas side would also relish ANEEL's current knowledge of regulating distribution activities and deregulated markets. Therefore, merging with the current ANP should be evaluated. No area of ANP can be merged, or some areas or all areas of ANP can be merged into the new energy agency to be created.

In parallel with the creation of the energy agency, a mathematical model should be developed immediately to support the government's decision to expand the natural gas network or construct thermal power plants to convert gas into electricity [13] [108] [109] [110]. As discussed, the best option is the direct use of natural gas; however, it can primarily reach the consumer as electricity because of its distribution networks. Although the current situation brings us to constructing power plants, it is necessary to consider the best option for the country. There is no technical or in-depth evaluation of what is better for a country.

7. Policy Implications

Natural gas presents several advantages. It is a clean, low-cost source that can contribute significantly to Brazil's energy security. Energy security is related to the complementation of intermittent renewable energy generation and collaboration in controllable low-cost generation in times of a hydrological crisis.

Brazil's prevailing natural gas transportation network is still deplorable and has a limited consumer reach. The projected growth of the network for the decade contributes little to the spread of this commodity. Therefore, for Brazil to exploit the advantages of natural gas and incorporate it into its energy matrix, it

must be converted into electrical energy.

In Brazil, natural gas power plants have a short history of only 20 years; however, their installed capacity is expected to increase over the next decade. Several regulatory barriers need to be addressed. In 2016, the Brazilian government has begun working in a structured manner to achieve these goals. Many measures have already been taken; however, there are still measures to be considered by the government. Some of these measures are in higher decision level than the current measures are being threated. It implicates that decision makers with more power, as ministers, should be involved. However, in addition to the gains obtained with the already implemented measures, there are lessons learned in the treatment of each of these measures, which can make future treatments more efficient.

In this way, by analyzing the actions taken so far, one concludes that the measures to be selected for development by the government should focus on issues related to the supply of natural gas to thermal plants and the improvement of integration between the electric and natural gas sectors. Although these measures are more complex and laborious, they bring better results to the market and consequently to society.

Several actions have contributed to the expansion of natural gas thermal plants in Brazil and will continue to bring progress in this sense. However, outstanding success will depend on a continuous policy that anticipates social problems, so that it can substitute hydraulic generation with a more competitive source, contributing to Brazil's energy cost competitiveness during hydrological crisis.

Furthermore, the Brazilian Federal Constitution (FC) does not allow centralized regulation, and the progress and quality of natural gas market regulation become limited and confusing for the players. For this reason, FC must be changed to centralize all natural gas chain regulations in the federal sphere by targeting a continuous improvement regulation to circumvent the barriers. It will allow that natural gas distribution activity will be regulated and centralized in the country, bringing a more reliable and precise business atmosphere. Moreover, tax legislation should be changed to avoid conflicts that could create legal insecurity.

Additionally, electricity and natural gas regulations have much relation. Natural gas and electricity's purpose is the same for society, especially for the final consumer. Once the purpose of the society is the same, changing only the way to attend to the same necessity, the regulation should be merged. Natural gas regulations nationwide should be merged with the current ANEEL to create an energy agency in Brazil. It is possible to consider the total merge of ANP and ANEEL, but at least the natural gas downstream business should be in the same agency as electricity. If ANP and ANEEL do not merge totally, their interaction should increase for the integration of big projects.

Brazil has an excellent methodology to evaluate electricity generation expansion, focusing on the equilibrium of the best energy source, location, cost and

availability to expand electricity generation. It also considers the optimum way to expand the electricity transmission system. Although, when it is necessary to decide on a natural gas direct use or to transform it into electricity to be supplied to society, there is no scientific data available for the decision making. A mathematical model is required to combine the electricity domain and natural gas for correct decision making for distribution network expansion, electricity generation expansion, and energy adequacy at the lowest cost. It will contribute even to evaluating how a NGPP can develop the natural gas availability for a particular region. Although it can represent a higher cost in the short term, it can present a lower cost to society in the long term.

Finally, the most crucial aspect is the mindset that electricity and gas do the same good for consumers and energy. The entire energy problem should be addressed instead of only considering electricity or gas. Market players have individual targets based on their economic situation and can strongly influence the government's decisions, which typically have less information than the market. The government must take the power of decision making into its hands by understanding the real impact of its choices on the people of Brazil.

8. Conclusions

This paper reaches its original targets and contributes to society, science and Brazilian policy. Society because it brings supply stability at the lowest cost to the consumers. For the science, due to a qualitative methodology that can be applied to other country facing the challenges of natural gas and electricity integration. Finally, our recommendations for policymakers and regulators may be followed to integrate natural gas and electricity to surpass those bottlenecks analyzed.

As a limitation, the Brazilian market suggestions cannot be directly applied to other countries. Overcoming the natural gas and electricity integration depends on each country's economic background, culture, energy picture and other specific facts. Only the methodology described itself can be applied to any country. The solutions suggested for Brazil can be used, at most, as a reference for a similar situation in a country with a similar background. Even in this case, other countries with similar characteristics should also be considered as a reference.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Chen, R., Zhu, B. and Duan, T. (2020) Role of Natural Gas Power Generation in China's Energy Transformation and Suggestions on Its Development. *Natural Gas Industry*, **40**, 120-128.

[2] Lin, J. and Mou, D. (2021) Analysis of the Optimal Spatial Distribution of Natural Gas under 'Tran-Sition from Coal to Gas' in China. *Resource and Energy Economics*, **66**, Article 101259. https://doi.org/10.1016/j.reseneeco.2021.101259

[3] Tolmasquim, M.T. (2016) Thermoelectric Energy: Natural Gas, Biomass, Coal, Nuclear. Empresa de Pesquisa Energética (EPE), Rio de Janeiro.

[4] Zhang, B.J., Tang, Q.Q., Zhao, Y., Chen, Y.Q., Chen, Q.L. and Floudas, C.A. (2018) Multi-Level Energy Integration between Units, Plants and Sites for Natural Gas Industrial Parks. *Renewable and Sustainable Energy Reviews*, **88**, 1-15. https://doi.org/10.1016/j.rser.2018.02.015

[5] Hafezi, R., Akhavan, A., Pakseresht, S. and Wood, D.A. (2021) Global Natural Gas Demand to 2025: A Learning Scenario Development Model. *Energy*, **224**, Article 120167. https://doi.org/10.1016/j.energy.2021.120167

[6] He, P. and Ni, X. (2022) Renewable Energy Sources in the Era of the Fourth Industrial Revolution: A Perspective of Civilization Development. *Journal of Physics*: *Conference Series*, **2301**, Article 012030. https://doi.org/10.1088/1742-6596/2301/1/012030

[7] Nan, L., Wu, L., Liu, T., Liu, Y. and He, C. (2020) Vulnerability Identification and Evaluation of Interdependent Natural Gas-Electricity Systems. *IEEE Transactions on Smart Grid*, **11**, 3558-3569. https://doi.org/10.1109/tsg.2020.2968178

[8] Luo, N., Li, M. and Yu, X. (2020) Natural Gas Power Generation Trends from a Technological Paradigm Perspective. *Journal of Physics*: *Conference Series*, **1549**, Article 042144. https://doi.org/10.1088/1742-6596/1549/4/042144

[9] Yang, J., Rizvi, S.K.A., Tan, Z., Umar, M. and Koondhar, M.A. (2021) The Competing Role of Natural Gas and Oil as Fossil Fuel and the Non-Linear Dynamics of Resource Curse in Russia. *Resources Policy*, **72**, Article 102100. https://doi.org/10.1016/j.resourpol.2021.102100

[10] Hashimoto, S. (2021) Why Doesn't Japan Have a Natural Gas Pipeline Network? Consideration from the Determinant of the Choice between LNG Tank Trucks and Pipelines. *International Journal of Energy Economics and Policy*, **11**, 346-353. https://doi.org/10.32479/ijeep.11049

[11] Wu, L. (2019) Forecasting Natural Gas Production and Consumption Using Grey Model with Latent Information Function: The Cases of China and USA. *Scientia Iranica*, **28**, 386-394. https://doi.org/10.24200/sci.2019.5378.1240

[12] Ministério de Minas e Energia (MME) and Empresa de Pesquisa Energética (EPE) (2020) Plano Decenal De Expansão De Energia 2029. Brasília.

[13] García Kerdan, I., Jalil-Vega, F., Toole, J., Gulati, S., Giarola, S. and Hawkes, A. (2019) Modelling Cost-Effective Pathways for Natural Gas Infrastructure: A Southern Brazil Case Study. *Applied Energy*, **255**, Article 113799. https://doi.org/10.1016/j.apenergy.2019.113799

[14] Larizzatti Zacharias, L.G., Antunes Costa De Andrade, A.C., Guichet, X., Mouette, D. and Peyerl, D. (2022) Natural Gas as a Vehicular Fuel in Brazil: Barriers and Lessons to Learn. *Energy Policy*, **167**, Article 113056. https://doi.org/10.1016/j.enpol.2022.113056

[15] Udemba, E.N. and Tosun, M. (2022) Energy Transition and Diversification: A Pathway to Achieve Sustainable Development Goals (SDGs) in Brazil. *Energy*, **239**, Article 122199. https://doi.org/10.1016/j.energy.2021.122199

[16] Brito, T.L.F., Galvão, C., Fonseca, A.F., Costa, H.K.M. and Moutinho Dos Santos, E. (2022) A Review of Gas-to-Wire (GtW) Projects Worldwide: State-of-Art and Developments. *Energy Policy*, **163**, Article 112859. https://doi.org/10.1016/j.enpol.2022.112859

[17] Coelho Junior, L.M., Fonseca, A.J.D.S., Castro, R., Mello, J.C.D.O., Santos,

V.H.R.D., Pinheiro, R.B., Sousa, W.L., Santos Júnior, E.P. and Ramos, D.S. (2022) Empirical Evidence of the Cost of Capital under Risk Conditions for Thermoelectric Power Plants in Brazil. *Energies*, **15**, Article 4313. https://doi.org/10.3390/en15124313

[18] Junior, L.M.C., Junior, E.P.S., Nunes, A.M.M., Simioni, F.J., Abrahao, R. and Junior, P.R. (2020) Concentration and Spatial Clustering of Forest-Based Thermoelectric Plants in Brazil. *IEEE Access*, **8**, 221932-221941. https://doi.org/10.1109/access.2020.3042945

[19] Operador Nacional do Sistema Elétrico (ONS) (2021) Nota à imprensa—Esclarecimentos em relação à nota técnica sobre avaliação das condições de atendimento eletroenergético. Brasília. https://www.ons.org.br/Paginas/Noticias/Nota-a-imprensa-Esclarecimentos-em-relacao-a-nota-tecnica-Avaliacao-das-Condicoes-de-Atendimento-Eletroenergetico-do-SIN.aspx

[20] Sousa, D.S., Neves, C.F., Silva, H.V.O., Schaffel, S.B., Luigi, G. and La Rovere, E.L. (2022) A Systemic Approach for Climate Risk Assessment Applied to Thermoelectric Power Plants in Northeastern Coast of Brazil. *Climate Risk Management*, **36**, Article 100424. https://doi.org/10.1016/j.crm.2022.100424

[21] Bezutti, N. (2021) The Greater the Thermal Availability, the Greater the Charge Value. MEGAWhat, São Paulo. https://megawhat.energy/noticias/politica-energetica/143064/quanto-maior-disponibili-dade-termi-ca-maior-valor-do-encargo-indica-analise-da-megawhat?utm_campaign=crise_hidrica&utm_medium=email&utm_source=RD Station

[22] De Castro Junior, D.J., De Almeida Costa, C.I., De Almeida Campos, R.B., Bonaldi, E.L., De Oliveira Assunção, F., Lambert-Torres, G., De Farias, R.S., Rossetto, R.R. and De Jesus, A.A.G. (2021) Virtual Reality Applied in a Thermoelectric Power Plant Planning. *Brazilian Archives of Biology and Technology*, **64**, e21210138. https://doi.org/10.1590/1678-4324-202121013

[23] Goldenberg, J. and Prado, L.T.S. (2003) Reform and Crisis of the Electricity Sector in the FHC Period. *Tempo Social*, **15**, 219-235. https://doi.org/10.1590/s0103-20702003000200009

[24] International Renewable Energy Agency (IRENA) (2018) Power System Flexibility for the Energy Transition, Part 1: Overview for Policy Makers. Abu Dhabi.

[25] Robinson, J., DiChristopher, T., Micek, K. and Watson, M. (2022) Renewables Capturing Market from Gas-Fired Generation. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/060821-natural-gas-in-transition-renewables-capturing-market-from-gas-fired-generation

[26] Borriello, A., Burke, P.F. and Rose, J.M. (2021) If One Goes up, Another Must Come down: A Latent Class Hybrid Choice Modelling Approach for Understanding Electricity Mix Preferences among Renewables and Non-Renewables. *Energy Policy*, **159**, Article 112611. https://doi.org/10.1016/j.enpol.2021.112611

[27] Directorate-General for Energy (2019) Potentials of Sector Coupling for Decarbonisation: Assessing Regulatory Barriers in Linking the Gas and Electricity Sectors in the EU: Final Report. European Commission, Brussels. https://doi.org/10.2833/000080

[28] Chang, J.W., Aydin, M.G., Pfeifenberger, J., Spees, K. and Pedtke, J.I. (2017) Advancing Past "Baseload" to a Flexible Grid How Grid Planners and Power Markets

Are Better Defining System Needs to Achieve a Cost-Effective and Reliable Supply Mix. The Brattle Group, Inc.

[29] Shaffer, B., Tarroja, B. and Samuelsen, S. (2015) Dispatch of Fuel Cells as Transmission Integrated Grid Energy Resources to Support Renewables and Reduce Emissions. *Applied Energy*, **148**, 178-186. https://doi.org/10.1016/j.apenergy.2015.03.018

[30] Ma, L. and Spataru, C. (2015) The Use of Natural Gas Pipeline Network with Different Energy Carriers. *Energy Strategy Reviews*, **8**, 72-81. https://doi.org/10.1016/j.esr.2015.09.002

[31] Mac Kinnon, M.A., Brouwer, J. and Samuelsen, S. (2018) The Role of Natural Gas and Its Infra-Structure in Mitigating Greenhouse Gas Emissions, Improving Regional Air Quality, and Renewable Resource Integration. *Progress in Energy and Combustion Science*, **64**, 62-92. https://doi.org/10.1016/j.pecs.2017.10.002

[32] Ogden, J., Jaffe, A.M., Scheitrum, D., McDonald, Z. and Miller, M. (2018) Natural Gas as a Bridge to Hydrogen Transportation Fuel: Insights from the Literature. *Energy Policy*, **115**, 317-329. https://doi.org/10.1016/j.enpol.2017.12.049

[33] PJM (2021) Natural Gas and Electric Market Coordination Issues. Norristown.

[34] Erbach, G. (2019) Energy Storage and Sector Coupling: Towards an Integrated, Decarbonised Energy System. European Parliamentary Research Service, Brussels.

[35] Wehbi, Z., Taher, R., Faraj, J., Castelain, C. and Khaled, M. (2022) Hybrid Thermoelectric Generators-Renewable Energy Systems: A Short Review on Recent Developments. *Energy Reports*, **8**, 1361-1370. https://doi.org/10.1016/j.egyr.2022.08.068

[36] De Castro Reis, J., Dos Santos Constant, R., Angulo Meza, L. and Soares De Mello, J.C. (2019) Multiobjective Linear Programming to Determine the Most Suitable Electrical Energy Matrix for Countries: A Case Study at Brazil. *IEEE Latin America Transactions*, **17**, 426-433. https://doi.org/10.1109/tla.2019.8863313

[37] Dos Santos, V.J., Calijuri, M.L. and De Assis, L.C. (2022) Land Cover Changes Implications in Energy Flow and Water Cycle in São Francisco Basin, Brazil, over the Past 7 Decades. *Environmental Earth Sciences*, **81**, Article No. 83. https://doi.org/10.1007/s12665-022-10210-5

[38] Carpejani, P., De Jesus, É.T., Bonfim Catapan, B.L.S., Gouvea Da Costa, S.E., Pinheiro De Lima, E., Tortato, U., Machado, C.G. and Richter, B.K. (2020) Affordable and Clean Energy: A Study on the Advantages and Disadvantages of the Main Modalities. In: Leal Filho, W., Borges de Brito, P. and Frankenberger, F., Eds., *International Business, Trade and Institutional Sustainability. World Sustainability Series*, Springer, Cham, 615-627. https://doi.org/10.1007/978-3-030-26759-9_35

[39] Mensah, J.H.R., Dos Santos, I.F.S., Raimundo, D.R., Costa De Oliveira Botan, M.C., Barros, R.M. and Tiago Filho, G.L. (2022) Energy and Economic Study of Using Pumped Hydropower Storage with Renewable Resources to Recover the Furnas Reservoir. *Renewable Energy*, **199**, 320-334. https://doi.org/10.1016/j.renene.2022.09.003

[40] Liu, L., Xu, S., Cui, L., Min, G. and Wang, H. (2019) Power Rationing for Tradeoff between Energy Consumption and Profit in Multimedia Heterogeneous Networks. *IEEE Journal on Selected Areas in Communications*, **37**, 1642-1655. https://doi.org/10.1109/jsac.2019.2916450

[41] Rakhmonov, I.U., Reymov, K.M. and Dustova, S.H. (2020) Improvements in Industrial Energy Rationing Methods. *IOP Conference Series: Materials Science and Engineering*, **862**, Article 062070. https://doi.org/10.1088/1757-899x/862/6/062070

[42] Avila-Diaz, A., Benezoli, V., Justino, F., Torres, R. and Wilson, A. (2020) Assessing Current and Future Trends of Climate Extremes across Brazil Based on Reanalyses and Earth System Model Projections. *Climate Dynamics*, **55**, 1403-1426. https://doi.org/10.1007/s00382-020-05333-z

[43] Pittol Martini, L.C. (2022) Changes in Rainfall Patterns in Southern Brazil over 1961-2020 Period Detected by Rain Gauge Data. *International Journal of Climatology*, **42**, 9101-9114. https://doi.org/10.1002/joc.7804

[44] Hunt, J.D., Nascimento, A., Caten, C.S.T., Tomé, F.M.C., Schneider, P.S., Thomazoni, A.L.R., De Castro, N.J., Brandão, R., De Freitas, M.A.V., Martini, J.S.C., Ramos, D.S. and Senne, R. (2022) Energy Crisis in Brazil: Impact of Hydropower Reservoir Level on the River Flow. *Energy*, **239**, Article 121927. https://doi.org/10.1016/j.energy.2021.121927

[45] Kolpakhchyan, P., Lobov, B., Ivanov, I. and Safin, A. (2020) An Integrated Approach to the Creation of Decentralised Power Supply Systems Based on Gas Turbine Plants in the Regions of the Far North. *E3S Web of Conferences*, **220**, Article No. 01074. https://doi.org/10.1051/e3sconf/202022001074

[46] Kotagodahetti, R., Hewage, K., Karunathilake, H. and Sadiq, R. (2023) Renewable Natural Gas as a Greener Energy Source: A Life Cycle Cost-Benefit Analysis. *Proceedings of the Canadian Society of Civil Engineering Annual Conference* 2021, Whistler, 26-29 May 2021, 679-692. https://doi.org/10.1007/978-981-19-0503-2_54

[47] Moreira Dos Santos, R. and Szklo, A. (2022) Planning Natural Gas Networks and Storage in Emerging Countries—An Application to Brazil. *Energy & Environment*, **33**, 1245-1264. https://doi.org/10.1177/0958305x211019011

[48] Onen, P.S., Mokryani, G. and Zubo, R.H.A. (2022) Optimal Expansion Planning of Integrated Natural Gas and Electricity Network with High Penetration of Wind and Solar Power under Uncertainty. In: 2022 *IEEE* 21*st Mediterranean Electrotechnical Conference* (*MELECON*), Palermo, 14-16 June 2022, 908-913. https://doi.org/10.1109/melecon53508.2022.9842898

[49] Silva, L.M.F., De Oliveira, A.C.R., Leite, M.S.A. and Marins, F.A.S. (2021) Risk Assessment Model Using Conditional Probability and Simulation: Case Study in a Piped Gas Supply Chain in Brazil. *International Journal of Production Research*, **59**, 2960-2976. https://doi.org/10.1080/00207543.2020.1744764

[50] Bricl, M. and Avsec, J. (2019) Evaluation of System for Economically Viable Thermal Power Plant Operation. *Tehnicki Vjesnik*: *Technical Gazette*, **26**, 1038-1043. https://doi.org/10.17559/tv-20180719184137

[51] Rech, S. and Lazzaretto, A. (2018) Smart Rules and Thermal, Electric and Hydro Storages for the Optimum Operation of a Renewable Energy System. *Energy*, **147**, 742-756. https://doi.org/10.1016/j.energy.2018.01.079

[52] Thang, V.V., Ha, T., Li, Q. and Zhang, Y. (2022) Stochastic Optimization in Multi-Energy Hub System Operation Considering Solar Energy Resource and Demand Response. *International Journal of Electrical Power & Energy Systems*, **141**, Article 108132. https://doi.org/10.1016/j.ijepes.2022.108132

[53] Wang, Y., Liu, Z., Cai, C., Xue, L., Ma, Y., Shen, H., Chen, X. and Liu, L. (2022) Research on the Optimization Method of Integrated Energy System Operation with Multi-Subject Game. *Energy*, **245**, Article 123305. https://doi.org/10.1016/j.energy.2022.123305

[54] Ye, L. and Jia, L. (2018) Multi-Objective Optimization for Thermal Power Plant Operation Based on Improved Working Condition. 2018 *IEEE* 7*th Data Driven Control and Learning Systems Conference* (*DDCLS*), Enshi, 25-27 May 2018,

502-507. https://doi.org/10.1109/ddcls.2018.8515906

[55] Martinez, P.H. and Colacios, R.D. (2016) Pre-Salt: Oil and Public Policies in Brazil (2007-2016). *Journal of Social, Technological and Environmental Science*, **5**, 145-167. https://doi.org/10.21664/2238-8869.2016v5i1.p145-167

[56] Azevedo Filho, E.T., Palma, M.A.M., Perestrelo, M., Da Hora, H.R.M. and Lira, R.A. (2019) The Pre-Salt Layer and Challenges to Competitiveness in Brazil: Critical Reflections on the Local Content Policy in the Oil and Gas Sector. *The Extractive Industries and Society*, **6**, 1168-1173. https://doi.org/10.1016/j.exis.2019.09.009

[57] Mein, T.F., Gimenes, A.L.V., Dias, E.M., Rebello Pinho Dias Scoton, M.L. and Udaeta, M.E.M. (2021) Environmental Vulnerability in Pre-Salt Oil and Gas Operations. *Energies*, **14**, Article 732. https://doi.org/10.3390/en14030732

[58] De Souza, L.S. and Sgarbi, G.N.C. (2020) The Brazilian Pre-Salt and the Regulatory Framework Evolution for Exploration and Production of Hydrocarbons in Brazil. *Anuário do Instituto de Geociências- UFRJ*, **43**, 354-373. https://doi.org/10.11137/2020_3_354_373

[59] Empresa de Pesquisa Energética (2020) PIG 2020—Plano Indicativo de Gasodutos de Transporte. Brasília.

[60] Empresa de Pesquisa Energética (2019) Plano Indicativo de Processamento e Escoamento de Gás Natural. Brasília.

[61] Solano, R.F., De Azevedo, F.B. and Oazen, E. (2013) Design Challenges of Gas Export Pipelines for Pre-Salt Area offshore Brazil. *Proceedings of the ASME* 2013 32*nd International Conference on Ocean, Offshore and Arctic Engineering. Volume 4A*: *Pipeline and Riser Technology*, Nantes, 9-14 June 2013, Paper No. 10093. https://doi.org/10.1115/omae2013-10093

[62] De Jesus Delgado, F., Goncalves, P.H.N. and Chambriard, M. (2020) Brazil Oil and Gas Sector Piece De Resistance: The Pre-Salt Play Developments. *Offshore Technology Conference Brazil*, Rio de Janeiro, 29-31 October 2019, Paper No. 29840.

[63] Bidart, A.M.F., De Melo, D.C., Passarelli, F.M., Do Nascimento, J.F., Silva, J.P., Sampaio Andrade, L.D., Dos Santos Pereira, L., De Rezende Tapajos, L. and Grava, W.M. (2015) Challenges in Offshore Natural Gas Processing. *OTC Brasil* 2015: *The Atlantic*: *From East to West—An Ocean of Innovation*, Rio de Janeiro, 27-29 October 2015, 1470-1475.

[64] Penha, H.S.P. (2014) Critical Reflections and Contributions to Improving the Complementarity of Thermoelectric and Industrial Consumption of Natural Gas. Master's Thseis, Universidade de São Paulo, São Paulo.

[65] Ministério de Minas e Energia (2020) Boletim Mensal de Acompanhamento da Indústria de Gás Natural. Brasília.

[66] Waine, C. (2020) Brazil-Bolivia Gas Talks Suspended. Petroleum Economist, London.

[67] Eini, S., Kontogeorgis, G.M. and Rashtchian, D. (2020) Cost Optimisation and Flexibility Analysis for the Liquefaction of an Associated Natural Gas Stream. *Journal of Energy Resources Technology*, **142**, Article 062801. https://doi.org/10.1115/1.4045459

[68] Jokar, S.M., Wood, D.A., Sinehbaghizadeh, S., Parvasi, P. and Javanmardi, J. (2021) Transformation of Associated Natural Gas into Valuable Products to Avoid Gas Wastage in the Form of Flaring. *Journal of Natural Gas Science and Engineering*, **94**, Article 104078. https://doi.org/10.1016/j.jngse.2021.104078

[69] Paltsev, S. (2015) Economics and Geopolitics of Natural Gas: Pipelines versus LNG.

2015 12*th International Conference on the European Energy Market* (*EEM*), Lisbon, 19-22 May 2015, 1-5. https://doi.org/10.1109/eem.2015.7216651

[70] Dos Santos, E.M., Carrera Zamalloa, G., Dondero Villanueva, L. and Fagá, M.T.W. (2002) Natural Gas: Strategies for a New Energy in Brazil. Annablume, São Paulo.

[71] Tovar, B., Ramos-Real, F.J. and Fagundes De Almeida, E.L. (2015) Efficiency and Performance in Gas Distribution. Evidence from Brazil. *Applied Economics*, **47**, 5390-5406. https://doi.org/10.1080/00036846.2015.1047093

[72] Aksyutin, O.E., Ishkov, A.G. and Grachev, V.A. (2018) Ecological and Economic Evaluation of Compressed Natural Gas Marine Transportation. 32*nd International Business Information Management Association Conference*, Seville, 15-16 November 2018, 3976-3988.

[73] Busetto, M. and Cijan, A. (2017) The New Era of Compressed Natural Gas Transportation. *Offshore Mediterranean Conference and Exhibition* 2017, Ravenna, 29-31 March 2017, 763.

[74] Vasconcelos, C.D., Lourenço, S.R., Gracias, A.C. and Cassiano, D.A. (2013) Network Flows Modeling Applied to the Natural Gas Pipeline in Brazil. *Journal of Natural Gas Science and Engineering*, **14**, 211-224. https://doi.org/10.1016/j.jngse.2013.07.001

[75] Goldstein, A. (2010) The Emergence of Multilatinas: The Petrobras Experience. *Universia Business Review*, **25**, 98-111.

[76] Goldstein, A. and Baena, C. (2010) Drivers of Internationalisation of Companies from Emerging Economies: Comparing Petrobras (Brazil) and PDVSA (Venezuela). *International Journal of Technological Learning, Innovation and Development*, **3**, 392-407. https://doi.org/10.1504/ijtlid.2010.039165

[77] Maragno, L. and Borba, J.A. (2019) Unearthing Money Laundering at Brazilian Oil Giant Petrobras. *Journal of Money Laundering Control*, **22**, 400-406. https://doi.org/10.1108/jmlc-03-2018-0027

[78] Ministério de Minas e Energia (2020) Visão do planejamento energético de médio e longo prazos-Levantamento de custos e riscos da interface dos setores de gás natural e energia elétrica. Brasília.

[79] Gomes, J. (2021) Turning up the Heat on Brazil's Gas Reforms. https://www.gov.br/economia/pt-br/assuntos/noticias/2019/07/acordo-entre-petrobras-e-cade-viabiliza-abertura-do-mercado-de-gas-natural

[80] Camarotto, M. (2021) Petrobras ganha mais prazo do Cade para vender ativos de refino e gás. https://valor.globo.com/empresas/noticia/2021/04/28/petrobras-ganha-mais-prazo-do-cade-para-vender-ativos-de-refino-e-gs.ghtml

[81] Mistry, L., Wahid, F. and Fitch, P. (2020) Gas to Wire or Gas to Shore: Evaluation of Transitional Clean Energy in Offshore UKCS. 2020 *SPE Annual Technical Conference and Exhibition*, Virtual Meeting, 27-29 October 2020, Paper No. 201602. https://doi.org/10.2118/201602-ms

[82] Schernikau, L. and Smith, W.H. (2022) Climate Impacts of Fossil Fuels in Todays Electricity Systems. *Journal of the Southern African Institute of Mining and Metallurgy*, **122**, 133-145. https://doi.org/10.17159/2411-9717/1874/2022

[83] Silveira, J.L., De Carvalho, J.A. and De Castro Villela, I.A. (2007) Combined Cycle versus One Thousand Diesel Power Plants: Pollutant Emissions, Ecological Efficiency and Economic Analysis. *Renewable and Sustainable Energy Reviews*, **11**, 524-535. https://doi.org/10.1016/j.rser.2004.11.007

[84] Ministério de Minas e Energia (2019) Atualização dos diagnósticos e das recomendações do relatório do Subcomitê 8 do Programa Gás para Crescer. Brasília. https://doi.org/10.2307/j.ctvt7x84v.5

[85] Supremo Tribunal Federal (STF) (2020) Ação Cível Originária 854 Mato Grosso do Sul—Resumo do Relatório e do Voto-conjunto das ACO's 854, 1.076 e 1.093. Brasília.

[86] Damico, A., De Medeiros Costa, H.K., Balliram, S., Pereira, E.G. and Dos Santos, E.M. (2022) The Expansion of the Natural Gas Market through the Provisions of Law 14.182/21 that Deals with the Privatisation of Eletrobras. *Research, Society and Development*, **11**, E7211830430. https://doi.org/10.33448/rsd-v11i8.30430

[87] Seciuk, C. (2022) Eletrobras' "Jabuti" Requires Thermal Plants Where There Is No Gas and Can Be Expensive. https://www.gazetadopovo.com.br/economia/jabuti-da-eletrobras-exige-termicas-onde-nao-ha-gas-e-pode-custar-caro/

[88] Roser, M. (2021) Why Did Renewables Become So Cheap So Fast? https://ourworldindata.org/cheap-renewables-growth

[89] Brazilian Federal Senate (2016) Lei No 13.360 de 17/11/2016—Altera a Lei No 5.655, de 20 de Maio de 1971, a Lei No 10.438, de 26 de Abril de 2002, a Lei No 9.648, de 27 de Maio de 1998, a Lei No 12.111, de 9 de Dezembro de 2009, a Lei No 12.783, de 11 de Janeiro de 2013, a Lei No 9.074, de. Brasília.

[90] José De Castro Vieira, S. and Tapia Carpio, L.G. (2020) The Economic Impact on Residential Fees Associated with the Expansion of Grid-Connected Solar Photovoltaic Generators in Brazil. *Renewable Energy*, **159**, 1084-1098. https://doi.org/10.1016/j.renene.2020.06.016

[91] Empresa de Pesquisa Energética (2021) Guia de perguntas da frente de atuação: Separação lastro e energia. Brasília.

[92] Brazilian Federal Senate (2021) Lei No 14.120 de 2021—Altera a Lei No 9.991, de 24 de Julho de 2000, a Lei No 5.655, de 20 de Maio de 1971, a Lei No 9.427, de 26 de Dezembro de 1996, a Lei No 10.438, de 26 de Abril de 2002, a Lei No 10.848, de 15 de Março de 2004, a Lei No 12.111, de. Brasília.

[93] Gonçalves, C.P. and Ramos, D.S. (2019) The Importance of Natural Gas for Supplying the Brazilian Electricity Market—An Analysis from the Perspective of Investment Feasibility. A Regulação Do GÁS Natural No Brasil, Foz do Iguaçú, 263-290.

[94] Ministério de Minas e Energia (2020) Portaria MME No 435 de 2020.

[95] Ministério de Minas e Energia, Agência Nacional do Petróleo, Gás Natural e Biocombustíveis, Pré-Sal Petróleo S.A, Empresa de Pesquisa Energética and Banco Nacional do Desenvolvimento. (2020) Estudo sobre o aproveitamento do gás natural do pré-sal. Rio de Janeiro.

[96] Rego, E.E. (2012) Proposal for Improving the Methodology of Electric Energy Auctions in the Regulated Environment: Conceptual, Methodological Aspects and Their Applications. Doctoral Thesis, University of São Paulo, São Paulo. https://doi.org/10.11606/T.86.2012.tde-28112012-093549

[97] Conselho Empresarial Brasileiro para o Desenvolvimento Sustentável (CEBDS) (2019) Guide to Corporate Power Purchase Agreements (PPA's) for Renewable Energy in Brazil. Rio de Janeiro.

[98] Sonibare, J.A. and Akeredolu, F.A. (2006) Natural Gas Domestic Market Development for Total Elimination of Routine Flares in Nigeria's Upstream Petroleum Op-

erations. *Energy Policy*, **34**, 743-753. https://doi.org/10.1016/j.enpol.2004.07.006

[99] Chidinma, U. (2013) Using Gas Turbine for Electricity Supply in a Typical Nigerian University: A Case Study of University of Port Harcourt. *Society of Petroleum Engineers—37th Nigeria Annual International Conference and Exhibition: To Grow Africa's Oil and Gas Production: Required Policy, Funding, Technol., Techniques and Capabilities*, Vol. 2, Victoria Island, 30 July-1 August 2013, 1166-1185. https://doi.org/10.2118/167600-ms

[100] Van Meurs, P. (2021) Nigeria's Petroleum Industry Bill and the Zero-Carbon Future. Van Meurs Energy, Panama City.

[101] Ojijiagwo, E.N., Oduoza, C.F. and Emekwuru, N. (2018) Technological and Economic Evaluation of Conversion of Potential Flare Gas to Electricity in Nigeria. *Procedia Manufacturing*, **17**, 444-451. https://doi.org/10.1016/j.promfg.2018.10.068

[102] Onwuka, E.I. and Iledare, O. (2015) Nigeria Gas to Power Value Chain Systems Economic Evaluation and Modeling. *SPE Nigeria Annual International Conference and Exhibition*, Victoria Island, 4-6 August 2015, Paper No. 178340. https://doi.org/10.2118/178340-ms

[103] Lee, W.W. (2004) US Lessons for Energy Industry Restructuring: Based on Natural Gas and California Electricity Incidences. *Energy Policy*, **32**, 237-259. https://doi.org/10.1016/s0301-4215(02)00287-2

[104] Ministério de Minas e Energia (2019) Proposta para o mercado brasileiro de gás natural. Brasília.

[105] CCEE (2020) CCEE Technical Note—CCEE06673-2021. https://www.ccee.org.br/documents/80415/919464/Nota%20T%C3%A9cnica%20CCEE%20-%20CCEE06673-2021.pdf/7a7f2707-0b43-5abd-05ac-938d0768c303

[106] Fritsch, J. and Poudineh, R. (2016) Gas-to-Power Market and Investment Incentive for Enhancing Generation Capacity: An Analysis of Ghana's Electricity Sector. *Energy Policy*, **92**, 92-101. https://doi.org/10.1016/j.enpol.2016.01.034

[107] Eisenhardt, K.M. (1989) Agency Theory: An Assessment and Review. *The Academy of Management Review*, **14**, 57-74.

[108] Jooshaki, M., Abbaspour, A., Fotuhi-Firuzabad, M., Moeini-Aghtaie, M. and Lehtonen, M. (2019) Multistage Expansion Co-Planning of Integrated Natural Gas and Electricity Distribution Systems. *Energies*, **12**, Article 1020. https://doi.org/10.3390/en12061020

[109] Kanelakis, N.G., Biskas, P.N., Chatzigiannis, D.I. and Bakirtzis, A.G. (2020) A Stochastic Two-Stage Model for the Integrated Scheduling of the Electric and Natural Gas Systems. *IEEE Open Access Journal of Power and Energy*, **7**, 453-466. https://doi.org/10.1109/oajpe.2020.3030193

[110] Shabazbegian, V., Ameli, H., Ameli, M.T. and Strbac, G. (2020) Stochastic Optimisation Model for Coordinated Operation of Natural Gas and Electricity Networks. *Computers & Chemical Engineering*, **142**, Article 107060. https://doi.org/10.1016/j.compchemeng.2020.107060