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Article

Underground Natural Gas Storage: Enhancing Flexibility in Brazil's Electricity Sector

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Abstract: Supply flexibility is an essential attribute for the development of natural gas markets. In countries that have a mature market, gas storage capacity is used to deal with variations in demand. In Brazil, the natural gas market is still developing, and flexibility is an important challenge. In most of the more mature natural gas markets, the seasonality of demand is closely linked to temperature (harsh winter), and flexibility mechanisms were developed for this purpose. In Brazil, demand volatility is determined by the thermoelectric segment, as gas thermal plants have a complementary role to the hydroelectric park. This situation has brought challenges to the development of the gas market in Brazil. Thus, flexibility mechanisms can generate significant efficiency gains by avoiding underutilization of infrastructure. The article analyzes the Underground Storage of Natural Gas (UGS) as a "flexibility" tool, suitable for the Brazilian market to guarantee a balance of supply versus demand without deficits and in an optimized way, considering the randomness of gas demand. The economic value added by UGS to the electricity sector is illustrated through a case study of a natural gas thermoelectric plant that uses pre-salt associated gas. Thus, using the Monte Carlo simulation method, this study demonstrated the economic value for the Brazilian electricity sector of contracting underground natural gas storage capacity to be used in the dispatch of natural gas-fired thermal power plants as part of a trade-off with liquefied natural gas (LNG).

Keywords: Underground Natural Gas storage; Economic Value; Market Design; Power Sector

1. Introduction

The national production of natural gas in Brazil is predominantly offshore and associated with oil, accounting for around 80% of gross production. The non-thermoelectric gas demand has been stagnant throughout the entire decade, around 50 MMm^3/d, but the thermal demand fluctuates due to the flexibility required by the electricity sector. The thermal dispatch using gas fluctuates around 30 MMm^3/d in the annual average of recent years, and can reach around 50 MMm^3/d in critical hydrological periods, as in 2015.

In Brazil, hydroelectric preponderance and the renewable expansion of the matrix reduce the space for gas entry. Thermoelectric generation was structured to be flexible, as a backup for adverse hydrological scenarios. Generation occurs in order of merit when the plant's variable cost is lower than the system's marginal operating cost. The hydrological uncertainty and the significant storage capacity of the reservoirs made the perspective of thermal generation not very predictable. **Figure 1** shows the profile of gas-fired thermal generation gas demand as a result of its dispatch.

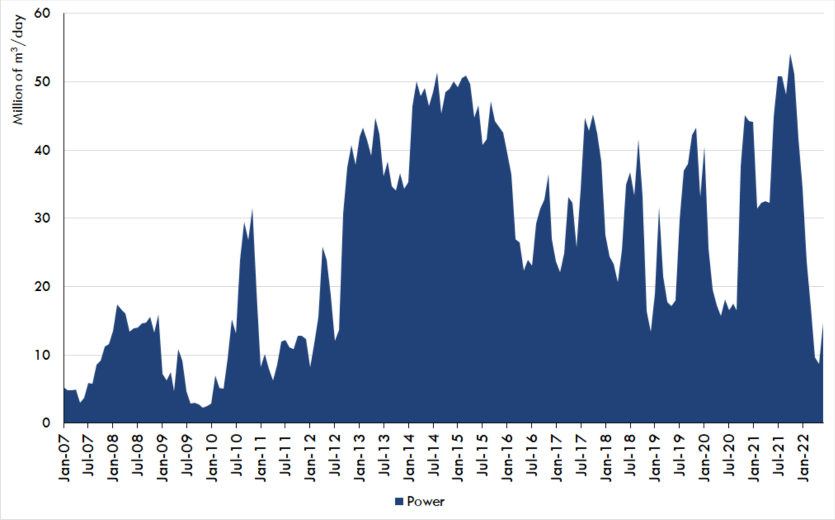

Figure 1. Natural gas demand by gas-fired power plants in Brazil.

The low predictability of thermoelectric dispatch contrasts with the inflexibility of national gas production, mostly associated with oil in offshore fields. The flexibility required by the electricity sector was handled by the import of LNG in the spot market and the development of several regasification terminals.

Between 2009 and 2014, Petrobras implemented three regasification terminals with a combined capacity of 41 MMm^3/d. In recent years, five new private regasification terminals have been built and three others are under construction or planned (**Figure 2**).

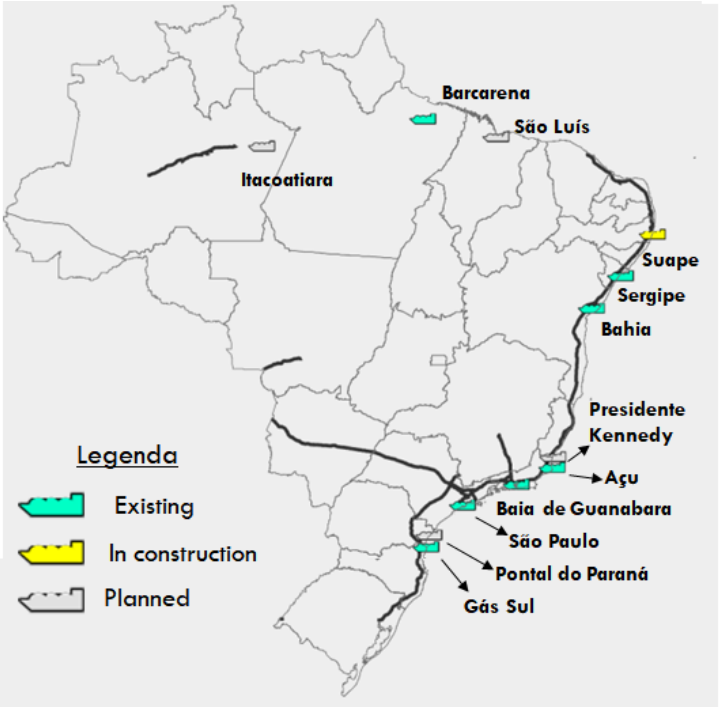

Figure 2. LNG terminals in the Brazil.

In 2021, the Brazilian government approved a new gas law, and since 2022, the Brazilian gas market has been liberalized, allowing new gas suppliers to compete with Petrobras. New gas suppliers in Brazil will face an extremely complex problem, which is how to supply gas to the market with a supply flexibility compatible with the variability of gas demand from distributors, large final consumers, and, particularly, thermoelectric plants (**Figure 3**). This problem is especially complex for associated gas producers in Brazil, which corresponds to 80% of the total domestic supply and around 90% of the gas supply to the interconnected gas system. These producers cannot significantly vary their gas supply without compromising oil production, which is responsible for most of the added value of the field. Additionally, these producers find it challenging to guarantee a supply 100% of the time, as there are scheduled and unscheduled stops on the platforms.

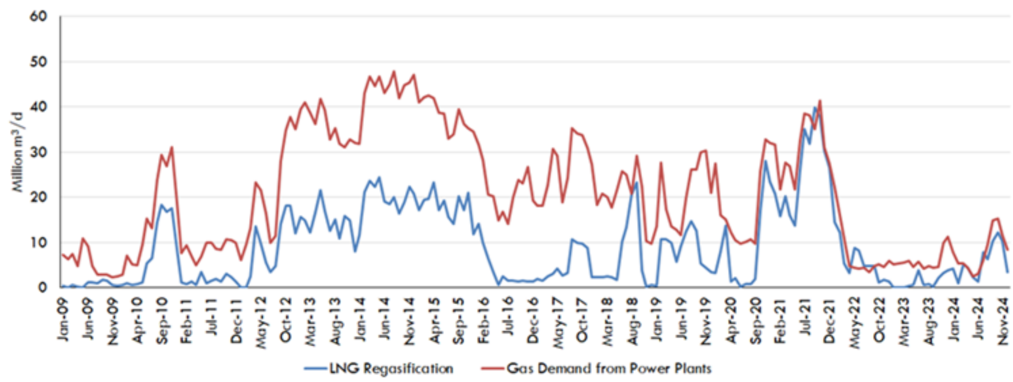

Figure 3. LNG imports and gas demand from thermoelectric plants (right axis).

The question of the lack of supply flexibility represents a non-negligible threat to the security of supply in the country at times of strong thermoelectric dispatch, without adequate gas storage. It is important to remember that an emergency importation of LNG does not arrive in the country in less than 12 days, considering only the navigation time. Even a supplier that is an importer of LNG may face specific difficulties in serving a market of flexible thermoelectric plants if its LNG stock is limited to the capacity of an FSRU.

Faced with this scenario, the time has come for the energy authorities to discuss a policy for the feasibility of underground gas storage projects in Brazil. About the regulatory framework and market design, it should be noted that there are great synergies between the transport and storage markets. In the large liberalized gas markets, there is a strong integration between transport and storage services. In the United States, for example, gas trading centers such as the Henry Hub operate transport and storage systems in an integrated manner. In Europe, on the other hand, there is a separation between transport and storage activities, but with market designs that allow a strong coupling between transport and storage services. In this way, it is worth reflecting on how to integrate storage projects into transport systems in Brazil, in particular, on how to design a transport tariff system that allows low-cost access to future gas storage infrastructure by all shippers.

In brief, inflexible domestic gas production tends to increase and exceed than the firm gas demand. Liberalization of the gas market increases the demand for flexibility in the gas sector. The cost of spot LNG has skyrocketed, creating high costs to the power sector. Therefore, gas underground storage is a natural solution to increase the flexibility of gas supply in Brazil.

Thus, although the importance of flexibility in the natural gas market in Brazil is clear, the Underground Storage of Natural Gas (UGS) has not yet been implemented. The paper aims to investigate the potential contribution of UGS in the Brazilian electricity sector via a Case Study. The economic value of UGS facilities for the power sector in Brazil is estimated, given the specificities of the Brazilian power and gas sectors. Moreover, the papers also show the need for regulation to make it possible to implement UGS to meet the Brazilian electricity sector's needs.

Although there are various alternative storage methods to UGS, such as pumped hydro storage, batteries, and hydrogen. This article focuses on UGS because it is a mature technology with characteristics interesting to complementing thermoelectric projects, such as compatible project scale and proximity to thermoelectric generation projects.

The paper is organized as follows: Section 2 presents a brief literature review regarding the UGS and economic evaluation of UGS projects; Section 3 shows Case study description; Section 4 Results of the Stochastic Net Present Value (NPV) of an UGS facility combined with the operation of the Vale Azul II Thermal Plant, Case Study; and Section 5 presents the conclusions and recommendations.

2. Review of Literature and Methods of Economic Evaluation Applied to UGS Projects

2.1. Underground Natural Gas Storage Literature

UGS is, in a simplified manner, an instrument capable of providing flexibility to markets [1,2]. Its primary function is to ensure a better balance between gas supply and demand, especially in covering the seasonal fluctuations between warm and cold seasons, as well as ensuring demand fulfillment during short-term peaks—a precautionary mechanism. However, it serves other purposes such as arbitrage, a business strategy for gas producers, energy security, and reducing electricity costs.

For managing seasonal variations, UGS is particularly important in temperate climate countries. The first documented gas storage case was in Ontario, Canada, in 1915. An already depleted natural gas reservoir was used for storage [3]. Due to the need for heating during the winter months, gas demand in homes and businesses significantly increases. Conversely, in summer, low demand leads to lower prices. If consumption shows high volatility, supply tends to be inflexible in the short term [4]. In this context, buying cheaper gas in warmer seasons and storing it for use in winter is beneficial. UGS, in this case, can be seen as a price stabilizer [1,2,5,6].

In mature and well-developed markets, underground natural gas storage can also be used for arbitrage, i.e., speculation. Arbitrage aims to purchase at lower prices and sell when the commodity is more expensive [1]. Maricic and Danilovic [7] highlight the relevance of storage for gas producers' business strategies. If the UGS investor is also involved in production, exploiting the spread favors the company. Hence, it is a mechanism that can be used for strategic price adjustments [8].

Regarding reducing electricity tariffs, UGS can be characterized as a tool that supports tariff moderation. In countries with climate seasonality, low gas demand in summer allows storage for generating electricity from thermal plants [5,9]. In the case of Brazil, with a predominantly tropical climate year-round, storage does not serve to meet seasonal demand. However, UGS can influence tariffs uniquely. The country relies primarily on hydropower generation. During rainy periods, reservoirs fill up, leading to lower electricity tariffs. Conversely, during droughts, electricity prices skyrocket. Thus, injecting gas into UGS during rainy periods for withdrawal in dry seasons results in energy security and cheaper tariffs for consumers [10]. Therefore, storage mitigates price risks.

Another function of UGS relates to energy security and service continuity. Several approaches exist in literature: (i) reducing external dependency, especially on LNG imports [11,12]; (ii) ensuring continuous energy supply during adverse situations like political conflicts, wars, infrastructure accidents, and natural disasters [8–12]; (iii) energy security associated with aiding in meeting environmental goals, as stored natural gas can act as a backup for intermittent sources like wind energy [13].

2.2. Methods of Economic Evaluation Applied to UGS Projects

Underground natural gas storage projects have two main economic characteristics. The first is the need for high initial investment volumes (CAPEX). In contrast, the second economic characteristic is the low operational costs (OPEX), concentrated during gas injections and withdrawals [10]. These projects require economies of scale to dilute fixed costs, thus resembling a natural monopoly where regulating non-discriminatory third-party access is crucial.

Ejarque [6] supports this by stating that project revenue should cover CAPEX, OPEX, and ensure fair capital remuneration via expected returns. However, Chaton et al. [2] caution against price caps as regulation, though efficient in price smoothing, could discourage storage due to reduced company financial gains with decreasing price differentials between warm and cold seasons.

However, some argue differently. Cavaliere et al. [14] disagree that UGS activities exhibit natural monopoly characteristics. Despite scale economies, competition among agents is possible. In many countries, the minimum efficient scale for underground gas storage projects is less than the total storage demand. The authors cite the UK and the Netherlands as examples of competitive UGS markets.

The evaluation of UGS projects involves numerous methodologies found in the literature. Evaluations can be intrinsic or extrinsic [4,15]. In intrinsic evaluation, the focus is on price differences due to demand fluctuations. In extrinsic evaluation, a portion of storage can be used multiple times via annual cycles. While this approach enhances project value, it is significantly more complex to evaluate. Evaluations can be economic, considering revenues and costs, or computational, based on simulation and optimization models, with Monte Carlo least squares models being a primary tool [4,16,17].

From an economic perspective, Almeida et al. [10] calculated the Net Present Value (NPV) and Internal Rate of Return (IRR) of natural gas storage in Brazil in various scenarios, finding economic value in all of them. Anyadiegwu et al. [18] and Atoyebi [19] analyzed the economic feasibility of depleted reservoirs in Nigeria using NPV with different discount rates, IRR, discounted cash flow, and pay-out, proving attractiveness even with high discount rates. Budny et al. [20] utilized Monte Carlo simulations to model risk, future electricity and gas prices, combined with NPV calculations. Escobar et al. [15] suggested using discounted cash flow for UGS project economic evaluations.

In optimization approaches, Devine and Russo [8] used stochastic mixed complementarity models to assess gas storage infrastructure projects in Ireland, potentially reducing annual gas costs by up to 2% for consumers. De Jong [4] applied Monte Carlo least squares for valuing three UGS projects in the UK. Dynamic systems models were employed by Chen et al [11] in the Chinese storage market. Qiao et al [9], using linear programming, indicated that gas storage could reduce EU electricity production costs by up to 40% in scenarios of supply scarcity and high spot market prices. Finally, Bjerksund et al [21] used Monte Carlo simulations combined with repeated intrinsic value maximization rules for UGS project valuation.

3. Case Study

On December 20, 2017, an auction was held in which, in addition to wind power, gas-fired power plants stood out in the A-6 auction. Two thermal projects were winners and will be built in Rio de Janeiro, with investments of R$4.7 billion, according to information released by the Chamber of Electric Energy Commercialization. The largest project is GNA Porto do Açu III, by Prumo Logística, which will have an installed capacity of 1,672.6 MW and will require investments of R$3.432 billion. The plant sold 1,450 MW average in the auction for R$213.91/MWh.

The other project is the Vale Azul II thermal plant, belonging to the Marlim Azul consortium, composed of Vale Azul Energia and Mitsubishi Hitachi Power Systems. The plant will have 466.3 MW of installed capacity and sold 420.9 MW in the auction for R$211.90/MWh. Shell is in exclusive negotiations for the supply of natural gas to the unit. This thermal plant has a low unit variable cost and should operate in the base load, coming into operation in November 2023.

3.1. Feasibility Study of an UGS Installation Combined with the Vale Azul II Thermal Plant

The inflexible volume declared by the Vale Azul II Project (1.85 MMm^3/day, from November to April) will serve as a premise for the feasibility study of a UGS installation, which will have its storage capacity contracted and managed by the Brazilian power sector. It should be anticipated that an imperfect proxy is being adopted, but with the numbers based on data from a Real Case Study, A-6 Auction (12/20/17).

It is important to highlight that the declared Unit Variable Cost (CVU) includes the cost of natural gas made available to the thermal plants, with flexible character, including taxes and all other charges. On the other hand, the author assumes that the investors of the thermal plants in the ACR Auctions include part of the fuel costs (natural gas), of a flexible nature, in their fixed revenues (RF).

Finally, with the guidelines proposed in the A-6 auction of 12/20/17, which established inflexibility of up to 50% throughout the year for gas-fired thermal plants, the Vale Azul II Project (declared inflexibility in the rainy season) practically made the operation of the enterprises in the base load viable, due to the declared CVUs and having been a very competitive bidding strategy in the auction.

The present Case Study seeks to evaluate whether there would be economic value for the Brazilian power sector to have UGS capacity.

UGS could represent for the Brazilian power sector a new energy storage capacity, similar to the storage of hydroelectric reservoirs. This integration would occur in a way to increase the flexibility of thermal dispatch for the power system and, at the same time, preserve the purchase of a minimum gas flow by the thermal plants. In conceptual terms, once the hydroelectric and thermal plants are dispatched and their respective amounts are defined each week by the National System Operator - ONS, the following strategy would be possible:

- In adverse scenarios of reservoirs and/or rainfall indices, the ONS requests the dispatch of a large number of natural gas-fired thermal plants instead of hydroelectric ones, with the natural gas price priced at the LNG spot market.

  Therefore, the following hypothetical operating

- Once the ONS (National Electric System Operator) has defined which hydroelectric and thermal plants will be dispatched and their respective amounts each week, the following strategy could be adopted:

During favorable reservoir and rainfall periods, natural gas volumes already contracted for the Vale Azul II thermal plant, which declares itself inflexible from November to April, would not be directed to the plant. Instead, these volumes of natural gas could be injected into UGS facilities.

IMPORTANT: Note that the cost of this gas will be paid by the electricity sector in the Fixed Revenue (RF) declared by the Vale Azul II thermal plant.

On the other hand, during adverse reservoir and/or rainfall periods, the ONS would request the withdrawal of natural gas stored in the UGS to supply the thermal plants due to the increased dispatch of this type of plant, resulting in less liquefied natural gas (LNG) importation. In other words, the cost of this gas withdrawn from the UGS would have the same value as the cost of importing LNG.

IMPORTANT: Note that the actual cost of this gas withdrawn from the UGS has already been paid by the electricity sector previously (gas stored from inflexible thermal plants during favorable rainfall periods).

It is worth noting that the LNG regasification terminals, which are currently already implemented in Brazil and priced in spot loads, serve as a flexibility tool for the natural gas supply.

3.2. Assumptions for the Technical and Economic Feasibility Study of an Underground Natural Gas Storage (UGS) Facility Combined with the Operation of the Vale Azul II Thermal Plant

3.2.1. Assumptions for the Economic Feasibility Study

The next step would be to calculate the potential economic value for the Brazilian electricity sector if an underground natural gas storage capacity were made available in Brazil. To do so, the following assumptions in **Table 1** were adopted.

Table 1. Assumptions adopted.

Assumptions	Value	Obs.
CAPEX – Investment (US$ MM)	231	Working Gas * 0,385US$/m³ Source: INFRASTRUCTURE UNIT INVESTMENT COST=GAS (20-07-2015) from Agency for Cooperation of Energy Regulators (UE).
OPEX – Injection and Withdrawal Cost (US$ per m³)	0.01725	(International Gas Union, 2000; Goraeib et al., 2005b).
Cushion Gas Volume to be Injected (MMm³)	0	Depleted Fields (Assuming no gas injection is required for Cushion Gas formation).
Working Gas Volume to be Injected (MMm³)	600	Adopted volume.
PLD value that defines natural gas injection (R$/MWh)	< or = 45	Important: The PLD prices (electricity spot price in Brazil), month by month, were defined by the spreadsheet "CMO A4-A6-2017", made available for the auction with 2000 scenarios, for the period 2022 to 2026, which was repeated for the periods 2027–2031; 2032–2036 and 2037–2041.
PLD value that defines natural gas withdrawal (R$/MWh)	> or = 250	Important: The PLD prices (electricity spot price in Brazil), month by month, were defined by the spreadsheet "CMO A4-A6-2017", made available for the auction with 2000 scenarios, for the period 2022 to 2026, which was repeated for the periods 2027–2031; 2032–2036 and 2037–2041.
Injection and Withdrawal Capacity (MMm³/day)	1.85	Declared inflexibility volume by Power Plant from natural gas – Vale Azul II (from November to April).
Inflexible Demand of Power Plants (MMm³/day)	1.85	Maximum adopted value.
Value of inflexible gas already paid by the electricity sector, from November to April (US$ per mmbtu)	0	Paid by the Fixed Revenue (RF) declared by Power Plant – Vale Azul II.

Table 1. *Cont.*

Assumptions	Value	Obs.
Total Cost per GN injected in UGS (Natural Gas US$ per mmbtu) Additional Generated Electric Energy (R$ MWh based on monthly PLD)	Injection Cost + EE = Monthly PLD	Total Cost per GN injected in UGS = US$0 per mmbtu for the volume of natural gas injected in UGS (the volume of GN is already paid through the RF of the Térmica – inflexible portion); plus the additional cost of generating electric energy, through hydroelectric plants, which will be priced based on the Monthly Energy Cost of PLD per MWh, converted to US$, plus the cost of injecting GN in UGS (Opex).
Pricing of Natural Gas withdrawn from UGS (US$ per mmbtu)	Imported LNG value from the period	For Economic Feasibility Study, three fixed price scenarios were evaluated for the entire period: 6US$/mmbtu; 8US$/mmbtu and 10US$/mmbtu.
Restrictions on electricity flow and natural gas movement	There are no restrictions, except for injections and withdrawals of natural gas from UGS limited to a maximum of 1.85 m^3/day	
USD/BRL exchange rate	5,559 BRL	Fixed for the entire period of EVTE – (Source: Central Bank – 14/07/2025 - https://www.bcb.gov.br/conversao).
Discounted Cash Flow Evaluation Period of UGS	2022 a 2041	Discounted Cash Flow Evaluation Period of UGS from 2022 to 2041.

3.3. Method and Equations for Calculating the Technical and Economic Feasibility Study UGS Facility Combined with the Operation of Vale Azul II Thermal Plant

Step 1: CMO provided for the public auction (60 months of marginal operating cost (CMO) in 2,000 series)

$$\text{CMOxy}$$

CMO = Marginal Operating Cost provided in the public auction, where x = 60 months and y = 2000 series (on December 20, 2017)

Step 2: Injection (Volumes and Costs)

$\text{Injection(ij)} = \text{IF}(\left(\text{WorGas storage(ij)} < 600\ \text{MMm}^3\text{; and; CMO(xy)} \leq \text{R\$}\frac{45{,}00}{\text{MWH}}\right);$

$\text{then Injection (ij)} = 1.85\ \text{MMm}^3 \times 30\ \text{days})$

$\text{Opex inj (ij)} = \text{Injection(ij)} \times \text{US\$0.015/m}^3\ \text{(injected)}$

(Opex: US$ MM)

$\text{Energ Generated to Injection (ij)} = \text{IF}\left(\text{CMO(xy)} \leq \text{R\$}\frac{45{,}00}{\text{MWH}}\right);$

$\text{then Themal Power} \times 24 \times 30\text{; if not} = 0$

$\text{Cost of Energ Generated to Injection (ij)} = \text{SE}(\left(\text{WorGas Storage(ij)} < 600\ \text{MMm}^3\right);$

$\text{then CMO(xy)} * \frac{\text{(Energ Generated to Injection)}}{\text{Exchange}=\frac{\text{US\$}}{\text{R\$}} \times 1000000}$

[Cost of Energy Generated considering the Injection of Natural Gas in the UGS (US$ MM)]

Step 3: Gas Withdraw from the UGS

$\text{Withdraw (ij)} = \text{IF}\left(\text{WorGas Storage(ij)} > 0;\ \text{AND;}\ \text{CMO(xy)} \geq \text{R\$}\frac{250}{\text{MWH}}\right);$

$\text{then Withdraw (ij)} = 1.85\ \text{MM} \times 30\ \text{days})$

$\text{Value of withdraw gas (ij)} = \text{Withdraw gas(ij)} * 0.036 * \text{LNG value fixed}$

(Withdraw gas - US$ MM)

$\text{Opex Withdraw gas(ij)} = \text{Withdraw(ij)} * 0.01725/\text{m}^3$

[Opex Withdraw de gas (US$ MM)]

Step 4: Working Gas Stored

$\text{Working Gas Storage(ij)}$
$= \text{IF (Injection(i + 1,j + 1) + Working Gas Storage(i,j)}$
$< 600\ \text{MM;}\ \text{AND;}\ \text{InjGN(i + 1,j + 1) + Working Gas Storage(i,j)}$
$-\text{Withdraw(i + 1,j + 1)} > 0);\ \text{then Working Gas Storage (i + 1,j + 1)}$
$= \text{Injection (i + 1, j + 1) + Working Gas Storage (i,j) - Withdraw (i + 1,j + 1);}$
$\text{IF (InjGN(i + 1,j + 1) + Working Gas Storage(i,j) - Withdraw (i + 1,j + 1)} \leq 0);$
$\text{then Working Gas Storage(i + 1,j + 1)} = 0;$

Ifnot; Working Gas Storage (i + 1,y + 1) = 600 MM

Step 5: Calculation of Stochastic Cash Flow and Stochastic Technical and Economic Feasibility Study (NPV)

Cash Flow(i,j)= Capex + Value of withdraw gas — Opex Withdraw gas(ij) — Opex inj (ij) — Cost of Energ Generated to Injection (ij)

$$\text{NPV(i,j)} = \text{CAPEX} + \sum_{1}^{240} \text{Cash Flow(i,j)}$$

Obs. NPV(i,j) Calculated by replicating the CMO (60 months) to (240 months – 20 years)

Average NPV = $\sum_{1}^{j} \frac{\text{NPV(ij)}}{2000}$

4. Results of the Stochastic NPV of an (UGS) Facility Combined with the Operation of the Vale Azul II Thermal Plant

Based on the assumptions adopted in the **Table 1**, the following histogram of the NPV is presented in the **Figure 4** for the two thousand scenarios, as well as the expected average value for the NPV; with LNG and priced exchange rate, for the entire period (2022 to 2041) at 8US$/MM and the exchange rate 1US$ = 5.599R$ (Source: Central Bank; 07-14-2025).

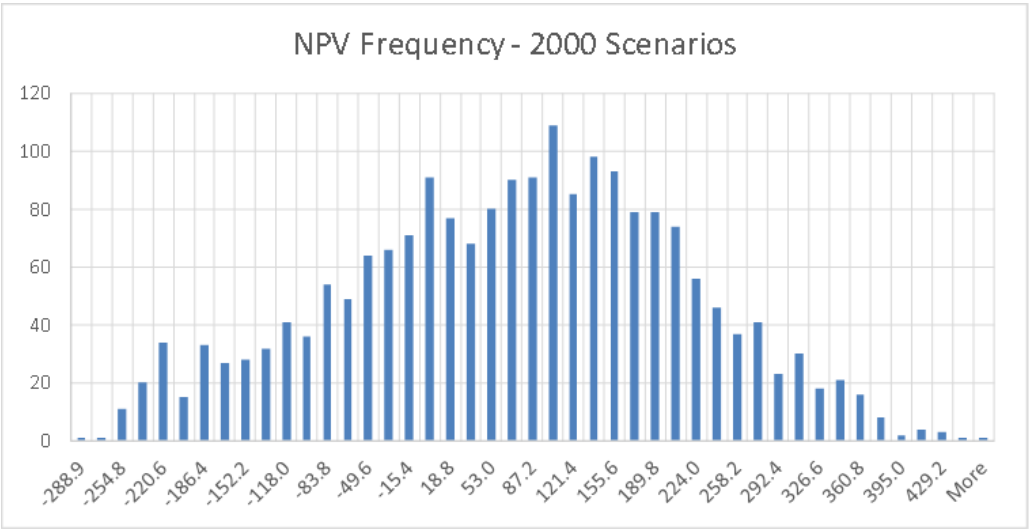

Figure 4. Frequency of NPV values (MM US$) - 2000 Scenarios.

Note: Average NPV = US$ 65.60 Million.

Aiming to evaluate the economic results found (NPVs) of the Availability EVTE for UGS to meet the Brazilian electric sector, the following sensitivity analysis of the variables with the greatest weight in the EVTE results will be presented, varying the CAPEX of the UGS facilities and the reference price of LNG adopted for the entire period (2022 to 2041).

For CAPEX, the estimated value for an installation with 600 million m^3 of useful gas (working gas) would be around US$231 MM (**Table 2**). Thus, the expected average NPV indicators were calculated for a variation of 50% more and less.

Table 2. Sensitivity analysis for UGS CAPEX (US$ MM) with LNG at US$ 8.00/MMBTU (for the entire period).

Variation	CAPEX (MM US$)	Expected average NPV (MM US$)
50%	346.5	–49.9
0%	231	65.6
–50%	115.5	181.1

For LNG, the estimated value was US$8/MMBTU of NG for the entire UGS period (**Table 3**). Thus, NPV indicators were calculated for a LNG price variation of 25% more and less.

Table 3. Sensitivity analysis for LNG for the period (US$ per MMBTU) with CAPEX at US$ 231 MM (for the entire period).

Variation	LNG (US$ per MMBTU)	Expected average NPV (MM US$)
25%	10	153.51
0%	8	65.6
−25%	6	−22.32

Therefore, based on the sensitivity analysis, both for CAPEX and LNG, it is still validated that the availability of capacity for UGS, under certain assumptions, can have economic value for the Brazilian electric sector.

4.1. Case Study Results (Update Sensitivity)

The Case Study presented an economic value calculation for the electric sector to have this type of installation, which was shown to be positive under certain assumptions. Therefore, there is evidence that there may be economic value for the Brazilian electric sector to have this type of installation. **Figures 5** and **6**, based on the sensitivity analyses for UGS CAPEX and spot LNG price (with all other parameters remaining fixed over the period), presented in Section 4 of the Case Study, show the possibility of there being economic value for the Brazilian electric sector to have this type of installation.

It should be highlighted that the use of UGSs, in the Brazilian case, also involves an attempt to create better conditions for predicting the dispatch of thermal plants and their respective demands for natural gas, as well as a specific regulatory framework for the application of UGS.

Thus, the Case Study suggests the strategy of evaluating the "trade-off" between offers in future natural gas thermal plant auctions, specifically between offers for plants without "take or pay" versus offers for plants with "take or pay" (between 30% to 60%), combined with the installation of UGS facilities, whose injection/withdrawal management would be the responsibility of the National Operator System (ONS).

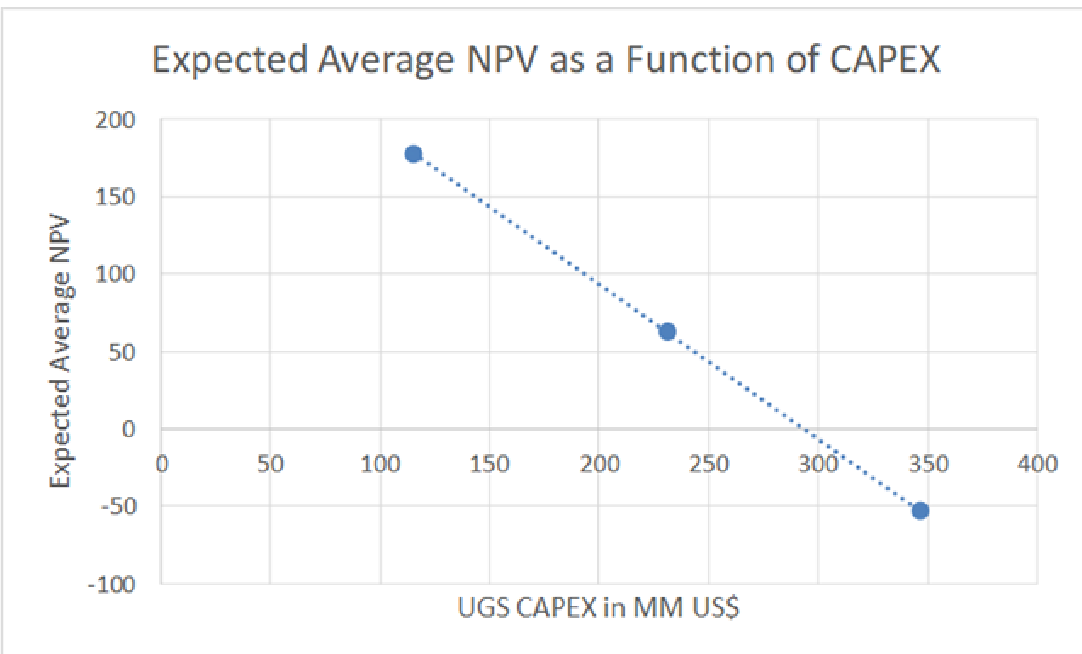

Figure 5. Expected Average NPV as a Function of CAPEX.

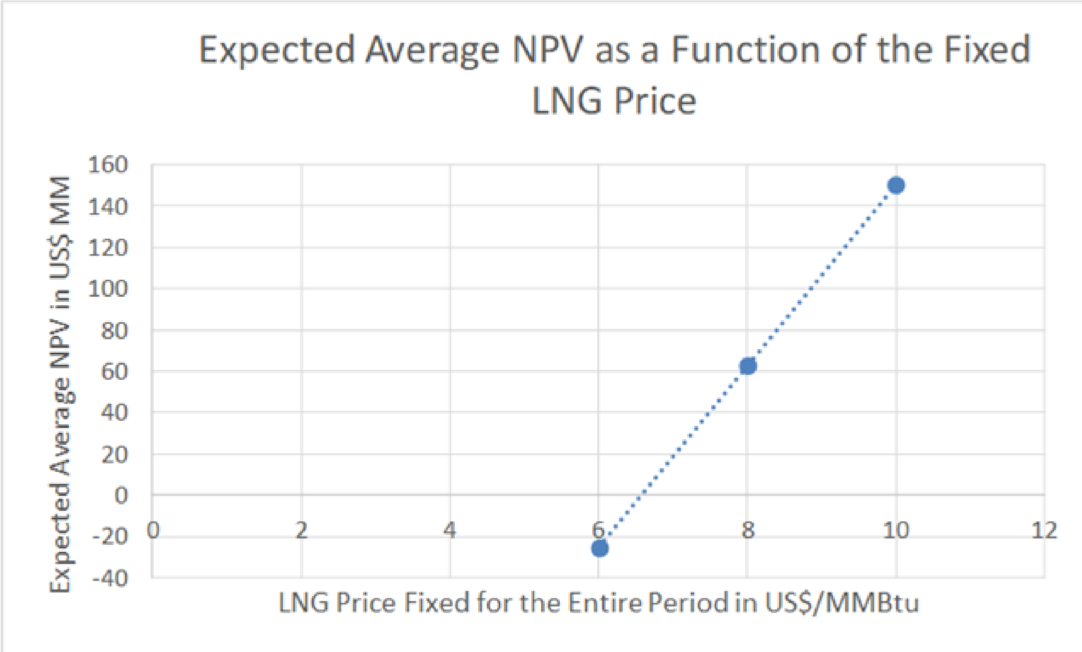

Figure 6. Expected Average NPV as a Function of the Fixed LNG Price.

4.2. ONS (Brazilian ISO) Strategy to Calculate the Economic Value for the Brazilian Power Sector to Have Access to UGS

The ONS could calculate the economic value for the Brazilian power sector to have access to UGS capacity through a simulation of the hydrothermal system with a stochastic dispatch model of the electrical system that also represents UGSs as a resource.

The simulation could consist of two stages, namely:

1. Hydrothermal dispatch of the National Interconnected System (SIN) representing Take or Pay as operational inflexibility and without the possibility of gas storage: representing the operation as it is currently done (optimization of hydroelectric reservoirs only);
2. Hydrothermal dispatch of the SIN, allowing Take or Pay to be stored in the gas reservoir: representation of how the operation can be performed with the possibility of gas storage (optimization of hydroelectric reservoirs together with gas reservoirs).

As a result, it is possible to compare the expected reduction in operating costs with the investment in UGS, in order to obtain the economic benefit of its implementation.

As a suggestion for future studies, it is proposed to evaluate probabilistic simulations of the hydrothermal system operation over a predefined period in order to measure the economic benefit (in terms of operating cost reduction) when implementing UGSs. These benefits would then be compared with the costs of UGS construction and objectively verified to determine if this alternative is economical or not.

Finally, once the economic value of the electricity sector to have this type of installation is verified, the next challenge would be to create a specific economic regulation to allow the implementation of UGSs in Brazil, adapted to our conditions.

4.3. Limitations and Suggestions for Improvement

The article focused on the application of UGS to support the natural gas-fired thermoelectric market segment due to its high seasonality and complementarity to the Brazilian hydroelectric park.

However, other possible applications for UGS were not addressed in the article due to the current stage of the natural gas industry in Brazil. In future studies, it would be interesting to evaluate the potential for synergy among the various possible applications of UGS, as a suggestion to enhance the topic and its applications in Brazil.

5. Conclusions

This paper concludes that the applicability of UGS for the Brazilian market will differ from that in the North American market. This is because the natural gas market in Brazil does not show a seasonal demand behavior, but rather a random character associated with the demand of the thermoelectric segment, which is complementary to the national hydroelectric generation.

The section 4 of this article presents a case study calculation of an economic value for the electricity sector to have this type of installation (UGS), which proved positive under certain assumptions. Therefore, there is evidence that there may be economic value for the Brazilian electricity sector to have this type of installation. Additionally, the article also concludes that the applicability of UGS for the Brazilian electricity market will not be viable through a Perfect Competition Markets model, in function of thermoelectric dispatch random behavior.

Therefore, the article advocates for the need for regulation to enable the implementation of UGS to meet the Brazilian electricity sector's needs. Finally, as final considerations, it should be mentioned that the maturity level of the industry is of great relevance for a nation to define the next steps to follow in the development of these two important and strategic industries, which are the Natural Gas and Electricity Industries.

However, another concept, not yet discussed in this article, deserves reflection and should be combined with those mentioned above when defining the new steps of these industries: the concept of energy security. The concept of energy security is inseparable from the commercialization of natural gas and electricity. With the advent of energy integration presenting itself as a possible evolution in the Southern Cone of South America (especially Brazil, Bolivia, and Argentina), this theme gains even more dimension. The case of the Brazil-Bolivia gas pipeline (GASBOL) illustrates the importance of the concept of energy security.

Thus, the definition of a regulatory model for the natural gas industry in Brazil, in addition to being conditioned by energy policy and macroeconomic objectives, must take energy security into account, given the increase in energy integration.

Therefore, when there is a possible implementation of an economic regulation aiming to provide Underground Natural Gas Storage capacity for the Brazilian electricity sector, the energy security perspective presents itself as a tendency to be contemplated as well, in an economic regulation design.

Just to illustrate, it is worth mentioning that in Europe its regulation provides for a volume called Strategic Reserves—Minimum Security Stocks: To illustrate, specifically in Spain, the Strategic Reserves provides for the total usable capacity of UGS, it must be reserved a volume equivalent to 20 days of sales or consumption per month (without interruptions) in the previous year, carried out by retailers. In this way, it is considered a trend that the Brazilian State should contemplate the energy security theme as part of the volumes to be stored in future UGS in Brazil.

Finally, given the ongoing expansion of wind and solar energy worldwide, alongside their inherent intermittency, this approach can serve as a reference to evaluate the potential economic value for UGS even in countries with predominantly thermal electrical generation matrices.

Author Contributions

Conceptualization: J.R.U.C.A.; Methodology: J.R.U.C.A.; Validation: E.d.A., F.R. and L.L.; Formal analysis: J.R.U.C.A., E.d.A. and L.L.; Investigation: J.R.U.C.A., E.d.A., F.R. and L.L.; Data curation: L.L.; Writing—original draft preparation: J.R.U.C.A., E.d.A., F.R. and L.L.; Writing—review and editing: J.R.U.C.A., E.d.A., F.R. and L.L.; Visualization: J.R.U.C.A., E.d.A., F.R. and L.L.; Supervision: J.R.U.C.A. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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