# Simulation Model of Natural Gas Demand for Contracting Decision in High Thermal Dispatch Scenarios

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**Abstract.** In Brazil, there is a volatile demand for natural gas, especially due to the characteristics of the energy matrix highly dependent on water resources. Furthermore, with most associated gas fields, in which oil and gas production occurs simultaneously, new production projects prioritise firm demand, with gas imported by pipelines or liquefied natural gas to meet thermoelectric demand in high dispatch scenarios. In this article, an analysis of the demand for natural gas in Brazil was made using a static simulation model. The analysis serves as the basis for the decision to contract a liquefied natural gas supply ship, mitigating the supply risk and generating energy security.

**Keywords:** Natural gas, Simulation, Oil & Gas, Balance of supply and demand.

## 1 Introduction

Natural gas is a substance composed of hydrocarbons that remain in a gaseous state under normal atmospheric conditions. This can be classified into two categories: associate and non-associated. The associated gas is one that, in the geological reservoir, is dissolved in oil or takes the form of a gas cover. In this case, the initial production of the oil is usually favoured, using the gas to maintain the pressure of the reservoir. On the other hand, non-associated gas is free of oil and water in the reservoir; its concentration is predominant in the rocky layer. Once produced, natural gas is distributed among several sectors of consumption for energy purposes. The main sectors are the generation of thermoelectric energy, vehicular, trade, services, and households, and non-energy, used as raw material in the petrochemical and fertiliser industries [1].

The natural gas industry is an example of a network industry characterised by distinct but interconnected activities. Figure 1 illustrates, in a simplified way, the stages of the natural gas chain.

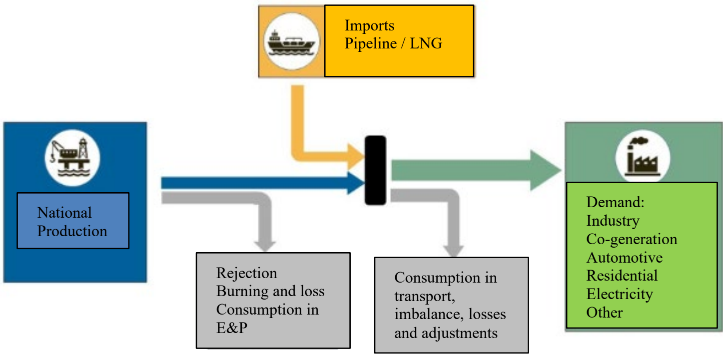


Fig. 1 – Natural Gas Flow Balance in Brazil
Source: Ministry of Mines and Energy – https://www.gov.br/mme/pt-br.

In this chain, the agents involved are (i) importers or producers of gas, (ii) transporters, (iii) local distribution companies and (iv) final consumers, including domestic, industrial and thermoelectric markets. Brazil is a country producing and importing natural gas, with its main sources being the national supply (associated and non-associated) and imported gas (pipelines and Liquefied Natural Gas – LNG).

Brazil has considerable remaining natural gas resources but needs more infrastructure to monetise them. Furthermore, when most of the natural gas extraction derives from associated gas, this results in high reinjection rates in production fields combined with fuel imports to deal with an increasingly variable demand [2].

Brazil presents a trade-off between the electricity and gas sectors in that, while the electricity sector needs flexible gas to supply thermoelectric plants in periods of unfavourable hydrology, the gas sector prefers an inflexible gas demand to pay its costs, which are mainly fixed and ensures oil production is optimised [3].More recently, LNG started to be considered an option to ensure the adequacy of natural gas supply for power generation. Brazil is one of the countries leading the process of implementing regasification facilities in Latin America [4]. Regasification in Latin America is well documented in countries like Argentina [5,6], Chile [6], and Colombia [7]. Moreover, it has been under the attention of major petroleum companies such as Shell for decades [8].

The implementation of the LNG terminals in the Bay of Guanabara, in the State of Rio de Janeiro, and the port of “Pecém”, in the State of Ceará are considered the best technical and economical solution to make the supply of gas flexible for the markets of thermal and non-thermal generation of energy. Furthermore, the supply of LNG permits modulating the purchase according to demand. As a result, the Brazilian natural gas market has the potential to expand. It is characterised by a flexible demand associated with the generation of electricity and by a stable demand represented by industry, transport, and residential uses [9].

This paper will evaluate whether the inventories of two LNG supply ships connected to the regasification terminals are sufficient to meet the natural gas demand of a large Brazilian oil & gas company in high dispatch scenarios, based on the simulated data of the four segments: non-thermal (distributors), refining, fertiliser and thermal.

# 2 Analysis of the Balance of Demand and Supply in Brazil

The next section will analyse the balance of supply and demand of natural gas in Brazil to elaborate on the static simulation model and the analysis of LNG stocks to mitigate the risks of supply failure.

## 2.1 Gas supply

About 86% of Brazilian natural gas production is associated with oil, and 84% has offshore origin [10]. Thus, the national supply, most of the natural gas reserves associated with oil reserves, implies the need for production and consumption to occur regularly and coordinated so as not to harm oil production. Much of the national production does not even reach the market since it is directed to the oil production itself, which is the main product that guarantees the project's economic viability. The investment costs in these projects amount to billions of dollars, comprising production systems, wells and production and injection equipment (terrestrial and subsea).

The Monthly Bulletin for Monitoring the Natural Gas Industry [11], September 2022 edition, shows that in Brazil, from October 2021 to September 2022, of the total production of 136 million m³/day, about 67 million m³/day of natural gas was reinjected, 14.5 million m³/day of gas were consumed in exploration and production (E&P) activities, 3.5 million were losses and burning in the producing units, and 4 million m³/day of gas were converted into other products (such as liquified petroleum gas - LPG - and other natural gas liquids) in the treatment process, leaving a national supply of approximately 47 million m³/day of gas. Among the imported gas offerings, an average of 17 million m³/day of gas came from Bolivia and 8 million m³/day of liquefied natural gas (LNG) from various parts of the world. A new agreement between Bolivia and Brazil establishes a maximum annual average of 20 million m³/day of natural gas [12]. In the face of the drop in Bolivian gas imports to Brazil, the agreement between supply and demand is carried out by LNG.

The LNG regasification terminals connected to the pipeline network are located in Rio de Janeiro (Guanabara Bay Terminal), Bahia (Todos os Santos Terminal) and Ceará ("Pecém") [12]. However, in the case of "Pecém", due to the transport network that has bottlenecks between the stretch called "Nordestão" and "GASFOR", this terminal ends up being used exclusively to serve thermal plants in the region and, for this reason, in this article, only the terminals of Bahia and Rio de Janeiro will be considered.

The flexible LNG terminals have a floating wharf with the capability to receive a supply ship on one side and a regasification ship on the other [9]. Both terminals are considered to have a regasification capacity of 20 million m³/day of gas, and each has a supply ship with around 90 million cubic meters of gas capacity. In addition, the average replacement time of a supply ship can be estimated at thirty days.

## 2.2 Gas demand

The gas market began to gain more relevance in Brazil with the construction of the Bolivia-Brazil Gas Pipeline at the beginning of the 2000s. Furthermore, with initiatives such as the Priority Thermoelectricity Program (PPT), the anchor demand for natural gas in large thermoelectric plants helped considerably expand the pipeline network in this period. Since then, the gas market in Brazil has been developing with new offshore gas flow routes and the implementation of LNG regasification terminals along the coast. While domestic production and gas imported from Bolivia had the main consumption profile to meet the firm demands, the LNG terminals brought flexibility to supply with short-term and flexible contracts, ideal for dynamic thermal power dispatches in the country [13].

The National Electric System Operator (ONS) is responsible for dispatching thermal power plants on the order of merit, intending to meet the market safely and at the lowest possible operating cost [14]. That is, the dispatch order considers thermal plants with a variable unit cost lower than the marginal cost of operation. In this sense, the marginal cost of the operation, the basis for the formation of the Settlement Price of Differences, is the cost of serving an additional unit of load, that is, for the production of one additional Megawatt-hour (MWh). Therefore, the dispatch order is valid for one specific period, and these thermal plants' dispatch determine the price of power generation during that period [14].

According to the Settlement Price of Differences logic, only plants that had the lowest values should receive the dispatch order; however, either by physical restriction by the absence of connection of the power plant to the power grid or even by strategic decision of the National Electric System Operator (ONS – from the Brazilian acronym), thermal plants may not be ready to be dispatched. Then, other plants come into replacement, even if they have a higher cost of power generation than that determined by the Settlement Price of Differences and are therefore outside the merit order [14]. In the energy industry, the term 'merit order' describes the sequence in which power plants are designated to deliver power to optimise the electricity supply economically. The merit order is based on the lowest marginal costs.

Due to the predominance of hydroelectric plants in generating national electricity, thermal sources are necessary to meet the demand during climatic adversity [15]. In 2021, hydroelectric plants accounted for 56.8% of the Brazilian electricity matrix, while natural gas came in second with 12.8%, followed by wind energy with 10.6% [16].

Natural gas storage is technically viable and would be a way of balancing inflexible supply and volatile demand. There are three major types of natural gas storage facilities: a) underground storages (depleted gas/oil fields, salt caverns and aquifers), b) LNG tanks and c) pipelines (the amount of gas contained in the pipes is called "line-pack" and can be controlled raising and lowering the pressure). These storage facilities are different in terms of capacity (working volume) and maximum withdrawal rates [17]. Brazil still lacks the geological or underground storage facilities to support its rapidly expanding gas industry, as well as important tools for meeting fluctuating demand and production and improving supply security [18]. This would be a physical approach to optimise the relationship between the electricity and gas sectors with a relatively low-cost impact on the gas value chain [3]. Thus, exercising the function of the balance between supply and demand, in Brazil market we have (i) the pipelines that integrate transport logistics, (ii) the LNG supply ships connected to the regasification terminals and (iii) the flexibility to modulate the national production with import from Bolivia. In the new context of multiple agents accessing the transport network, the pipeline imbalance is not tolerable; on the contrary, the shipping companies are penalised for such conduct.

The operational and commercial flexibilities that allow market service is used in low-demand scenarios. In the opposite scenario of high demand, where LNG is necessary to meet the market connected to the integrated network, embedded LNG is used.

Flexible asset as Floating Storage and Regasification Units (FSRU) can be relocated to meet seasonal demands due to the lack of rainfall for the hydroelectric power plants, as it occurs in Brazil. FSRU storage capacities of typically 135,000 – 173,000 $m^3$ do not provide sufficient buffer storage for delivery by 173,000 $m^3$ tankers. This may require the tanker to wait until sufficient capacity is available in the FSRU and incurring demurrage charges [19]. LNG cooled to about -160°C has a volume about 600 times lower than natural gas under normal temperature and pressure conditions. Therefore, it can be transferred to a relief ship via offloading for its sale to the consumer market [13]. Therefore, i.e., a 175,000 $m^3$ of LNG ship corresponds to approximately 90 million cubic meters of natural gas.

EPE projections predict an increase in demand of 25 million $m^3$/day by 2032, with the total demand for the integrated mesh reaching 126 million $m^3$/day [12] ]. Considering these patamars of volumes and the characteristics of gas supply in Brazil, logistics alternatives for supply and demand balance become even more essential.

## 3 Simulation Model

### 3.1 Demand Modelling

Starting with the analysis of natural gas, the authors had access to the database of a large Brazilian oil & gas company that sells natural gas to the four segments object of this study: non-thermal, refining, fertiliser and thermal. The database comprises the period between January 2012 and October 2022. It is a database with monthly daily averages, that is, average demand for each day in the month, totalling 6,240 data, which were grouped in the four study segments. Data from months without value were excluded from the analysis.

Figure 2 presents the demand distributions for each segment. The Kolmogorov-Smirnov test demonstrates good adherence, with a p-value greater than 0.05, for the distribution models for the four segments of non-thermal, refining, fertiliser and thermal demand. Because of this, the monthly data between 2012 and 2022 was used for the simulation model.

### 3.2 Generation of Demand-by-Simulation scenarios

Based on the parameters of the distributions of the demand data for each segment, new random scenarios were simulated in the *Input Analyzer*. Then, 300 random values were generated for each demand segment to evaluate the offers.

### 3.3 Evaluation of the storage capacity of regasification vessels to meet the demand

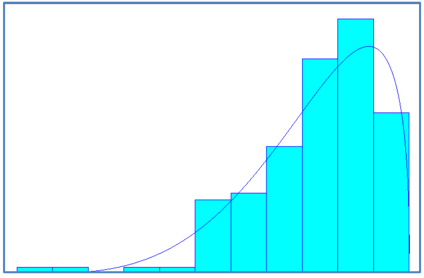
Fixed supply values were used to meet the simulated demand scenarios, as shown in Table 1 below. On the supply side, inventory variations, operational and extraordinary losses and gas consumption of the gas use of the pipeline network system were not considered.

**Table 1.** Capacities of natural gas per supply source in Brazil.

| Supply source | The capacity of natural gas |
|---|---|
| National | 47 million cubic meters per day (MM cm/d) |
| Bolivian | 20 million cubic meters per day (MM cm/d) |
| LNG regasification | 40 million cubic meters per day (MM cm/d) |
| Supply Ship | 180 million cubic meters (MM cm/d) |

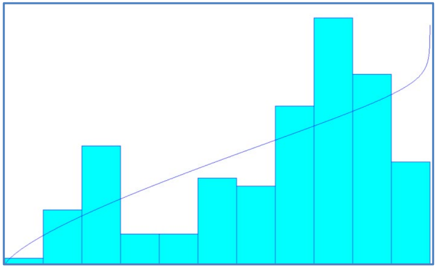
The evaluation considered three scenarios of replacement of LNG supply ships, and the frequency of arrivals and the number of ships being received simultaneously were varied, as detailed in Table 2.

a)



Non-thermal demand.
Distribution: Beta
Expression: 2.57e+04 + 1.51e+04 * BETA(4.5, 1.41)
Quadratic error: 0.004385
Kolmogorov-Smirnov Test
Statistic Test = 0.0639
P-value > 0.15

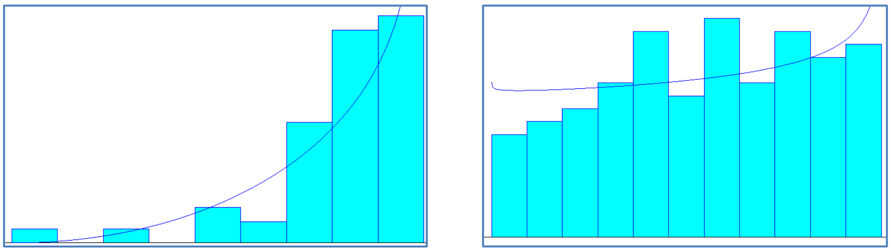
b)



Refine demand.
Distribution: Beta
Expression: 8.26e+03 + 6.01e+03 * BETA(1.71, 0.96)
Quadratic error: 0.023474
Kolmogorov-Smirnov Test
Statistic Test = 0.0978
P-value = 0.131

c)

d)



Fertiliser demand.
Distribution: Beta
Expression: 834 + 1.93e+03 * BETA(2.99, 0.745)
Quadratic error: 0.026484
Kolmogorov-Smirnov test
Statistical Test = 0.129
Corresponding P-value = 0.0895

Thermal demand.
Distribution: Beta
Expression: 6.91e+03 + 3.42e+04 * BETA(0.99, 0.861)
Quadratic error: 0.003795
Kolmogorov-Smirnov Test
Statistic Test = 0.0617
P-value > 0.15

Fig. 2. Probability distributions of the demands: a) non-thermal; b) refine; c) fertiliser; d) thermal

**Table 2.** Capacities of natural gas per supply source in Brazil.

| Scenery | Charging frequency | Number of ships | Charging capacity |
|---|---|---|---|
| Base case | Monthly | Two | 180 million cubic meters (MM cm/d) |
| Sensitivity #1 | Every ten days | One | 90 million cubic meters (MM cm/d) |
| Sensitivity #2 | Weekly | One | 90 million cubic meters (MM cm/d) |

The profile of the simulated demand for gas in an integrated gas pipeline network by market segment is presented in Figure 3. For each data simulated by market segment, it was considered the demand of a given day, thus totalling a simulation period of 300 days.

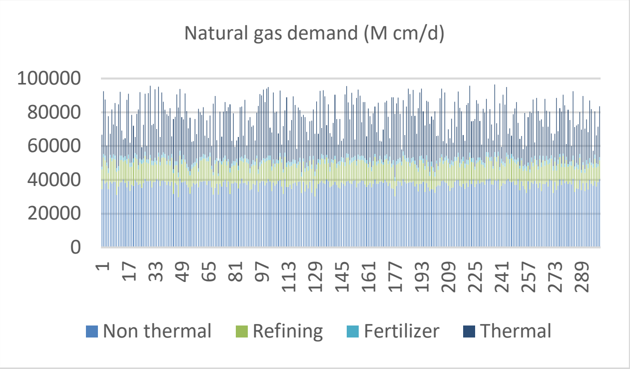


Fig. 3. Natural gas demand in the integrated network by market segment

Based on the simulated data, the service capacity was evaluated by considering the supply sources and the ships' stock. Table 3 presents an example of the balance made with the simulation of the demand for thirty-one consecutive days.

**Table 3.** Balance of supply and demand

| Day | Demand (M cm/d) | Offers | | | LNG ships | | | Failures (0-no or 1-yes) |
|---|---|---|---|---|---|---|---|---|
| | | National (M cm/d) | Bolivia (M cm/d) | LNG (M cm/d) | Initial stock (M cm/d) | Final stock (M cm/d) | Additional charge | |
| 1 | 66659 | 47000 | 1965 | 0 | 180000 | 180000 | 2 | 0 |
| 2 | 92411 | 47000 | 20000 | 25411 | 180000 | 154589 | 0 | 0 |
| 3 | 87572 | 47000 | 20000 | 2057 | 154589 | 134017 | 0 | 0 |
| 4 | 60287 | 47000 | 13287 | 0 | 134017 | 134017 | 0 | 0 |
| 5 | 77664 | 47000 | 20000 | 10664 | 134017 | 123353 | 0 | 0 |
| 6 | 67371 | 47000 | 20000 | 370.7 | 123353 | 122982 | 0 | 0 |
| 7 | 81772 | 47000 | 20000 | 14772 | 122982 | 108210 | 0 | 0 |
| 8 | 72803 | 47000 | 20000 | 5802,7 | 108210 | 102408 | 0 | 0 |
| 9 | 85462 | 47000 | 20000 | 18462 | 102408 | 83946 | 0 | 0 |
| 10 | 71850 | 47000 | 20000 | 4850 | 83946 | 79096 | 0 | 0 |
| 11 | 84773 | 47000 | 20000 | 1777 | 79096 | 61322 | 0 | 0 |
| 12 | 92046 | 47000 | 20000 | 25046 | 61322 | 36277 | 0 | 0 |
| 13 | 69217 | 47000 | 20000 | 2217 | 36277 | 34060 | 0 | 0 |
| 14 | 63945 | 47000 | 16946 | 0 | 34060 | 34060 | 0 | 0 |
| 15 | 64584 | 47000 | 1758 | 0 | 34060 | 34060 | 0 | 0 |
| 16 | 87344 | 47000 | 20000 | 20344 | 34060 | 13716 | 0 | 0 |
| 17 | 90984 | 47000 | 20000 | 23984 | 13716 | 0 | 0 | 1 |
| 18 | 62045 | 47000 | 15045 | 0 | 0 | 0 | 0 | 0 |
| 19 | 78490 | 47000 | 20000 | 11490 | 0 | 0 | 0 | 1 |

| Day | Demand (M cm/d) | Offers | | | LNG ships | | | Failures (0-no or 1-yes) |
|---|---|---|---|---|---|---|---|---|
| | | National (M cm/d) | Bolivia (M cm/d) | LNG (M cm/d) | Initial stock (M cm/d) | Final stock (M cm/d) | Additional charge | |
| 20 | 72062 | 47000 | 20000 | 5062 | 0 | 0 | 0 | 1 |
| 21 | 65346 | 47000 | 18346 | 0 | 0 | 0 | 0 | 0 |
| 22 | 79034 | 47000 | 20000 | 12034 | 0 | 0 | 0 | 1 |
| 23 | 81685 | 47000 | 20000 | 14685 | 0 | 0 | 0 | 1 |
| 24 | 91835 | 47000 | 20000 | 24835 | 0 | 0 | 0 | 1 |
| 25 | 59379 | 47000 | 12379 | 0 | 0 | 0 | 0 | 0 |
| 26 | 72544 | 47000 | 20000 | 5544 | 0 | 0 | 0 | 1 |
| 27 | 91006 | 47000 | 20000 | 24006 | 0 | 0 | 0 | 1 |
| 28 | 60130 | 47000 | 13130 | 0 | 0 | 0 | 0 | 0 |
| 29 | 91292 | 47000 | 20000 | 24292 | 0 | 0 | 0 | 1 |
| 30 | 95626 | 47000 | 20000 | 28626 | 0 | 180000 | 2 | 1 |
| 31 | 72457 | 47000 | 20000 | 5457 | 180000 | 174543 | 0 | 0 |

The results presented in Table 3 show that, in scenarios of continuous electrical dispatch where the use of LNG is required, more than the capacity of two ships is required to supply the market in certain periods, with supply failures occurring from the 17th day. Table 4 presents consolidated results for each offer scenario.

**Table 4.** Balance of supply and demand

| Scenario | Number of failures | Failure Percentage |
|---|---|---|
| 1 charge every seven days | - | 0% |
| 1 charge every ten days | 49,00 | 16% |
| Two charges every 30 days | 117,00 | 39% |

Considering the arrival of a ship every seven days, there was no failure to meet the market. However, in the scenarios of ship arrival less frequently, there is an incidence of supply failures, 16% for the arrival scenario of a ship every ten days and 39% when receiving two ships every 30 days. That is, if an improvement in logistics were obtained to increase the arrival frequency of ships to one every seven days, this would be enough for a flawless service. The costs related to the contracting of ships and the maintenance of gas stocks were not included because the company considers it sensitive to disclosure.

## 4 Conclusions

An overview of the balance of supply and demand of natural gas in Brazil was presented, and the characteristics of demand, highly affected by thermal dispatch, and the supply of gas in associated fields, which requires great regularity in production to avoid losses in production and oil, were verified. With mostly associated production fields, in which oil and gas production occurs simultaneously, these end up prioritising firm demand, with gas imported by pipelines or LNG meeting thermal power demand in high dispatch scenarios.

From the evaluation of the demand pattern, it was possible to establish a static simulation model that demonstrated statistically significant test consistency. Furthermore, the simulated supply and demand balance results show that optimising LNG supply ship arrivals may be sufficient to meet 100% of demand, even in continuous electrical dispatch scenarios, avoiding supply and generating energy security.

The results of the study demonstrate that considering the arrival of a ship every seven days, there was no failure to meet the market. However, in the scenarios of ship arrival less frequently, there were incidences of supply failures, 16% for the arrival scenario of a ship every ten days and 39% when receiving two ships every 30 days. Therefore, the proposed policy for arrival frequency of ships could be sufficient to attend current demand pattamars in an environment of lack of other alternatives in storage for improving supply security.

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