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Brazilian ssm-FLNG Offshore, a Conceptual Solution of a System as a New Frontier of National Production and Technological Innovations

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Abstract

The Brazilian Liquefied Natural Gas (LNG) market is expanding, driven by regulatory changes, new investments, and the search for cleaner, more flexible energy sources. The infrastructure for gas transportation from offshore wells to the coast currently depends on Routes 1, 2, and 3, which are already operating at their full capacity, limiting its availability on the continent. Therefore, Small-Scale Maritime LNG emerges as an alternative bringing natural gas to the shore for inland distribution, using road, railroad, and waterway transport. Recently, a strategic opportunity has arisen to use offshore Floating Liquefied Natural Gas (FLNG) platforms, connected to Brazil's pre-salt platforms, to monetize natural gas that was previously mostly reinjected into reservoirs. This technological solution allows gas to be liquefied and exported directly from the sea, overcoming logistical challenges and increasing resource utilization. The Búzios Field, in the pre-salt Santos Basin, is an emblematic example. Considered the largest ultra-deepwater field in the world, Búzios has a large volume of associated gas, and FLNG initiatives are being studied to enable the commercialization of this gas, reducing reinjection and adding value to the asset. On the other hand, the high carbon dioxide content in the raw natural gas could be reinjected into oil wells after being separated before gas liquefaction process. The opening of the sector and the entry of new players have promoted greater competition and diversification, reducing dependence on Petrobras. Despite the existence of several regasification terminals, many operate below capacity due to the predominance of hydroelectric power. However, the demand for energy security is expected to increase the use of LNG during critical periods. The main challenges include market concentration, logistical limitations, and the need for innovation to enable gas access in remote regions. LNG, especially with the use of FLNG, is considered strategic for the energy transition, with potential for decarbonization and regional integration displacing heavy fuel oil, diesel oil, and gasoline. The development of innovative logistical solutions and the consolidation of a free gas market are fundamental for strengthening the sector in Brazil, in addition to enabling the meeting of fuel demand for future replacement by biogases and green hydrogen.

Keywords

Liquefied Natural Gas (LNG), Floating Liquefied Natural Gas (FLNG), Brazilian Energy Transition, Monetization of Brazilian Natural Gas

1. Introduction: The Strategic Turn toward Offshore LNG

The Brazilian Liquefied Natural Gas (LNG) market is at a pivotal moment, driven by regulatory transformations, technological advances, and the pursuit of cleaner and more flexible energy alternatives. In recent years, the country has established itself as a central hub for offshore natural gas exploration and production, especially in the pre-salt layers, with the Búzios field standing out as the world's largest ultra-deepwater oil and gas field by volume. However, the efficient monetization of this resource still faces structural, logistical, and regulatory challenges that limit the full exploitation of Brazil's energy potential.

Brazil's energy matrix has traditionally depended on hydropower. However, climate change, extreme weather events, and the need for energy security have prompted diversification efforts, with LNG emerging as a strategic alternative. The transportation and distribution infrastructure for natural gas, however, remains concentrated along the coastal regions, restricting access to the resource in inland areas and limiting the expansion of the national market. In this context, innovative solutions such as small-scale LNG and the use of offshore gas liquefaction platforms are becoming increasingly relevant for expanding supply and serving remote or isolated markets mainly by road, or sometimes by railroad, and waterway.

The liberalization of the natural gas sector, with new players entering and reducing reliance on Petrobras, has encouraged more competition and drawn investments in regasification terminals and gas-fired power projects. Although many LNG terminals exist, most operate below their capacity because of the dominance of hydropower and seasonal demand fluctuations. As a result, logistical innovation and increased operational efficiency are crucial for strengthening the industry.

One of Brazil's main opportunities lies in the adoption of commercial-scale offshore natural gas liquefaction technologies, particularly through Floating Liquefied Natural Gas (FLNG) platforms. These floating units enable the liquefaction and export of gas directly at offshore locations, connecting to pre-salt production platforms and making it possible to monetize volumes that were previously mostly reinjected into reservoirs. The Búzios field exemplifies this potential: with large volumes of associated gas, FLNG initiatives are being studied to transform surplus gas into exportable LNG, adding value to the asset and reducing reinjection.

The adoption of FLNG platforms directly addresses the logistical challenges faced by the sector, overcoming the limitations imposed by pipeline infrastructure and expanding commercialization possibilities for Brazilian natural gas. Furthermore, the use of small-scale FLNG units offers flexibility and mobility, adapting to the demand of different projects and markets and allowing service to specific niches such as isolated power plants and medium-sized industries, as well as industrial districts.

The development of FLNG technologies follows global trends in decarbonization and energy integration, with representative projects already in operation in Australia (Prelude, Shell), Mozambique (Coral South, ENI), and Malaysia (DUA and SATU, Petronas). In Brazil, adapting these solutions to the pre-salt environment demands consideration of factors such as production scale, economic viability, operational safety, and socio-environmental impacts.

LNG logistics must be continuously optimized to meet market demand while maintaining high standards of reliability and safety. The choice between traditional onshore terminals, Floating Storage Regasification Units (FSRU), and FLNG platforms involves detailed analysis of capital expenditures (CAPEX), operational expenditures (OPEX), modularity, implementation timelines, and operational flexibility. Comparative studies indicate that FSRUs offer cost and agility advantages, making them attractive alternatives for markets that are growing or seasonal.

Natural gas production in the pre-salt, especially in offshore environments far from the coast, such as the Santos Basin fields, demands innovative monetization solutions. Traditionally, subsea pipelines transported gas to onshore Natural Gas Processing Units (NGPU), but the capacity of these routes is approaching its limit, requiring alternatives for the flow of additional volumes. Offshore liquefaction, followed by transportation via LNG carriers to domestic or international regasification terminals, broadens commercialization opportunities and can position Brazil as a significant player in the global LNG market.

In addition to LNG, the separation and monetization of fractions, mainly LPG and C_5+[1], add value to the production chain, diversifying revenues and optimizing resource utilization. The replicability of the solutions proposed for the Búzios field in other pre-salt projects and emerging markets such as Guyana reinforces the innovative and strategic nature of these technologies.

[1]Hydrocarbons as pentane and above.

Despite the promising outlook, challenges persist, including market concentration, logistical limitations, the need for infrastructure investments, and regulatory adaptation. Developing innovative logistical solutions, consolidating the free gas market, and regional integration are essential to ensuring the sector's competitiveness and sustainability. LNG is becoming a key element in Brazil's energy transition, offering avenues for decarbonization, value creation, and integration into the global energy market.

This work was limited to establishing basic conceptual conditions for solving the problem related to the structural limitation on monetizing the natural gas potential present in Brazil's pre-salt fields. It highlights the main points related to the proposal and also provides a reference for financial economic analysis, which was carried out in full in the work mentioned and referenced in this paper. This work does not include assessments regarding operational safety, efficiency, and technological limitations.

2. Understanding the Current Brazilian Gas Market

As mentioned by [1], the increase in LNG operations by Brazilian companies, becoming a significant factor in the Brazilian NG matrix, makes the Brazilian energy market part of the global energy market, thus leading to dependencies and price fluctuations of global energy resources such as NG. Although Brazil does not depend on Russian supply, it also becomes susceptible to the reduction of the NG supply [2].

In 2022, there was an increase in long-term LNG contracts, as Europe sought to reduce its dependence on Russia. Given the heating up of the NG and LNG markets worldwide, global suppliers of these commodities are increasing the weight of oil in the indexation of new NG and LNG contracts to ensure price security for their contracts, resulting in a more challenging scenario for the opening of the Brazilian market via LNG [3].

It is worth noting that with the growth of LNG imports by Brazilian companies, there has been a correction of the national NG price to align with global prices [3]. Imported LNG is considered a relevant energy source for the development of new energy sources in an intermittent manner in the short and medium term through plants operating under the GtW (gas-to-wire) and RTW (reservoir-to-wire) models. Given the potential and constraints, this study aimed to evaluate the prospects of using LNG as an alternative energy source [4].

Brazil still faces the need for significant investments across the entire supply chain to implement or expand new markets, such as LNG-powered trucks or other alternative fuel technologies. These projects require careful evaluation and decision-making, as the infrastructure for refueling must be implemented alongside the vehicles, with each being dependent on the other. This creates a heavier investment burden. As highlighted by [5], the establishment of LNG refueling infrastructure may be prohibitive for truck use across Brazil's vast highway network, especially in a context of international market pressures and high prices. On the other hand, compressed natural gas-powered trucks (CNG-trucks) already started running in Brazil, enabling gas stations to store LNG so that high-pressure gasification, storage, and refueling can be performed by cryogenic pumps, a significantly more economical alternative in terms of CAPEX and OPEX.

Since the pricing for thermoelectric fuel supply adheres to international market basket indexation rules, consumers will feel the financial impact. Amid market uncertainty and high prices, consumers are cutting back on purchases, and industries are reducing production [6].

Inflation in Brazil has returned to levels not seen in years, with bank interest rates once again reaching triple-digit levels. This has led to increases in fuel and food prices due to the conflict, consequently reducing economic growth prospects [2]. Since NG is the primary input to produce fertilizers imported by Brazil from Russia and is essential for the country's food production, this crisis is likely to have a significant impact on the entire food chain and Brazil's agribusiness market. Overall, low-income countries are particularly vulnerable to higher food prices, exacerbated by the rising costs of energy and fertilizers [6].

For Brazil, as well as for other emerging markets like it, where the economic fragility of the population results in food and energy costs weighing heavily on household budgets—alongside housing expenses, which make up the largest portion of their budgets—the rise in inflation has a significant impact. This situation delays social and energy progress, exacerbating poverty conditions among these more vulnerable communities [6].

Even though the rise in most commodities has negatively impacted Brazilian imports, diesel oil, which began to be embargoed by Russia in February 2023 [7], could bring good news for Brazil. With the European market closing, Russia may be forced to reduce its diesel prices to open new markets, potentially benefiting Brazil. This is a contrasting effect to the impact caused by other energy products purchased by Brazil.

In September 2023, Russia announced temporary restrictions on diesel and gasoline exports, which directly affected Brazil, as it was the largest supplier of diesel to the South American country. This led to a direct increase in energy prices for Brazil, rising from USD 10 per barrel to USD 40 per barrel [8]. By the end of 2023, Brazil had already become the largest buyer of Russian diesel, surpassing Türkiye and even France, which had been overtaken earlier in the year [9].

In countries that are not self-sufficient in all forms of energy and thus need to import it, high fuel and electricity prices reduce industrial production and business production costs, consequently negatively impacting the national macroeconomy. This leads to a reduction in household incomes while simultaneously increasing the cost of living due to rising inflation.

On the other side of the balance are energy-exporting countries, which benefit from rising energy commodity prices, increased national income, expanded production, and more attractive investment opportunities. This creates a shift of wealth within the global economy, exacerbating social and economic disparities between nations and hindering global growth. Energy-exporting economies tend to save more and spend less of their income compared to energy-importing economies [10].

As energy prices continue to rise, further disrupting this balance between importing and exporting countries, industrial supply chains become increasingly dependent on the costs of their energy inputs. This may result in an industrial exodus from countries with higher production costs to those with lower costs, driving investors to favor economies that are more energy advantaged [6].

The indirect impact does not stop there. In addition to the effects on food supply chains linked to inflation in the Brazilian economy, uncertainty traditionally drives investors worldwide, including those in Brazil, to seek safer assets, such as shares of American companies, the US dollar, and gold. This shift significantly affects investment prospects in Brazilian industries, impacting the indices and values of Brazilian stocks traded on both domestic and international stock exchanges [2].

Global trade flows are undergoing a new reorientation, with importing regions prioritizing domestic resources whenever possible to ensure their energy security. This often involves limiting exposure to volatile international markets before considering support for commercial partners in other countries [6]. These dynamic highlights that importing countries can never fully guarantee their energy security, remaining subject to the strategies of their export partners. Therefore, concerns about energy security must be addressed by increasing local energy sources, whether renewable or not.

In Brazil, the energy matrix is composed mainly of domestic production, primarily from renewable sources, as well as national oil and GN production from pre-salt and post-salt fields. However, LNG imports are a reality, used to sustain electricity generation. Petrobras has constructed regasification terminals to receive imported LNG and transport it to the thermoelectric market, aimed at addressing drought periods affecting hydroelectric plants [11]. As noted by [12], their evaluation of a decade of LNG regasification to meet national market demands underscores the importance and necessity of natural gas-based energy sources in conjunction with hydroelectric sources. This trend is expected to expand in the coming years [11] [12].

Brazil has been following the global trend of increasing electricity generation from natural gas-fired power plants. This shift aims to reduce greenhouse gas (carbon dioxide—CO_2) emissions previously associated with coal or other fossil fuel-based power generation, while ensuring energy security through the provision of controllable and dispatchable power. This approach is more reliable than renewable sources like wind and solar, which depend on weather conditions to produce electricity. Within this trend, some countries are adopting electricity production known as GtW or Gas-to-Power (GtP) [13].

Gradually, the Brazilian market is evolving—not at the expected pace, but state distributors are intensifying their search for new suppliers to reduce their dependence on Petrobras [14]. According to estimates from the consultancy Gas Energy, which evaluated publicly available contracts disclosed by ANP, all new suppliers in their study offered prices lower than those of Petrobras, which had previously been the leading supplier [14]. This serves as a practical demonstration of market liberalization.

For example, as reported in national news outlets, the 2022 NG sales price from the private producer 3R to the state distributor Bahiagás ranged from USD 6 to 7/MMBtu, based on Brent crude prices fluctuating between USD 75 and 125 per barrel. In comparison, Petrobras charged over USD 14/MMBtu during the same period for new contracts with distributors [14].

This reflects the natural evolution of the market, which, as seen in many global markets during their early liberalization phases, often involves significant contractual disputes between traditional and new models. Such disputes, leading to widespread judicialization, are almost inevitable until the market reaches a new phase of maturity, recognition, and acceptance of new standard commercial conditions.

In this situation, Petrobras justified the price increases as resulting from higher costs associated with imported LNG, which had risen due to the global context. Meanwhile, the distributors viewed the adjustments as an abuse of Petrobras' market power [14].

However, in 2023, Petrobras remains the leading supplier of NG to state distributors, continuing to follow a pricing formula linked to the international variation of Brent crude oil and the exchange rate between the dollar and the real. The distributors signed new contracts with the state company in 2022 under this pricing model, without including global LNG prices in the formula, justified by the argument that the cost of LNG imports would increase [15].

With the long-awaited opening of the Brazilian NG market, where Petrobras is no longer the sole supplier of all domestic NG, the supply risk for other market players increases. From this perspective, all sources have their importance, and LNG, which is starting to play a unique role in ensuring large-scale supply to remote areas without pipeline coverage, is crucial [1] [11]. This situation occurs at the extremes of Brazil, such as the South region, where there are no regasification terminals for receiving LNG ships, relying heavily on the limitations of the Gasbol[2] pipeline. The same situation occurs in the Northeast. In both regions, there are plans for the construction of several new terminals to supply the local industry as well as for electricity generation [1]. Some projects are already well advanced, such as the terminal to be installed in Paraná by the company Nimofast, which has already secured its first supply contract with a local customer, a private gas trading company currently seeking additional clients [3], representing an actual case of a free market in operation. In these areas, LNG is an important alternative for energy security and increasing the supply of NG in the region. Addi-

[2]Gasbol—The Bolivia-Brazil pipeline, built in 1996, connects the national gas network with Bolivia's production to the Brazilian grid.

tionally, the increase in the number of LNG terminals along the Brazilian coastline could contribute to the development of cabotage transportation on both large and small scales [11] [16].

Looking at the national NG matrix, in addition to LNG imports, Brazil also imports via the Gasbol pipeline, which connects the country's gas network to Bolivia's production. Since 2015, Bolivian production has been declining year after year, with few discoveries and limited supply from mature fields. As a result, production is expected to decline at a much faster pace, creating an uncertain future for Brazil's energy security [17]. The forecast is that Bolivia will stop exporting and start importing gas if no discoveries are made in the country [14]. This could also impact Brazil and Argentina's exports, as they are the largest consumers of Bolivian gas.

In 2023, with the start of President Luís Inácio Lula da Silva's government, Brazil renewed an old rapprochement with another neighboring country, Argentina, focusing on energy integration between the two nations. After years of the agenda, South American energy integration is back on the table, but this time in a different context, as Brazil's past interest had been focused on Bolivia, which no longer guarantees the necessary supply for the future. This makes Argentina an attractive and timely option [14]. Furthermore, other factors contribute to this shift, such as the fact that in the 2000s, when Brazil and Argentina maintained an energy agenda leading to the construction of a Brazilian thermal power plant at the border in Uruguaiana, Brazil had not yet discovered its pre-salt reserves, among other significant developments that make the current situation unprecedented in this relationship. The current Brazilian market is more open and advanced, with several LNG terminals in operation, providing more import options [14].

The rapprochement with Argentina, initiated this year, occurs at a time of geopolitical changes and shifts in the NG market in South America. Argentina is moving towards self-sufficiency in the coming years through the exploration of the Vaca Muerta field, which may make the Bolivian gas currently exported to Argentina available for Brazil in the second half of the decade [14].

A gas pipeline already connects Brazil and Argentina. However, full integration has never been realized since the 1990s with the establishment of the thermoelectric power plant in Uruguaiana, Rio Grande do Sul state, powered by NG. Brazil did import gas from Argentina for occasional operations, but from 2000 onwards, the plant operated only sporadically and was shut down in 2009 due to a lack of Argentine gas. New prospects for Argentina's gas industry, driven by the increase in unconventional gas production through fracking technology in Vaca Muerta, have reignited plans for integration between the two countries [18]. Argentina is committed to supplying Brazil with cheaper NG than that from Bolivia via the pipeline, which would allow for the flow of unconventional reserves from Vaca Muerta in Neuquén, near the province of Santa Fe, replacing Brazil's imports of Bolivian gas [19].

Considering the disruptions and uncertainties in global LNG prices over recent years, many buyers are reevaluating their long-term contracts due to concerns about potential supply shortages. In Asia, confidence in short-term contracts has been lost due to high costs, while in Europe, buyers are more confident due to the need for gas. As for the Chinese, they are relying on the balance between supply and demand [20]. In the state of Rio de Janeiro, there are plans to establish supply points to create a corridor for LNG and other fuels [21].

3. The Global LNG Trend

The complexity of using LNG processes and the market for this energy source, which requires large investments in infrastructure, are emerging market barriers. In restricted-size markets, such as developing countries like Brazil, the investment in a pipeline network is often not justified given the limited consumption that will be generated from this structure. This is one of the main reasons that delays the development of the Brazilian NG market, as well as the LNG market.

Despite the significant size and global potential of the NG trade, the corresponding supply chain operations are not flexible and practical. NG projects are among the most demanding in terms of cost, requiring tens of billions of dollars in investment.

The global cost to build a large-scale LNG plant with an estimated capacity of 1 million tons per year (MTPA[3]) is around 1.5 billion dollars [20] [22].

Another important factor tied to the risk of significant investments is, as already seen in this article, the various possibilities related to geopolitical uncertainties, price volatility of related or substitute energy sources to NG, which can make investments in mega-projects such as pipelines lose their attractiveness, at the risk of not having a market for which they were planned, leaving an entire structure meaningless and becoming a financial liability.

The impact of the Russia-Ukraine conflict can be considered an example of the crisis unexpectedly triggered for any country involved [20] [23], where energy policies depend on NG as an energy source within the plan for a zero-carbon emissions transition [24]. As an option for NG supply, any country with access to the sea may consider LNG as a supply source.

The adoption of appropriate technological and logistical solutions can ensure significant flexibility and reduce financial and operational risks. The development of LNG is a challenge for inexperienced countries, which should learn from mature markets and seek alternative optimized solutions without assuming risks [20].

In the electricity generation sector—which accounts for the largest share of Brazilian NG consumption—the addition of 8 GW of NG-fired power capacity could reduce Brazil's electric system costs by 20% compared to conventional systems, according to cost projections for 2050 [25].

[3]MTPA—The acronym for Million Tons per Annum, which is one of the units of measurement for LNG used worldwide.

4. The Possibilities for Brazil to Become an LNG Exporter

The increase in LNG prices has had a significant impact on Brazil, causing a shift in its energy model towards this product, as well as the possibility of becoming an LNG exporter. The rise in prices justifies the investment in LNG production, which comes from offshore platforms exploring and producing from Brazil's pre-salt reserves. At this point, another conclusion drawn from the study is the use of small-scale structures for LNG production offshore, such as Small-Scale Mobile Floating, Liquefaction, Storage and Offloading of LNG (ssm-FLNG), which fit the dimensions of NG production from pre-salt basins, as well as the size of specific demand from Brazilian consumer markets. This could also generate financial viability by taking advantage of high LNG prices, enabling Brazil to export LNG and thereby position the country among the world's leading LNG producers and exporters.

Currently, Brazil's NG matrix depends on Bolivian gas and LNG imports to balance its energy needs. However, there could be a surplus of NG from the pre-salt reserves once an economically viable solution is developed. Alternatively, a hybrid scenario could be explored, where, even with LNG imports, Brazil becomes an LNG exporter from its pre-salt reserves. This is possible because production is offshore, far from the coast, as seen on pre-salt platforms. In this scenario, the offshore production could be transformed from NG into LNG, transported to the coast, and then reprocessed into NG again for consumption.

5. The Promise of LNG for Brazilian Gas Monetization

In Brazil, despite the enormous share already played by renewable energy in the country's energy mix, less than 50% [26], the government's Ten-Year Energy Plan 2031 suggests that natural gas will double its share in the national energy mix from the current 7% to around 14% in 2031 [26].

In 2022, 46% of Brazil's gas consumption was used for electricity generation, 12.2% by the energy sector (such as in oil refineries, gas processing and compression plants, etc.), and 0.6% for non-energy uses. In other words, the other direct gas uses accounted for only 5.5% of Brazil's total domestic energy supply. This is a tiny share compared to global statistics. With the gas supply potential available in the country, it is reasonable to envisage a multiplication by two in the NG share in Brazil's energy mix.

In Brazil and most of Latin America, the lack of robust and centralized coordination for planning and promoting the expansion of NG infrastructure makes it more difficult to envisage significant gas construction pipelines connecting Brazil's different regions and Brazil to its neighboring countries. Such a perspective makes a strong case for LNG to become an even more relevant alternative for Brazil to diversify its NG supply.

Natural gas prices are complex and sensitive to geopolitical and seasonal factors. The entry of the United States as a significant LNG exporter to Asia and Europe has changed global price dynamics, increasing the international search for diversification and more secure NG supply. The construction of LNG Regasification Terminals over the Brazilian coast follows the same rationality, with more significant consumers looking for new sources of supply that can significantly increase their energy security.

In addition, introducing the "blue corridors" in Brazil shall promote the direct use of compressed and liquefied NG in heavy vehicles (road, rail, waterway, and maritime). Such a trend represents an essential innovation in Brazil's trajectory to reduce greenhouse gas emissions (GHG) emissions and other pollutants, particularly in the transportation sector. The country wisely searches for more sustainable alternatives to reduce the national dependence on less sustainable fossil fuel sources, such as diesel oils, heavy fuel oils, and coke, mainly in reducing iron ore and agrobusiness transportation.

LNG presents itself as a palatable and cost-compatible solution for less developed economies like Brazil to promote reductions in GHG emissions without major and dangerous disruptions in the nationwide energy system. In addition to reducing GHGs, it is also necessary to consider decreasing other air pollutants such as soot, carbon monoxide, sulfur oxides (SO_x) and nitrogen oxides (NO_x). Especially in large cities, in the medium term, the reduction of pollutants will lead to a reduction in public health costs.

Additionally, the scenario of international conflict between Russia and Ukraine imposed the need, especially in countries on the European continent, to develop new trading partners that can add new sources of supply for the commercialization of NG. This new framework of global gas geopolitics generates a unique perspective of international insertion for the Brazilian NG industry, which may turn the abundant available reserves in the pre-salt offshore production zones into an eventual exporting product.

In Brazil, most hydrocarbon reservoirs are in ultra-deep seawaters. The Brazilian oil reserves in the pre-salt rock layers already represent more than 60% of the national production and have high gas-to-oil ratios (GORs). Until now, domestic gas has faced monetization difficulties. However, the new scenarios described above, with growing perspectives on LNG, represent an excellent opportunity for the country to increase the exploitation of domestic gas for both the domestic and the international markets.

Critical technological challenges remain for Brazilian offshore gas, especially regarding extraction from rock depths beyond 7000 meters and water depths of 3000 meters, as well as the near absence of infrastructure for moving gas from the production platforms to the domestic or international markets. The distances from the production areas to the Brazilian coast exceed 300 km, making it challenging to build robust pipeline systems before firm anchor markets have been identified.

Throughout the first fifteen years of pre-salt production, offshore operators in Brazil became the primary (if not sole) users of the produced gas in the energy-intensive activities developed in the upstream business or by reinjecting the gas into the reservoirs to keep them pressurized, increasing, therefore, the fields' recoverable factors for oil.

However, in the coming decades, the reinjected gases tend to be recirculated in the fields, which may reduce their profitability or even anticipate the end of production. The NG will demand alternative markets so that the pre-salt production remains robust, competitive, and sustainable without resorting to unacceptable gas-flaring practices.

Not to mention the even more complex issues related to CO_2. Many pre-salt production fields, as will be shown throughout this report, have high levels of CO_2. Any simplistic solution of venting and emitting this CO_2 into the atmosphere is ruled out in times of growing concern about climate change and the decarbonization of oil and gas production activities.

In Brazil, the supply of "domestic NG" to "domestic markets" is done almost exclusively through pipelines, following an international trend, as pointed out by [27]. However, as the pre-salt reservoirs are far from the coast and submarine pipeline structures are expensive, the flow of the pre-salt NG through offshore pipelines has been proven to be an essential challenge to overcome.

The pipeline solutions proposed in the government Indicative Plans for Transport Gas Pipelines [28] [29], such as Routes 4, 4B, and others, have already coexisted over decades of pre-feasibility studies without material economic and financing solutions. One of the factors would be the depletion of NG production from wells over time, rendering the pipeline unusable.

This research assumes that Floating Liquefied Natural Gas platforms (FLNG) are an innovative solution for outflowing Brazilian offshore NG from the producing zones to markets in Brazil or abroad. Regarding the NG depletion over time, the FLNG could be moved to another FPSO to restart full production again.

FLNG projects have many challenges themselves, as detailed by [30], due to the need for onboard processing plants and thermally insulated tanks. This results in cryogenic hulls with much larger dimensions than most oil exploration platforms.

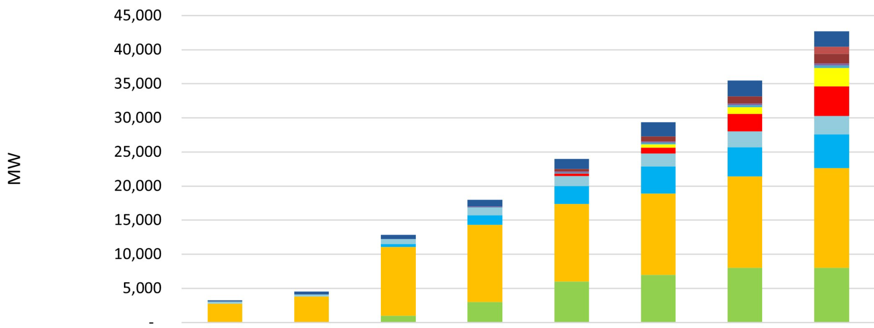
The most prominent FLNG vessels are Shell's Prelude, installed and operating off the west coast of Australia, and Petronas' FLNG (PFLNG), which operates in deep waters at a Malaysian NG field, Rotan Gas Field. Both are large-scale projects aiming primarily at exporting to Asian markets.

Prelude's production, specifically, is around 3.6 million tons per annum (MTPA) of liquefied natural gas (LNG), 1.3 MTPA of condensates, and 0.4 MTPA of liquefied petroleum gas (LPG), as described in [31]. Prelude is 488 m long and 74 m wide and is one of the world's most significant offshore structures ever installed.

Until 2020, the giant Shell-led project in Australian waters was about to become a potential commercial failure. The investments of about US$17 billion exceeded the initial forecasts, and the project suffered significant delays as it had to face unforeseen operational difficulties, primarily due to the large scale of the processes, including potential safety and reliability difficulties. Nonetheless, the war scenario revitalizing the global LNG market allowed Prelude's strategic and financial turnaround.

During the initial years, Prelude also did not prove to be an attractive business for Australia, as cost overruns inhibited profit generation, and this meant that operators were unlikely ever to pay the Australian government the rents and taxes due for the exported gas. The government is tied to the project's ability to generate profit. In addition, Prelude also used negligible local content during construction. It contributed little to the reduction of Australia's greenhouse gas emissions, as the dimensions of the project were inappropriate for serving domestic markets. It was an exclusively LNG exporting project.

Large-scale FLNG solutions, such as Prelude, are expected to encounter even greater energy, financial, and technological barriers within the Brazilian economic reality and are discarded in this research project.



	2,024	2,025	2,026	2,027	2,028	2,029	2,030	2,031
Others	200	400	600	1,000	1,500	2,100	2,311	2,311
Nuclear	-	-	-	-	-	-	-	1,000
Coal	-	-	-	-	350	700	1,050	1,400
Urban Solid Residues	-	-	50	100	150	200	250	300
Biomass	-	-	-	80	160	240	320	400
Solar Power	-	-	-	-	-	500	1,000	2,700
Wind Power	-	-		-	344	844	2,544	4,344
Small Hydro	300	300	700	1,100	1,500	1,900	2,300	2,700
Hydropower	-	-	426	1,401	2,614	3,995	4,297	4,947
NG Flexible	2,764	3,800	10,082	11,313	11,369	11,901	13,424	14,624
NG Inflexible	-	-	1,000	3,000	6,000	7,000	8,000	8,000

Figure 1. PDE 2031 Indicative cumulative power capacity expansions per year and per source for the reference scenario. Source: [26].

The project proposal aims at the technological development of unprecedented FLNG solutions that are more compatible with the country's economic, financial, energy, and technical realities. The searched innovation shall enable the monetization of the abundant NG from the pre-salt polygon in both the domestic markets (matching growing NG consumptions expected from the Brazilian society) and the eventual insertion of Brazil in the global LNG market.

To briefly explore Brazil's future gas consumption foreseen in the PDE 2031 [26], **Figure 1** shows the expected indicative cumulative power capacity expansions per year and per source for the reference scenario. NG is expected to play a significant role over the whole decade. In every year of the scenario, NG-fired power generation accounts for more than 50% of the total new capacity added to the system. Once such a scenario materializes, power generation will be Brazil's primary consumption vector for NG.

However, as intermittent renewable sources already dominate the Brazilian electricity system and renewables keep growing, NG will increasingly become the ultimate complementary source to deal with high intermittence on the supply side. As such, most of the expected required NG-fired power plants shall be contracted and operated flexibly, adapting to the demands of the national electricity grid.

6. Brazil's Natural Gas Market: Opportunities and Constraints

The logistics process involving LNG must be adapted to the market demand in which it will operate, with the goal of continuous optimization at all levels while maintaining operational reliability and safety. In the case of Brazil, when discussing scale, one must consider the market potential for adding new volumes to the national NG matrix. This, in turn, depends on industrial growth and electricity production, as both uses are the main drivers of Brazil's NG demand.

6.1. Pipelines

Brazil's NG production from the pre-salt in an offshore environment, up to 500 km from the mainland and at a depth of approximately 5 km, is primarily based in the Campos and Santos Basins. Until then, all this production was brought for domestic consumption and monetized through pipelines that transport the hydrocarbon to the Natural Gas Processing Units (UPGNs) on the Brazilian coast. The investment in these pipelines presented significant construction challenges and environmental concerns, as they operate at great depths and encounter substantial variations in underwater terrain.

As shown in **Figure 2**, two routes are currently in operation for utilizing pre-salt gas. Route 1, operating since 2011 with a capacity of 10 million m^3/day, with a delivery point at the UPGN in Caraguatatuba, São Paulo, and Route 2, operating since 2016, with a capacity to transport up to 16 million m^3/day, with a delivery point in Cabiúna, Rio de Janeiro. Route 2 has already been approved for expansion by the ANP, and once implemented, it will have an additional capacity of 20 million m^3 per day. In addition to these routes, a new route, designated as Route 3, with a capacity of 18 million m^3/day, is currently under construction. It will have its delivery point in Maricá, Rio de Janeiro, and will be connected via a land pipeline in Itaboraí.

There are studies for a fourth route to serve the Santos Basin up to the city of Cubatão in São Paulo, thus supplying the large consumer center of the state of São Paulo. The company Cosan is studying this project.

The existing pipeline infrastructure can function and operate, transporting NG volumes from different agents until it reaches its installed capacity. It is estimated that the limit for transporting NG from the Pre-Salt, considering only the existing and under-construction infrastructure, will be reached in 2026, based on the reference scenario of the PDE 2029.

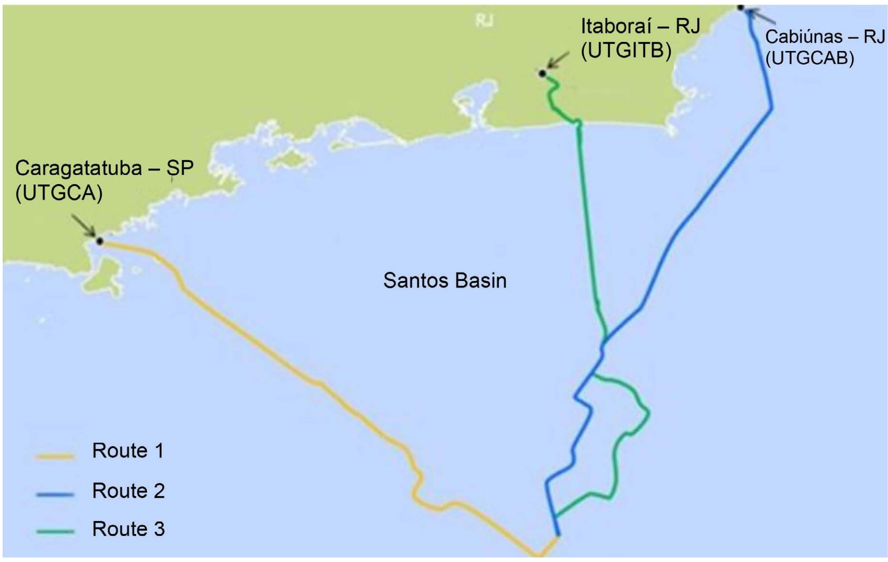


Figure 2. Brazil's pre-salt pipelines. Source: Extracted from [32].

According to [33], additional volumes to the existing and upcoming capacity will depend on investment decisions by the agents that can be monetized. Several monetization options have been examined, with transportation pipelines being just one option. Other options include transporting compressed natural gas (CNG), LNG, or liquid fuels. However, it is essential to note that these alternatives necessitate technical, economic, and socio-environmental analyses for each specific case. Not all of them may be suitable for every project.

6.2. FSRU: Floating Storage Regasification Unit

To expand the production of NG from the pre-salt and thus increase the viability of offshore platforms through the monetization of discoveries not covered by Routes 1, 2, and 3, the option of transforming NG into LNG on offshore platforms and transporting it to regasification terminals on the coast is shown on the map in **Figure 3**.

This LNG can also be exported to any LNG- or natural gas-consuming country by being equipped with a storage and regasification terminal. This way, the opportunities and possibilities increase, bringing the commercial value of LNG to the global market as a reference for the feasibility study of these projects.

The Floating Storage Regasification Unit (FSRU) was first developed in 2005, as pointed out by [34] and [20]. It is originally a reused LNG tanker ship, modified into a floating dock terminal with some process equipment modifications. The FSRU is responsible for receiving and unloading LNG while ensuring safe mooring and operational delivery. Currently, FSRU storage capacities range from 30,000 m^3 up to 200,000 m^3 as described in [35].

Figure 3. Most prominent Brazilian LNG terminals in operation and planned. Source: Extracted from [29] with modifications by the authors.

According to [36], by the end of 2021, the global fleet consisted of approximately 700 LNG tankers, with 48 of these operating FSRUs worldwide, representing an 11% increase compared to the previous year. Meanwhile, the LNG market grew by 4.3% [37]. An FSRU vessel can be built from an existing LNG tanker through a transformation process that includes the addition of transshipment, regasification equipment, and mooring systems.

The financial viability and resulting profitability are the most important decision factors when choosing the appropriate type to be used, as shown in **Table 1**, which summarizes a comparative study between the CAPEX required for classic onshore terminals and FSRUs with a capacity of 3 MTPA The comparison shows a cost difference of 35%, in favor of the FSRU. Regarding operational costs, they range between $20,000 and $45,000 per day for FSRUs, compared to a range of $20,000 to $40,000 per day for onshore terminals [38].

Table 1. Required CAPEX comparison between an LNG terminal and FRSU (3 MTPA).

Component	CAPEX LNG Terminal	CAPEX FSRU
Dock including piping	USD 60 million	USD 60 million
Unloading lines	USD 100 million	Not applicable
Tanks 1 × 180,000 m^3	USD 85 million	On FSRU
FSRU vessel	Not applicable	USD 250 million
Process equipment	USD 130 million	Na FSRU
Utilities	USD 60 million	Not applicable
Onshore infrastructure	Not applicable	USD 30 million
Land fees and others	USD 125 million	USD 20 million
Total	USD 560 million	USD 360 million

Source: [38].

Modularity is another key benefit of the FSRU, making it particularly vital for small or developing markets, such as the Brazilian market. According to [39], when evaluating the needs of an onshore terminal, selecting a suitable port with stable mooring conditions and favorable weather is necessary. Conversely, the FSRU requires minimal land space and provides flexibility for potential relocation. Regarding the construction and delivery timeline, an FSRU can be delivered more quickly than an onshore terminal, which involves a longer civil works schedule in a coastal area, resulting in higher costs and increased construction risks. [40] noted that the FSRU can be considered safer because it is built in a controlled shipyard, rather than constructed temporarily in a remote location. Another reason would be the granting of an environmental license within a shorter period of time.

[20] also mentioned that FSRU ship buyers can choose from various leasing options to initiate operations for a specified period. Depending on the business model, leasing is typically more cost-effective than purchasing. This provides quicker access to LNG for emerging countries entering the LNG market.

Another option that should not be forgotten, in a country like Brazil, where natural gas has not yet advanced much inland. It would be the construction of onshore cryogenic storage tanks from which, in addition to gasification to pipelines, trucks and isotanks could be supplied, enabling the advance into the interior, forming a consumption matrix that would make future gas pipelines viable.

6.3. Case Study: Búzios Field

The Búzios Field's contract was established during the first round of surplus volumes derived from the "Onerous Assignment Regime" in 2019, involving a consortium led by Petrobras (85%), CNOOC (10%), and CNODC (5%). According to [41], in 2022, Búzios ranked as the second-largest oil-producing area in Brazil, following the Tupi field, reaching the production of 800,000 barrels of oil equivalent per day (BOE/d) [42].

According to [42], the Búzios Field holds the largest volume of oil and gas in deep waters globally, spanning 852 km^2 and located approximately 200 km off the coast of Rio de Janeiro, at water depths ranging from 1600 m to 2100 m. Pré-Sal Petróleo S.A. (PPSA), Brazil's state-owned company managing pre-salt reserves, announced on April 15, 2024, that the field had produced 1 billion barrels of oil. Petrobras operates the field through a consortium with CNOOC and CNODC, while PPSA manages the contract. Production has been ongoing since 2018 from five operational units of the FPSOs P-74, P-75, P-76, P-77, and Almirante Barroso [43] [44].

Petrobras initially operated the project and held over 95% of the stake. The remaining shares were split equally between CNOOC and CNODC, a CNPC subsidiary. By the end of 2022, CNOOC increased its stake to 7.34% after acquiring rights from Petrobras. This suggests that CNOOC's Búzios production in 2022 was approximately 42,000 BOE/d. In 2022, Búzios contributed over 3% of CNOOC's total global output of 1.3 million BOE/d, which represented approximately 9% of CNOOC's overseas production of 480,000 BOE/d. The anticipated increase in Búzios production through 2030 significantly supports CNOOC's goal of reaching 2 million BOE/d in global output by that year.

The Búzios field is expected to operate at its maximum with twelve FPSO-type platforms. Currently, five platforms (P-74, P-75, P-76, P-77, and FPSO Almirante Barroso) are already installed and operational. Another six were in the design or implementation phase (FPSO Almirante Tamandaré, P-78, P-79, P-80, P-82, and P-83).

The Búzios FPSOs are among the most prominent production units in operation in Brazil. Búzios concentrates the most productive wells in the country. The field had already broken records in July 2023, with 680,000 barrels/day of oil and 30 million m^3/day of NG [44].

The last unit to begin operations was the FPSO Almirante Barroso, which started in May 2023. This unit can produce up to 150,000 barrels/day of oil and 6 million m^3/day of NG. The FPSO Almirante Tamandaré will be the largest producer on the Brazilian coast, with a planned capacity of 225,000 barrels/day of oil and 12 million m^3/day of NG.

All platforms have dimensions that make them suitable case studies for this research, and their NG production aligns with the necessary size for attaching the ssm-FLNG units to the FPSOs, as seen in **Table 2**.

Table 2. Natural gas production by FPSO at the búzios field.

FPSO	Status	NG production (in m^3/day)	NG production (in Billion m^3/year)	NG production (in MTPA)
Almirante Barroso Location Búzios 5	In operation since May 2024	6,000,000	2.19	1.56
P-74 Location Búzios 1	In operation since March 2018	6,000,000	2.19	1.56
P-75 Location Búzios 2	In operation since December 2018	6,000,000	2.19	1.56
P-76 Location Búzios 3	In operation since October 2019	6,000,000	2.19	1.56
P-77 Location Búzios 4	In operation since April 2020	6,000,000	2.19	1.56
Almirante Tamandaré	In operation since February 2025	12,000,000	4.38	3.12
P-78	Forecast 2025	12,000,000	4.38	3.12
P-79	Forecast 2025	12,000,000	4.38	3.12
P-80	Forecast 2026	12,000,000	4.38	3.12
P-82	Forecast 2026	12,000,000	4.38	3.12
P-83	Forecast 2027	12,000,000	4.38	3.12

Source: Adapted by the authors from [1].

7. Proposed Solution: Small-Scale Mobile FLNG

7.1. Why Small-Scale Mobile?

The inherent modularity and flexibility of FSRUs, particularly in terms of quick deployment, minimal land use, and adaptability to varying market sizes, naturally align with the evolving needs of Brazil's energy sector. This creates an opportunity for the adoption of small-scale FLNG solutions, which offer the same mobility and scalability while providing the added advantage of enabling localized LNG production tailored to the country's unique offshore resources and demand patterns. By utilizing small-scale mobile FLNG units, Brazil can address the fluctuating consumption patterns and infrastructure limitations of its NG market while also benefiting from the operational efficiencies and relocation capabilities of FSRU technology.

Table 3 presents a comparison of the advantages and disadvantages of using a small-scale FLNG versus the traditional approach.

Table 3. Advantages and disadvantages of the two FLNG models.

	FNLG traditional	Smal-scale FLNG
Production	From 2 to 4 MTPA	From 0.1 to 1 MTPA
Dimensions	Lengths ranging from 350 m up to 450 m	Lengths up to 320 m
CAPEX	Higher	Lower
Economies of scale	Higher	Lower
Development time	Higher	Lower
Mobility	Lower	Higher

Source: Prepared by the authors.

Given that the system is designed for quick location changes, we can enhance the small-scale solution by emphasizing its mobility feature ssm-FLNG. This approach is a relatively new concept in the offshore and LNG industries. However, traditional large-scale FLNGs are already well-known and widely developed. In 2011, Shell launched its first FLNG project, Prelude, to develop gas fields in the Browse Basin off the coast of Western Australia. The project started processing gas in 2018. Other significant initiatives include ENI's Coral South FLNG in Mozambique and Petronas' DUA and SATU FLNG projects in Malaysia. These are recognized as major projects.

Conversely, small-scale projects are rapidly growing in emerging LNG markets worldwide, meeting the demand of power plants and small to medium-sized industries. There is also potential for LNG supply to remote locations that are not reachable by pipeline, especially where inland waterways or archipelagos make pipeline development impractical. Additionally, these projects work well in areas where alternative fuels are costly compared to LNG or where regulations require CO_2 emission reductions, and there is intermittent GN supply due to seasonal changes.

7.2. ssm-FLNG Description

Based on the described scenario, this research assumes that small-scale and mobile FLNG platforms will be the most advantageous supply solution to match intermittent NG demands for power purposes in Brazil with domestic offshore NG from producing fields in the pre-salt.

The analyses to be developed essentially for Brazil are replicable for other countries with gas markets that are still in their early evolution (often also with intermittencies like in Brazil), or even for mature and robust markets where the growing adoption of renewable energies marginally changes the formerly firm NG demand, which will become increasingly volatile. Smaller-scale LNG supply options that better meet flexibility requirements may become attractive for these markets. Brazil may find opportunities to enter the global LNG trade in these niche markets.

The research explores the thematic line of FLNG. As suggested in the introduction, the need to exploit economies of scale tends to favor large-scale FLNG units, such as Prelude.

However, Prelude proved to be a complex endeavor. The technical execution of the project led to construction delays and cost overruns, and the already challenging economics of the project almost became a "financial disaster" for developers and the Australian government. Such a large-scale solution must find a harsher technological, economic, and financial environment in the Brazilian reality.

The proposal aims to examine the advantages, disadvantages, and challenges of smaller-scale FLNG units. Furthermore, "mobility" appears to be a solid competitive advantage worth exploring, helping to balance the supply and demand sides. The modular ssm-FLNG units also allow for partial transfer to another location, as the crude gas flow is depleted, ensuring CAPEX payback across all modules.

Feasibility studies will be developed to examine the commercial viability of the proposed solution. However, the strategic dimensions of the project must be highlighted, as they are essential to consider. Some of those strategic dimensions were already introduced above, *i.e.*: 1) for a developing country like Brazil, keeping such a "highly demanded" NG as stranded and not monetized natural resource is a tremendous social cost to be avoided, 2) as time progresses, the current strategy of re-injecting gases into the pre-salt rock layers can jeopardize the productivity of productive fields since the gas-oil ratio will increase rapidly, leading to gas recirculation and an early drop in oil recovery rates, and 3) delays in the monetization of domestic offshore NG will reduce options and could increase the costs of Brazil's energy transition towards net-zero.

Figure 4 illustrates the water, oil, and gas production processes on a typical FPSO platform, predominantly used in the Brazilian pre-salt.

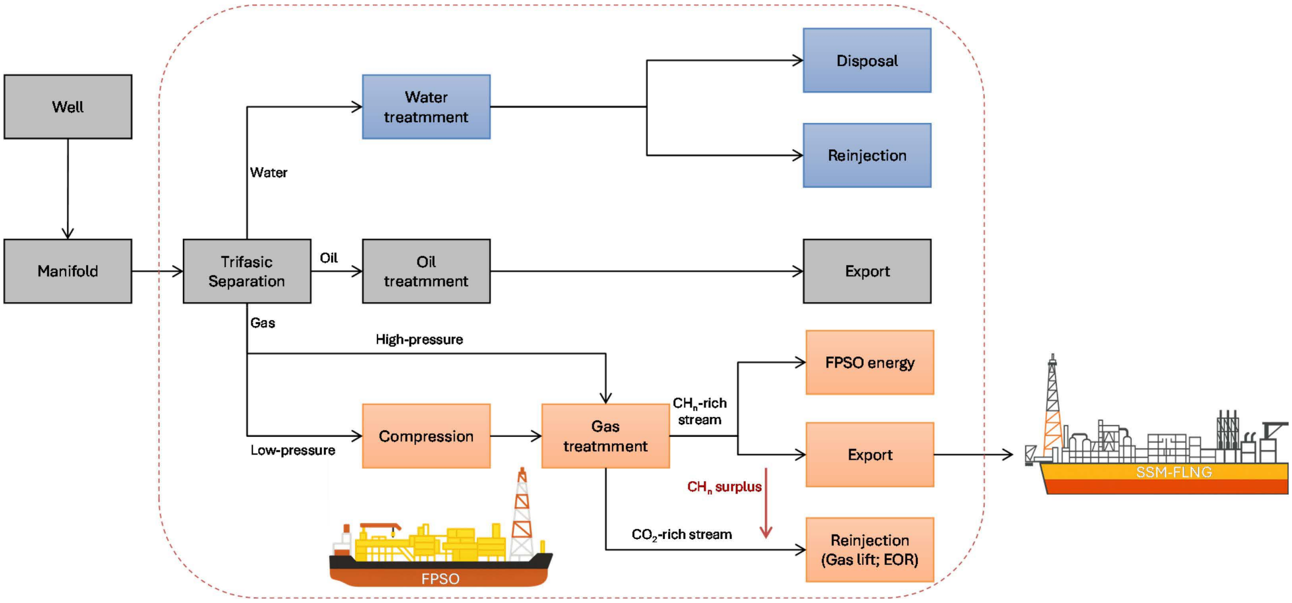


Figure 4. General flowchart for FPSO production. Source: Adapted from [45].

After being extracted through the well, the mixture (oil, gas, and water) is directed to a manifold, a set of remotely operated valves that control the flow of fluids. From the manifold, the production is directed to the FPSO vessel through an overhead pipeline called "riser". Once on the FPSO, the mixture undergoes an onboard three-phase separation [46].

The first product generated is water that undergoes treatment and has two main destinations: it can be dispensed into the sea or used for water reinjection and field pressure maintenance. The second product is oil, the platform's sole monetized product. The oil is processed and stored in the FPSO's tanks for later export through offloading operations.

The third product is crude natural gas, transported through high and low-pressure pipelines after separation from water and oil. The high-pressure gas goes to the processing unit, while the low-pressure gas is compressed before use. After treatment, the gas is split into two main streamlines, one rich in CO_2 and a second line rich in hydrocarbons (typically CH_4).

The hydrocarbon line serves two primary purposes: firstly, to complement the platform's power generation, and secondly, to export for commercialization. The gas outflow needs specific infrastructure to make the NG exporting to final users possible, as well as LPG and C_5+. Otherwise, monetizing the NG becomes tricky, and operators must manage the called stranded gas. The carbon-rich line will reinject the CO_2 into the rock formation through reinjection wells. In Brazil and wherever gas venting and flaring are prohibited, the stranded natural gas will be mixed with the carbon dioxide stream, and both will be reinjected into the oil field.

Gas reinjection is normal for upstream operators (onshore or offshore). Through gas reinjection, operators perform EOR (Enhanced Oil Recovery) or gas lift, which are processes to increase oil recovery (see further information about

EOR in [47]. However, in cases like the Brazilian pre-salt, marked by the production of lighter crude oil and high CO_2 and CH_4 contents in the field, the reinjection process can be more efficient and less costly, avoiding the reinjection of large quantities of potentially monetized gas.

Operators facing growing environmental pressures are seeking decarbonization strategies for their platform's operations. Eventually, operators will seek greener power options to supply the platform, for example, by promoting the development of renewable power connected to the platform (see the expected boom in offshore wind power that may emerge in Brazil and elsewhere). Such a more sustainable strategy will increase the amount of gas that operators need to manage, with the advantage of increasing monetization.

Increasingly, the reinjected CO_2, after performing operational optimization and boosting oil production, is expected to be permanently captured and stored in the rock formation, *i.e.*, carbon capture and storage (CCS). Regarding CH_4 and other hydrocarbons, reinjection is typically a temporary solution, merely postponing gas monetization to an uncertain future. However, geological conditions may not favor gas recovery. Eventually, in the future, operators will monetize only some of the reinjected gas, which may represent an additional cost that operators will need to avoid.

The present research proposes using a complementary floating unit to receive, liquefy, store, and export excess gas as LNG. This unit is called ssm-FLNG. An exporting hydrocarbon streamline connects the FPSO and the ssm-FLNG. This will supply a dedicated liquefaction topside plant to produce up to 1.0 MTPA (a smaller-scale facility).

As shown in **Figure 5**, LNG is stored in large cryogenic tanks inside the floating unit hull. These tanks can hold several days' worth of LNG production, and export occurs via LNG carriers that connect to and support the SSM-LNG unit. The LNG carrier transports LNG to local or international markets, typically covering shorter distances or capitalizing on high prices during periods of high demand.

A typical FLNG topside is composed of modules to handle three main functions: Pretreatment, Liquefaction, and Utilities. Simplifying the handling modules on the topside and reducing the hull size are crucial to making small-scale FLNG flexible, less costly, and competitive.

The composition of the gas inlet has a significant impact on the complexity and cost of pretreatment systems. In small-scale FLNG applications, the inlet typically contains hydrocarbons that an upstream FPSO unit has already processed. This pre-processed stream reduces the need for extensive pretreatment infrastructure, such as acid gas removal units, dehydration systems, mercury removal modules, and MEG recovery units (recovery and regeneration of monoethylene glycol). Each of these modules is crucial for ensuring the gas entering the liquefaction cycle is free of contaminants that could reduce efficiency or damage equipment. Simplified pretreatment results in a smaller topside footprint and helps lower costs.

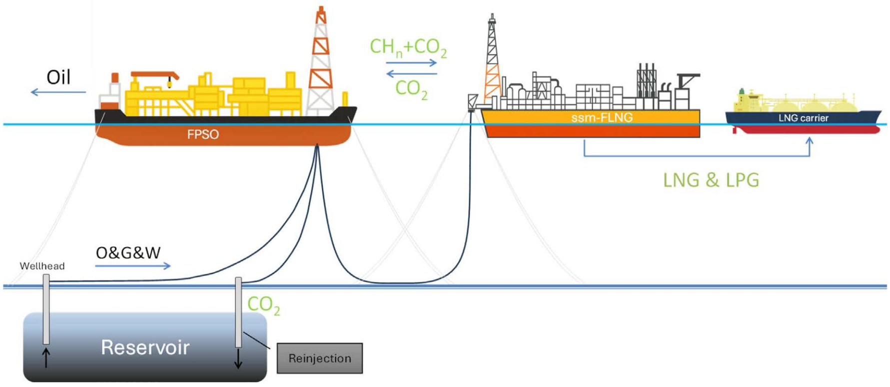


Figure 5. The export process of the rich hydrocarbon line to ssm-FLNG, followed by the liquefied gas export operation using LNG carriers. Source: Prepared by the authors.

Pretreatment waste must be disposed of in an environmentally friendly manner, in accordance with local legislation.

At the core of the FLNG unit is the liquefaction module, where the pretreated natural gas is cooled to approximately −165˚C, transforming it into a liquid suitable for storage and transportation. Several liquefaction technologies are commercially available, each with distinct advantages and trade-offs. The primary methods used in the industry today include:

- Cascade Cycles: These systems use a series of refrigerants with progressively lower boiling points (typically propane, ethylene, and methane) in separate cooling loops to gradually reduce the temperature of the natural gas. While highly efficient, their complexity and large footprint make them more suitable for large-scale onshore facilities.
- Mixed Refrigerant (MR) Processes: These technologies utilize a single stream of mixed hydrocarbon refrigerants (and sometimes nitrogen) to cool and liquefy the natural gas in a primary cryogenic heat exchanger. Variations include the highly efficient Propane Pre-cooled Mixed Refrigerant (C3MR) and Dual Mixed Refrigerant (DMR) processes, commonly used in large base-load LNG plants. The Single Mixed Refrigerant (SMR) process represents a simpler, more compact version.
- Linde and Claude Cycles: Based on the Joule-Thomson effect, the Linde process involves the expansion of high-pressure gas to achieve cooling. The Claude cycle is a more efficient variation that incorporates an expander to extract work from the gas during the cooling process.
- Nitrogen Expander Cycles: These cycles use nitrogen as the sole refrigerant in a closed-loop Brayton cycle. The expansion of high-pressure nitrogen through a turbo-expander generates the cooling required to liquefy the natural gas.

For small- to mid-scale FLNG operations, the Nitrogen Expander (TE-N_2) process offers a compelling alternative. This method uses the inert and non-flammable nitrogen gas as the refrigerant in a reverse Brayton cycle. The TE-N_2 system eliminates the need for complex refrigerant management, offering simplified operations, fast startup, and enhanced safety. It also requires fewer process equipment, making it ideal for installations with limited topside space. Its successful implementation in the Petronas FLNG (PFLNG) Satu unit demonstrates the viability of this configuration for offshore deployment.

Another key aspect of the FLNG topside is the heat exchange systems that facilitate the liquefaction process. The two main types used in FLNG are Spiral-Wound Heat Exchangers (SWHE) and Plate-Fin Heat Exchangers (PFHE). SWHEs are sturdy and capable of handling large volumes, making them common in high-capacity setups. Conversely, PFHEs offer a more compact and lightweight design, supporting modular construction and efficient space utilization, which is particularly beneficial for the TE-N_2 process, where space and weight are limited.

FLNG vessels must also include several auxiliary utility systems that support safe and efficient operation. These utilities include gas-fired turbines for power generation, Boil-Off Gas (BOG) compressors to control pressure in storage tanks, air compression systems, nitrogen recycling, water treatment units, and flaring systems for managing surplus gas. Additionally, the topside features are essential infrastructure, including control centers, accommodation modules, and pipe racks, all of which must be integrated into the overall vessel layout.

Storage capacity and the offloading system are vital for the economic success of FLNG projects. Typically, liquefied gas is stored in prismatic membrane tanks integrated into the hull. Unlike spherical tanks Moss-type LNG carriers, which are less suitable for compact layouts, prismatic tanks make better use of space and facilitate the installation of processing equipment above the storage area. An emerging trend is retrofitting decommissioned LNG carriers, mainly Moss-type, into FLNG units, which can significantly cut CAPEX and reduce construction time, while also providing environmental benefits through asset reuse. There are two primary offloading methods: side-by-side and tandem. The side-by-side approach involves mooring the LNG carrier alongside the FLNG unit for direct transfer using loading arms; however, this method is less effective in rough seas. Tandem offloading, on the other hand, employs cryogenic hoses for LNG transfer over longer distances, maintaining safe vessel separation, increasing safety, and expanding operation windows in harsher offshore conditions, making it the preferred method in more exposed environments.

The justification of nitrogen cycle for offshore liquefaction of natural gas instead of SMR and DMR is the flexibility and relative simplicity. This is very important in the case of offshore LNG liquefaction due to variations in ambient and feed gas conditions as well as potentially lower capital costs. On the other hand, SMR processes offer higher thermodynamic efficiency because they match the natural gas and refrigerant temperature profiles closely, but this better efficiency is more sensitive when the liquefaction plant is installed in environments where external operating conditions vary, such as on offshore platforms.

The main advantages of the nitrogen cycle are flexibility and robustness being more resilience to changes in ambient temperatures, cooling water changes and natural gas composition. Also, nitrogen cycles have simpler designs lowering the capital costs and being more suitable for more limited spaces such as offshore platforms. Dealing a single component as nitrogen is less complex to handle than a multi-component mixture.

The disadvantages of the nitrogen cycles are the lower energy efficiency resulting in higher energy operating costs due to the power consumption for compression. Being a single component (nitrogen), its boiling point presents greater temperature differences between the hot and cold streams in the heat exchanges, providing less efficient heat transfer.

7.3. ssm-FLNG Preliminary Sizing

This initial sizing aims to estimate the project's CAPEX and OPEX. During this stage, it is essential to determine the main hull dimensions, storage capacity, mooring equipment, and the piping required to transfer gas between the FPSO and the FLNG, as well as the wet gas pre-treatment at FPSO. The first step involves establishing the design premises, which can be summarized as follows:

- Maximum Production: 1 MTPA;
- Production Fraction (mass): 75% LNG/25% LPG;
- LNG mean density: 0.47 t/m^3;
- LPG mean density: 0.55 t/m^3;
- Saltwater density: 1.025 t/m^3;
- Hull Specific Volumetric weight: 0.0901 t/m^3;
- Hull weight margin: 3%;
- Ballast tank permeability: 98%;
- LNG tank permeability: 97%;

From these requirements, the next step is to determine the minimum length and width of the deck that can support the liquefaction plant and personnel living quarters. Considering a 1 MTPA production, estimates from existing projects suggest that the deck length should exceed 304 meters, and the beam should be greater than 51.6 meters. Using these minimum values as a starting point, it is possible to calculate the hull depth, assuming a typical aspect ratio of B/D = 1.7, which results in a depth of 30.0 meters.

Table 4. Modules in a typical FLNG topside classified by main functions.

Pretreatment	Liquefaction	Utilities
Turret MEG recovery (recovery and regeneration of monoethylene glycol) Equipment admission Removal of acid gas Dehydration Mercury removal	Refrigeration system Liquefaction system BOG compressor Cooling intake system	Power generators Air System Bleeding Nitrogen Flare Water treatment Accommodation Control Center Pipe rack

Source: [48]-[50].

The hull features two chamfers at the bow and stern to decrease buoyancy moments at the extremes. These chamfers are 29.8 meters long, aligning with the living quarters at the stern. Consequently, the LNG storage tank can be positioned outside the chamfer area, as the living quarters must not be located above the tank region—a key restriction imposed by most classification societies. Storage tanks for LPG and C_5+ cannot be forgotten either.

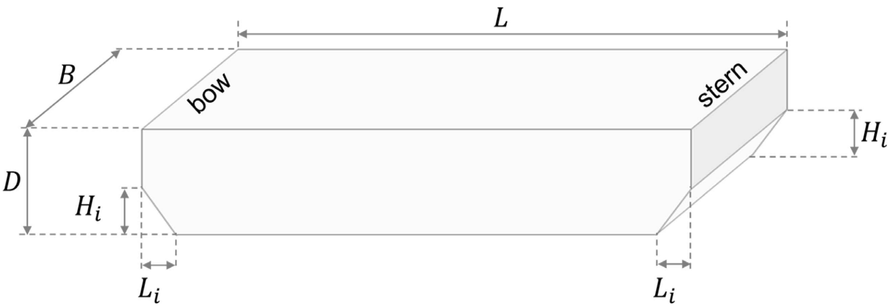


Figure 6. ssm-FLNG hull parameterization. Source: Prepared by the authors.

The main dimensions of the external hull are outlined as shown in Table 4. The geometrical relationship of each parameter is illustrated in Figure 6.

Regarding the hull's internal layout, the FLNG will feature ten tanks arranged in two rows of five. The prismatic tanks have a thermal isolation wall approximately 0.5 meters thick. These tanks are located within an area enclosed by the double bottom, double side, and double deck. The double bottom and double side can serve as water ballast tanks. The ssm-FLNG hull main dimensions are shown in Table 5. The internal arrangement dimensions are shown in Table 6 corresponding to the dimensions outlined in Figure 7.

Table 5. ssm-FLNG hull main dimensions.

Item	Description	Value	Unit.
LOA	Length overall	304.0	m
B	Beam	51.6	m
D	Depth	30.0	m
L_i	Chamfer length	29.8	m
H_i	Chamfer height	10.0	m

Source: Prepared by the authors.

These properties help improve both the initial cost assessment and ongoing operational planning for the ssm-FLNG vessel. Understanding these details enables more precise modeling of storage capacity, production rates, and the timing needed for offloading operations, which are essential for optimizing logistics and preventing unnecessary production delays. This approach supports a solid financial planning process and ensures that key hull design features align with the overall efficiency and reliability goals of the proposed system, while also providing a more detailed CAPEX and OPEX estimate.

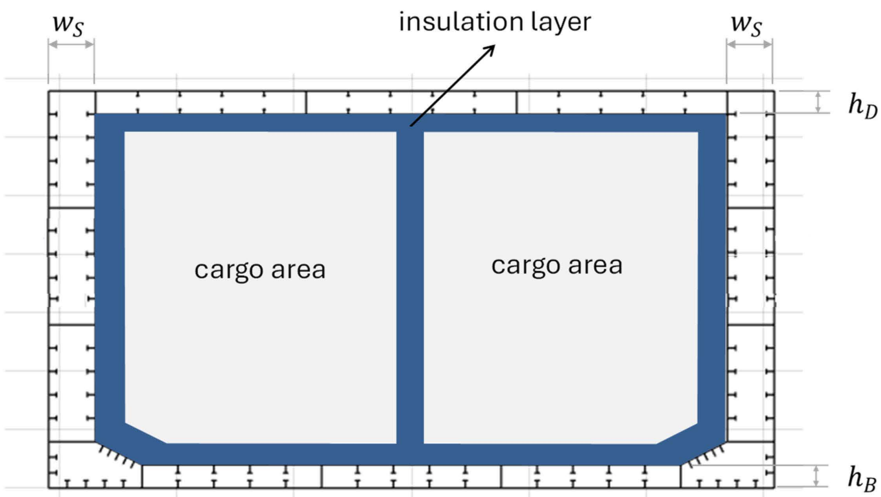


Figure 7. ssm-FLNG internal hull parameterization. Source: Prepared by the authors.

At maximum production, the ssm-FLNG is expected to produce 2740 tons of LNG. With a storage capacity of 124,127 tons, this equates to approximately 46 days of production needed to fill the tanks. The offloading operation must occur within this timeframe. A typical LNG carrier of the Q-flex class has a deadweight of 98,750 tons, which is 80% of the ssm-FLNG capacity or roughly 37 days of production. The best approach is to carry out offloading when the storage volume is near 90% full. This provides an 8% margin that can be used efficiently in logistics to avoid production stoppages, considering the maximum filling level of 98% as specified by the International Gas Carrier (IGC) Code.

Table 6. Internal hull parameters.

Item	Description	Value	Unit
w_s	Double side width	2.5	m
h_b	Double bottom height	2.5	m
h_d	Double deck height	1.0	m
L_{tank}	Length of each tank	48.6	m
B_{tank}	Width of each tank	23.3	m
H_{tank}	Height of each tank	26.5	m

Source: Prepared by the authors.

Table 7 displays the distribution weights used in the seven main areas of the ssm-FLNG. These areas include: Topside, Hull Structure, Tank Structure and Isolation Layer, LNG Cargo, Water Ballast, Mooring System, and Riser System.

Table 7. Weight and Center distribution for Full and Ballast loading conditions.

		Full Condition		**Ballast Condition**	
	Cargo	100	%	0	%
	Ballast	0	%	100	%
	Draft	15.5	m	11.7	m
	GM	3.8	m	10.4	m
#	**Item**	**Weight [t]**	**VCG [m]**	**Weight [t]**	**VCG [m]**
1	Topside	36923.0	41.9	36923.0	41.9
2	Hull Structure	43672.3	15	43672.3	15
3	Tank Struc. + Isolation	24718.6	15.75	24718.6	15.75
4	Cargo	124127.7	15.75	0.0	0
5	Ballast	0.0	0.0	63574.6	8.8
6	Mooring	2700.0	0	2700.0	0
7	Riser	570.0	0.0	570.0	0.0
	Total	**232711.6**	**19.54**	**172158.5**	**18.32**

Source: Prepared by the authors.

The first group includes the topside structures, which consist of all the process plant equipment, generator modules, and the superstructure of the living quarters. The second group is the hull structure, made up of all the steel required to construct a hull that meets classification society standards. The third weight group comprises modular tank structures and the associated cryogenic isolation layer. The fourth and fifth groups consist of the LNG in the cargo tanks and the water ballast needed to maintain system stability and an operational draft. The sixth and seventh groups include mooring lines and risers used to transfer gas from the FPSO and to return the CO_2 produced in the liquefaction plant.

Figure 8 shows the preliminary general arrangement of how the equipment described above is distributed within the ssm_FLNG hull.

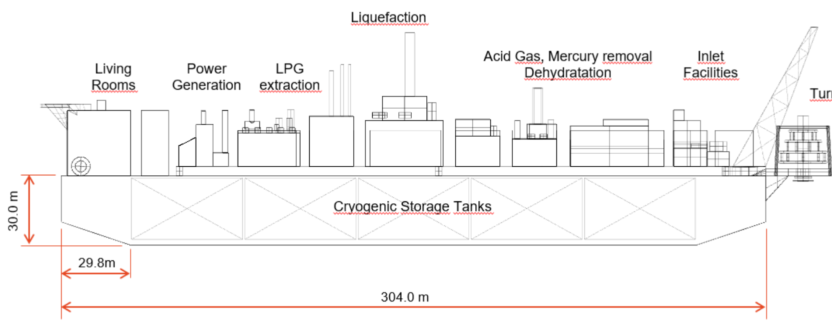


Figure 8. ssm-FLNG preliminary general arrangement. Source: Prepared by the authors.

8. Financial Assessments

The Búzios field in the Brazilian pre-salt is the largest oil and gas field in Brazil, with production projections of up to 2 million barrels per day (bpd) and colossal volumes of associated natural gas [51]. The efficient monetization of this gas is a strategic imperative, especially given the potential saturation of existing and planned pipeline infrastructure.

The study prepared by [52] an economic-financial model, developed in spreadsheets, to assess the viability of an offshore ssm-FLNG unit, focusing on monetizing the gas.

This tool enables the economic and financial evaluation of the proposed ssm-FLNG, a small-scale, modular floating platform for natural gas processing and LNG generation. The modeling assumes that this FLNG will receive natural gas with a purity level suitable for liquefaction, with all pre-processing performed by an adjacent FPSO. The oil and gas production data for the Búzios FPSOs used in this modeling are obtained from the Environmental Impact Study/Environmental Impact Report (EIA/RIMA) prepared by Petrobras for [53]-[57], ensuring a robust and regulatorily validated database, as well as from actual production data available on the ANP's production dashboard [58].

The study developed and modeled a tool that allows scenario simulations by changing input data and adjusting assumptions. The economic evaluation was conducted for a specific scenario, whose input data and assumptions were thoroughly described in previous sections of the report.

The simulation results demonstrate that the ssm-FLNG configuration added positive economic value, as evidenced by the economic viability indicators. The Net Present Value (NPV) and Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA) were favorable, indicating the project's attractiveness under the adopted assumptions.

The in-depth analysis of the financial indicators provides a robust understanding of the ssm-FLNG configuration's economic performance.

Given the scale of the Búzios field and the global demand for LNG, the [52] demonstrated a positive NPV for the FLNG unit. The FLNG's specialization in liquefaction, receiving already cleaned gas from the FPSO, optimizes the CAPEX and OPEX of the FLNG unit, contributing to greater economic attractiveness. The ability to monetize Búzios' associated gas, which might otherwise be flared or reinjected, confers additional strategic value to the project, aligning it with Brazil's energy security and resource optimization goals.

To understand the results, it is essential to comprehend the impact of the assumptions at each stage, as detailed below. The flow at each stage is described, with the contribution of **Figure 9**.

The resulting **Figure 10** illustrates the contribution of each analyzed component to the overall revenue, NPV, and EBITDA, providing an aggregated view of their effect.

This is presented as an additional contribution to the habitual oil production of the Búzios Field platforms during the production years from 2016 to 2055, covering 40 years of field production.

As a summary conclusion, we have each analysis below; however, the complete analysis of the modeling, simulations performed and assumptions considered can be consulted, in a broad and detailed manner, in the material [52].

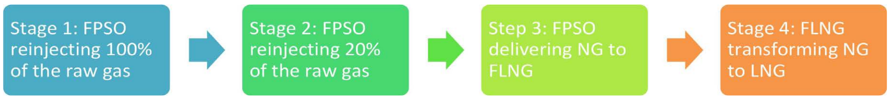
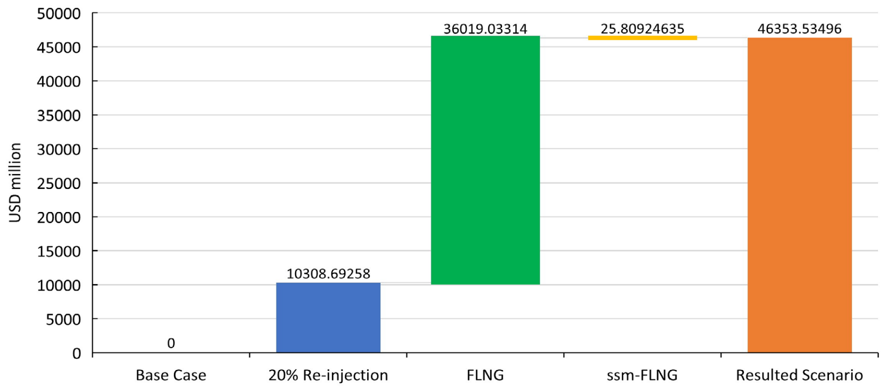
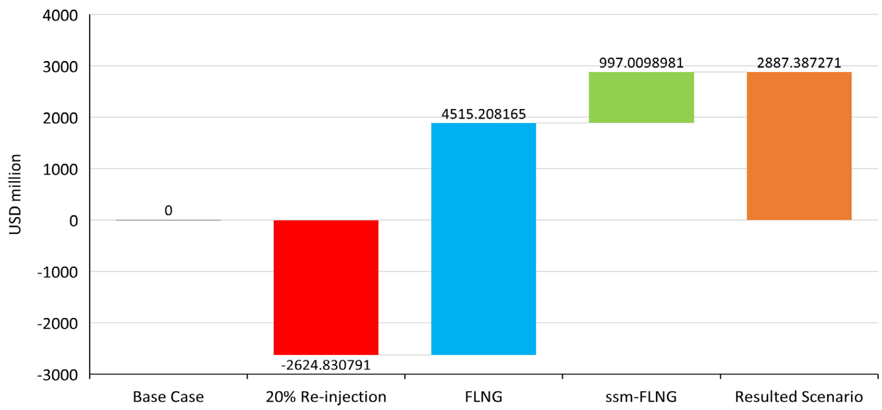


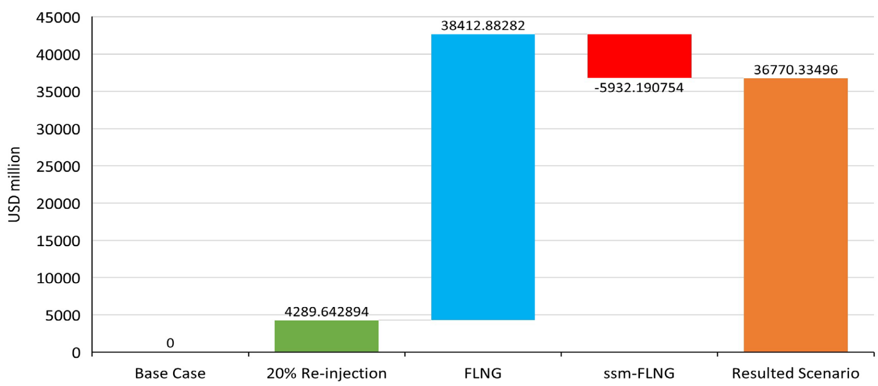
Figure 9. Division into stages from raw gas processing to transformation into LNG. Source: Authors, (2025).



(a)



(b)



(c)

Figure 10. Analysis considering all Búzios Fields over 40 years of operation: (a) Revenue increase; (b) NPV analysis; (c) EBTIDA analysis. Source: Authors, (2025).

a) Revennue Increase: The proposed system for NG utilization, which involves transforming it into LNG via an ssm-FLNG unit, demonstrates significant revenue potential over a 40-year operational period. Selling the raw NG at the wellhead would generate a total revenue of US$10.3 billion across 12 Búzios FPSOs. However, by liquefying the NG and selling it on the global market as LNG, the total revenue dramatically increases to US$46.3 billion. The implementation of the small-scale ssm-FLNG model contributes an additional US$26 million to this total, highlighting the revenue-generating advantage of processing and exporting the gas as LNG at international prices rather than simply selling it at the wellhead.

b) NPV: The NPV calculation for the ssm-FLNG configuration resulted in a positive value, indicating that the project is economically attractive. This positive NPV shows that the present value of the project's benefits is greater than the present value of its costs, generating a surplus that creates wealth for investors. Specifically, while the initial NG production on the FPSO had a negative discounted cash flow of US$ −2.6 billion, the use of FLNG resulted in a positive discounted cash flow of US4.5 billion. Ultimately, the ssm-FLNG configuration yielded a final discounted cash flow of US2.8 billion, demonstrating that the investment is financially advantageous and creates excess value.

c) EBTIDA: The EBITDA for the ssm-FLNG configuration was positive, demonstrating the project's ability to generate cash from its core operations. EBITDA is a key metric for operational profitability. It shows that the project can generate gross profits, which is crucial for covering operational costs and servicing debt. While the initial FLNG operations generated an impressive EBITDA of US38 billion, the incorporation of small-scale units reduced this by US5.9 billion, resulting in a final aggregate EBITDA of US$32.1 billion. However, it's important to note that since EBITDA doesn't account for taxes, interest, or depreciation.

To evaluate attractive ranges that yield positive results, this study simulated the extreme limits of certain variables while maintaining the evaluated indicators at a level attractive enough to justify the use of ssm-FLNG platforms.

The assumptions from Figure 11 were chosen for scenario simulations, yielding the results shown in the table. It is essential to note that these limits maintain attractive and positive results, with each assumption being varied one at a time.

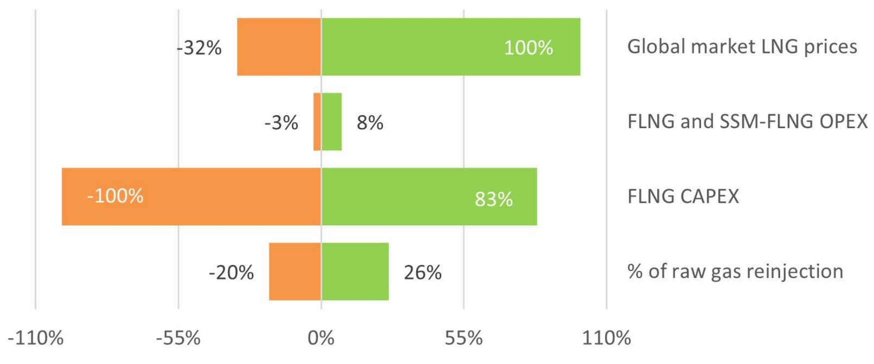


Figure 11. LNG Sensitivity analysis of the main variables. Source: Authors, 2025.

This figure uses the variables FLNG CAPEX, percentage of reinjection of raw gas, OPEX (considering the percentage of total CAPEX applied per year) or price of LNG in the global market that have a representative influence on the indicators analyzed in this work, in order to take these variables to the extreme limits, both lower and upper, without making the work indicators unviable, whether jointly or individually. The variables for the percentage of CAPEX adopted as annual OPEX cost and the reinjection percentage are measured in this work as percentages, so in this graph, they present the lower limit as the limit where they would result in a zero absolute value. The other two variables, such as the overall LNG value and FLNG CAPEX, are already in absolute financial values, meaning that their upper and lower limits reach the total percentage, depending on the case.

Analyzing **Figure 11** above helps to overcome the difficulty of this work in obtaining real OPEX and CAPEX values for the analyzed structures. In other words, even without such values, this graph allows us to understand that within the FLNG structure's CAPEX range, extrapolating up to 83% of the value considered in this work, the proposed work is still viable. This also applies to the reinjection of raw gas from −20% to 26% beyond the values considered here, as well as to the other variables, each with its own outcome.

9. Conclusions

This study aimed to provide a comprehensive overview of the Brazilian NG and liquefied natural gas LNG) market, identifying key aspects that can foster national economic prosperity and provide a clear path for companies to achieve financial viability. Our findings highlight a significant opportunity for Brazil to not only bolster its energy security but also emerge as a key player in the global LNG trade, driven by the unique characteristics of its pre-salt reserves.

The global NG and LNG markets operate as a highly interconnected system. The price of various energy products in major markets like the U.S., Europe, and Asia influences global pricing, regardless of the commodity being traded. This interconnectedness makes LNG a powerful enabler of market convergence, efficiently linking regional markets across continents. For example, fluctuations in LNG prices can indirectly affect electricity prices in Brazil by influencing the cost of gas used in local thermoelectric plants. Similarly, LNG can impact the price of fertilizers, which are essential inputs for Brazil's agricultural sector.

Our analysis demonstrates that the high prices of globally traded NG make the production of NG from Brazil's pre-salt basins economically viable. This finding is crucial because it transforms Brazil from a gas-importer to a potential large-scale producer and LNG exporter. This shift would not only ensure Brazil's energy independence but also elevate its standing in the global energy landscape.

A central conclusion of this study is the suitability of using ssm-FLNG units for offshore gas production. This approach is well-suited to the moderate production capacities of Brazil's pre-salt basins and the specific demands of the domestic market. Furthermore, this strategy offers financial feasibility by leveraging high LNG prices, which justifies the significant investments required for offshore exploration and production. By adopting this model, Brazil is positioned to join the ranks of the world's leading LNG-producing and exporting nations.

Our economic simulation, which used the Búzios field as a reference, provided compelling evidence for the financial attractiveness of the ssm-FLNG concept. The positive and robust economic results demonstrate that ssm-FLNG can be a cost-effective solution for monetizing offshore natural gas. These findings have significant practical implications for the oil and gas industry.

The confirmed viability of ssm-FLNG presents a promising path for developing associated gas fields in deep waters and remote areas where building traditional export infrastructure is either too expensive or logistically unfeasible. This viability could directly influence investment decisions and strategic planning for energy companies, positioning ssm-FLNG as a competitive alternative to conventional methods. The adoption of this technology could accelerate project development and the monetization of gas assets that were previously considered marginal.

From a theoretical perspective, our conclusions align with existing knowledge on the economic evaluation of offshore energy projects. The results provide valuable empirical data that can be used to refine analytical models for cost optimization and value maximization in complex operational environments. While these results are dependent on the specific assumptions of our simulated scenario, they offer a powerful framework for future analysis and strategic decision-making.

In summary, this study provides a roadmap for Brazil to leverage its vast pre-salt reserves and become a formidable force in the global LNG market. By embracing innovative, small-scale solutions tailored to its unique offshore environment, Brazil can unlock a new era of economic growth and energy prosperity.

The conclusions reached here are limited to the scope of this work, however, as a way of responding more broadly to the solution presented here in the context of challenges such as operational safety, efficiency and technological limitations, it is necessary to develop works focused on generating technical knowledge and conclusions, as well as carrying out case studies or simulations that illustrate real-world engineering tests and results, in order to, together with the conclusions reached here, strengthen the credibility of the solution proposed in this work.

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Conflicts of Interest

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

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