Energy and Power Engineering, 2025, 17(8), 191-216
https://www.scirp.org/journal/epe
ISSN Online: 1947-3818
ISSN Print: 1949-243X

Exploring the Synergy of Gas-Integrated Technologies in the Búzios Pre-Salt Field: A Case Study for a Pioneering Strategy in Early Monetization of Deep-Water Offshore Gas

Cristiano M. Borges[1], Lauron Arend[1*], Hirdan Katarina de Medeiros Costa[1], Daniel Prata Vieira[2], Xuefeng Hu[3], Junkai Feng[3], Kazuo Nishimoto[2], Edmilson Moutinho dos Santos[1], Marcio A. Sampaio[4]

[1]Institute of Energy and Environment, University of São Paulo, São Paulo, Brazil
[2]Department of Naval Architecture & Ocean Engineering, Polytechnic School, University of São Paulo, São Paulo, Brazil
[3]CNOOC Petroleum Brasil Ltda, Beijing, China
[4]Department of Mining and Petroleum Engineering, Polytechnic School, University of São Paulo, São Paulo, Brazil
Email: *lauron@usp.br, cristiano.borges7@gmail.com, lauron@usp.br, hirdan@usp.br, daniel.prata@usp.br, huxf@cnoocbrasil.com, fengjk@cnoocbrasil.com, knishimo@usp.br, edsantos@iee.usp.br, marciosampaio@usp.br

How to cite this paper: Borges, C.M., Arend, L., Costa, H.K.M., Vieira, D.P., Hu, X.F., Feng, J.K., Nishimoto, K., Moutinho dos Santos, E. and Sampaio, M.A. (2025) Exploring the Synergy of Gas-Integrated Technologies in the Búzios Pre-Salt Field: A Case Study for a Pioneering Strategy in Early Monetization of Deep-Water Offshore Gas. *Energy and Power Engineering*, **17**, 191-216.
https://doi.org/10.4236/epe.2025.178011

Received: June 12, 2025
Accepted: August 5, 2025
Published: August 8, 2025

Abstract

The effective utilization of natural gas from offshore fields presents both logistical and economic challenges, particularly in high associated gas production regions such as the Brazilian Santos Basin in the Pre-Salt Cluster. Conventional approaches, including methane-rich gas reinjection, often lead to economic inefficiencies and underutilized resources. This study evaluates an integrated solution that combines Small-Scale Mobile Floating Liquefied Natural Gas (ssm-FLNG) technology with a CO_2 Water-Alternating-Gas enhanced oil recovery strategy, aiming to optimize gas monetization while simultaneously supporting oil recovery and long-term CO_2 storage. Results indicate that ssm-FLNG can achieve competitive liquefaction costs, making it a feasible alternative to flaring or reinjection. Additionally, the CO_2 Water-Alternating-Gas enhanced oil recovery approach enhances oil recovery by a revenue of 5.2 billion USD, generating additional revenue streams while reducing the carbon footprint. The combined system improves overall project economics, with a projected net present value of 12 billion USD and an internal rate of return surpassing industry benchmarks. By analyzing the feasibility of this approach in the Santos Basin, this study highlights the potential for ssm-FLNG, in conjunction with CO_2 Water-Alternating-Gas enhanced oil recovery and CO_2 storage, to enhance sustainability, reduce gas wastage, and improve the economic viability of pre-salt field development.

Keywords

Monetization of Stranded Offshore Natural Gas, Floating Liquefied Natural Gas (FLNG), Small-Scale and Mobile Facilities, Techno-Economic Assessment

1. Introduction

The Santos Basin Pre-salt Cluster (SBPC) is in ultra-deep waters in Brazil [1]. According to the analysis carried out by [2], SBPC has the potential to produce more than 19.7 billion barrels of oil and 21.2 trillion standard cubic feet (scf) of natural gas and can generate up to 1.97 trillion dollars of income, assuming an oil price of 75.98 USD/bbl and a gas price of 4.0 USD/MM BTU. Having such a significant natural resource at its disposal would bring several economic and social benefits to Brazilian society. It would provide an affordable energy source for the foreseeable future, as well as income in terms of taxes and royalties, and would lead to job creation. Based on the recent analysis [2]-[4], the exploitation of the SBPC could generate up to 450 USD billion in taxes, 197 USD billion in royalties, and 20 USD billion in local Research & Development (R&D), as well as create more than one million jobs [3]. The latter is currently addressing a critical need in Brazil.

Exploiting this natural resource could achieve social and economic prosperity, but it requires overcoming significant exploration and environmental issues. The former arises from operating at challenging water depths far from the coast and dealing with high-pressure and high-temperature reservoirs spread over large areas immediately below a thick salt layer. The latter arises from dealing with large amounts of associated gas with a high CO_2 content.

In the Santos Basin Pre-Salt Cluster (SBPC), a significant portion of natural gas (NG) production is currently utilized for energy generation on the production platform and reinjected into the reservoir along with CO_2 to maintain pressure and enhance oil recovery. While this reinjection strategy maximizes reservoir utilization, redirecting NG towards commercialization presents an opportunity to improve the economic viability of the basin. By monetizing NG through a small-scale Floating Liquefied Natural Gas (FLNG) approach, local financial benefits can be realized through increased revenues, job creation, and infrastructure development. Additionally, this strategy offers an affordable and scalable solution for a developing country like Brazil, enabling better resource utilization while reducing reliance on more capital-intensive gas infrastructure. To ensure a comprehensive assessment, this study quantitatively compares the economic and operational trade-offs between NG reinjection for enhanced oil recovery (EOR) and NG commercialization via FLNG, presenting clear data in tables to highlight the local benefits and overall financial impact of each approach.

Considering that NG is a fossil fuel that emits the least CO_2 per kilogram of fuel, owing to the high hydrogen-carbon ratio of its main component, methane [5] [6], it is considered a cleaner fuel if compared to other fossil fuels [7]-[9]. Ensuring energy supply within the energy transition period until the share of renewable energy sources completely meets the growing global demand for energy, with NG seen as a transition fuel [10], and will help to reduce greenhouse gas emissions and improve worldwide sustainability [11]. The use of NG has been growing since the 21st century due to its clean-burning properties. It is predicted to be the second largest fuel in the global energy matrix, right after oil, according to the International Energy Agency's forecast (IEA) [12] [13].

The global concern with reducing greenhouse gas (GHG) emissions makes NG more relevant than ever. Where strict environmental regulations, concerns about energy security, and increased competition have made countries and companies increase their use of NG, causing an increase in supply [14]. This exploration is moving towards remote offshore ultra-deepwater areas, with shore distances from the coast over 250 km involving high NG transportation costs [15] [16].

The problematic production environment of SPBC, including the need to manage associated gases, both CH_4 and CO_2 streams, the lack of gas pipelines, and potential environmental hazards, has already been discussed in literature by several authors [15] [17]-[25]. The consensus is that the main technological barrier to be overcome is how to optimally extract oil with associated gas at a high gas-oil-ratio (GOR) and how to deal with the high CO_2 content of the produced gas. In addition to the lack of sufficient infrastructure to move natural gas to onshore consumption centers, the high CO_2 content within the gas stream makes it difficult to achieve the necessary financial thresholds to justify the monetization of associated gas. Consequently, the current view is that most of the associated gas produced will be reinjected and may not be appropriately monetized. If this is the case, Brazilian society will not capture the benefits of having access to this readily available energy source, which otherwise could play a significant role in the country's forthcoming energy transition strategy. In this work, we explore alternative approaches to avoid re-injecting the whole gas stream using gas-integrated technologies that can offer viable alternatives.

Several works have already looked at viable alternatives. [26] evaluated CO_2 separation alternatives by considering early enhanced oil recovery (EOR) as the CO_2 destination. [27] provided a laboratory displacement study of several Water-alternating gas (WAG) methods for improving oil recovery by considering two options: associated gas/water and CO_2/water injections. Based on this work, it is possible to assume that CO_2-WAG anticipates oil production, even though it might reduce the total oil recovery when it achieves recoverable levels above 80%, which is not the case in this field on an operational scale. [28] and [29] indicate that CO_2 injection is an efficient EOR method. It improves the oil recovery factor by providing temperature and pressure so that all the CO_2 is dissolved in oil. [30] and [31] performed an economic evaluation of CO_2-EOR combined with CO_2 storage, showing that deploying this technology results in better cash flows from oil production. Bachu (2000) [32] stated that CO_2 disposal in sedimentary basins is the best option currently available for the long-term sequestration of CO_2.

Even within the global energy transition scenario, oil and natural gas are still expected to supply more than half of the world's energy supply for the next 30 years. To serve the value chain of these energy sources, they will need to be transported safely and with the best respect for the environment. This is crucial to maintaining each country's economic success and providing a sustainable domestic energy supply for the future [33].

Therefore, the main objectives of this work are to analyze the key technical and economic factors influencing the viability and competitiveness of ssm-FLNG integrated with CO_2-WAG and CO_2 storage. Additionally, this study aims to propose strategies for optimizing the management of CH_4 and CO_2 streams in the SBPC field, reducing environmental impact while maximizing resource utilization. The findings may provide valuable insights for policymakers and investors in implementing gas-integrated technologies efficiently in Brazil and other regions.

The lack of current infrastructure in SBPC raises serious issues about how to transport natural gas most efficiently to the coastal sites. Liquifying natural gas also offers a plausible alternative to pipelines. Alkhatib (2009) [34] conducted a historical overview of the development of the liquefied natural gas (LNG) industry, indicating that it represents the only economical alternative to natural gas transport by pipelines. It also provides greater flexibility in contrast to pipelines.

LNG provides a safer and more economical alternative for transportation and increases its storage capacity. The liquefaction process involves cooling the NG through various cryogenic methods and depressurizing it to atmospheric conditions for easier and safer storage. LNG transported in cryogenic vessels offers several advantages compared to natural gas transport through pipelines, especially when gas-consuming areas are far from gas-producing areas, as occurs in the high seas offshore production scenario [9]. To reduce the costs of transporting NG over long distances, the use of LNG has become a good opportunity, with transport requiring less investment compared to the gas pipeline option [9], making it a viable fuel for long-distance tankers with a cleaner life cycle compared to traditional fuels [35]. LNG production has experienced significant growth in recent years across the world, which has been reinforced by current geopolitical crises between Russia and Europe [36], with liquefaction technology accounting for around half of all costs related to the use of LNG for transportation [8] [37]. Since LNG is a clean energy source, it creates an opportunity to diversify energy supplies for many countries, become recognized in all energy markets [38], and be categorized as a global commodity [12].

Markou (2016) [39] performed a detailed and more recent review of LNG-related technologies, as well as an in-depth analysis of the status of the market by 2015, indicating that one of the significant trends in LNG technology is to extend it to offshore application by employing floating LNG technology (FLNG), and with that, the new technical challenges that need to be investigated and studied to overcome the new restrictions raised by offshore operability, as projects must be implemented in areas with safe environmental conditions where effects such as the movement of floating structures combined with design and operating parameters that will affect the behavior of LNG inside partially filled tanks, among other technical concerns, must be considered [29] [40] [41].

Wang & Liu (2014) [42] proposed a development plan for using FLNG in China and concluded that FLNG technology would be practical and feasible for developing difficult-to-produce offshore reservoirs. Bukowski *et al.* (2011) [43] discussed the challenges related to liquefaction on a floating platform, including the motion of the production vessel (significant in less favorable ocean conditions), weight and space limitations, and corrosion and flammability issues. They indicate that some issues can be addressed using new purpose-built heat exchangers and compressors offering exceptional mechanical strength and performance. Rattanavich & Thompson (2012) [44] stated that small-scale FLNG (ssm-FLNG) projects usually face diseconomies of scale in comparison to larger plants. Nevertheless, the advantages of constructing SS-FLNG plants are faster construction time, simpler liquefaction processes, lower maintenance, and lower initial capital costs. Those are essential positive aspects of ss-FLNG regardless of any other additional advantage associated with marketing strategies for produced gas. Tan & Barton (2015) [45] investigated the deployment of onshore mobile (and modular) SS-LNG plants (SSM-LNG) as an attractive alternative to offshore gas monetization. The author proposes a multi-period optimization framework that determines the optimal dynamic allocation and operating decisions, considering time-varying supply, price, and demand. The work indicates that utilizing mobile plants offered a profitable and flexible method to monetize associated gas in the Bakken shale play in the Mississippi region.

The commercial exploration of remote, small, and less accessible gas fields, or even the use of basins composed of several fields with different periods of exploration over the years, will require the development of new technologies suitable for such activity. LNG technologies are a possible solution for the exploitation of such fields. However, economies of scale are not favorable to financial analysis; restrictions on offshore installation and adverse environmental conditions require compact solutions to be efficient. Even though several liquefaction technologies have become available for small and medium-sized LNG facilities during the last decade, comparing these technologies from an economic point of view is limited to process efficiency and some qualitative parameters [46]. Along with the increase in the spot LNG market and the development of offshore technologies, companies and designers focus on the small-scale LNG market, providing the development of new and modern LNG structures for this scale of production [14].

Although a few techniques have been studied to address the noted production and environmental issues, the previous works have neither systematically analyzed the techno-economic performance nor examined the benefits of combining different technologies. Therefore, in this study, we perform a techno-economic evaluation of a particular gas-integrated technology comprising small-scale mobile FLNG plants (ssm-FLNG) operating with CO_2-WAG-EOR and CO_2-storage.

2. Methodology

To ensure a structured, transparent, and replicable approach, this study develops a comprehensive techno-economic model for evaluating the deployment of small-scale mobile Floating Liquefied Natural Gas (ssm-FLNG) combined with CO_2-Water-Alternating-Gas (CO_2-WAG) enhanced oil recovery and permanent CO_2 storage. The methodology follows a systematic step-by-step framework, making it adaptable for future research on similar offshore gas fields. By integrating gas monetization strategies into existing economic models, the study enhances prior analyses by offering a more holistic evaluation of offshore gas development. However, it is important to acknowledge the limitations associated with the assumptions and constraints within the model, as discussed in detail below.

2.1. Study Scope and Selection Criteria

This study focuses on the Búzios field, one of the largest fields in the Santos Basin Pre-Salt Cluster (SBPC). The field was selected based on its high gas-oil ratio (GOR) and elevated CO_2 content [47]-[52], making it a representative case for broader application within the SBPC. The estimated potential volume of natural gas to be produced in the Búzios field is approximately 5.4 billion m^3/year, equivalent to 15.04% of Brazil's total NG consumption [51]. This selection criterion ensures that the methodology can serve as a reference for other similar pre-salt reservoirs. While the case study approach provides valuable insights, one key limitation is that the findings may not be fully generalizable to fields with significantly different geological and economic conditions.

2.2. Development of the Techno-Economic Model

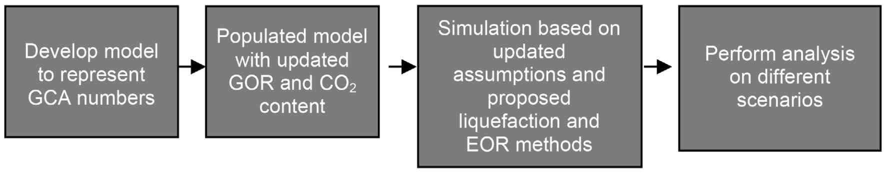
The foundation of this study's methodology is the development of a techno-economic model based on the work of Gaffney, Cline & Associates (GCA) [2], which performed a review and economic evaluation of ten selected prospects in SBPC. The Brazilian National Agency for Petroleum, Natural Gas, and Biofuels (ANP) originally commissioned GCA to assess hydrocarbon resources, with a primary focus on oil volumes. Our study expands upon this benchmark by integrating gas monetization strategies into the model, making it more relevant in the context of energy transition and carbon management.

One of the strengths of this approach is its ability to incorporate updated data and real-world constraints, improving the accuracy of economic projections. However, a limitation is the reliance on assumptions regarding future market conditions and policy frameworks, which may evolve in unpredictable ways.

2.3. Data Collection and Model Calibration

To refine the production profiles, we incorporated updated GOR and CO_2 content data from Petrobras reports submitted to IBAMA. This step ensured that the analysis reflects the latest field conditions and production constraints. Additionally, based on [27], we simulated the impact of liquefying the CH_4-rich stream via ssm-FLNG after gas separation, while the CO_2-rich stream was reinjected using the CO_2-WAG method for enhanced oil recovery and permanent CO_2 storage. The model was calibrated against historical production data to improve accuracy.

A key strength of this methodology is its reliance on empirical calibration, which enhances model reliability. However, the availability of high-quality field data remains a potential limitation, as missing or outdated information could affect model precision.



Source: Prepared by author (2025).

Figure 1. Schematic representation of research methodology.

Figure 1 has a simplified representation of the described methodology, which starts by developing a techno-economic model to represent GCA numbers, passing through populating the model, performing a simulation, and finally performing the required analysis.

2.4. Scenario Analysis

Table 1. A summary of key data input that is relevant to explain our methodology and analysis.

	Base	Expected	High	Low
GOR (m^3/m^3)	197.38	353.58	426.47	197.38
CO_2 (%)	-	32.77%	48.50%	24.30%
Oil Prices (USD/bbl)	75.98	50.00	75.00	25.00
NG Prices (USD/MM BTU)	4.00	5.50	8.25	2.75
Unit Capex LNG (USD/MTPA)	-	1000	800	1200
Unit Capex SSLNG (USD/MTPA)	-	1070	856	1284
Δ Opex LNG and SSM-FLNG as a function of Δ Capex	-	5.00%	4.00%	6.00%

Sources: [2] [51] [55], and author's estimation.

To assess the economic feasibility of the proposed solution, four distinct scenarios were modeled:

Base Case Scenario (Benchmark): GCA's original evaluation, considering conventional WAG reinjection of associated gases.

Expected Case Scenario: Incorporates updated assumptions with the most probable outcomes.

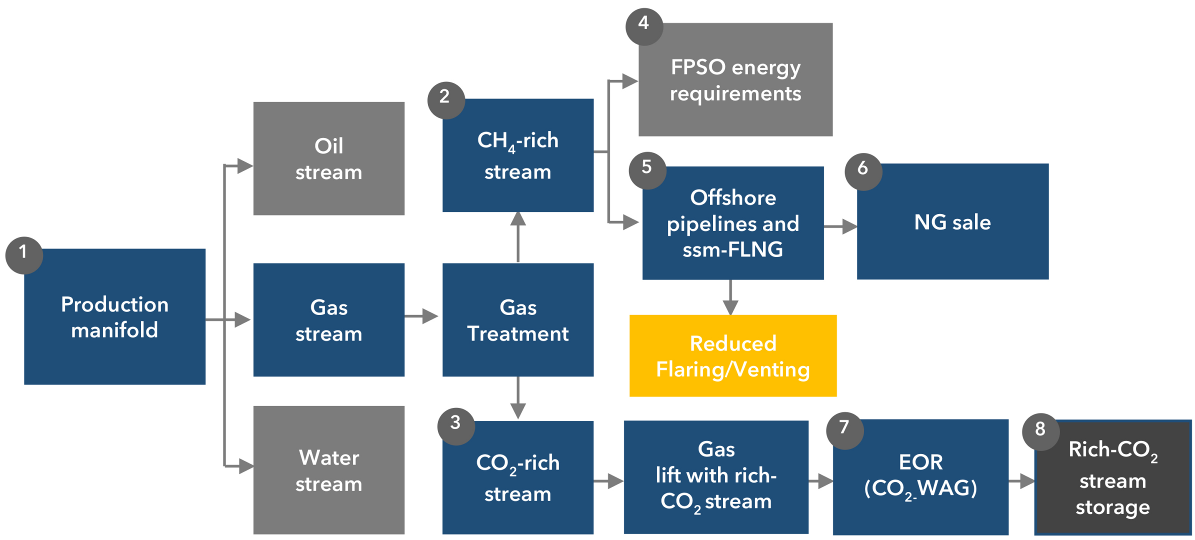
High Case Scenario: Assumes improved economic results, driven by favorable market conditions.

Low Case Scenario: Represents a conservative estimate with unfavorable economic conditions.

The key assumptions driving these scenarios—including oil prices, NG prices, unit capital expenditure (Capex), and operational expenditure (Opex)—are summarized in Table 1. The structured scenario framework allows for straightforward replication in future studies on similar offshore reservoirs. While this approach provides a robust comparative framework, a key limitation is the inherent uncertainty in forecasting long-term economic and policy trends.

2.5. Simulation of Gas Management Strategies

A comparative analysis between the conventional gas management approach and the proposed gas management strategy was conducted. Figure 2 and Figure 3 illustrate these approaches:



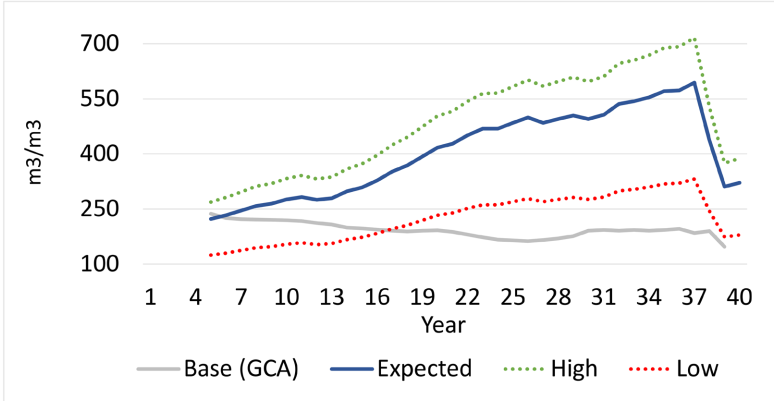
Source: Prepared by author (2025).

Figure 2. Proposed gas management (Búzios Pre-salt field).

Conventional Approach: The CH_4-rich stream is primarily used as fuel for the FPSO, with any surplus either reinjected with CO_2 (WAG) or flared if reinjection capacity is exceeded.

Proposed Approach: Deploys ssm-FLNG to commercialize the CH_4-rich stream, reducing flaring and venting while optimizing CO_2-WAG for enhanced oil recovery and permanent CO_2 storage.

A key advantage of this comparative analysis is that it highlights the potential environmental and economic benefits of the proposed approach. However, one limitation is that external factors such as regulatory changes, infrastructure constraints, and market dynamics could influence the actual feasibility of large-scale implementation.



Source: Author's model (2025).

Figure 3. Gas-oil-ratio (GOR), Búzios Pre-salt field.

2.6. Economic and Environmental Assessment

The impact of each scenario was evaluated based on key performance indicators, including:

a. Oil and gas production profiles;

b. Capital and operational expenditures (Capex/Opex);

c. Revenue projections;

d. Net present value (NPV) calculations.

The methodology applies a sensitivity analysis to account for fluctuations in oil and gas prices, plant utilization rates, and cost variations, ensuring that the findings are robust and generalizable to other offshore fields. While the inclusion of sensitivity analysis strengthens the model's applicability, the limitation remains that it cannot fully account for disruptive technological changes or policy shifts that could impact long-term project viability.

2.7. Replicability and Future Applications

To facilitate replication of this methodology in other studies, we provide a clear breakdown of assumptions, data sources, and modeling parameters. The structured approach—including stepwise model development, data calibration, scenario analysis, and sensitivity testing—ensures adaptability to different offshore environments with varying reservoir conditions.

Researchers can apply this framework to assess gas monetization strategies in other developing countries facing similar challenges in balancing economic viability with sustainable resource management. However, one key limitation is that this methodology does not explicitly account for geopolitical risks, financing constraints, or operational challenges unique to each region, which may affect its practical implementation.

3. Technical Aspects

This section provides a detailed examination of the technical considerations underlying this study, focusing on the gas-oil ratio (GOR), CO_2 content in the gas stream, and the integration of gas monetization technologies, including ssm-FLNG and EOR (CO_2-WAG).

3.1. Gas-Oil Ratio (GOR)

The gas-oil ratio (GOR) is a fundamental parameter influencing hydrocarbon field profitability and the feasibility of gas monetization strategies. It represents the volume of gas released per unit of oil produced under standard conditions. In this study, GOR values were estimated based on data from Gaffney *et al.* (2010) [2] and Petrobras reports [47]-[52], ranging between 184.34 and 426.47 m^3/m^3. This variability affects not only the volume of methane (CH_4) available for commercialization but also the technical and economic feasibility of gas utilization solutions.

3.2. CO_2 Content in the Gas Stream

The concentration of CO_2 in the associated gas stream is a key factor in determining the commercial value of methane and the operational requirements for gas processing and transportation. High CO_2 levels can lead to increased processing costs, pipeline corrosion risks, and lower hydrocarbon revenues. However, when effectively managed, CO_2 can be reinjected into reservoirs as part of an Enhanced Oil Recovery (EOR) strategy, improving oil recovery rates while simultaneously serving as a means of permanent CO_2 storage. Based on Petrobras' production forecasts [51], the CO_2 content in the gas stream at the Búzios field varies between 24.30% and 48.50%, reinforcing the need for integrated CO_2 management strategies.

3.3. Gas Monetization and Enhanced Oil Recovery Technologies

To maximize the economic potential of the Búzios field while addressing CO_2 emissions, this study evaluates three complementary technologies:

Liquefied Natural Gas (LNG): A conventional approach for transporting natural gas in liquid form via cryogenic cooling.

Small-Scale Mobile Floating Liquefied Natural Gas (ssm-FLNG): A flexible offshore liquefaction solution tailored for fields with variable gas output.

Enhanced Oil Recovery with CO_2 Storage (CO_2-WAG): A method to boost oil production while providing a long-term CO_2 sequestration solution.

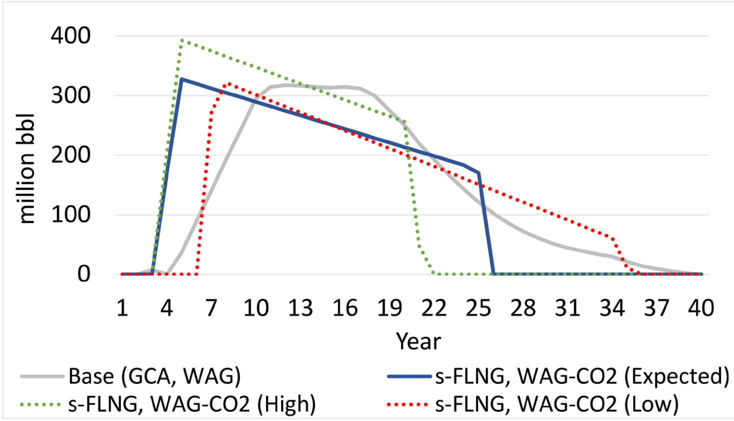
Each of these technologies plays a distinct role in optimizing CH_4 and CO_2 management, as described below.

3.3.1. Liquefied Natural Gas (LNG)

LNG involves cooling natural gas to cryogenic temperatures (−162˚C) to convert it into a liquid state for transportation and storage. This well-established technology enables large-scale gas exports and has evolved into a cost-effective solution for global gas markets [19]. In the context of the Búzios field, LNG provides a stable monetization pathway, particularly for CH_4-rich streams that exceed local demand or pipeline transport capacity.

3.3.2. Small-Scale Mobile Floating Liquefied Natural Gas (ssm-FLNG)

Unlike conventional large-scale LNG plants, Small-Scale Mobile Floating Liquefied Natural Gas (ssm-FLNG) offers a more adaptable solution for offshore gas monetization. This technology integrates gas processing and liquefaction on a floating unit, allowing it to be deployed near production facilities and relocated as needed.



Source: Author's model (2025).

Figure 4. Oil production based on different GOR assumptions and EOR methods, Búzios Pre-salt field.

In this study, a dynamic allocation model (**Figure 4**) illustrates how SSM-FLNG can optimize CH_4 utilization in the Búzios field:

Phase A: Initial deployment of ssm-FLNG units near FPSOs with high CH_4 availability.

Phase B: Relocation of units to FPSOs with increasing CH_4 output.

Phase C: Further redeployment within the Santos Basin Pre-Salt Cluster (SBPC) as localized CH_4 reserves decline.

The key advantage of ssm-FLNG is its ability to adjust production capacity based on gas availability, reducing the financial risks associated with large-scale infrastructure investments [45]. Additionally, it minimizes flaring and venting by commercializing CH_4 that would otherwise be wasted. However, technical challenges such as start-up/shutdown stability, gas composition variability, and offloading safety under offshore conditions must be carefully managed [34]. In this study, ssm-FLNG utilization rates were modeled between 33.33% and 87.00%, reflecting different operational scenarios.

3.3.3. Enhanced Oil Recovery with CO_2 Storage (CO_2-WAG)

CO_2 injection is widely used in Enhanced Oil Recovery (EOR) to improve oil displacement efficiency and increase overall recovery factor [28] [53]. The Water Alternating Gas (WAG) method enhances this process by periodically injecting CO_2

and water in alternating cycles, maximizing oil production while simultaneously facilitating long-term CO_2 sequestration [54].

This study integrates CO_2-WAG into the techno-economic model to evaluate its impact on oil production, gas management, and project economics. Key considerations include: a) Oil Recovery Optimization: CO_2-WAG enhances oil displacement efficiency, increasing the recovery factor beyond conventional methods; b) CO_2 Storage Potential: The method provides a dual benefit by securely storing CO_2 underground, mitigating emissions from hydro-carbon production; c) Economic Sensitivity: Multiple production scenarios (expected, high, and low cases) assess the viability of CO_2-WAG adoption under different market conditions; d) By incorporating CO_2-WAG into the overall field development strategy, this approach aligns with global sustainability goals while improving project economics.

4. Economic Aspects

This section introduces key economic factors affecting gas-integrated technology deployment, focusing on price volatility and commercial feasibility.

Oil and Gas Prices

Price volatility represents a significant challenge for investment decisions. Historical oil prices (**Figure 5**) have ranged from USD 10.00 to USD 123.00 per barrel in real terms. Based on these fluctuations, this study assumes a base oil price of USD 50.00 per barrel, with a sensitivity range of −50% (USD 25.00) and +50% (USD 75.00) to reflect market uncertainties.

5. Commercial Aspects

Market access remains a qualitative value driver excluded from the techno-economic model but crucial for assessing business feasibility. The Brazilian oil and gas market includes 88 exploration and production companies, with Petrobras controlling 95% of gas production. This market concentration creates barriers for independent producers, making gas monetization heavily dependent on Petrobras' infrastructure investments.

Floating regasification vessels offer a potential solution, providing flexibility for new operations in areas with limited infrastructure. These units can accelerate market entry and reduce investment costs, making natural gas from pre-salt reserves more accessible to end consumers, particularly in southeastern Brazil.

Data for Modeling

For modeling purposes, LNG plant capacity was considered 1.0 MTPA based on information from [55], and for ssm-FLNG, a plant capacity of 0.5 MTPA was assumed. It was believed that plants should achieve at least 33.33% of nameplate capacity; otherwise, they would not be implemented due to excessive idle capacity. Conversely, it was presumed that liquefaction plants do not exceed 87.00% of nameplate capacity.

In the case of critical assumptions, in the GCA base case scenario, the oil price was considered at 75.98 USD/bbl and increased annually by inflation (2.0% per year). In the expected case, the oil price was considered at 50.00 USD/bbl and the natural gas price at the wellhead at 5.50 USD/bbl, both with a 50% plus and minus variation for high and low scenarios, increasing by inflation over the years (2.0% per year).

According to the International Gas Union (IGU), plant costs vary widely and depend on oil and gas prices, location, capacity, and liquefaction process, among other cost drivers. The average liquefaction estimated by IGU for 2017-2022 is around 500 to 1541 USD/tonne (IGU, 2017). Based on that information and the correlation between Capex and oil prices, a unitary floating capital expense (Capex) was assumed to range from 800 to 1200 USD/tonne, with the expected case at 1000 USD/tonne.

In the case of ssm-FLNG, an additional unitary Capex of 7.00% was assumed, mainly due to the diseconomy of scale and mobility requirements, delivering an equivalent value of USD 1070 USD/tonne. This additional Capex for ssm-FLNG considers the net effect between diseconomy of scale partially compensated by savings relating to reducing space utilization on the Floating Production Storage and Offloading (FPSO) deck. Then, a 20% plus and minus variation was considered for high and low scenarios. In **Table 1**, there is a summary of Capex for base, expected, high, and low cases.

Finally, regarding operational expenses (Opex), it was assumed that applying the evaluated gas-integrated technologies would result in a minor increase in Opex. Since most of the Opex is linked to the existing oil and gas production system, including treating the associated gas, we assumed that annual operational expenses relating to the deployment of integrated-gas technologies will vary in line with yearly corresponding capital expenses variance, based on the following metric: Δ Annual Opex = Δ Annual Capex X 5%. This rationale applies to either FLNG or ssm-FLNG technologies.

This work proposes to develop an alternative and improved management of gas streams by promoting a better allocation of natural gas (CH_4-rich stream) and carbon dioxide streams (CO_2-rich stream). The hypothesis is that the appropriate allocation and monetization of CH_4 and the enhanced substitution of WAG by CO_2-WAG improve these products' profitability and intrinsic utility. To achieve this goal, it is necessary to fill the logistics gap through the effective deployment of ssm-FLNG combined with enhanced oil recovery (CO_2-WAG) and permanent storage of CO_2.

Figure 2 shows a schematic description of the conventional gas management (base case) versus the proposed gas management, considering deploying ssm-FLNG in the Búzios field. The process starts in the production manifold (1), where you separate oil, gas, and water. Then, the gas, a by-product of oil production, is treated and split into two major streams. One stream (2) is rich in natural gas

(CH_4), and the other (3) is rich in carbon dioxide (CO_2).

In conventional gas management, the CH_4-rich stream is primarily used to fuel the FPSO (4), and the remaining volume is used for gas lifting and sold through pipelines whenever possible (5 and 6). If, at this point, there is still CH_4 available, it will join the CO_2-rich stream and be reinjected (WAG) (7). Finally, there is still residual CH_4 that cannot be reinjected for any technical reason. In that case, it will be sent to flaring or venting, which has environmental issues (highlighted in the red box). Therefore, the proposed strategy is to allocate as many volumes of CH_4 as possible to commercial activities that will allow its monetization, such as final users' electricity production, transportation fuel, and high-value chemicals. In the case of the CO_2-rich stream, the goal is to allocate as much as possible volumes of CO_2 to sweep oil from reservoirs based on the theory that pure CO_2-rich streams have better sweeping properties than a mixed gas stream [56].

Figure 2 represents the proposed gas management, which aims to increase the sales volume of CH_4 by offshore pipelines and ssm-FLNG units (5). Consequently, the flaring and venting of CH_4 would be reduced compared to the conventional process described in **Figure 2**. At the same time, most of the rich CO_2 stream would be allocated to low-value activities such as gas lifting and CO_2-WAG enhanced oil recovery (7) with permanent CO_2 storage (8).

6. Results

The model outputs are the revised profile of oil and gas production curves with corresponding Capex, Opex, and economic indicators, such as revenue and net present value, which are detailed in this section. The equations of oil production curves are indicated in **Table 2**.

Table 2. Equations of oil production curves.

	Oil production curves per year (MM bbl./year, year 1 to 40)	
Base Case (WAG)	$y = 5.0062x^2 + 396.48x - 2257.5$	(1)
Expected Case (CO_2-WAG)	$y = -3.7941x^2 + 361.46x - 1213.7$	(2)
High Case (CO_2-WAG)	$y = -4.5529x^2 + 43{,}375x - 1456.4$	(3)
Low Case (CO_2-WAG)	$y = -3.1617x^2 + 301.21x - 1011.4$	(4)

Source: Author's model (2025).

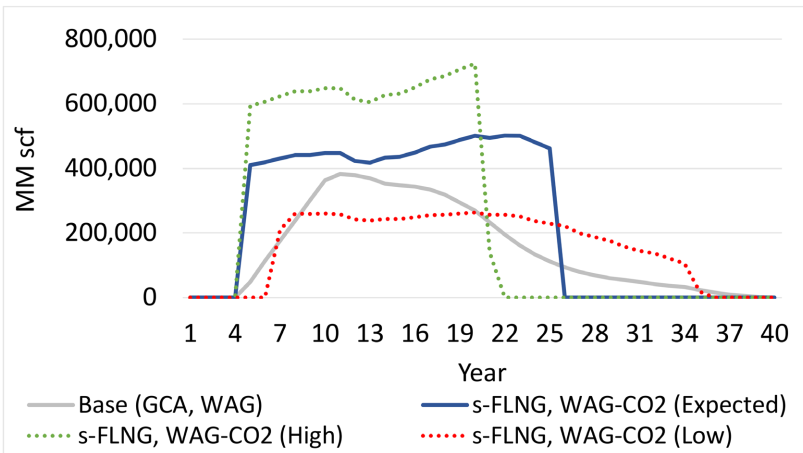
6.1. Production Profile

Figure 3 represents four scenarios of the gas-oil ratio (GOR) over the production cycle. There is the base case scenario, based on Gaffney *et al.* (2010) [2], and there are the expected, high, and low case scenarios, based on updated information from Petrobras.

The grey line represents the base case [2]. The peak is in year 5 (GORmax 237.05 m^3/m^3) and slightly reduces over time, reaching year 26 (162.82 m^3/m^3), and then there is a reversal, and GOR starts growing gradually until year 36, reaching 196.65 m^3/m^3. From year 36 onwards, GOR presents a sharp reduction, going to 147.00 m^3/m^3 in year 39 just before ending its production lifetime by the 40th year. The blue line represents the revised expected case, the dotted green line represents the high case, and the dotted red line represents the low case.

This work reviews the values and shape of the GOR curve over the project lifecycle and, consequently, on oil and gas production curves. In the specific case of GOR, the original curve decreased over time, and the updated curves (expected, high, and low cases) increased over time. The updated shape of the curves was calculated based on the forecasted oil and gas volumes that Petrobras informed IBAMA [52]. This new shape, which has a higher GOR over time, is also consistent with enhanced oil recovery (EOR), considering gas reinjection. Unlike the base case, the expected, high, and low cases, GOR consistently grows from year five to the peak of production by year 37.

Using the same scheme of colors and line types, in **Figure 4**, the grey line indicates the base case forecasted oil production by [2]. The production ramp-up starts in year 5 and goes up to year 11, when it reaches a plateau until year 18, and then goes down. Simulating new oil production, considering updated GOR and CO_2-WAG application as the enhanced oil recovery method, there is an anticipation in oil production compared to the GCA base case. It was assumed that the CO_2-WAG method anticipates oil production in all updated scenarios, keeping the same amount of total oil recovery by the end of the production lifetime, as indicated by Ahmadi *et al.*'s (2015) study.



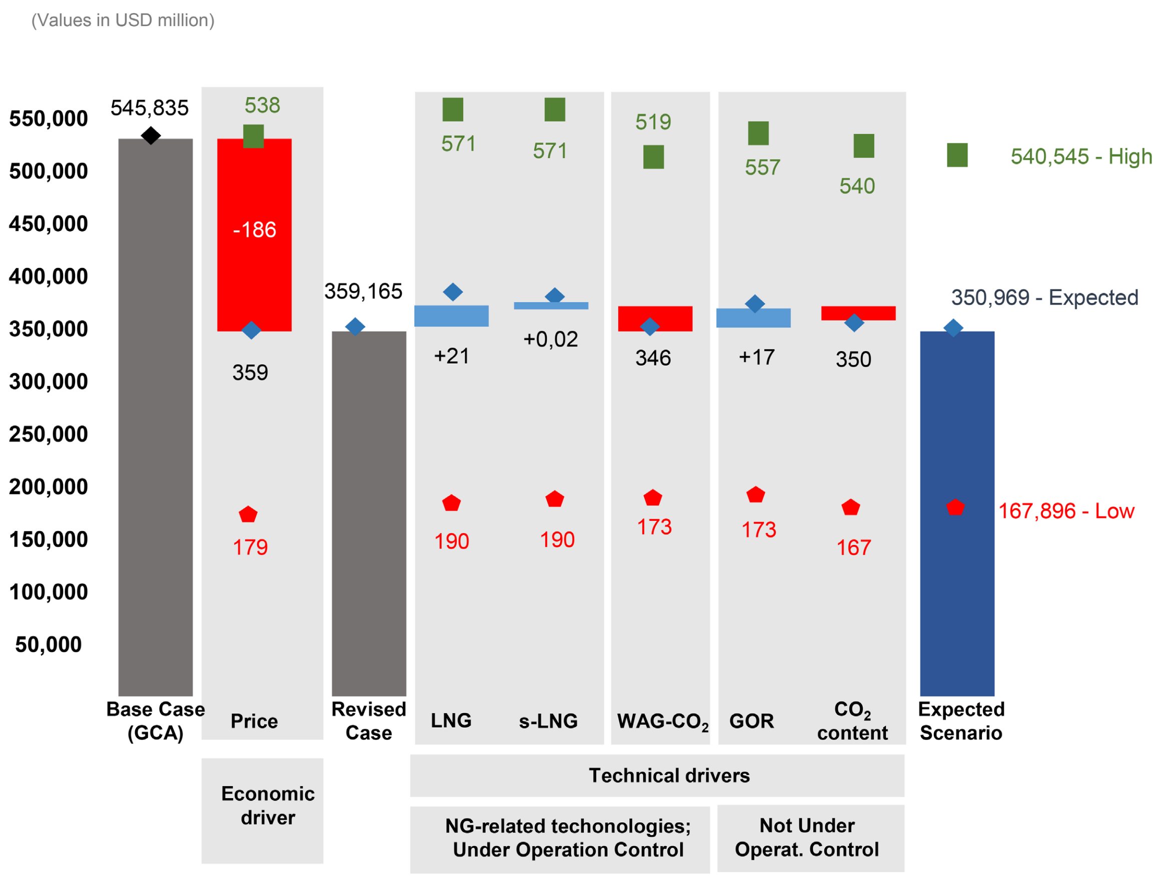
Source: Author's model (2025).

Figure 5. Gas production based on different GOR assumptions and EOR methods, Búzios Pre-salt field.

The following figure utilizes the same scheme of colors and lines as the previous figures. Thus, the grey line indicates the base case forecasted oil production by [2], and the other lines show the impact of GOR variance and CO_2-WAG application in gas production. As indicated in **Figure 5**, the material variance of gas production over the years can imply a material idle capacity of assets or monetizing a tiny portion of the total produced gas, resulting in poor economic results. Thus, deploying mobile, modular plants, such as ssm-FLNG, has been identified as an attractive solution to overcome that issue [44]. Thus, assuming the possibility of allocating these plants with higher utilization rates improves the project's financial numbers.

6.2. Revenue Breakdown and Corresponding Benefits for Society and Industry

Gaffney *et al.* (2010) [2] estimated revenue generation from the Búzios field at 545.84 USD billion (oil price at 75.98 USD/bbl). This work revised the financial evaluation initially developed by Gaffney *et al.* [2], considering updated and complementary techno-economic information over the last years.



Source: Authors' economic model (2025).

Figure 6. Revenue analysis considers base, expected, high, and low scenarios.

The first point to highlight in the revenue analysis is related to oil and natural gas prices, representing a non-technical factor outside operational control. This factor has the most considerable impact on the base case revenue forecast. The revised prices reduced revenues by 186.67 USD billion (−34%). It is mainly driven by an oil price update that, in the expected scenario, reduces from 75.98 to 50.00 USD/bbl (−34%). On the other hand, the price of natural gas is expected to increase from 4.00 to 5.50 USD/MMBTU (+38%), which had a minor financial impact.

In **Figure 6**, there is a step-by-step illustration of the initial revenue [2] and the revised revenue calculated by the model. In addition to the expected result, high and low scenario ranges for each value driver are analyzed.

It is essential to highlight that oil price variation impacts revenue streams for social programs. **Table 3** summarizes oil and gas price variation and the corresponding impact on revenue generation for social services, considering the different case scenarios.

Table 3. Oil and natural gas prices vary, impacting revenue and corresponding cash into social services (nominal and present value) (values are USD million).

	Expected Case	High Case	Low Case
Revenue impact on Búzios project	(186,670)	(5290)	(377,939)
Revenue impact on social services	(32,425)	(919)	(65,648)
Public health	(4666)	(132)	(9454)
Public Education	(14,000)	(397)	(28,361)
Local R&D	(1867)	(53)	(3779)
Social contribution	(11,891)	(337)	(24,075)

Source: Authors' economic model (2025).

The expected price will reduce the project's revenue and, subsequently, the corresponding revenue stream for social projects, projected to be reduced by USD 32,425 million. In the high-case scenario, this reduction would reduce to USD 919 million; in the low-case scenario, the reduction would achieve USD 65,648 million.

The fourth, fifth, and sixth columns in **Figure 6** indicate the evaluated gas-integrated technologies that aim to promote better management of associated gas and corresponding gas streams (CH_4 and CO_2-rich). Regarding technology options to liquefy natural gas, it was identified that LNG increases revenue by USD 21,738 million and ssm-FLNG supplements with a limited revenue of USD 20 million (chart 6, fourth and fifth bars).

On the other hand, in the case of CO_2-WAG, it reduces revenue by USD 21,306 million, leading to a lower financial contribution in terms of the combined result of gas-integrated technologies at USD 452 million.

Table 4 summarizes the nominal revenue impact driven specifically by gas-integrated technologies for the different scenarios. According to **Table 4**, gas-integrated technologies would increase nominal revenue by USD 452 million, increasing social services' revenue by USD 79 million.

Table 4. Gas-integrated technologies impact project revenue with corresponding cash into social services, considering different scenarios (values are in USD million).

	Expected Case
Revenue impact on Búzios project	452
Revenue impact on social services	79
Public health	11
Public Education	34
Local R&D	5
Social contr.	29

Source: Authors' economic model (2025).

One of the key assumptions analyzed in this work is the gas-oil ratio (GOR), which is indicated in **Figure 6** and **Figure 7** as the seventh bar. Gaffney *et al.* (2010) [2] indicated that GOR for Búzios would range from 184.34 to 225.31 m^3/m^3. From the informed production volumes, an average of 197.38 m^3/m^3 was calculated.

Additionally, Petrobras reported that GOR starts at 223.00 m^3/m^3 and grows over the 35-year production period to an equivalent average of 36,003 m^3/m^3. Based on the developed model and updated information from Petrobras, the projected GOR average for the Búzios field was revised to 35,358 m^3/m^3 (an increase of 79.14% versus Gaffney's base case).

Considering the assumption of monetizing part of this gas volume through the liquefaction and commercialization of natural gas (CH_4-rich stream), the GOR growth represents an equivalent revenue increase of 17,219 USD million (expected case).

The positive contribution in terms of potential revenue increase coming from GOR growth assumes that total oil production remains the same and, consequently, there is a corresponding increase in gas production. This assumption is aligned with the latest Petrobras reports, which indicate that the expected recoverable oil from the Búzios field is higher than forecasted in preliminary contracts.

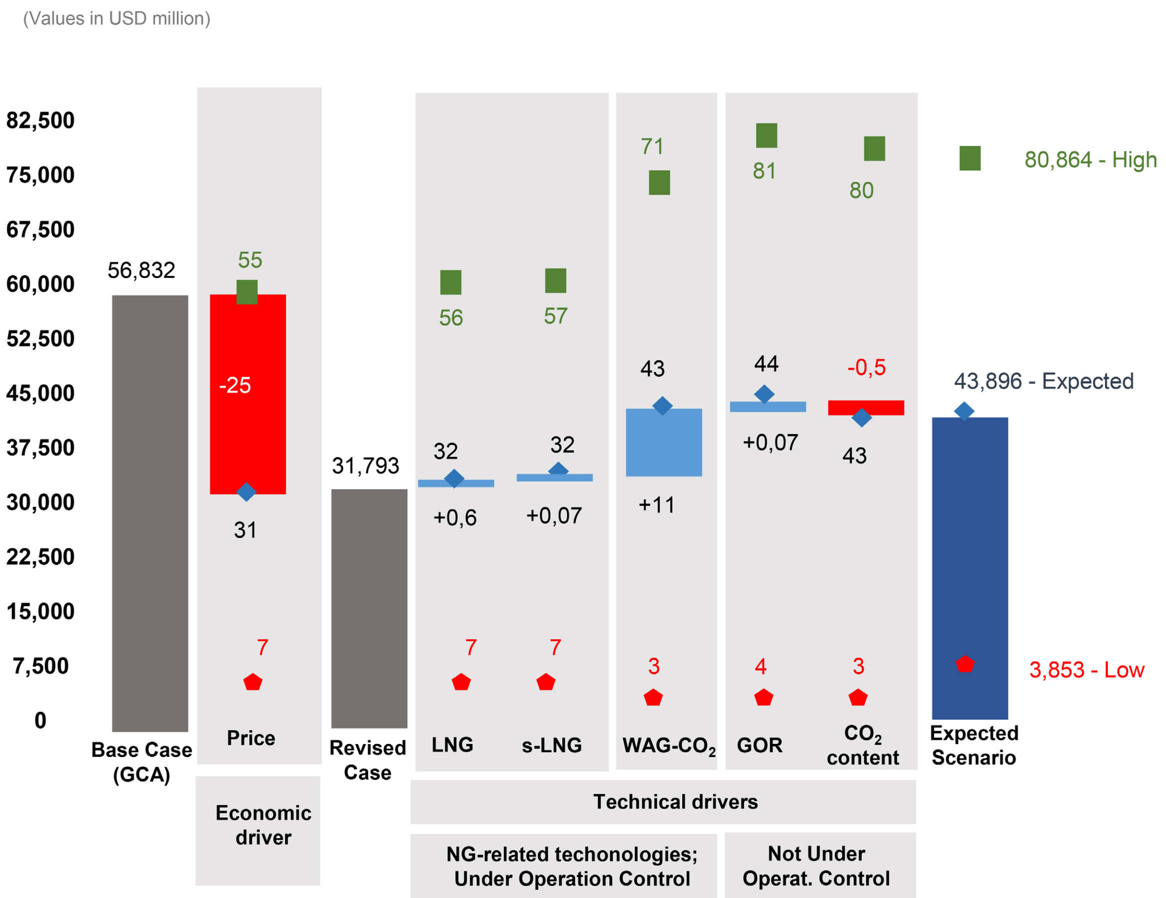
The last value driver analyzed is CO_2 content in associated gas and its corresponding impact on revenues. From a financial perspective, it was calculated that a CO_2 content of 32.77% would reduce revenue by 12,773 million, assuming that it would reduce the availability of natural gas (CH_4) that could be commercialized.

In summary, **Figure 6** indicates that the initial revenue forecast from Gaffney was USD 545,835 million, and this study revised it down considering the revised lower oil price forecast. On the other hand, deploying gas-integrated technologies combined with higher GOR could partially compensate for this loss, delivering a final revenue of USD 350,969 million.

6.3. Net Present Value (NPV) and Breakdown

Concerning the project's value, the net present value (NPV) from the Búzios field was estimated at 56,832 USD million [2]. Considering the revised expected price for oil and gas, NPV would drop to 31,793 USD million, representing a reduction of 44.06%.

Pricing is the most critical value driver for value creation. In the case of gas-integrated technologies (fourth, fifth, and sixth columns), they can potentially increase NPV by 6449 USD million (20.28% increase), most of this result relating to CO_2-WAG, which accelerates oil extraction. The gas-oil ratio (GOR) has an expected NPV contribution of USD 739 million, and CO_2 content in gas is expected to reduce NPV by USD 490 million. As can be analyzed by **Figure 7** regarding NPV.



Source: Authors' economic model (2025).

Figure 7. NPV analysis considers base, expected, high, and low scenarios.

The model indicates that ssm-FLNG application has a significantly higher utilization rate (**Table 5**) than LNG plants.

In summary, the NPV forecast from Gaffney *et al.* (2010) [2] was USD 56,832 million over the production cycle, and then it was revised considering the revised oil price forecast. On the other hand, deploying gas-integrated technologies could partially compensate for this loss, delivering a final NPV of USD 38,491 billion.

Table 5. Utilization rate per liquefaction technology (Búzios Pre-salt field).

	Base	Expected	High	Low
LNG	34.20%	48.43%	47.81%	39.03%
SSM-FLNG	70.95%	75.50%	77.95%	71.02%

Source: Authors' economic model (2025).

7. Conclusions

This study developed a techno-economic model to evaluate the deployment of integrated gas monetization technologies in the Búzios Pre-Salt field, focusing on ssm-FLNG and CO_2-enhanced oil recovery (CO_2-WAG). The primary objective was to assess whether this approach could enhance the economic viability of associated gas utilization while supporting emissions reduction through permanent CO_2 storage. The findings indicate that this integrated model presents a feasible and economically attractive alternative to traditional gas reinjection.

The analysis yielded four key insights:

a) Increased Associated Gas Availability and Monetization Potential: The study identified a higher-than-anticipated volume of associated gas in the Búzios field, with an estimated 21.2 trillion standard cubic feet of natural gas available for monetization. While conventional reinjection remains widespread, utilizing this excess gas through LNG production could contribute 8767 million USD annually to Brazil's energy market.

b) Economic Feasibility of Modular Liquefaction: The cost structure of ssm-FLNG, with estimated liquefaction costs, demonstrates financial viability compared to large-scale LNG projects. The modular and mobile design enables flexible deployment, improving utilization rates from 48.4% to 75.5%, thereby optimizing capital efficiency.

c) Oil Production Acceleration and Enhanced Project Economics: The adoption of CO_2-WAG instead of conventional WAG reduces the production cycle from 40 to 25 years, leading to an NPV increase of $12 million. This acceleration enhances cash flow generation and strengthens financial returns.

d) Environmental and Economic Synergies Through CO_2 Storage: The ability to permanently store CO_2 within the pre-salt reservoirs not only mitigates carbon emissions but also aligns with global sustainability policies. This strategy enhances regulatory compliance while maintaining economic competitiveness.

e) Strategic Implications: The deployment of ssm-FLNG and CO_2-WAG in the Santos Basin presents a dual opportunity: improving economic returns through optimized natural gas utilization while contributing to long-term emissions reduction goals. The results suggest that a dynamic asset allocation strategy— relocating liquefaction plants to fields with higher gas output as production declines—can further enhance project economics. Additionally, the synergy between enhanced oil recovery and carbon storage strengthens the role of this approach in sustainable hydrocarbon production.

By integrating modular liquefaction with CO_2-WAG, the proposed framework offers a scalable, financially viable, and environmentally responsible model for offshore gas monetization. These insights provide a foundation for policymakers and industry stakeholders to consider new pathways for optimizing Brazil's pre-salt resources in alignment with energy transition objectives.

8. Final Considerations

The results indicate that integrating ssm-FLNG with CO_2-WAG represents a financially viable and environmentally responsible approach to hydrocarbon production in the Búzios Pre-salt field. Further research should focus on detailed evaluations of asset utilization strategies, regulatory frameworks, and long-term market dynamics to refine and optimize deployment plans. These insights could extend beyond Búzios, benefiting the broader Santos Basin Pre-salt Cluster (SBPC) and setting a precedent for future offshore energy projects.

A comprehensive comparative analysis with alternative gas monetization strategies, such as direct pipeline transport to shore or conversion to other products, was deemed beyond the scope and current timeframe of this study. Such an in-depth evaluation would necessitate a more extensive and dedicated research effort, involving detailed techno-economic modeling and market assessments for each alternative. Therefore, we propose this comparative analysis as a crucial direction for future work, which could further elucidate the optimal role of the proposed FLNG-integrated hub solution within the broader landscape of Brazilian pre-salt gas monetization.

Funding

This research was funded by CNOOC Petroleum Brasil Ltd., through the Brazilian R&D levy regulation established by the Petroleum, Natural Gas and Biofuels Agency (ANP) (ANP's Resolution n° 918/2023). The Brazilian Federal Agency supported a seminal PhD Thesis related to this research, named Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

Acknowledgements

We gratefully acknowledge the support of CNOOC Petroleum Brasil Ltd., and the strategic importance of the support given by ANP (Brazil's National Oil, Natural Gas and Biofuels Agency) through the R&DI levy regulation (ANP Resolution n° 918/2023). The authors also gratefully acknowledge the seminal support from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES). The present publication reflects only the authors' views, and the scholarship's sponsors are not liable for any use of the information contained here.

Conflicts of Interest

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

References

[1] Moczydlower, B., Salomão, M.C., Branco, C.C., Romeu, R.K., Homem, T.R., Freitas, L.C., *et al.* (2012) Development of the Brazilian Pre-Salt Fields—When to Pay for Information and When to Pay for Flexibility. *SPE Latin America and Caribbean Petroleum Engineering Conference*, Mexico, 16-18 April 2012. https://doi.org/10.2118/152860-ms

[2] Gaffney, Cline and Associates (2010) Review and Evaluation of Ten Selected Discoveries and Prospects in the Pre-Salt Play of the Deepwater Santos Basin, Brazil.

[3] de Almeida, E., *et al.* (2023) Custo e benefícios da atual política de conteúdo local. Ciclo de Debates sobre Petróleo e Economia-Texto para Discussão. https://www.ibp.org.br/personalizado/uploads/2016/09/2016_TD_Custos-e-Benefícios-da-Política-Conteúdo-Local.pdf

[4] Araujo Rodrigues, L. and Luís Sauer, I. (2015) Exploratory Assessment of the Economic Gains of a Pre-Salt Oil Field in Brazil. *Energy Policy*, **87**, 486-495. https://doi.org/10.1016/j.enpol.2015.09.036

[5] Naveiro, M., Romero Gómez, M., Arias Fernández, I. and Baaliña Insua, Á. (2021) Energy Efficiency and Environmental Measures for Floating Storage Regasification Units. *Journal of Natural Gas Science and Engineering*, **96**, Article 104271. https://doi.org/10.1016/j.jngse.2021.104271

[6] Padilla-Rivera, A., Paredes, M.G. and Güereca, L.P. (2019) A Systematic Review of the Sustainability Assessment of Bioenergy: The Case of Gaseous Biofuels. *Biomass and Bioenergy*, **125**, 79-94. https://doi.org/10.1016/j.biombioe.2019.03.014

[7] Machado, G. (2019) Gás Natural Offshore: Panorama, análise e alternativas para otimi-zação da produção na costa brasileira. https://doi.org/10.17771/pucrio.acad.46708

[8] Interlenghi, S.F., de Medeiros, J.L. and de Queiroz F. Araújo, O. (2021) On the Sustainability of Small-Scale Expansion-Based Natural Gas Liquefaction: Supersonic Separator, Joule-Thomson, and Turbo-Expander. *Journal of Natural Gas Science and Engineering*, **95**, Article 104212. https://doi.org/10.1016/j.jngse.2021.104212

[9] Kumar, S., Kwon, H., Choi, K., Lim, W., Cho, J.H., Tak, K., *et al.* (2011) LNG: An Eco-Friendly Cryogenic Fuel for Sustainable Development. *Applied Energy*, **88**, 4264-4273. https://doi.org/10.1016/j.apenergy.2011.06.035

[10] Safari, A., Das, N., Langhelle, O., Roy, J. and Assadi, M. (2019) Natural Gas: A Transition Fuel for Sustainable Energy System Transformation? *Energy Science & Engineering*, **7**, 1075-1094. https://doi.org/10.1002/ese3.380

[11] IEA (n.d.) International Energy Agency, Global Energy & CO_2 Status Report 2019-Emissions. https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions

[12] Chen, Z., An, H., Gao, X., Li, H. and Hao, X. (2016) Competition Pattern of the Global Liquefied Natural Gas (LNG) Trade by Network Analysis. *Journal of Natural Gas Science and Engineering*, **33**, 769-776. https://doi.org/10.1016/j.jngse.2016.06.022

[13] Zarezadeh, F., Vatani, A., Palizdar, A. and Nargessi, Z. (2022) Simulation and Optimization of Sweetening and Dehydration Processes in the Pretreatment Unit of a Mini-Scale Natural Gas Liquefaction Plant. *International Journal of Greenhouse Gas Control*, **118**, Article 103669. https://doi.org/10.1016/j.ijggc.2022.103669

[14] Khan, M.S., Karimi, I.A. and Wood, D.A. (2017) Retrospective and Future Perspective of Natural Gas Liquefaction and Optimization Technologies Contributing to Efficient LNG Supply: A Review. *Journal of Natural Gas Science and Engineering*, **45**, 165-188. https://doi.org/10.1016/j.jngse.2017.04.035

[15] Ciotta, M., Peyerl, D., Zacharias, L.G.L., Fontenelle, A.L., Tassinari, C. and Moretto, E.M. (2021) CO_2 Storage Potential of Offshore Oil and Gas Fields in Brazil. *International Journal of Greenhouse Gas Control*, **112**, Article 103492. https://doi.org/10.1016/j.ijggc.2021.103492

[16] Nogueira, T., Rochedo, P.R.R. and Szklo, A. (2022) Evaluation of Offshore CO_2 Transport Alternatives in Brazil. *International Journal of Greenhouse Gas Control*, **116**, Article 103629. https://doi.org/10.1016/j.ijggc.2022.103629

[17] de Almeida, E., *et al.* (2023) Gás do Pré-Sal: Oportunidades, desafios e perspectivas. https://www.ibp.org.br/personalizado/uploads/2017/04/2017_TD_Gas_do_Pre_Sal_Oportunidades_Desafios_e_Perspectivas-1.pdf

[18] Arinelli, L.O., de Medeiros, J.L. and Araújo, O.Q. (2015) Performance Analysis and Comparison of Membrane Permeation versus Supersonic Separators for CO_2 Removal from a Plausible Natural Gas of Libra Field, Brazil. Paper Presented at the OTC Brasil, Rio de Janeiro, Brazil.

[19] Balcombe, P., Anderson, K., Speirs, J., Brandon, N. and Hawkes, A. (2015) Methane and CO_2 Emissions from the Natural Gas Supply Chain an Evidence Assessment. https://unece.org/fileadmin/DAM/energy/se/pdfs/GC/mtgs/2015/6_forum.gc_dec2015/4_Balcombe_Industry_Forum.pdf

[20] Boyd, A., *et al.* (2015) Presalt Carbonate Evaluation for Santos Basin, Offshore Brazil. https://www.researchgate.net/publication/290391902_Presalt_Carbonate_Evaluation_for_Santos_Basin_Offshore_Brazil

[21] Da Silva, H.T.F. (2016) O Polígono do Pré-Sal: O reservatório, as potencialidades e a atuação da pré-sal petróleo s.a. (PPSA). https://www.presalpetroleo.gov.br/wp-content/uploads/2021/10/2016_09_26_FIEB_O_Poligono_do_pre-sal_Hercules.pdf

[22] Faria, R.M.B. (2014) CO_2 Injection in Carbonate Reservoirs in Brazil, Presentation at CEPAC: Center of Excellence in Research and Innovation in Petroleum, Mineral Resources and Carbon Storage (CEPAC). https://www.mendeley.com/catalogue/2ec34131-5275-3e35-9963-0c6dee176b0e/?utm_source=desktop&utm_medium=1.19.8&utm_campaign=open_catalog&userDocumentId=%7B2ec34131-5275-3e35-9963-0c6dee176b0e%7D

[23] Fraga, C.T.D.C., *et al.* (2015) Brazilian Pre-Salt: An Impressive Journey from Plans and Challenges to Concrete Results—OTC-25710-MS. https://doi.org/10.4043/25710-MS

[24] Pizarro, J.O.D.S. and Branco, C.C.M. (2012) Challenges in Implementing an EOR Project in the Pre-Salt Province in Deep Offshore Brassil. *SPE EOR Conference at Oil and Gas West Asia* 2012, Oman, April 2012, 954-966. https://doi.org/10.2118/155665-MS

[25] Sauer, I.L. and Rodrigues, L.A. (2016) Pré-sal e Petrobras além dos discursos e mitos: disputas, riscos e desafios. *Estudos Avançados*, **30**, 185-229. https://doi.org/10.1590/s0103-40142016.30880014

[26] de Queiroz Fernandes Araújo, O., de Carvalho Reis, A., de Medeiros, J.L., do Nascimento, J.F., Grava, W.M. and Musse, A.P.S. (2017) Comparative Analysis of Separation Technologies for Processing Carbon Dioxide Rich Natural Gas in Ultra-Deepwater Oil Fields. *Journal of Cleaner Production*, **155**, 12-22. https://doi.org/10.1016/j.jclepro.2016.06.073

[27] Ahmadi, Y., Eshraghi, S.E., Bahrami, P., Hasanbeygi, M., Kazemzadeh, Y. and Vahe-

dian, A. (2015) Comprehensive Water-Alternating-Gas (WAG) Injection Study to Evaluate the Most Effective Method Based on Heavy Oil Recovery and Asphaltene Precipitation Tests. *Journal of Petroleum Science and Engineering*, **133**, 123-129. https://doi.org/10.1016/j.petrol.2015.05.003

[28] Emadi, A., Sohrabi, M., Farzaneh, S. and Ireland, S. (2013) Experimental Investigation of Liquid-CO_2 and CO_2-Emulsion Application for Enhanced Heavy Oil Recovery -(SPE-164798). In *London* 2013, 75*th Eage Conference en Exhibition Incorporating SPE Europec*, London, 10-13 Jun 2013. https://doi.org/10.3997/2214-4609.20130508

[29] Moradi, B., Pourafshary, P., Jalali, F., Mohammadi, M. and Emadi, M.A. (2015) Experimental Study of Water-Based Nanofluid Alternating Gas Injection as a Novel Enhanced Oil-Recovery Method in Oil-Wet Carbonate Reservoirs. *Journal of Natural Gas Science and Engineering*, **27**, 64-73. https://doi.org/10.1016/j.jngse.2015.07.009

[30] van t Veld, K., Mason, C.F. and Leach, A. (2013) The Economics of CO_2 Sequestration through Enhanced Oil Recovery. *Energy Procedia*, **37**, 6909-6919. https://doi.org/10.1016/j.egypro.2013.06.623

[31] Azzolina, N.A., Nakles, D.V., Gorecki, C.D., Peck, W.D., Ayash, S.C., Melzer, L.S., *et al.* (2015) CO_2 Storage Associated with CO_2 Enhanced Oil Recovery: A Statistical Analysis of Historical Operations. *International Journal of Greenhouse Gas Control*, **37**, 384-397. https://doi.org/10.1016/j.ijggc.2015.03.037

[32] Bachu, S. (2000) Sequestration of CO_2 in Geological Media: Criteria and Approach for Site Selection in Response to Climate Change. *Energy Conversion and Management*, **41**, 953-970. https://doi.org/10.1016/s0196-8904(99)00149-1

[33] Taheri, H., Jones, C. and Taheri, M. (2022) Assessment and Detection of Stress Corrosion Cracking by Advanced Eddy Current Array Nondestructive Testing and Material Characterization. *Journal of Natural Gas Science and Engineering*, **102**, Article 104568. https://doi.org/10.1016/j.jngse.2022.104568

[34] Alkhatib, A. (2009) LNG: A New Era? Imperial College London.

[35] Al-Breiki, M. and Bicer, Y. (2021) Comparative Life Cycle Assessment of Sustainable Energy Carriers Including Production, Storage, Overseas Transport and Utilization. *Journal of Cleaner Production*, **279**, Article 123481. https://doi.org/10.1016/j.jclepro.2020.123481

[36] Qyyum, M.A. and Lee, M. (2018) Hydrofluoroolefin-Based Novel Mixed Refrigerant for Energy Efficient and Ecological LNG Production. *Energy*, **157**, 483-492. https://doi.org/10.1016/j.energy.2018.05.173

[37] Qyyum, M.A., Qadeer, K., Ahmad, A., Ahmed, F. and Lee, M. (2020) Two-Phase Expander Refrigeration Cycles with Ethane-Nitrogen: A Cost-Efficient Alternative LNG Processes for Offshore Applications. *Journal of Cleaner Production*, **248**, Article 119189. https://doi.org/10.1016/j.jclepro.2019.119189

[38] Sun, H., He Ding, D., He, M. and Shoujun Sun, S. (2016) Simulation and Optimisation of AP-X Process in a Large-Scale LNG Plant. *Journal of Natural Gas Science and Engineering*, **32**, 380-389. https://doi.org/10.1016/j.jngse.2016.04.039

[39] Markou, A. (2016) LNG Technology Overview, Market Analysis & Forecasting. Imperial College London.

[40] Zellouf, Y. and Portannier, B. (2011) First Step in Optimizing LNG Storages for Offshore Terminals. *Journal of Natural Gas Science and Engineering*, **3**, 582-590. https://doi.org/10.1016/j.jngse.2011.07.011

[41] Jourablou, M.M., Salimi, M. and Amidpour, M. (2025) A Comprehensive Analysis of the Nitrogen Expansion Process for Liquefied Natural Gas Industry from the Opera-

tional Point of View. *International Journal of Thermofluids*, **27**, Article 101200. https://doi.org/10.1016/j.ijft.2025.101200

[42] Wang, J. and Liu, B. (2014) A Techno-Economic Analysis of Using Floating LNG Technology to Develop Difficult-to-Produce Reserves. *Natural Gas Industry*, **34**, 129-133.

[43] Bukowski, J., Liu, Y.N. Boccella, S. and Kowalski, L. (2011) Innovations in Natural gas Liquefaction Technology for Future LNG Plants and Floating LNG Facilities. *International Gas Union Research Conference*, Seou, 22. https://www.academia.edu/19942927/Innovations_in_Natural_Gas_liquefaction_technology_for_floating_LNG

[44] Rattanavich, R. and Thompson, S. (2012) The Rise of Small-Scale LNG/FLNG Projects as an Alternative Approach to Sustain Global Gas Supply. 25*th World Gas Conference*, Kuala Lumpur.

[45] Tan, S.H. and Barton, P.I. (2015) Optimal Dynamic Allocation of Mobile Plants to Monetize Associated or Stranded Natural Gas, Part I: Bakken Shale Play Case Study. *Energy*, **93**, 1581-1594. https://doi.org/10.1016/j.energy.2015.10.043

[46] Castillo, L. and Dorao, C.A. (2010) Influence of the Plot Area in an Economical Analysis for Selecting Small Scale LNG Technologies for Remote Gas Production. *Journal of Natural Gas Science and Engineering*, **2**, 302-309. https://doi.org/10.1016/j.jngse.2010.07.001

[47] IBAMA (2024) Atividade de produção e escoamento de petróleo e gás natural do polo pré-sal da bacia de santos—Etapa 2 caracterização da atividade Ii.2.1, revisão 00. http://licenciamento.ibama.gov.br/

[48] IBAMA (2011) EIA/RIMA para a atividade de produção e escoamento de petróleo e gás natural do polo pré sal da bacia de santos—Etapa 1 II.2—Caracterização da ati-vida-de. Volume 00, Revisão 01.

[49] IBAMA (2014) RIMA, atividade de produção e escoamento de petróleo egás natural do polo pré-sal da bacia de santos—Etapa 2, Revisão 3. http://licenciamento.ibama.gov.br/

[50] IBAMA (2024) EIA/RIMA para a atividade de produção e escoamento de petróleo e gás natural do polo pré sal da bacia de santos—Etapa 1 II.2-Caracterização da Atividade. Revisão 02. http://licenciamento.ibama.gov.br/

[51] IBAMA (2024) Atividade de produção e escoamento de petróleo egás natural do polo pré-sal da bacia de santos—Etapa 3 II.2.—Caracterização da atividade. Revisão 00. http://licenciamento.ibama.gov.br/

[52] IBAMA (2010) EIA/RIMA-projetos integrados de produção e escoamento de petróleo e gás natural no pólo pré-sal, bacia de santos. EIA—Estudo de Impacto Ambiental, Volume 00, Revisão 00. http://licenciamento.ibama.gov.br/

[53] Green, D.W. and Willhite, G.P. (1998) Enhanced Oil Recovery. Henry L. Doherty Memorial Fund of the American Institute of Mining, Metallurgica, and Petroleum Engineers (AIME), Society of Petroleum Engineers, Richardson, Texas, 1-545.

[54] Gibbins, J. and Chalmers, H. (2008) Carbon Capture and Storage. *Energy Policy*, **36**, 4317-4322. https://doi.org/10.1016/j.enpol.2008.09.058

[55] IGU (2017) 2017 World LNG Report.

[56] Rüster, S., Neumann, A. and Ruester, S. (2023) Corporate Strategies along the LNG Value Added Chain—An Empirical Analysis of the Determinants of Vertical Integration Corporate Strategies along the LNG Value Added Chain an Empirical Analysis of the Determinants of Vertical Integration.

https://tu-dresden.de/bu/wirtschaft/bwl/ee2/ressourcen/dateien/lehrstuhlseiten/ordner_publikationen/publications/wp_gg_17_ruester_neumann_LNG_vertical_integration.pdf?lang=en