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Very Large Floating Structures as Catalysts for the Energy Transition: A SWOT Analysis for Decarbonization in the South Atlantic

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Abstract

Very Large Floating Structures (VLFS) have emerged as promising offshore solutions for energy production and logistics in the context of global decarbonization. However, despite extensive technical literature on their engineering feasibility, there remains a lack of strategic and comparative assessments that evaluate how VLFS can be effectively deployed in emerging economies, particularly in regions characterized by ultra-deepwater resources, regulatory complexity, and capital constraints, such as the South Atlantic and Brazil's pre-salt province. This gap limits informed decision-making regarding which VLFS-based energy pathways are most viable for supporting the energy transition. This study addresses this problem by developing an integrated strategic assessment of VLFS applications for offshore transformation of natural gas into blue hydrogen, blue ammonia, and methanol. The methodology combines a systematic literature review with a SWOT analysis grounded in empirical and conceptual evidence, followed by a weighted multi-criteria decision framework based on sixteen technical, economic, environmental, regulatory, and social criteria. Criteria weights were assigned through structured expert consultation, enabling a semi-quantitative comparison of the three technological alternatives under Brazilian offshore conditions. The results indicate that, while all pathways present strategic opportunities, blue ammonia achieves the highest overall performance, particularly in the most heavily weighted criteria of greenhouse gas reduction and economic viability. Its advantages in storage, transport, market maturity, and alignment with Brazil's domestic fertilizer demand position it as a lower-risk and more immediately deployable option compared to blue hydrogen and offshore methanol. The study concludes that

VLFS-based blue ammonia production represents a strategically robust pathway for monetizing offshore gas while advancing decarbonization in the South Atlantic. The novelty of this work lies in moving beyond engineering-focused VLFS studies by integrating strategic management tools, expert-weighted criteria, and regional context into a transparent comparative framework. This approach provides actionable insights for policymakers and investors and offers a replicable methodology for evaluating offshore energy transition infrastructures in other Global South regions.

Keywords

Very Large Floating Structures, South Atlantic, Energy Transition, Decarbonization

1. Introduction

Long-term offshore systems based on large floating structures are an important innovation in maritime engineering, having implications that extend beyond technical concerns and may have political consequences for the international system. Above all, the maritime environment is a strategic issue for the International System because it frequently serves as the site of hostilities sparked by state disputes. However, the classic perspective of security, which implies the existence of an adversary, becomes largely obtuse as new dangers consist of various typologies not included in the definition of traditional war and conflict.

These systems, also known as Very Large Floating Structures (VLFS), are essentially large artificial islands that float on the sea surface and can be classified as semi-submersible or fully floating. In recent years, VLFS have piqued the interest of architects, urban planners, engineers, and environmentalists because they provide innovative and environmentally favorable options for the development of maritime infrastructure. VLFS has numerous applications, including floating piers, hotels, fuel storage facilities, stadiums, bridges, airports, and even floating cities.

The concept of Very Large Floating Structures (VLFS) was first proposed in 1924 to enable transoceanic air routes. Initial balance tests were conducted in tanks, with advancements continuing until Armstrong's passing in 1955. As population density increased in coastal areas, interest grew in utilizing surrounding seas for purposes beyond traditional transportation or marine resource exploitation. In the 1950s, architects began exploring floating city designs, a concept partially demonstrated at the Okinawa International Ocean Exhibition in 1975 through a semi-submersible city unit. Similarly, the idea of constructing a floating airport was proposed in 1973, eventually resulting in the Kansai International Airport. In this context, Hideyuki provides a comprehensive historical overview of these developments [1].

Very Large Floating Structures (VLFS) have been extensively studied over the past decades as innovative offshore solutions for infrastructure development, logistics, and energy production. The existing literature has demonstrated their technical feasibility, structural resilience, and multifunctionality in applications ranging from floating airports and bridges to offshore LNG terminals and renewable energy hubs. Recent studies have further explored the potential of VLFS as platforms for low-carbon energy production, particularly for hydrogen and ammonia, within the broader context of global decarbonization and energy transition.

Despite these advances, current research remains largely concentrated on technical performance, hydrodynamic behavior, and conceptual system design, with limited integration of strategic, economic, and governance dimensions. Moreover, most empirical and pilot-scale experiences are located in developed economies with consolidated maritime industries, such as Japan, Norway, China, and Singapore. As a result, there is a clear gap in the literature regarding the applicability of VLFS in emerging economies, particularly in the Global South, where institutional constraints, regulatory uncertainty, capital scarcity, and infrastructure asymmetries significantly shape technology adoption pathways [1].

In the Brazilian context, this gap is especially pronounced. Brazil possesses one of the world's largest offshore oil and gas provinces, with substantial associated natural gas volumes in ultra-deepwater pre-salt fields. However, logistical constraints, limited gas transportation infrastructure, and environmental considerations have hindered the full monetization of these resources. While VLFS have been suggested as potential solutions for offshore gas processing and low-carbon fuel production, no study to date has systematically assessed, from a strategic and comparative perspective, which VLFS-based energy pathways are most viable under Brazilian and South Atlantic conditions.

Since the 1970s, advancements in VLFS technology have closely mirrored evolving societal and industrial demands, driving increasingly diverse applications across multiple sectors. These structures have evolved from their initial roles in maritime transport and logistics to becoming integral components of renewable energy production, offshore living spaces, and industrial hubs. Their adaptability has allowed them to address challenges ranging from land scarcity in urban coastal areas to the need for sustainable energy solutions in offshore environments. This growing variety in design and functionality has made it increasingly challenging to categorize VLFS based on a single criterion, as they now serve as a convergence point for engineering, environmental sustainability, and economic innovation [1].

VLFS technology continues to be a promising solution for the commercialization of natural gas reserves in Brazil's Pre-salt regions. In 2023, the average natural gas production in Brazil reached 150 million m^3/day, representing an 8.7% increase compared to 2022. Projections by the Energy Research Company (EPE) indicate that gross natural gas production could reach approximately 275.9 million m^3/day by 2030. Implementing VLFS in these offshore fields can address logistical and economic challenges associated with transporting gas over long distances to the coast. An alternative involves hydrogen (H_2) production via natural gas reforming, integrated with CO_2 capture and storage, adding value to the extracted gas. Furthermore, converting hydrogen into fuels such as ammonia can capitalize on existing maritime infrastructure and meet demand, particularly in regions lacking viable low-carbon alternatives under current economic conditions [2] [3].

This research incorporates a literature review to map current technological advancements, evaluate existing VLFS applications, and analyze their suitability for deep-sea environments. It also examines strategic, logistical, safety, legal, economic, and environmental considerations. In this article, such solutions are considered in the field of integrated planning for broader energy, mineral, and economic exploitation of ocean resources, in the context of decarbonization and energy transition of the oil and gas (O&G) industry. Since there is an abundant potential supply of energy in the Brazilian pre-salt layer, in the form of combustible gases, which, to date, have proven difficult to transport to the Brazilian coast or for export.

To assess the benefits, opportunities, threats, and weaknesses of investing in VLFS in the Brazilian pre-salt, the SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) is used, also known as FOFA (Forces, Opportunities, Weaknesses, and Threats) analysis. This methodological tool allows a comprehensive and structured view of the competitive advantages, technical and logistical challenges, opportunities for technological innovation and integration with low-carbon energy sources, as well as the threats associated with this type of undertaking. By applying the SWOT analysis, it is expected to clearly identify the strengths that can be exploited, the areas that require attention and improvement, the development opportunities that can be capitalized on, and the possible threats that must be mitigated, thus ensuring a strategic and well-informed approach to the implementation of VLFS in the South Atlantic, especially in the Brazilian pre-salt.

This study addresses this gap by combining a literature-grounded SWOT analysis with a weighted multi-criteria decision framework to evaluate VLFS-based production of blue hydrogen, blue ammonia, and offshore methanol. By explicitly incorporating technical, economic, environmental, regulatory, and social criteria, and by contextualizing the analysis within Brazil's regulatory environment and Global South constraints, the study offers a novel strategic assessment that goes beyond purely technical feasibility. The main contributions of this paper are as follows:

- It provides a literature-grounded SWOT analysis of Very Large Floating Structures applied to offshore energy transition, explicitly linking technical, economic, environmental, regulatory, and social dimensions.
- It develops a weighted multi-criteria framework to compare VLFS-based production of blue hydrogen, blue ammonia, and offshore methanol, reducing subjectivity inherent in purely qualitative assessments.

- It contextualizes VLFS deployment within the Brazilian pre-salt and South Atlantic region, incorporating national regulatory structures, supply chain capabilities, and geopolitical considerations.
- It identifies blue ammonia as the most robust short- to medium-term pathway for VLFS implementation under Brazilian conditions, based on greenhouse gas reduction and economic viability.
- It contributes to the Global South literature by demonstrating how modular offshore infrastructures such as VLFS can support decarbonization while accommodating capital intensity, institutional constraints, and uneven technological access.

2. Methodology

This study adopts a mixed-methods approach that combines bibliographic and documentary research with strategic analysis, aiming to assess the feasibility of Very Large Floating Structures (VLFS) as a technological and strategic solution for the energy transition and decarbonization, particularly in the context of Brazil's pre-salt offshore reserves.

The first phase consisted of a comprehensive literature and document review, focusing on the state of the art of VLFS technologies and their international applications in offshore production clusters. Technical aspects were examined, including structure classifications (semi-submersible or fully floating), operational conditions, and diverse use cases such as logistics platforms, energy hubs, and offshore living environments. Reports from public institutions, such as Brazil's Energy Research Company (EPE) and the National Agency of Petroleum, Natural Gas and Biofuels (ANP), were also consulted to better understand the current landscape of natural gas production and the logistical and economic barriers to monetizing offshore gas.

In the second phase, a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) was conducted to evaluate the strategic viability of VLFS platforms for offshore transformation of natural gas into high-value products—specifically, blue hydrogen, blue ammonia, and methanol, all incorporating carbon capture and storage (CCS). The SWOT methodology is well-established in strategic management literature as a structured means of analyzing internal and external factors relevant to decision-making, as detailed by Sabbaghi and Vaidyanathan, as well as Mirzakhani *et al.* [4] [5].

To guide this analysis, a set of sixteen evaluative criteria was defined, covering technical, economic, environmental, logistical, and social dimensions. These included: the potential for greenhouse gas emissions reduction, the efficiency and integration of consolidated energy use, the opportunity for international export, the demand in the Brazilian domestic market, the capacity to stimulate technological innovation, the creation of employment and contribution to economic growth, the availability of storage and efficient logistics for product outflow, the overall economic viability of each product, the operational risks and safety concerns, the need for research, development, and innovation (R&D&I), the level of competition with alternative energy sources, the regulatory uncertainties and access to financing, the reluctance toward new technological uses, the resistance from local communities, the possibility of gaining from economies of scale, and the technological challenges associated with offshore deployment.

The attribution of weights to the evaluative criteria was conducted through a structured expert consultation process. A panel of six experts was convened, selected based on their direct professional and academic experience in fields relevant to the scope of the study. The panel comprised specialists in offshore engineering, energy systems and infrastructure, energy economics, environmental and climate policy, industrial project development, and sustainability assessment, ensuring a multidisciplinary perspective aligned with the technical, economic, and environmental dimensions of VLFS deployment.

Each expert independently assigned a weight ranging from 1, corresponding to the lowest relevance, to 10, corresponding to the highest relevance, to each of the sixteen criteria, based on its perceived importance for the successful implementation of large floating structures in offshore energy transition projects. Following the individual assessments, the results were consolidated and discussed in a structured consensus round, during which divergences in weighting were examined and justified. Where discrepancies arose, weights were adjusted through deliberation until convergence was achieved, reflecting a shared judgment among the panel rather than a simple arithmetic average.

Two criteria, reduction of greenhouse gas emissions and economic viability, were unanimously identified by the experts as conditio sine qua non for project feasibility. Consequently, both were assigned the maximum weight of 10, reflecting their critical alignment with international decarbonization commitments under the UNFCCC framework and the financial sustainability requirements necessary for industrial-scale implementation.

Each product was then qualitatively assessed across all sixteen criteria, receiving impact scores from 1 to 10 based on its expected performance in each category. These scores were multiplied by their corresponding weights to generate weighted scores per criterion. The aggregation of these weighted scores resulted in a final composite score for each product, enabling a direct, semi-quantitative comparison among the three technological alternatives.

This methodology integrates structured expert judgment with a transparent weighted scoring system, providing analytical rigor while maintaining clarity and reproducibility. It thus offers a robust and defensible foundation for strategic decision-making regarding the adoption of VLFS in offshore energy transition projects in Brazil.

3. Literature Review

Very Large Floating Structures (VLFS) have emerged as a critically relevant area of research and innovation in maritime engineering, offering transformative potential for applications in offshore energy, logistics, and environmental issues. These structures—defined as extensive artificial floating platforms—provide innovative solutions to overcome logistical and operational challenges in deep and ultra-deepwater environments. The specialized academic literature underscores their strategic relevance in addressing contemporary energy demands, especially within the context of decarbonization and the global energy transition [6] [7]. Such a scenario makes VLFS an imperative subject of study for structured feasibility assessments, such as SWOT (Strengths, Weaknesses, Opportunities, and Threats) analyses, particularly concerning their application in Brazil's pre-salt reserves.

For the elaboration of this review, a systematic literature search was conducted using the descriptors: "Very Large Floating Structures," "offshore energy transition," "floating hydrogen production," "VLFS Brazil," "blue ammonia," "floating LNG," and "maritime decarbonization." Searches were performed in prominent academic databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, as well as institutional repositories, such as the University of São Paulo's Integrated Library System (SIBiNet). The search period spanned from 2007 to 2024, allowing for the inclusion of both seminal works and the most recent advancements in the field. A total of 86 articles and reports were screened, from which 27 were selected for detailed analysis based on criteria of relevance, methodological rigor, and applicability to the Brazilian offshore context.

Pioneering research on VLFS predominantly focused on hydrodynamics and wave-structure interactions, as evidenced in the works of Suzuki and Riggs, Wang and Tay, and Watanabe *et al.* Such studies established the foundations for understanding the technical feasibility and structural integrity of VLFS in harsh marine environments, particularly highlighting the importance of dynamic stability for maintaining operational safety and predicting hydrodynamic behavior under complex maritime conditions [8] [9].

More recent contributions have emphasized the integration of VLFS with low-carbon energy technologies. Notable examples include the studies by Ning *et al.*, Karasalihović Sedlara *et al.*, and Hatton *et al.*, which investigate the role of VLFS as offshore platforms for clean energy production, with a focus on blue hydrogen and ammonia synthesis. This research corroborates that the proximity of VLFS to natural resource extraction sites enhances logistical efficiency while minimizing the environmental footprint associated with the transportation of raw materials and products [10] [11].

Geographically, research on VLFS is concentrated in countries with strong maritime and technological traditions, such as China, Japan, Norway, South Korea, and Singapore, where pilot projects have ranged from floating LNG terminals to renewable energy hubs. In the Brazilian context, although the literature is still incipient, emerging studies—such as those by Lamas-Pardo *et al.* and Cunanan *et al.*—demonstrate a growing national interest, especially regarding the strategic use of VLFS in offshore LNG infrastructure. The work of Takagi *et al.* further supports the versatility of VLFS for energy storage, conversion, and industrial co-location, aligning with global trends in energy system integration [12]-[14].

Furthermore, recent analyses such as that by Salmon and Bañares-Alcántara provide economic models for green ammonia production on VLFS, presenting scenarios in which large-scale renewable energy deployment becomes feasible and cost-effective. This perspective is corroborated by the findings of Hatton *et al.*, published in the journal *Energies*, which demonstrate the modular and scalable potential of VLFS for decarbonized fuel production. Such contributions reinforce the strengths and opportunities identified in SWOT analyses concerning technological innovation and sustainability [15].

On the other hand, several studies raise important challenges and limitations. Ning *et al.* and Hatton *et al.* point out that, despite the promising potential of VLFS, capital expenditures (CAPEX) and operational expenditures (OPEX) remain substantial, and regulatory frameworks are still incipient or underdeveloped, especially in emerging economies. Similarly, Lamas-Pardo *et al.* highlight the lack of empirical data regarding the long-term environmental impacts of VLFS on marine biodiversity, sedimentation, and ecosystem dynamics. Such concerns are particularly pertinent in biodiverse and sensitive zones, such as Brazil's offshore regions [16].

Additionally, a Brazilian academic perspective is offered by the doctoral research of Cunanan, available in the USP repository. This work analyzes the national energy planning scenario and the role of offshore floating infrastructure in aligning Brazil's energy strategy with the Sustainable Development Goals (SDGs). The thesis highlights institutional inertia and inconsistencies in energy governance as systemic barriers to the deployment of VLFS-based solutions [17].

The main limitations of this literature review include: i) the scarcity of field data from pilot VLFS deployments in Brazil; ii) the predominance of theoretical and modeling approaches, often lacking validation in real-world offshore environments; and iii) limited integration between engineering literature and environmental impact assessment frameworks. Furthermore, few studies address community engagement, local acceptability, and policy enforcement mechanisms, all of which are essential for long-term feasibility in Brazilian waters.

Nevertheless, the body of literature examined provides a solid foundation for a strategic assessment of VLFS applications. The identified strengths include their structural adaptability, capacity to support multi-functional offshore operations, and alignment with global decarbonization goals. Opportunities lie in their use as platforms for clean energy generation and for monetizing offshore resources, particularly in the Brazilian pre-salt. However, weaknesses such as high technical complexity and capital intensity, and threats involving regulatory uncertainty and potential environmental risks, underscore the need for careful planning, in-depth risk analysis, and robust inter-institutional coordination [17].

The SWOT analysis developed in this study is explicitly grounded in the findings of the reviewed international and national literature on VLFS and offshore energy systems. Rather than relying on generic categorizations, each strength, weakness, opportunity, and threat identified in the SWOT matrix was derived from recurring themes, empirical evidence, and analytical conclusions reported in the cited studies.

Strengths were identified based on demonstrated technical feasibility, multifunctionality, and environmental performance reported in the literature. For example, the high energy efficiency and low carbon emissions associated with blue hydrogen and blue ammonia are supported by global decarbonization pathways outlined by the IEA and reinforced by system integration studies such as Takagi *et al.* and Hatton *et al.*, which highlight the suitability of VLFS for modular, scalable, and integrated energy production. Similarly, the versatility and export potential attributed to methanol are grounded in analyses of offshore gas monetization and energy carrier flexibility discussed by Cunanan and Salmon and Bañares-Alcántara [18].

Weaknesses were mapped directly from limitations emphasized in the literature. High capital and operational costs, storage safety concerns, energy-intensive production processes, and corrosivity or toxicity risks are consistently reported by Ning *et al.*, Hatton *et al.*, and Lamas-Pardo *et al.* These studies explicitly point to CAPEX and OPEX constraints, technological complexity, and unresolved safety and handling challenges, which informed the inclusion of items such as limited infrastructure, storage security risks, and technological challenges across the three products.

Opportunities were defined based on structural trends and future-oriented insights identified in the literature. The expansion of global demand for low-carbon fuels, integration with renewable energy systems, and the potential role of VLFS as offshore energy hubs are supported by the IEA, Salmon and Bañares-Alcántara, and Hatton *et al.* In the Brazilian context, the opportunity to reduce fertilizer imports through blue ammonia production and to monetize offshore natural gas via methanol aligns with national energy planning analyses presented by Cunanan and sectoral data from PLANAFE and ABH2. These sources substantiate the SWOT items related to market expansion, export potential, and alignment with Brazil's energy transition strategy [18]-[20].

Threats were identified from regulatory, environmental, and social risks emphasized in the literature. Regulatory uncertainty, gaps in maritime and environmental governance, and financing constraints are recurrently highlighted by Ning *et al.* and Cunanan, particularly in emerging economies. Concerns regarding environmental impacts on marine ecosystems, as discussed by Lamas-Pardo *et al.*, directly informed the inclusion of threats related to environmental regulation and public perception. Additionally, competition from alternative technologies and challenges related to social acceptance are consistent with broader transition risk discussions in IEA and Hatton *et al.* [20].

This systematic mapping ensures that the SWOT analysis is not a standalone qualitative exercise but a structured synthesis of the literature. The SWOT matrix thus functions as an intermediate analytical step, translating dispersed empirical and conceptual insights into a coherent strategic framework. This literature-anchored SWOT subsequently serves as the empirical basis for the weighted multi-criteria evaluation applied in the following stages of the methodology, ensuring traceability, analytical rigor, and consistency between the review of prior studies and the comparative assessment of technological alternatives.

In summary, the reviewed literature provides robust evidence of the technical feasibility and potential versatility of VLFS, as well as growing interest in their application for low-carbon energy production. However, most studies focus on isolated technologies, specific engineering aspects, or idealized economic scenarios, often detached from regional institutional realities. Comparative assessments across alternative energy products remain limited, and few studies explicitly integrate strategic management tools with multi-criteria evaluation to support decision-making under uncertainty. Furthermore, the challenges faced by Global South countries, such as regulatory fragmentation, financing constraints, and uneven industrial capabilities, are rarely addressed in a structured analytical framework [20].

Against this background, the present study differentiates itself by systematically linking insights from the literature to a SWOT-based strategic assessment and by translating qualitative findings into a semi-quantitative, weighted comparative analysis. This approach allows for a transparent comparison between blue hydrogen, blue ammonia, and methanol in the specific context of Brazil's pre-salt and the South Atlantic, thereby advancing the literature from descriptive and conceptual analyses toward applied strategic decision support.

Unlike the framework proposed by Wang and Tay, which focuses primarily on engineering applications, structural typologies, and technological readiness of Very Large Floating Structures, the present study adopts a strategic and decision-oriented perspective. While Wang and Tay provide foundational knowledge on VLFS design and applications, they do not address comparative evaluation across alternative energy products, nor do they integrate regulatory, economic, and social criteria into a unified assessment model [6].

This study advances the literature by coupling technical feasibility with strategic management tools, enabling cross-product comparison under real-world constraints. The incorporation of expert-weighted criteria and regional context distinguishes this approach from earlier engineering-centric frameworks and enhances its relevance for policy-making and investment decisions in emerging economies.

4. Strategic Potential of VLFS for Energy Transition in the South Atlantic

VLFS are large floating structures that can be used for various purposes in the marine environment. There are two main types of VLFS: semi-submersible and fully floating, as described by Wang and Wang and Zhou et al. Semi-submersible structures have submerged parts to provide stability, while fully floating structures rest entirely on the water surface. These structures are usually constructed with materials such as steel, concrete, and advanced composite materials, which provide strength and durability in harsh marine conditions. The choice of material depends on the specific environmental conditions and operational needs of the structure, as noted by Zhou *et al.* and Luo and Jiang [21]-[23].

The VLFS structures analyzed in the project developed by the Institute of Energy and Environment of the University of São Paulo (IEE/USP) are designed to be installed in deep-sea environments, typical of where the largest offshore O&G exploration and production activities occur in Brazil, with specific references to the areas of the Pre-salt polygon and, particularly, those associated with the Búzios and Libra fields. These large floating structures can then be conceived as central elements to compose greener offshore hubs, that is, activities that allow for integrated exploration of maritime resources, through economic exploration routes with a lower carbon footprint.

In Brazil, despite the greatness and long tradition of national offshore oil production, with its well-known technological mastery discussed by Ortiz Neto and Costa, nothing even close to a VLFS has been designed or built. For various reasons that cannot be fully explored in this paper, Brazil has specialized in less capital-intensive solutions, with faster construction and installation times. This has led to Brazil's expertise and leadership in the field of Floating Oil Production, Storage and Offloading Units, also called FPSOs, as analyzed by Batalha [24] [25].

VLFS have a relatively recent history, with significant developments occurring in the last decades. One of the most notable examples is the Mega-Float, a floating airport built in Tokyo Bay, Japan, which has been documented by Hideyuki and Lamas-Pardo *et al.* This structure demonstrated the technical and economic feasibility of VLFS for large-scale applications. Other examples include floating piers in marinas, floating hotels in tourist resorts and offshore fuel storage facilities. The application of VLFS is not limited to the tourism and leisure sector. They are also used in transportation infrastructure, such as floating bridges and airports, as well as industrial facilities, such as O&G platforms – the application proposed here. Recently, there has been an increase in interest in VLFS for floating cities, as explored by Penice, driven a priori by the need to adapt to climate change and sea level rise [26].

Several international projects stand out for their innovative application of VLFS. The Mega-Float in Japan is a pioneering example, providing a stable platform for airport operations in the Tokyo area, detailed by Watanabe *et al.*, Hideyuki, and Lamas-Pardo *et al.* Norway is home to notable floating bridges, including the Bergsøysund Floating Bridge and the Nordhordland Bridge, which has a floating section, demonstrating that floating platform designs can be adapted to extreme conditions. In Singapore, the Marina Bay Floating Platform is a versatile structure used for public events and military parades, as described by Koh and Lim. Vietnam also has an example with the construction of a floating hotel. These projects exemplify the multifunctionality of VLFS, offering a practical solution to land scarcity in densely populated urban areas or in remote offshore areas, as emphasized by Wang and Wang [27].

The implementation of VLFS involves complex technical considerations. The stability of the structure is one of the critical factors, especially in harsh sea conditions, a point stressed by Zhou *et al.* and Luo and Jiang. VLFS engineering must ensure that the structure can withstand waves, currents, and strong winds without compromising safety and structural integrity. In addition, the maintenance of these structures is challenging due to constant exposure to the marine environment, which can cause corrosion and wear. Advanced technologies, such as anti-corrosive coatings and composite materials, are often used to extend the service life of VLFS

Even in the face of these complexities, the South Atlantic, notably the Pre-salt, in areas of great depth, such as the Búzios and Libra fields, presents a promising scenario for the application of VLFS, monetizing offshore natural gas. These structures can be used to facilitate transportation and logistics operations, providing stable platforms for loading and unloading cargo. In addition, VLFS can become greener offshore hubs or even sustainable offshore hubs. The exploration of energy resources can go beyond combustible gases and benefit from VLFS technology, since floating platforms can serve as hubs for the production, storage and distribution of living, mineral and energy resources, such as hydrocarbons and fauna itself, which are of great importance to the national economy, contributing to the decarbonization of the energy matrix and economic development [28].

VLFS offer significant environmental advantages, especially when compared to traditional land creation methods. The construction of conventional artificial islands involves dredging and sediment deposition, causing negative impacts on marine ecosystems, as indicated by Erftemeijer and Aziz *et al.* In contrast, VLFS float on the surface of the water, minimizing disturbance of the seabed. Furthermore, VLFS can be equipped with technologies to reduce carbon emissions, such as carbon capture and storage systems or even renewable energy systems – aiding the transition to a lower carbon economy and positively impacting technology competitiveness by promoting technological compliance with the climate emergency [28] [29].

However, the implementation of VLFS is conditioned by a complex set of regulations and public policies. In many countries, maritime and environmental laws need to be adapted to accommodate the use of floating structures, in addition to the gaps in international legislation. In addition, government incentives and subsidies can play a crucial role in the economic viability of these projects. In Brazil, the National Agency of Petroleum, Natural Gas and Biofuels (ANP) and the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) are some of the main entities involved in the regulation of offshore activities. Harmonizing regulations and creating favorable policies are essential for the success of VLFS in the Pre-salt context.

In summary, the most relevant internal factors of the three possible products for this analysis are presented, that is, the strengths and weaknesses related to the production of these products, and the external factors highlighting the opportunities and threats. This somehow consolidates the previous discussion, in Table 1.

Table 1. SWOT matrix of blue hydrogen, blue ammonia and methanol analysis in VLFS.

Category	Blue Hydrogen	Blue Ammonia	Methanol
Forces	- High energy efficiency - Known technology - Low carbon emissions	- Ease of storage and transportation - Established industrial uses-Low carbon emissions	- Versatility - Export potential - Lower emissions
Weaknesses	- High costs-Limited infrastructure Storage security risks	- Toxicity-Energy efficiency-Energy intensive production	- Energy density - Corrosivity-Toxicity risks
Opportunities	- Expansion of demand - Integration with renewable energies - Government support for the product	- Various applications - Development of new markets-Government support for the product	- Expanding market - Integration with renewables - Demand for biodiesel production
Threats	- Competition from other technologies - Regulatory variability-Challenges of public acceptance	- Technological competition from other technologies - Environmental regulations - Public perception	- Competition from other technologies - Regulatory challenges-Perception of security

By 2030, global hydrogen production must reach 200 million tons, with 70% originating from low-carbon technologies, and rise to 500 million tons by 2050. Hydrogen is essential for achieving net-zero emissions, particularly in hard-to-decarbonize sectors like heavy industry and transportation. In Brazil, the hydrogen market is primarily focused on industrial processes such as ammonia production, with internal refining capacity surpassing demand. Its benefits include reducing carbon emissions, fostering economic stability, and promoting innovation and diversification. However, challenges such as reliance on fossil fuels, technical and logistical issues, and competition with other energy sources remain significant barriers [29].

The global ammonia market is expected to grow steadily, driven by an increase in capacity from new plants, particularly in Asia and the Middle East. In Brazil, approximately 85% of fertilizer needs are met through imports, with only 5% of nitrogen fertilizer demand produced domestically. Blue ammonia presents an opportunity to reduce dependency on imports, lower carbon emissions, and create export potential. Despite these advantages, adoption is limited by high costs, technological hurdles, and regulatory uncertainties.

Methanol production has experienced robust growth worldwide, particularly in Northeast Asia. While Brazil currently lacks methanol production compared to other commodities like ethanol, the country has abundant natural resources and technologies to expand capacity. Methanol offers opportunities to monetize offshore natural gas, reduce environmental impacts, and contribute to a low-carbon economy. However, challenges such as high production costs, environmental risks, and competition from alternative energy sources may hinder its large-scale adoption. However, SWOT analysis alone is insufficient for a comprehensive comparison of the products, as its qualitative nature limits objectivity. To address this, a weighted approach was applied, summarizing the analysis into 16 measurable criteria, such as greenhouse gas reduction, economic viability, and export potential. By assigning relative weights to each criterion and calculating product impacts, qualitative insights were transformed into a quantitative framework. This method enables a structured comparison, providing a clearer and more objective evaluation of each product's potential to meet strategic and environmental goals [29].

Methanol, while presenting significant opportunities to monetize offshore natural gas and contribute to Brazil's transition to a low-carbon economy, exemplifies the need for such a quantitative approach. Its potential advantages, such as environmental benefits and economic contributions, must be weighed against challenges like high production costs, environmental risks, and competition with other energy sources. The weighted framework ensures that these trade-offs are objectively assessed, allowing methanol's feasibility to be evaluated alongside hydrogen and blue ammonia in a holistic manner, thus supporting strategic decision-making for Brazil's energy future.

Table 2. Synthetic-comparative matrix.

Category	Adjusted Weight	Impact	Blue Hydrogen	Weighted Impact	Blue Ammonia	Weighted Impact	Offshore Methanol	Weighted Impact
Greenhouse Gas Reduction	0.15	10	8	12.00	8	12.00	7	10.50
Consolidated Energy Use	0.055	7	6	2.31	7	2.69	8	3.08
Export Opportunity	0.065	8	7	3.64	8	4.16	8	4.16
Brazilian Demand	0.055	7	6	2.31	7	2.69	6	2.31
Stimulating Technological Innovation	0.045	6	8	2.16	6	1.62	7	1.89
Employment Opportunities and Economic Growth	0.055	7	6	2.31	7	2.69	7	2.69
Storage Capacity and Flow Logistics	0.045	6	6	1.62	7	1.89	7	1.89
Economic Viability	0.15	10	5	7.50	6	9.00	7	10.50
Operational Risks and Security	0.045	6	5	1.35	6	1.62	6	1.62
Need for R&D&I	0.035	5	7	1.23	6	1.05	6	1.05
Competition with Other Energy Sources	0.055	7	4	1.54	5	2.31	6	2.54
Regulatory Uncertainties and Financing	0.055	7	6	2.31	6	2.31	6	2.31
Reluctance for New Uses	0.035	5	5	0.88	6	1.05	6	1.05
Resistance of Local Communities	0.035	5	5	0.88	5	0.88	5	0.88
Economy of Scale	0.045	6	6	1.62	6	1.62	7	1.89
Technological Challenges	0.045	6	6	1.62	6	1.62	6	1.62
Total				**47.96**		**55.20**		**53.18**

The resulting table (**Table 2**) shows that while all products present significant opportunities, blue ammonia stands out as the most promising choice, with a score of 55.10, compared to offshore methanol's score of 53.18 and blue hydrogen's score of 47.96. This conclusion is supported by the higher weighted scores, reflecting its ability to reduce carbon emissions, meet domestic and foreign demand, and promote technological innovation and economic growth.

Thus, the production of ammonia using VLFS, in this case, has signs of being a solution to explore and benefit from the abundant potential supply of energy in the Brazilian pre-salt layer, in the form of combustible gases, which, to date, have proven difficult to transport to the Brazilian coast or for export, with subsequent application throughout the South Atlantic, with other low-carbon solutions. And, in this context, the potential for implementing these projects becomes a global challenge. After all, how is it possible for South Atlantic nations to take advantage of the vast maritime resources available in coastal regions in order to reduce carbon emissions, meet internal and external demand, promote technological innovation and economic growth, given the capacity to finance such capital-intensive projects. To respond to this challenge and create favorable conditions for this development, the answer will possibly involve multilateralism in the Global South, allowing cooperation between nations to overcome common challenges.

Given the specific challenges faced by countries in the Global South, such as limited infrastructure and restricted access to advanced technologies, it is crucial to promote knowledge transfer and capacity building through multilateral partnerships. This could include technical assistance programmes, sharing of best practices and collaboration in research and technology development. However, it is crucial to ensure that VLFS projects are carried out in a safe, sustainable and economically viable manner. This requires the implementation of effective regulations, rigorous safety standards and comprehensive environmental impact assessments. Multilateralism in the Global South can facilitate the exchange of experiences and collaboration on regulatory and compliance issues, ensuring that VLFS projects benefit not only coastal countries but also the global community as a whole.

This perspective is corroborated by the fact that the seas of the South Atlantic have witnessed important historical events since the early periods of Iberian colonization. Furthermore, the strategic importance of the sea for Brazil was highlighted during periods such as the Second World War and the Cold War. During the transition from the late 20th century to the early 21st century, security-related issues, both traditional and non-traditional, have become increasingly relevant in Brazil's national strategy. In addition to the defense of Brazilian maritime territory, new threats have emerged in the Atlantic, such as human and drug trafficking, piracy and marine pollution. Therefore, the means to promote the occupation and adequate exploration of the Brazilian pre-salt layer have become a fundamental issue, given the direct impact on the country's economy, given the concentration of the population and the presence of strategic ports along the Brazilian coast, as analyzed by Moraes and Lacerda *et al.* [30] [31].

Research on Very Large Floating Structures (VLFS) for offshore energy production and related applications still faces several notable limitations. Many studies, such as those by Cunanan and Suzuki and Riggs, remain at a conceptual or simulation-based level, lacking real-world validation or large-scale implementation. Economic and feasibility analyses often overlook critical variables such as logistics, maintenance in harsh marine environments, and integration with existing energy infrastructure, a point raised by Salmon and Bañares-Alcántara and Lamas-Pardo *et al.* Furthermore, methodological heterogeneity and the absence of standardized data hinder comparative assessments across proposed scenarios. The literature also shows a significant gap in addressing regulatory frameworks, socio-environmental impacts, and community engagement, which are essential for a comprehensive evaluation of VLFS deployment. Finally, while there is growing focus on advanced technologies such as blue hydrogen and ammonia, as seen in Hatton *et al.* and Ning *et al.*, current research provides limited insight into the challenges of implementing these solutions in regions with low energy demand or limited infrastructure.

5. Contextualization of Results for the South Atlantic and the Brazilian Case

While the SWOT categories employed in this study are analytically generic by design, their empirical relevance is grounded in the specific institutional, regulatory, and geopolitical context of Brazil and the South Atlantic. In the Brazilian case, regulatory complexity is not merely an abstract threat but is shaped by the interaction between sectoral regulators such as the National Agency of Petroleum, Natural Gas and Biofuels (ANP), environmental licensing authorities such as IBAMA, and broader fiscal and industrial policy instruments linked to offshore activities. The absence of a dedicated regulatory framework for VLFS, combined with fragmented maritime governance, increases uncertainty in project approval timelines and financing conditions, directly affecting the criteria related to regulatory uncertainty, operational risk, and economic viability identified in the SWOT analysis.

From a supply chain perspective, Brazil's offshore industry exhibits strong capabilities in FPSO construction, subsea systems, and offshore operations, but limited experience with the fabrication and integration of Very Large Floating Structures at the scale required for multi-product energy hubs. This creates localized weaknesses associated with technological challenges, need for R&D&I, and reliance on imported components or specialized engineering services. At the same time, Brazil's pre-salt geography, characterized by ultra-deep waters, large associated gas volumes, and proximity to strategic shipping routes in the South Atlantic, constitutes a unique opportunity for VLFS-based solutions that cannot be fully replicated in other regions.

Geopolitically, the South Atlantic occupies a strategic position in Brazil's national development and security agenda, as highlighted in the literature on maritime governance and defense. VLFS-based offshore hubs may therefore play a dual role, not only as energy transition infrastructures but also as instruments of maritime presence, industrial occupation, and regional integration. These regional factors reinforce the relevance of opportunities and threats identified in the SWOT analysis, grounding them in concrete Brazilian and South Atlantic conditions rather than abstract global trends.

6. Interpretation of the Synthetic-Comparative Matrix and Implications for Brazil

The results of the synthetic-comparative matrix indicate that blue ammonia achieves the highest aggregate performance, particularly in the two most heavily weighted criteria: greenhouse gas reduction and economic viability. This outcome reflects both technical and market-related factors. From a decarbonization standpoint, blue ammonia enables significant emission reductions when coupled with carbon capture technologies, while offering advantages in storage, transport, and handling compared to hydrogen. These characteristics directly explain its higher scores in logistics, storage capacity, and export opportunity, as reflected in the weighted assessment.

Economically, blue ammonia benefits from an established global market, mature industrial applications, and Brazil's structural dependence on fertilizer imports. The alignment between domestic demand, potential import substitution, and export opportunities to global markets enhances its economic viability relative to hydrogen, which faces infrastructure and storage constraints, and methanol, which, although versatile, presents higher exposure to market volatility and competition from alternative fuels. The matrix therefore suggests that blue ammonia represents a lower-risk entry point for VLFS deployment in Brazil, particularly in the short to medium term.

From an investment and policy perspective, these results imply that prioritizing blue ammonia projects could improve capital mobilization by reducing uncertainty for investors and aligning projects with existing industrial policies related to fertilizers, agribusiness, and export logistics. For policymakers, the findings highlight the importance of targeted regulatory frameworks, fiscal incentives, and public–private coordination mechanisms to support ammonia-based offshore hubs as a strategic component of Brazil's energy transition.

7. Integration with the Global South Perspective

The findings of this study also speak directly to the broader challenges faced by Global South countries, particularly those with extensive maritime zones and resource endowments but limited access to capital and advanced technologies. The weighted comparative analysis demonstrates that not all low-carbon pathways impose the same financial and technological burdens. Blue ammonia, as identified in this study, offers a pathway that balances decarbonization objectives with economic feasibility, making it more compatible with the structural constraints typical of Global South economies.

Moreover, the emphasis on VLFS as modular, scalable platforms aligns with the need for flexible infrastructure solutions that can be adapted to varying levels of demand, financing capacity, and institutional maturity. In this sense, the results support the argument that multilateral cooperation within the Global South can facilitate risk-sharing, technology transfer, and regulatory learning, particularly in regions such as the South Atlantic where countries face similar logistical, environmental, and governance challenges.

By explicitly linking the SWOT analysis and the synthetic-comparative matrix to Brazil's regulatory environment, industrial structure, and geopolitical context, this study demonstrates that VLFS-based blue ammonia projects are not merely technically viable but strategically aligned with the development needs of Brazil and other Global South nations. The results therefore contribute to a more nuanced understanding of how offshore energy transition infrastructures can be designed and prioritized in contexts characterized by capital intensity, institutional complexity, and asymmetric access to technology.

8. Assumptions and Limitations

This study is based on several explicit assumptions. First, it assumes that Very Large Floating Structures can be technically deployed in ultra-deepwater environments under conditions comparable to those reported in international case studies. Second, it assumes the availability of carbon capture and storage technologies at a maturity level compatible with industrial-scale offshore deployment. Third, market demand projections for hydrogen, ammonia, and methanol are assumed to follow international outlooks and Brazilian sectoral plans currently available in the literature.

The study also presents important limitations. The analysis relies predominantly on secondary data and modeling-based evidence, given the absence of operational VLFS projects in Brazil. As a result, real-world performance data related to long-term maintenance, logistics, and environmental impacts remain uncertain. Additionally, the weighted multi-criteria assessment reflects expert judgment, which, despite being structured and consensual, inherently carries subjectivity. Regulatory analysis is constrained by the lack of a dedicated VLFS framework in Brazil, requiring inference from adjacent offshore and environmental regulations. Finally, social acceptance and community engagement aspects could not be empirically validated and were therefore addressed qualitatively.

9. Results and Discussion

The proposed methodology outperforms traditional qualitative approaches by integrating literature-driven SWOT analysis with a weighted multi-criteria evaluation framework. Unlike conventional SWOT applications, which remain descriptive and non-comparative, the proposed approach translates qualitative insights into a structured, semi-quantitative assessment. This allows explicit trade-offs between environmental performance, economic viability, and operational risks to be evaluated simultaneously.

The superior performance of the approach lies in its ability to prioritize criteria according to strategic relevance, particularly greenhouse gas reduction and economic viability. These criteria, identified as necessary conditions for feasibility, strongly influenced the final ranking of alternatives. As a result, blue ammonia achieved the highest aggregate score, reflecting not only its emission reduction potential but also its logistical advantages, established markets, and compatibility with existing maritime transport systems.

The experimental design could be expanded in future studies by incorporating sensitivity analyses, scenario-based weighting variations, and probabilistic risk modeling. Nevertheless, the current framework already captures the most relevant technical, economic, regulatory, and social dimensions required for strategic offshore energy planning.

10. Conclusions

Very Large Floating Structures (VLFS) represent a transformative innovation in maritime engineering with far-reaching implications for decarbonization, energy transition, and sustainable development. Their multifunctionality—ranging from transport and logistics infrastructure to renewable energy hubs and platforms for low-carbon production—positions them as a cornerstone of future offshore operations. In the South Atlantic context, particularly within Brazil's Pre-salt region, VLFS offers a viable solution to overcome the logistical, environmental, and economic challenges of offshore energy production while minimizing the ecological footprint.

The SWOT analysis conducted highlights the strategic potential of VLFS in addressing critical aspects such as greenhouse gas reduction, technological innovation, and export opportunities. Blue ammonia emerges as a particularly promising application due to its established industrial uses, ease of transportation, and alignment with global decarbonization goals. However, the success of VLFS projects depends on overcoming significant challenges, including high capital expenditures, regulatory uncertainties, and the complexities of operating in harsh marine environments.

Brazil, despite its leadership in offshore oil production through FPSOs, lacks experience in VLFS deployment. This gap underscores the urgent need for innovation and investment to leverage the country's vast maritime resources sustainably. The global urgency of the climate crisis presents an opportunity for Brazil and other South Atlantic nations to lead in implementing VLFS as part of the energy transition. This requires fostering multilateral cooperation within the Global South, promoting knowledge transfer, and building technological and regulatory capacity.

Multilateral partnerships are crucial for addressing the unique challenges faced by countries in the Global South, such as limited infrastructure, technological barriers, and funding constraints. Collaborative efforts can facilitate the sharing of expertise, best practices, and advanced technologies, while ensuring the alignment of local and international regulatory frameworks. Furthermore, government support through public policies, incentives, and financing mechanisms is indispensable for creating favorable conditions for VLFS development. Such support not only accelerates the transition to a low-carbon economy but also reinforces energy security and economic resilience in the region.

Beyond the technical and economic dimensions, VLFS projects carry significant geopolitical and strategic implications. The sustainable occupation and exploration of Brazil's Pre-salt layer have direct impacts on national and regional economies, as well as on the strategic positioning of the South Atlantic in global energy dynamics. Historically, the South Atlantic has been a stage for both cooperation and conflict, and the deployment of VLFS could strengthen the role of this region as a hub for innovation and sustainability. By addressing traditional and non-traditional security threats, such as resource competition, environmental degradation, and maritime security, VLFS contribute to a more stable and prosperous South Atlantic.

Looking ahead, the integration of VLFS into Brazil's offshore energy strategy demands a multidisciplinary approach, combining engineering excellence, environmental stewardship, and socio-economic foresight. Investments in research and development, alongside a commitment to sustainability, will be essential to ensure that VLFS become a driving force in the energy transition. By positioning itself at the forefront of VLFS innovation, Brazil can not only enhance its energy independence and economic growth but also establish itself as a global leader in low-carbon maritime solutions.

In conclusion, VLFS are more than an engineering solution; they are a strategic asset for addressing some of the most pressing challenges of our time, including energy transition, climate change, and sustainable economic development. Their successful implementation in Brazil's Pre-salt and the broader South Atlantic region could serve as a model for global cooperation in tackling the intertwined challenges of energy security and environmental sustainability. This vision, however, requires collective action, robust public policies, and a shared commitment to building a more sustainable and resilient future for all.

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Conflicts of Interest

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

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Annex 1: List of Acronyms and Abbreviations

O&G	Oil and Gas
LNG	Liquefied Natural Gas
UNFCCC	United Nations Framework Convention on Climate Change
IBAMA	Brazilian Institute of Environment and Renewable Natural Resources
PLANAFE	National Fertilizer Plan of Brazil
FPSOs	Floating Production, Storage and Offloading Units
CNOOC	China National Offshore Oil Corporation
VLFS	Very Large Floating Structures
CCS	Carbon Capture and Storage
IEA	International Energy Agency
ANP	National Agency of Petroleum, Natural Gas and Biofuels