

Developing an Integrated Logistics Framework for Very Large Floating Structures: The Case of Brazil's Pre-Salt and Ammonia Production

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Abstract

This article proposes an integrated logistics framework to enable the use of Very Large Floating Structures (VLFS) in the Brazilian pre-salt region, connecting the monetization of offshore natural gas to ammonia production with carbon capture and storage (blue ammonia). The framework derives from four analytical pillars: operational governance, operational excellence, strategic vision, and stakeholder relations. It is operationalized through ten guiding principles that address planning, governance, performance management, technological innovation, sustainability and regulatory compliance, supporting infrastructure, stakeholder engagement, safety and resilience, digitalization, and economic viability. The study situates VLFS within the historical evolution of large floating systems and emphasizes their energy applications and construction strategies. A case study using natural gas from the Búzios field, in the Brazilian pre-salt, illustrates a modern ammonia production route that combines carbon storage with established technology for ammonia production, involving the unit operations of desulfurization, pre-reforming, autothermal reforming with pure oxygen, high- and low-temperature shift reactions, selective CO₂ removal with MDEA, methanation, and Haber-Bosch synthesis, supported by cogeneration, air separation units, and water and effluent treatment with high availability of natural gas from the pre-salt. The logistics chain integrates subsea pipelines, offshore processing, cryogenic storage at -33°C, specialized terminals with biweekly shipments on vessels of up to 40,000 m³, under strict safety, traceability, and contingency planning requirements. Policies and regulations, including IMO standards and regional initiatives, and clean logistics technologies are discussed in terms of carbon emissions reduction

and competitiveness. Innovations in the field, such as the use of drones and unmanned surface vessels, indicate operational gains and a lower greenhouse gas footprint. The analysis concludes that a multidisciplinary, data-driven logistics model adapted to Brazilian specificities is central for minimizing financial, safety, and sustainability risks, positioning Brazil as a benchmark in low-carbon offshore value chains.

Keywords

VLFS, Offshore Logistics, Blue Ammonia, CCUS, Pre-Salt, Logistics 4.0, Operational Governance, Decarbonization

1. Introduction

According to the Logistics Management Council, “Logistics is the part of Supply Chain Management that plans, implements, and controls the efficient and economical flow and storage of raw materials, semi-finished materials, and finished products, as well as the information related to them, from the point of origin to the point of consumption, with the objective of meeting customer needs” (apud [1]).

In the oil, gas, and biofuels sector, logistics encompasses multiple stages, with a critical emphasis on the safe transportation of products, typically via pipelines, tankers, or trucks. Furthermore, storage at terminals and refineries represents a key logistical concern.

Effective supply chain management is essential, as it involves planning and coordinating multiple operations to ensure timely and efficient delivery to the market. Environmental regulations also play a significant role, directly influencing logistics practices and operational compliance in the sector [1].

The following sections analyze the key logistical dimensions in the oil, gas, and biofuels industries, including objectives, strategies, supply chain, and logistics support systems, applying this oil and gas industry model to offshore blue ammonia production. Logistics is essential at all stages of the value chain, from production to final distribution, each presenting specific requirements and challenges [2].

2. Large Floating Structures and Their Use in the Brazilian Pre-Salt

In Brazil, projections show that natural gas production will grow from approximately 139 million m³/day in 2019 to 253 million m³/day by 2029. In this scenario, the use of VLFS in the pre-salt region emerges as a strategy to monetize offshore natural gas locally, avoiding the logistical challenges of transporting the gas to the coast. A promising venture, leveraging existing offshore infrastructure, is the production of hydrogen by reforming natural gas with carbon capture and storage (CCS), which is subsequently converted to ammonia, responding to the growing

global demand for low-carbon energy [3].

This paper places VLFS in integrated planning for the energy, mineral, and economic exploitation of ocean resources in the context of decarbonization and energy transition in the O&G sector.

Types of Structures and Applications

Studies classify VLFS by geometry (pontoons or semi-submersibles), location (coastal or offshore), or function (transportation platforms, residential platforms, multipurpose platforms, and energy platforms) (Lamas-Pardo *et al.*, 2015; Jiang *et al.*, 2023). This article focuses on the latter, energy platforms, as illustrated in item “b” of **Figure 1**.

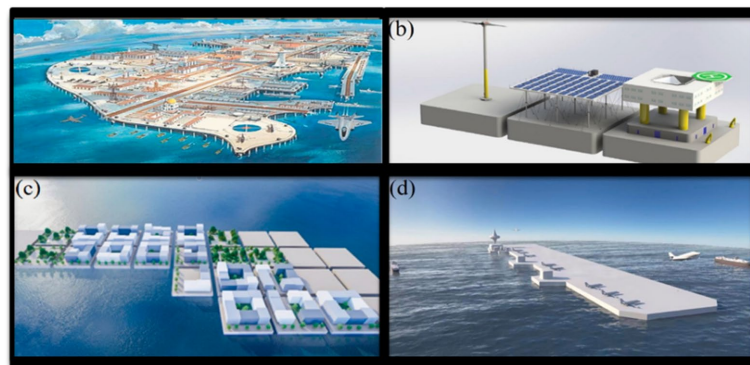


Figure 1. Examples of VLFSs for various applications: (a) logistics, (b) energy, (c) live, (d) others designed for various activities. (Source: Jiang *et al.*, 2023)

Pontoon-style VLFS are typically deployed in coastal areas characterized by calm waters, such as bays, inlets, or lakes, close to the shore. Coastal VLFS projects often adopt the pontoon configuration (also known as “Mega-Floats”) due to its structural simplicity, which is suitable for sheltered environments. Due to their shallow draft relative to their length (1,000 to 10,000 meters), these structures are also described in the literature as “mat-style” VLFS [4].

Mega-floats offer several advantages, including structural simplicity, low construction costs, short construction times, and ease of maintenance. Pontoon-type VLFS have been extensively studied and implemented, particularly in calm waters [5]. Compared to other offshore structures, pontoon-type VLFS exhibit high flexibility, making elastic deformations more significant than rigid-body movements [4]. Structurally, pontoon-type VLFS resemble extremely thin plates that float on the water surface, with their bottom surface aligned with the static water level (SWL) [5].

As illustrated in **Figure 2**, a Mega-Float comprises a substantial floating pontoon structure equipped with mooring or anchoring systems to maintain its position. It also includes an access bridge or floating road connecting it to the mainland, and when significant wave heights exceed 4 meters, a breakwater is incorporated to mitigate wave forces acting on the structure [6].

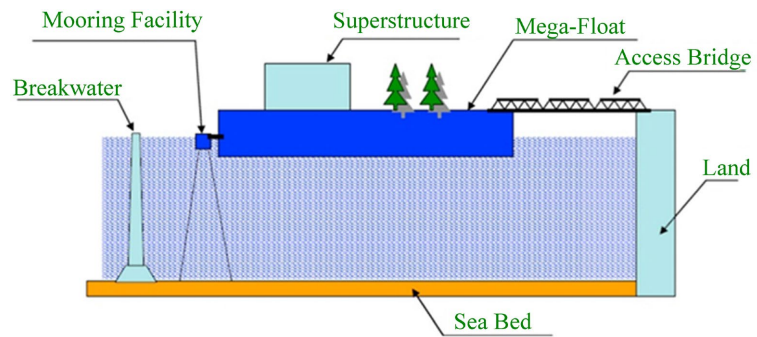


Figure 2. Schematic arrangement of the elements of a Mega-Float. (Source: Watanabe *et al.*, 2004)

Regarding the construction system, the Mega-Float features a structural design analogous to that of a steel ship hull. This type of construction, long used in ship-building, is recognized for its strength, reliability, and relatively low weight. The construction standards applied are similar to those governing conventional vessels and offshore oil platforms. The assembly process involves prefabricated modules, typically ranging from 100 to 300 meters in length, fabricated onshore and subsequently joined at sea through welding, as illustrated in **Figure 3** [4].

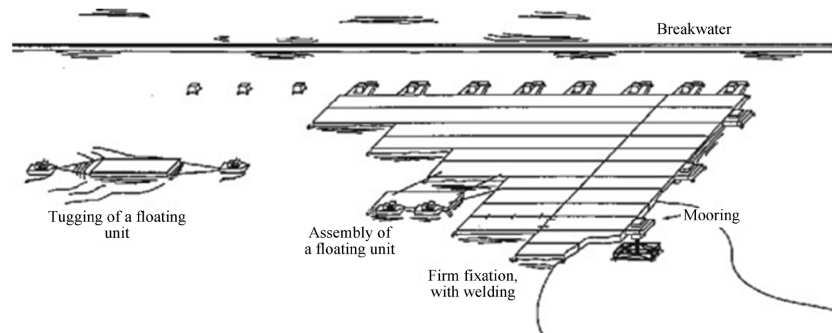


Figure 3. Example of the structural design of a Mega-Float. (Source: Prepared by the authors, adapted from Pardo *et al.*, 2015)

Energy-focused Very Large Floating Structures (VLFS), the central topic of this article, are designed to collect or store various forms of energy, including solar, wind, wave, and other renewable sources, as well as chemical energy.

In terms of energy storage, floating facilities have proven effective in storing hydrocarbons off the coast of Singapore, as well as crude oil in Japan and the Republic of Congo. These floating storage units offer not only efficient storage capacity but also operational flexibility in offshore positioning and ease of relocation [5].

VLFS concepts, such as Mobile Offshore Base (MOB) and Mega-Float, are highlighted due to their minimum dimensions of around 1,000 meters in length and a maximum of 10,000. These values exceed those of conventional floating structures by at least an order of magnitude in length, representing significant challenges for contemporary engineering [4].

Unlike ships, which have evolved gradually through accumulated experience and advances in analytical techniques, VLFS represents a new class of floating systems. Their uniqueness lies not only in their scale and displacement, but also in their cost, estimated between US\$ 5 billion and US\$ 15 billion, and their projected service life, which ranges from 50 to 100 years. **Figure 4** illustrates several of these considerations, further emphasizing the distinctive nature of VLFS [7].

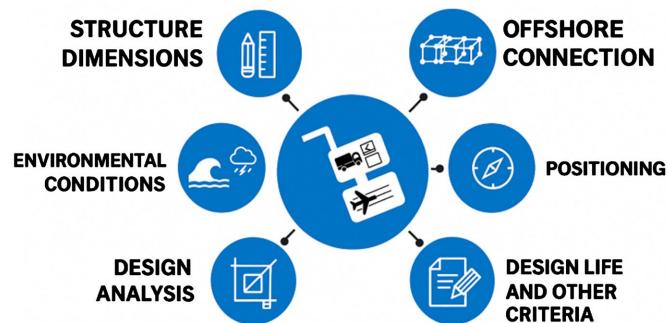


Figure 4. Characteristics of singularities in VLFS projects. (Source: Prepared by the authors themselves)

The use of Very Large Floating Structures (VLFS) in the Brazilian pre-salt layer is an innovative approach to monetizing natural gas offshore. VLFS offers significant advantages in terms of design and efficiency, eliminating the need for pipelines to transport natural gas to shore and from shore to offshore, transporting CO₂ for storage. This makes the solution economically attractive and aligned with the energy sector's decarbonization goals.

Thus, the application of VLFS-type structures for the production of blue ammonia in the Brazilian pre-salt represents a technological advance, positioning Brazil at the forefront of the application of these structures to create low-carbon value chains.

3. Logistics in the Oil and Gas Industry and Its Application in Offshore Ammonia Production

The oil, gas, and biofuels supply chain is highly complex, encompassing multiple steps and processes, in addition to specialized labor, as well as a wide range of suppliers of materials, components, and services [8] [9].

This supply chain can be broadly categorized into four main blocks of activities: Exploration and Production, Refining, Distribution, and Marketing [9]. According to Branski [2], the oil supply chain is traditionally divided into two main segments: upstream and downstream. The upstream segment includes exploration, development, and production activities, while the downstream segment comprises refining, distribution, and marketing operations [10].

The high degree of interconnection within the supply chain in the oil and gas industry means that the efficiency of each stage depends on the performance of the others. Regarding ammonia logistics, its production requires well-structured

logistics, which involve everything from the supply of raw materials, processing, storage, and transportation of the product [11] [12].

In raw material logistics, the main raw materials for the process are natural gas, which provides hydrogen for the process, and nitrogen obtained from atmospheric air. The supply of these raw materials must be constant and reliable, as supply interruptions affect the entire production chain. Natural gas is primarily transported via pipelines, while nitrogen is captured directly from the air at the industrial unit [13].

The choice of the four pillars, Exploration and Production, Refining, Distribution, and Marketing, reflects the main stages of the oil and ammonia supply chain as recognized in supply-chain and offshore-logistics theory. Exploration and production correspond to the upstream segment, where coordination between offshore operations and supply bases is essential to reduce transaction costs and ensure continuity of production. Refining represents the process-integration stage, in which synchronized material and information flows add value and minimize operational bottlenecks [14]. Distribution aligns with systems theory, emphasizing multimodal coordination between pipelines, terminals, and maritime transport to ensure the efficient flow of outputs. Finally, Marketing connects to demand-driven supply-chain theory, highlighting the importance of responsiveness to market signals and adaptive logistics planning to match production with consumer needs [15].

Offshore blue ammonia production shifts the focus away from “supply-driven” raw material logistics, where production plants are traditionally located near natural gas distribution networks. Offshore blue ammonia is installed near natural gas production fields and geological areas with technical feasibility for CO₂ storage.

After production, ammonia is stored in pressurized tanks or in a liquid state, depending on demand and transportation conditions. In addition to controlling the quantity stored and the physical state of ammonia, storage logistics requires safety systems to prevent leaks that can be harmful to the health of workers and the environment due to its toxicity.

Regarding ammonia transportation logistics, it can be transported by tanker trucks, rail cars, or ships, depending on the distance and volume. Transportation requires special attention to safety standards due to the toxic and corrosive nature of the product. The entire transportation and distribution chain must comply with environmental and safety regulations, with adequate documentation and training for the professionals involved [16]. In the case of ammonia transported by ship, the infrastructure of storage terminals in industrial ports must be considered in the logistics.

It should be noted that offshore blue ammonia production requires storage of the CO₂ generated in the process, which, in the offshore case, can be transported to the storage site via pipelines or ships. Furthermore, it is necessary to control the amount of CO₂ sent to geological storage and monitor any leaks.

The logistics of ammonia production are complex and involve multiple challenges, from the sourcing of raw materials to the delivery of the product to the customer. Efficiency, safety, and sustainability are essential to ensure the success of the operation and compliance with legal and environmental requirements [16].

Ammonia is emerging as an energy carrier for hydrogen and as a fuel for maritime transportation. This new role will require a significant expansion of export and import infrastructure, which will impact ammonia logistics [16].

Offshore logistics in Brazil began in 1966 with seismic surveys. Since then, it has been improving to incorporate sustainable resource management and environmentally responsible practices, and thus supports all platform operations through inventory management, acquisition, material movement, storage, and transportation. These activities depend on supply vessels, helicopters, and communication systems [17] [18].

4. Barriers and Challenges of Offshore Logistics for Ammonia Production, Transportation, and Storage in the Oil, Gas, and Biofuels Sector

The logistics of offshore blue ammonia production, like the oil, gas, and biofuels sector, face a series of technical, economic, environmental, and regulatory challenges that directly affect efficiency, safety, and sustainability. Offshore production is located in remote areas and relies on specialized vessels and helicopters to transport equipment, materials, and personnel, often in adverse weather conditions. Port infrastructure limitations, logistical bottlenecks, and fragmented supply chains further increase complexity, leading to higher costs and the risk of communication failures and synchronization issues [18]-[21].

The logistics of blue ammonia production present barriers in terms of its danger and safety, transportation, and global infrastructure. The dangerous nature of ammonia requires extremely strict safety protocols and specialized equipment, increasing the costs and complexity of logistics.

Global long-distance transportation infrastructure requires the adaptation or construction of vessels, pipelines, and export and import terminals specifically for ammonia, entailing a massive capital investment that takes years to implement. Operational delays or weather disruptions can saturate storage capacity, causing vessel idleness and significant financial losses [22]. Compounding these bottlenecks is compliance with stringent safety and environmental regulations, coupled with a shortage of skilled professionals and the high volatility of global energy prices, which further increase project risks [22].

5. Pillars of the Logistics Model

One of the fundamental pillars of this article is Operational Governance, addressing key aspects of transportation, storage, distribution, and materials management in the oil and gas industry. This pillar also explores the logistics tools and systems that can increase the efficiency and effectiveness of operations, especially

when applied to VLFS-related activities.

The second pillar, Strategic Vision, focuses on how the industry is preparing for future challenges by adopting emerging technologies such as Artificial Intelligence, automation, and optimization of maritime logistics routes. This forward-looking perspective highlights the transformative potential of digital innovation in offshore logistics.

The third pillar, Stakeholder Relations, examines the interaction between logistics and external factors, such as environmental concerns, sustainability, and regulatory frameworks. While these elements often pose challenges in offshore operations, they can also become strategic enablers when properly addressed and integrated into planning and execution.

The Operational Excellence pillar emphasizes the importance of planning, control, and efficiency in logistics. It also analyzes how the oil and gas supply chain can benefit from applying best practices and methodologies already established in other industrial sectors.

These four pillars and their respective drivers are illustrated in **Figure 5**, which provides a visual summary of the proposed logistics model for VLFS in the oil and gas industry.



Figure 5. Basic principles of the model. (Source: Prepared by the authors)

5.1. Excellence Operational

Logistics planning integrates all stages of the supply chain, aiming for efficiency, safety, and profitability. Effective planning prevents bottlenecks, ensures adequate capacity, and avoids unnecessary inventory accumulation [18]. Offshore operations rely on helicopters, vessels, and specialized transportation, while onshore

operations rely heavily on roads and railways. Information technologies, such as Logistics Management Systems (LMS) and tracking tools, improve decision-making and operational visibility. Increasingly, sustainability practices, optimized routes, emissions reduction, and the adoption of low-carbon fuels are being incorporated into logistics planning.

In the offshore environment, support bases play an important role, serving as hubs for distribution, equipment maintenance, communication, and emergency response. They also provide accommodation, food, and leisure for workers, as well as a safe environment for training and medical care. Personnel logistics are highly structured, encompassing schedule planning, transportation reservations, security checks, embarkation and disembarkation, temporary accommodations, and emergency contingency measures [22].

5.2. Strategic Vision

Future logistics strategies point to digitalization and sustainability. Clean logistics technologies, such as hybrid/electric vehicles, route optimization software, real-time tracking, and intermodal transport, are seen as essential for reducing emissions and improving efficiency within the supply chain [22]-[24]. The adoption of clean logistics technologies, however, faces challenges such as high investment requirements, lack of standardization, and regulatory complexity [25]. Technological innovations in fuels (methanol, hydrogen), renewable energy-assisted propulsion, and optimized shipping routes support the energy transition and green logistics [26].

At the same time, digital transformation through AI, IoT, and big data is reshaping logistics. Smart logistics structures improve visibility, reduce labor dependency, and enhance analytical capabilities, offering more agile and accurate operations. Despite slow adoption, AI is expected to play a key role in the modernization and sustainability of logistics systems [26].

In short, AI is revolutionizing logistics, delivering significant efficiencies and fostering innovation, while also presenting complex challenges. However, future research must comprehensively assess this dynamic to ensure that AI's role in logistics evolves sustainably and ethically. Effective AI development will be relevant to driving industry standards and achieving operational excellence.

5.3. Use of New Technologies

The offshore sector has been investing in new technologies to improve logistics and operational safety. Two important innovations currently being implemented in Brazil's offshore sector are remotely piloted aircraft (drones) and unmanned and remotely piloted vessels (USVs).

- **Remotely piloted aircraft (drones):** capable of carrying up to 50 kg, this innovation has demonstrated its potential to optimize offshore air logistics, reduce costs, lower carbon emissions, and collect data for future routes. Drones can be used to transport goods between ports and platforms in a short time,

significantly shorter than traditional vessels. In addition to transporting goods, drones can also be used for high-altitude inspections, such as on *flares*, tanks, and cranes, and to monitor oil spills. Thus, drone technology in the offshore sector helps minimize worker exposure and reduce costs. **Figure 6** illustrates a remotely piloted aircraft (drone) owned by Petrobras. Petrobras expects drone testing to demonstrate the feasibility of long-range flights between the mainland and platforms, thus enabling a range of applications with this technology [27].



Figure 6. Remotely piloted aircraft (drones). (Source: Fernandes—Petrobras Agency 2024)

Unmanned and remotely piloted vessels: vessels enable fully remote underwater inspections of shallow-water infrastructure. Unmanned vessel inspections utilize advanced technologies such as unmanned surface vessels (USVs) and electric remotely operated vehicles (eROVs), ensuring safe, efficient, and sustainable inspections [28].

By eliminating the need for on-site personnel, the unmanned solution (see **Figure 7**) reduces carbon emissions and significantly mitigates the risks associated with traditional offshore operations. This solution enables near-real-time access to data, enabling faster decision-making. Compared to conventional manned vessels, USVs can collect more data and reduce mobilization time [27]–[29].



Figure 7. Fugro Vaquita USV (Unmanned Surface Vehicle), the first unmanned vessel in the Americas. (Source: PALLANICH, 2024)

Added to this, the fact that the ROV is powered by electricity means there is no risk of hydraulic fluid leaks, a common concern with conventional ROVs. This solution is estimated to achieve a reduction of over 90% in greenhouse gas emissions compared to a standard ROV. Traditional vessels typically perform underwater operations using hydraulic ROVs [30].

The lack of standardized practices and technologies across the logistics sector also hinders progress toward cleaner operations. The development and implementation of clean logistics solutions, such as the adoption of electric and hydrogen-powered vehicles, route optimization through advanced data analytics, and the improvement of intermodal transportation networks, are essential to achieving significant reductions in the sector's carbon footprint [24].

6. Integrated Logistics Framework for VLFS Implementation

The oil and gas supply chain can be broadly categorized into four main activity blocks: Exploration and Production, Refining, Distribution, and Marketing. According to Branski, this structure aligns with the traditional upstream-downstream segmentation, in which exploration, development, and production activities compose the upstream segment, while refining, distribution, and marketing operations constitute the downstream segment. The high degree of interconnection among these stages means that the efficiency of each depends directly on the performance of the others.

In the context of blue ammonia logistics, this interdependence is even more critical. Ammonia production requires a robust and well-structured supply chain encompassing the supply of raw materials, processing, storage, and transportation. The main inputs, natural gas, which provides hydrogen, and nitrogen obtained from atmospheric air, must be supplied reliably to avoid production disruptions. While natural gas is primarily transported via pipelines, nitrogen is typically captured on-site at the industrial facility [31].

Building upon this foundation, the implementation of Large Floating Structures (VLFS) requires a comprehensive and integrated logistics model capable of addressing the complexity of offshore operations. This model is structured around four strategic pillars: Operational Governance, Operational Excellence, Strategic Vision, and Stakeholder Relations, which together define the framework for sustainable and efficient offshore logistics [32]. Each pillar corresponds to an established theoretical foundation in supply-chain or offshore-logistics studies:

- 1) Operational Governance aligns with coordination and transaction-cost theory, emphasizing structured oversight to minimize inefficiencies in complex offshore environments.
- 2) Operational Excellence draws from process-integration theory, promoting standardization, continuous improvement, and performance benchmarking across the logistics chain.
- 3) Strategic Vision reflects systems theory, advocating integrated planning that connects upstream production with downstream markets through optimized

multimodal flows.

4) Stakeholder Relations are rooted in demand-driven supply-chain theory, emphasizing adaptive management, transparency, and responsiveness to market, community, and regulatory expectations.

From these four pillars arise ten guiding principles that operationalize the model: i) integrated logistics planning; ii) structured operational governance [1], [32]; iii) operational excellence and efficiency [33]; iv) technological innovation; v) sustainability and regulatory compliance; vi) support infrastructure and logistics bases; vii) stakeholder management; viii) operational safety and resilience [34]; ix) digitalization and Logistics 4.0 [35]; and x) economic viability and scalability [35], as illustrated in Gerhard & Maurer.

Logistical complexity requires specialized port infrastructure, especially for cryogenic operations, incorporating articulated loading arms, thermal insulation, operational redundancy, and continuous pressure and temperature monitoring. The integration among port terminals, production plants, and transport systems must be carefully planned to ensure uninterrupted flow and avoid bottlenecks. Safety is paramount when handling ammonia, a hazardous material subject to stringent international transport regulations, demanding certified equipment, trained personnel, and emergency response systems.

Technological innovation strengthens this framework through automation, digitalization, and artificial intelligence. The integration of drones, unmanned vessels, IoT sensors, and predictive analytics enhances monitoring, safety, and decision-making [36]. These technologies enable real-time control of operations, increasing resilience and transparency while reducing risks associated with offshore logistics.

Sustainability and regulatory compliance form another cornerstone of the model. Compliance with agencies such as ANP, IBAMA, and IMO ensures adherence to environmental and safety standards. Practices such as emissions offsetting, route optimization, and the use of alternative fuels in tankers contribute to reducing the carbon footprint and advancing decarbonization goals. Reverse logistics and contingency planning are also critical to resilience, ensuring operational continuity in the face of disruptions.

From an environmental perspective, the case study integrates Carbon Capture and Utilization (CCU), reinforcing the low-carbon profile of the blue ammonia chain. Supporting infrastructure and logistics bases provide the backbone for maintenance, storage, and specialized technical services. Institutional and stakeholder relationships are equally strategic, requiring transparent dialogue with communities, governments, and partners to foster legitimacy and shared value [37].

In the Brazilian context, the implementation and operation of Large Floating Structures (VLFS) for ammonia production and logistics would require coordination among several regulatory bodies with complementary jurisdictions. The National Agency of Petroleum, Natural Gas and Biofuels (ANP) oversees activities

related to offshore natural gas exploration, processing, and utilization, including the licensing of associated gas-to-ammonia facilities. The Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) is responsible for conducting the Environmental Impact Assessment (EIA/RIMA) and issuing the Environmental Operating License, particularly for offshore units handling hazardous substances such as ammonia. The Brazilian Navy, through the Directorate of Ports and Coasts (DPC), ensures compliance with maritime safety standards and the classification of floating units under the Normas da Autoridade Marítima (NORMAM) framework. Additionally, the National Waterway Transport Agency (ANTAQ) regulates port operations, terminal concessions, and vessel logistics, including cryogenic cargo handling and maritime transport authorization [38].

Despite this regulatory structure, significant approval gaps remain. Brazil does not yet have a specific regulatory framework addressing industrial VLFS platforms for ammonia or hydrogen derivatives, leaving uncertainties regarding jurisdictional overlaps between ANP, IBAMA, and the Navy. Moreover, the integration of carbon capture, storage, and utilization (CCUS) systems within floating industrial units is not explicitly covered under current offshore licensing procedures. The absence of clear inter-agency coordination protocols and standards for modular offshore production units also presents challenges for investors and operators. These gaps highlight the need for an integrated regulatory roadmap combining energy, environmental, maritime, and port authorities to ensure legal clarity, safety, and sustainability in Brazil's emerging blue ammonia industry.

To quantitatively evaluate the framework's performance, key performance indicators (KPIs) are proposed to demonstrate measurable advantages over conventional logistics models. Preliminary estimates suggest a reduction in the logistics cost per tonne of blue ammonia from approximately US\$ 45/t to US\$ 38/t, primarily due to modular integration and optimized port operations. Logistics uptime, the share of operational time without disruption, could increase from 92% to 97% through predictive maintenance and real-time monitoring. Additionally, by integrating energy-efficient processes and low-carbon transportation, the model could achieve an average reduction of 0.25 t CO₂ eq per tonne of ammonia compared to current practices, aligning with international decarbonization objectives [38].

Overall, this integrated framework provides a holistic foundation for VLFS logistics in Brazil, balancing economic viability, operational efficiency, safety, and sustainability. It offers a replicable model capable of guiding the development of offshore industrial infrastructure aligned with global energy transition goals.

7. Case Study—Ammonia Production from Pre-Salt Hydrocarbons

The production of ammonia (NH₃) from the vast hydrocarbon resources of Brazil's pre-salt layer represents a highly relevant strategic initiative, aligning the exploitation of Brazil's natural resources with the growing global demand for ferti-

lizers, which are essential for food security, and for chemicals important to various industrial value chains. The pre-salt layer, a set of reservoirs located beneath a thick layer of salt on the ocean floor off the Brazilian coast, is a prolific source of natural gas, predominantly methane (CH_4).

This gas is the main raw material for the production of hydrogen (H_2), an essential precursor in the synthesis of ammonia through the renowned Haber-Bosch process. The ammonia produced in this way, when combined with carbon capture and storage (CCS), is often classified as “blue ammonia,” positioning it as a viable alternative in the transition to a low-carbon economy [38].

Traditionally, ammonia production involves the catalytic reaction between nitrogen (N_2), obtained cryogenically from atmospheric air separation, and hydrogen (H_2), produced primarily through steam methane reforming (SMR) or other hydrocarbon-based processes [39]. However, the plant in this case study, strategically located near the Búzios field in the Santos Basin, adopts a technologically advanced approach to hydrogen generation. It employs a combination of catalytic pre-reforming and autothermal reforming (ATR) using pure oxygen (instead of air). This configuration not only increases the energy efficiency of the process but also results in a more concentrated CO_2 stream, simplifying and reducing the cost of its subsequent capture and mitigating the need to treat large volumes of CO_2 diluted in flue gases [39]-[41].

The process flow begins with the critical step of natural gas desulfurization. The gas, sourced directly from offshore fields, is treated in a fixed catalytic bed containing zinc oxide (ZnO) operating at approximately 370°C . This unit achieves over 98% efficiency in removing sulfur compounds (such as H_2S and mercaptans), which are potent poisons for the catalysts used in the subsequent reforming and synthesis steps [42] [43]. After purification, the natural gas is mixed with steam in a tightly controlled molar ratio of 2.5 moles of steam per mole of carbon and fed to an adiabatic pre-reformer. In this unit, hydrocarbons heavier than methane (C_2+ , such as ethane, propane, and butane) are catalytically converted into a mixture of H_2 , carbon monoxide (CO), carbon dioxide (CO_2), residual methane (CH_4), and water vapor (H_2O), preventing soot formation and protecting the main reformer [44].

Pre-reformer effluent is directed to the autothermal reformer (ATR), where it reacts with pure oxygen (typically $> 99.5\%$ purity) supplied by a dedicated Air Separation Unit (ASU). The use of pure oxygen, instead of atmospheric air, is a strategic choice that avoids the introduction of large amounts of inert nitrogen into the system, which would otherwise result in larger equipment, lower conversion efficiency, and a diluted syngas stream [44]. Autothermal reforming combines partial oxidation and steam reforming in a single vessel, generating syngas rich in H_2 and CO_2 , with a lower CO_2 footprint per unit of energy produced compared to traditional steam reforming without optimized integration [44].

The resulting synthesis gas, still hot, is then routed to carbon monoxide conversion reactors (shift reaction). This process occurs in two stages: a high-temper-

ature shift (HTS) reactor, typically using an iron oxide-chromium catalyst, and a low-temperature shift (LTS) reactor, using a copper-zinc catalyst. In these reactors, CO reacts with steam to produce additional CO₂ and, crucially, more H₂ ($\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$), maximizing hydrogen yield.

The CO₂ generated in the reforming and displacement stages is subsequently removed from the syngas stream. For this plant, chemical absorption using methyl-diethanolamine (MDEA) was chosen, a tertiary amine known for its selectivity for CO₂ and lower regeneration energy requirements. This process occurs in absorption columns operating at approximately 2.5 MPa and 38 °C. The CO₂-rich MDEA solvent is regenerated by thermal desorption in a stripping column, and the recovered, high-purity CO₂ is compressed to approximately 15.27 MPa, reaching its dense phase for transportation and subsequent geological storage or utilization [45] [46].

The purified syngas stream, now with a very high concentration of H₂, undergoes a final purification step known as methanation. In this unit, residual traces of CO and CO₂ (typically in the ppm range) are catalytically converted into methane (CH₄) and water (H₂O) using a nickel-based catalyst. This step is essential, as carbon oxides are toxic to the ammonia synthesis catalyst [47]. After methanation, the synthesis gas, composed primarily of H₂ and inert CH₄, is mixed with high-purity nitrogen (also from the ASU) in a stoichiometric ratio of approximately 3:1 (H₂:N₂) and compressed to high pressures [47].

This mixture is then fed to the Haber-Bosch ammonia synthesis reactor, which operates under harsh conditions, typically 400 °C - 500 °C and 150 - 250 atm (in this case, 450 °C and 200 atm), using an iron-based catalyst promoted with oxides such as K₂O, CaO, and Al₂O₃ to facilitate the reaction $\text{N}_2 + 3\text{H}_2 \rightleftharpoons 2\text{NH}_3$ [48]. The reactor effluent, containing ammonia and unconverted reactants, is cooled to condense the ammonia. Liquid NH₃ is separated and subsequently cooled to -32 °C for storage and transportation in cryogenic tanks, while unreacted gases (H₂, N₂, and inerts) are recycled to the reactor to maximize overall conversion [48].

The plant is supported by a robust suite of utilities, including systems for generating steam and electricity through waste heat recovery (cogeneration), significantly improving overall energy efficiency [49]. The ASU is essential for supplying oxygen to the ATR and nitrogen for ammonia synthesis. Additional systems include seawater intake, water treatment units (for process, cooling, and potable water), and effluent treatment units to meet stringent environmental standards [50]. The project was designed for a production capacity of 77.4 tons of ammonia per day, equivalent to approximately 21,696 m³ of liquid ammonia per week, operating continuously (24 hours a day, 7 days a week) for 346 days a year, with 95% availability.

Integrated production logistics is a complex component, ranging from offshore hydrocarbon extraction to final ammonia distribution. Natural gas from pre-salt platforms is transported via subsea pipelines to the onshore processing unit. After production, liquid ammonia is stored in large-capacity cryogenic tanks at -33 °C.

To ensure product safety and minimize evaporation, a minimum level of 10% of the tanks' total capacity is maintained [51] [52]. Ammonia is exported by liquefied gas tankers with capacities of up to 40,000 m³, dispatched biweekly to serve the domestic and international markets.

Logistical complexity also requires specialized port infrastructure for cryogenic loading, with articulated loading arms, thermal insulation, operational redundancy, and continuous pressure and temperature monitoring. The integration between the port terminal, the production plant, and the transportation systems must be carefully planned to ensure continuous flow and avoid bottlenecks or unplanned shutdowns. Furthermore, safety is paramount when handling ammonia, a hazardous substance subject to strict transportation regulations, requiring trained personnel, certified equipment, and emergency response systems. Innovations such as cargo traceability and the digitalization of logistics operations, including IoT sensors and real-time management systems, are increasingly being adopted to ensure efficiency, safety, and regulatory compliance [53] [54].

Reverse logistics and contingency planning for transportation failures or infrastructure unavailability are equally important to ensure supply chain resilience. With growing global concern about decarbonization, the adoption of sustainable logistics practices, such as the use of alternative fuels in tankers, emissions offsetting, and route optimization, has become a relevant competitive differentiator. Thus, logistics not only enables production flow but is also a key element in the economic, environmental, and operational viability of the entire blue ammonia value chain [55]-[57].

From an environmental and sustainability perspective, the case study actively incorporates Carbon Capture, Utilization, and Storage (CCUS) technologies. In addition to the MDEA-based chemical absorption already described for the main CO₂ stream, other CCS technologies could be considered for smaller streams or as future optimizations. These include physical absorption (using solvents such as Selexol or Rectisol, effective at high CO₂ partial pressures), adsorption on solids (e.g., PSA—Pressure Swing Adsorption, using materials such as zeolites or activated carbon), separation by selective membranes (polymeric or inorganic), and cryogenic CO₂ separation technologies (liquefaction and fractional distillation) [58] [59].

Selecting the most suitable CCS technology for each gas stream is a multifactorial decision, taking into account CO₂ partial pressure, temperature, gas composition, desired CO₂ purity, capital (CAPEX) and operating (OPEX) costs, and technological maturity. The captured CO₂ is destined for geological storage in suitable formations, such as deep saline aquifers or depleted oil and gas reservoirs, or for use in processes such as Enhanced Oil Recovery (EOR) [60] [61].

Despite the clear economic benefits, such as monetizing domestic natural gas, replacing fertilizer imports, creating jobs, and the environmental advantages of producing blue ammonia with a lower carbon footprint compared to traditional routes without CCS, the project faces significant challenges. Among them is the high initial investment in infrastructure (CAPEX), both for the process plant and for the CCS systems and associated logistics. The ongoing need for technological

innovation to optimize efficiency, reduce costs and emissions, and ensure strict compliance with a complex and evolving regulatory framework (environmental, safety, and technical) is also a critical factor.

The sustainability of the logistics chain is also a key focus, with efforts to optimize transport routes, employ more efficient vessels, and, in the future, explore low-carbon fuels for maritime transport. The long-term viability of the project is intrinsically linked to its ability to remain economically competitive, manage technological and market risks, and maintain strong socio-environmental performance.

8. Conclusions

Large Floating Energy Structures (FLEEs) represent a promising and multifunctional solution for the sustainable use of maritime space, particularly in a global context marked by the growing demand for clean energy and the urgent need to decarbonize the energy matrix. The historical development of FLEEs demonstrates the evolution of the concept and its progressive adaptation to contemporary needs, from early 20th-century projects to more recent applications in airports, floating cities, and offshore power generation units.

Pre-salt regions, the use of EFLEE emerges as a viable and strategic alternative for monetizing natural gas reserves, whose full exploitation is hampered by logistical constraints and high transportation costs. The production of hydrogen and its derivatives, such as ammonia, directly on offshore platforms can not only add value to available energy resources but also contribute to national energy security and the achievement of the country's environmental goals.

Logistics plays a strategic and decisive role in the viability of projects in the oil, gas, and biofuels industry, particularly regarding the implementation of large floating structures in offshore environments. Based on the analysis developed throughout this article, the main logistical challenges associated with such operations were identified, including the complexity of transporting large components, the need for synchronization between different logistics modes, the limitations of Brazil's port infrastructure, and issues related to safety, sustainability, and environmental regulation.

The proposed logistics model aims to meet these demands in a structured manner, optimizing the flow of materials and information from module manufacturing to final offshore installation. The model design involved analyzing critical variables such as terminal load capacity, operational constraints on support vessels, weather conditions, availability of specialized labor, and the use of real-time monitoring and tracking technologies.

In addition to technical and economic considerations, the study also highlights the urgent need for improvements in the legal and regulatory framework, both nationally and internationally. Adopting a regulatory model that takes into account the specificities of VLFS is essential to ensuring their legal viability in Brazil. This includes adapting maritime and environmental legislation and strengthening governance over the sustainable use of ocean space.

Ammonia production from pre-salt hydrocarbons represents a significant opportunity for Brazil. With its vast reserves and technological potential, the country can not only meet domestic demand for fertilizers but also position itself as a strategic exporter in the global market. The combination of economic efficiency and sustainable practices can transform this industry into a fundamental pillar of Brazil's economic and environmental development in the coming years.

The logistics of ammonia production from pre-salt hydrocarbons involve a complex series of operations, from extraction to distribution of the final product. Careful planning and adequate infrastructure are essential to ensure the entire process is efficient and sustainable. Given the growing global demand for fertilizers and chemicals, optimizing this logistics chain is increasingly important for Brazil's economic development and for promoting a more sustainable future for the chemical industry.

The adoption of an integrated and multidisciplinary logistics model, adapted to Brazilian specificities, is essential to ensure efficiency, safety, and sustainability in the implementation of these floating structures. Furthermore, it is important that companies in the sector invest in long-term planning, digitalization of logistics processes, the formation of strategic partnerships, and modernization of national infrastructure to reduce logistical bottlenecks and increase the country's competitiveness in this segment.

This study reinforces the need for a systemic and innovative logistics approach that considers both the specificities of the oil and gas sector and the demands of technological advancement and sustainability. The development of customized logistics models, therefore, represents a competitive advantage for the success of large-scale offshore projects in Brazil.

The design and development of large floating structures must be approached in an integrated manner, considering technological, logistical, regulatory, and environmental challenges. Due to its geographic location and energy potential, Brazil has the opportunity to become an international leader in this emerging field, provided there is strategic planning, investment in innovation, and a firm commitment to the sustainable development of maritime resources.

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Conflicts of Interest

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

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