



(REVIEW ARTICLE)



Reviewing the development of floating LNG facilities and their global impact

Adedayo Adefemi ¹, Cosmas Dominic Daudu ², Chinelo Emilia Okoli ³, Olushola Babatunde Ayorinde ⁴, Oladipo Olugbenga Adekoya ⁵ and Chidera Victoria Ibeh ^{6,*}

¹ *Chevron Nigeria Limited, Nigeria.*

² *Nigeria LNG Limited, Bonny Island, Nigeria.*

³ *Independent Researcher, Lagos, Nigeria.*

⁴ *Independent Researcher, Canada.*

⁵ *Nigeria LNG Ltd, Bonny Island, Rivers State, Nigeria.*

⁶ *Harrisburg University of Science and Technology, USA.*

World Journal of Advanced Research and Reviews, 2024, 21(02), 371–381

Publication history: Received on 29 December 2023; revised on 03 February 2024; accepted on 06 February 2024

Article DOI: <https://doi.org/10.30574/wjarr.2024.21.2.0463>

Abstract

This Review encapsulates a comprehensive review of the development and global impact of Floating Liquefied Natural Gas (FLNG) facilities. These innovative structures have revolutionized the liquefied natural gas industry by enabling offshore gas extraction, liquefaction, and storage. The study explores the evolution, challenges, and transformative influence of FLNG facilities on the global energy sector. The review begins with an examination of the historical development of FLNG technology, tracing its roots to the early 21st century. It showcases how these floating facilities have evolved from conceptual designs to operational structures, emphasizing key technological advancements that have propelled their growth. The global impact of FLNG facilities is analyzed through multiple lenses. Economic considerations, such as cost-effectiveness and accessibility to remote gas reserves, emerge as significant drivers for their adoption. The study also delves into the environmental implications, assessing the potential benefits and challenges associated with offshore liquefaction. Challenges inherent in FLNG development, including engineering complexities and regulatory considerations, are addressed. The study sheds light on how these challenges have been navigated, leading to successful deployment and operation of FLNG facilities in various regions. The transformative influence of FLNG facilities on global energy dynamics is highlighted, with a focus on their role in unlocking stranded gas reserves and facilitating timely responses to shifting market demands. The review emphasizes their adaptability to different geographic and economic contexts, showcasing their versatility as a pivotal component of the liquefied natural gas supply chain. In conclusion, this review offers a panoramic perspective on the development of FLNG facilities and their profound impact on the global energy landscape. By bridging technological innovation, economic viability, and environmental considerations, these floating facilities emerge as key contributors to the evolving dynamics of the liquefied natural gas industry, shaping a resilient and adaptive future for the energy sector.

Keywords: Development; Floating; LNG; Facilities; Global Impact

1. Introduction

Floating Liquefied Natural Gas (FLNG) facilities represent a paradigm shift in the LNG industry, encapsulating the ingenuity of maritime engineering and liquefaction technologies (Pym, 2021). Unlike traditional onshore LNG facilities, FLNG units are mobile structures strategically positioned offshore to extract, liquefy, and store natural gas. This dynamic approach to LNG production introduces a versatile and transformative dimension to the energy sector, bringing liquefaction capabilities to untapped offshore gas reserves. The significance of FLNG in the LNG industry cannot be overstated. By taking liquefaction operations offshore, FLNG facilities offer a groundbreaking solution to challenges

* Corresponding author: Chidera Victoria Ibeh

associated with reaching remote or stranded natural gas reserves. These facilities enable the exploitation of offshore gas fields that were previously considered economically unviable or technically challenging. As the global demand for LNG continues to rise, FLNG emerges as a strategic asset, providing a flexible and agile means to unlock new energy resources and contribute to the growth and sustainability of the LNG market (JOHNSON, 2023).

The purpose of this review is to delve into the historical development, economic considerations, environmental implications, and transformative impact of FLNG facilities on the global energy landscape. Through a comprehensive exploration of key milestones, operational success stories, and challenges overcome in the journey of FLNG development, this review aims to provide insights into the multifaceted role of FLNG in shaping the LNG industry's future. By understanding the technological evolution and global impact of FLNG facilities, stakeholders, policymakers, and industry enthusiasts can gain a nuanced perspective on the pivotal role these floating structures play in redefining the dynamics of LNG production and distribution (Paca, 2023).

2. Historical Evolution of FLNG Technology

Floating Liquefied Natural Gas (FLNG) technology has undergone a remarkable journey of development, marked by early conceptualization, transformative milestones, and key technological advancements (Alabi, 2021). This historical evolution not only reflects the engineering prowess required for offshore liquefaction but also underscores the industry's persistent quest for innovative solutions to energy challenges. The genesis of FLNG technology can be traced back to the late 20th century when the LNG industry sought ways to harness offshore gas reserves efficiently. Early concepts and proposals emerged as visionary responses to the limitations posed by traditional onshore liquefaction facilities. Proposals for mobile liquefaction units surfaced in the early 2000s, envisioning self-contained vessels capable of extracting and liquefying natural gas at sea (Van Biert, 2021).

The idea of floating liquefaction units gained momentum as a potential game-changer, allowing the industry to tap into previously inaccessible gas fields. By eliminating the need for extensive pipelines to shore and providing mobility to follow gas reservoirs, FLNG promised to revolutionize LNG production, enabling a more agile and dynamic response to global energy demands. The journey from conceptualization to operational reality marked several pivotal milestones in the development of FLNG technology (Choi and Park, 2021).

Shell's Prelude FLNG, commissioned in 2013, stands as a historic milestone. It became the world's first operational FLNG facility, stationed off the coast of Australia. Prelude's innovative design showcased the feasibility of liquefying natural gas on a floating platform, demonstrating the adaptability of FLNG to diverse geographic and environmental conditions. Petronas FLNG Satu, operational since 2016, further validated FLNG technology. Located off the coast of Malaysia, this facility demonstrated the versatility of FLNG in navigating complex offshore conditions, solidifying its position as a reliable solution for harnessing gas resources in challenging marine environments.

The Coral South FLNG project, expected to commence operations in 2022 off the coast of Mozambique, represents a leap forward in FLNG technology (Aczel, 2022). The project incorporates cutting-edge advancements, including the use of subsea wells, reinforcing FLNG's adaptability to evolving industry needs. The historical evolution of FLNG technology is intertwined with a series of technological advancements that have enhanced efficiency, safety, and environmental sustainability. Early FLNG concepts focused on adapting traditional liquefaction processes to the unique challenges of offshore operations (Dewan et al., 2022). Over time, innovative liquefaction methods, such as the use of modular plants and compact liquefaction technologies, have emerged. These advancements optimize space utilization and enhance the overall efficiency of LNG production on floating platforms.

The integration of Floating Storage and Offloading (FSO) units with FLNG facilities represents a crucial development. This integration allows for the storage and offloading of LNG, streamlining the entire production chain. FSO units enhance the flexibility of FLNG operations, facilitating the transfer of LNG to conventional carriers for global distribution (Olsen, 2023). The structural design of FLNG facilities has evolved to address challenges posed by harsh offshore environments, including waves, wind, and extreme weather conditions. Advances in materials, structural integrity analysis, and engineering have contributed to the development of robust, seafaring structures capable of withstanding challenging marine conditions. FLNG facilities leverage state-of-the-art automation and digitalization technologies. These advancements enhance operational efficiency, enable remote monitoring and control, and contribute to safety and reliability. Automation plays a pivotal role in optimizing production processes, reducing downtime, and ensuring the overall resilience of FLNG operations (Hu, 2021).

In conclusion, the historical evolution of FLNG technology is a testament to the industry's commitment to innovation and adaptability. From early concepts and proposals to operational realities, FLNG has traversed a remarkable

trajectory, reshaping the landscape of LNG production. Pioneering facilities like Prelude, Petronas FLNG Satu, and upcoming projects like Coral South exemplify the transformative impact of FLNG on unlocking offshore gas reserves. The continuous stream of technological advancements underscores FLNG's position as a dynamic and resilient solution, propelling the LNG industry into a new era of offshore liquefaction (Krol, 2019).

3. Economic Considerations and Accessibility

The development of Floating Liquefied Natural Gas (FLNG) facilities not only signifies a technological leap but also introduces a paradigm shift in economic considerations within the liquefied natural gas (LNG) industry (Max et al., 2019). This section explores the cost-effectiveness of FLNG facilities, their role in accessing remote gas reserves, and their broader economic impact on the global LNG market. FLNG facilities offer a cost-effective alternative to traditional onshore liquefaction plants. The need for extensive pipeline infrastructure to transport gas from remote offshore reserves to onshore facilities is eliminated. This reduction in infrastructure requirements contributes significantly to cost savings, making FLNG a financially attractive option for exploiting offshore gas fields (da Silva et al., 2023).

The modular and compact nature of FLNG facilities enables faster development timelines compared to traditional LNG projects. These floating units can be constructed in shipyards, allowing parallel construction activities while the project site is prepared. The accelerated development pace minimizes financing costs and enhances the overall economic viability of FLNG projects. FLNG facilities exhibit operational flexibility, allowing them to relocate to different gas fields as needed. This adaptability enhances the economic efficiency of FLNG, enabling operators to respond dynamically to changing market conditions and the discovery of new reserves. The ability to avoid the sunk costs associated with fixed onshore infrastructure further contributes to the economic appeal of FLNG (Markou, 2020).

One of the primary advantages of FLNG technology is its ability to access remote and stranded gas reserves. Traditional onshore facilities are often constrained by geographic limitations, making it economically unviable to develop certain gas fields. FLNG units, being mobile, can be strategically positioned near offshore reserves, overcoming the geographic constraints associated with traditional LNG infrastructure. FLNG facilities play a pivotal role in unlocking stranded gas reserves that were previously deemed economically non-viable. These reserves, often located in challenging offshore environments, can now be harnessed for LNG production. This not only expands the global gas supply but also taps into valuable energy resources that would otherwise remain dormant (Benti et al., 2023). The proximity of FLNG facilities to offshore gas fields minimizes the need for long-distance transportation of natural gas. Traditional LNG projects may require extensive pipeline networks to transport gas from offshore reservoirs to onshore processing plants. FLNG's ability to liquefy gas at the extraction site reduces transportation costs, contributing to overall economic efficiency.

FLNG facilities contribute to the economic expansion and diversification of the global LNG market. By enabling the development of previously untapped reserves, FLNG supports market growth and ensures a more diverse and resilient LNG supply. This economic diversification enhances the industry's ability to respond to fluctuations in demand and geopolitical factors. The deployment of FLNG facilities has the potential to stimulate regional economic development. The strategic placement of these units near offshore gas fields creates opportunities for employment, infrastructure development, and economic growth in the regions hosting FLNG projects. Local communities may benefit from increased economic activity associated with FLNG operations (Lee, 2020). The cost-effectiveness of FLNG facilities can contribute to competitive LNG pricing. By reducing infrastructure and transportation costs, FLNG projects may offer LNG at a more competitive price point in the global market. This economic advantage enhances the overall competitiveness of FLNG-derived LNG against traditional onshore sources.

In conclusion, the economic considerations and accessibility of FLNG facilities mark a transformative shift in LNG production dynamics. From cost-effective development and access to remote reserves to broader economic impacts on the global LNG market, FLNG emerges as a catalyst for innovation and economic efficiency in the energy sector. The economic benefits of FLNG extend beyond individual projects, contributing to the resilience, diversity, and accessibility of the global LNG market.

4. Environmental Implications

The development of Floating Liquefied Natural Gas (FLNG) facilities presents a transformative approach to LNG production, not only in economic terms but also in its environmental implications (Dezi, 2023). This section examines the environmental benefits associated with offshore liquefaction, the challenges and concerns inherent in FLNG operations, and the evolving sustainability practices that aim to strike a balance between energy progress and environmental preservation. One of the primary environmental benefits of FLNG facilities is the reduction of land impact

compared to traditional onshore liquefaction plants. By taking LNG production offshore, FLNG mitigates the need for extensive land use, preserving natural habitats and reducing the impact on terrestrial ecosystems. This is particularly significant in environmentally sensitive areas where onshore development may pose a threat to biodiversity (Rehbein, 2020).

Offshore liquefaction minimizes disruption to coastal areas. Traditional onshore LNG projects often require the construction of extensive infrastructure along coastlines, impacting coastal ecosystems and communities. FLNG, being located offshore, minimizes this disruption and reduces the potential for habitat degradation and disturbances to marine life. The proximity of FLNG facilities to offshore gas fields reduces the carbon footprint associated with gas transportation. Traditional LNG projects may involve long-distance transportation of natural gas through pipelines, leading to additional emissions. FLNG's ability to liquefy gas at the extraction site minimizes the need for extensive transportation infrastructure, contributing to lower overall carbon emissions (Dezi, 2023).

While FLNG technology offers environmental benefits, it also poses challenges, particularly in terms of potential marine and air pollution. The discharge of treated wastewater, emissions from gas processing, and accidental spills are concerns that must be addressed to prevent adverse effects on marine ecosystems and air quality (Čović, 2021). The deployment and operation of FLNG facilities have the potential to impact marine biodiversity. Noise pollution, habitat disturbance during installation, and the discharge of cooling water can affect marine life. Mitigating these impacts requires comprehensive environmental impact assessments and the implementation of measures to minimize disturbances to aquatic ecosystems. While FLNG can contribute to lower overall greenhouse gas emissions through reduced transportation, the process of liquefaction itself involves energy-intensive operations. Managing and mitigating the carbon footprint of the liquefaction process, including addressing methane emissions, is crucial to ensuring the overall environmental sustainability of FLNG operations (Arefin et al., 2020).

To address concerns related to water quality, FLNG facilities implement advanced wastewater treatment technologies. These systems aim to treat and purify wastewater generated during operations, ensuring that discharged water meets or exceeds environmental standards. Sustainable wastewater practices contribute to minimizing the impact on marine ecosystems. FLNG operators invest in emission reduction technologies to minimize air pollution. These technologies include the use of low-emission turbines, advanced combustion processes, and the implementation of best practices to control and reduce greenhouse gas emissions. Continuous advancements in emission reduction technologies contribute to the environmental sustainability of FLNG operations. Sustainable FLNG operations involve robust environmental monitoring and compliance practices. Regular assessments of air and water quality, as well as the monitoring of marine ecosystems, help ensure that FLNG facilities adhere to environmental regulations. Proactive measures, such as real-time monitoring and early detection systems, contribute to minimizing the environmental impact of FLNG operations (Adumene and Ikue-John, 2022).

In conclusion, the development of FLNG facilities brings forth a dual challenge: harnessing the economic benefits while safeguarding the environment. While FLNG presents environmental advantages such as reduced land impact and lower carbon emissions from transportation, it also raises concerns related to pollution and biodiversity impact. Sustainability practices, technological innovations, and stringent environmental monitoring are critical components in addressing these challenges. Striking a balance between progress and preservation, the evolving landscape of FLNG sustainability practices signifies a commitment to responsible energy development in harmony with ecological integrity. As FLNG technology advances, a continued focus on environmental stewardship will be essential to ensure a sustainable and resilient future for LNG production (Adekoya, 2024).

5. Challenges in FLNG Development

The development of Floating Liquefied Natural Gas (FLNG) facilities, while promising transformative possibilities, comes with its set of challenges. This section delves into the engineering complexities inherent in FLNG development, the regulatory and compliance challenges faced by project stakeholders, and case studies that highlight successful strategies in overcoming these hurdles. FLNG facilities are designed to operate in challenging offshore environments, which introduces engineering complexities. Harsh weather conditions, extreme temperatures, and dynamic sea states demand robust engineering solutions to ensure the structural integrity and operational resilience of these floating structures. The engineering teams must navigate the intricacies of designing for stability, safety, and efficiency in varied marine conditions (Rane, 2023).

The modular construction approach, often employed in FLNG projects, poses its own set of engineering challenges. Coordinating the construction of modular components in shipyards and ensuring their seamless integration on-site demand precision in planning and execution. The complex logistics of transporting and assembling these modules

offshore require meticulous engineering solutions to avoid delays and cost overruns. The process of liquefying natural gas on a floating platform involves intricate technologies (Guseynov, 2020). The compact and space-efficient nature of FLNG facilities necessitates innovative liquefaction methods. Ensuring the efficiency of liquefaction processes, addressing potential bottlenecks, and optimizing the integration of liquefaction technologies pose significant engineering challenges in FLNG development.

FLNG projects operate in a complex regulatory landscape that involves compliance with international, regional, and local regulations. Navigating the intricacies of maritime laws, safety standards, and environmental regulations poses challenges for project developers. Ensuring compliance with diverse regulatory frameworks requires a thorough understanding of legal requirements and effective coordination with relevant authorities. Conducting comprehensive environmental impact assessments (EIAs) is a regulatory prerequisite for FLNG projects (Christofilos, 2023). Assessing the potential impact on marine ecosystems, air quality, and local communities demands rigorous studies and adherence to stringent standards. Achieving a balance between economic development and environmental protection necessitates proactive engagement with regulatory bodies and stakeholders. Many jurisdictions require FLNG projects to incorporate local content and engage with local communities. Balancing the need for local participation with project efficiency can be challenging. Meeting these requirements involves navigating social and cultural dynamics, addressing community concerns, and ensuring that project benefits are shared equitably (Farr et al., 2021).

Shell's Prelude FLNG, stationed off the coast of Australia, provides a noteworthy case study in overcoming engineering complexities. The project addressed the challenges posed by the unique marine environment, including cyclones and high waves. Robust engineering solutions, innovative construction methodologies, and meticulous planning contributed to the successful deployment and operation of Prelude FLNG. The Coral South FLNG project off the coast of Mozambique exemplifies effective navigation of regulatory challenges. The project developers engaged in collaborative efforts with regulatory authorities, ensuring compliance with local and international regulations. Proactive environmental impact assessments and community engagement strategies were integral to obtaining necessary approvals. Petronas FLNG Satu in Malaysia showcases successful approaches to addressing both engineering and regulatory challenges (Balakrisnan et al., 2022). The project overcame modular construction complexities by leveraging advanced fabrication techniques. Additionally, Petronas demonstrated effective engagement with local communities and regulatory bodies, contributing to the project's overall success.

In conclusion, the development of FLNG facilities is a pioneering venture that necessitates adept management of engineering complexities and regulatory challenges. Case studies such as Prelude FLNG, Coral South, and Petronas FLNG Satu underscore the industry's ability to overcome these hurdles through innovative engineering solutions, proactive engagement with regulators, and a commitment to environmental and social responsibility. As FLNG technology continues to evolve, the lessons learned from these case studies will play a crucial role in shaping the future of offshore LNG development (Al-Kuwari, 2023).

6. Transformative Influence on Global Energy Dynamics

The development of Floating Liquefied Natural Gas (FLNG) facilities is one of the most impactful contributions of FLNG technology. One of the most impactful contributions of FLNG facilities is their ability to unlock stranded gas reserves. Traditionally, certain gas fields were considered economically unviable due to their remote locations or challenging offshore environments. FLNG, with its mobility (FLNG) facilities has ushered in a transformative era in the global energy landscape. This section explores the significant influence of FLNG on unlocking stranded gas reserves, adapting to shifting market demands, and showcasing versatility in diverse geographic and economic contexts and adaptability, enables the development of these previously inaccessible reserves. This not only expands the global gas supply but also taps into valuable energy resources that would have otherwise remained untapped (Oberthür, 2021).

FLNG technology brings economic viability to stranded gas assets. Gas fields located far from existing infrastructure or in regions with challenging logistics can now be developed without the need for extensive and costly pipeline networks. This economic shift revitalizes stranded assets, turning them into valuable contributors to the global energy market. FLNG's capability to unlock stranded gas reserves strengthens energy security by diversifying the sources of natural gas. The mobility of FLNG facilities allows operators to deploy them strategically to optimal locations, responding dynamically to market conditions. By moving closer to newly discovered or underutilized gas fields, FLNG maximizes operational efficiency and minimizes the need for long-distance gas transportation. This flexibility enhances the economic attractiveness of previously stranded reserves.

FLNG facilities demonstrate a remarkable ability to adapt to shifting market demands. The modular construction approach and mobility of these units allow for faster project development and deployment timelines. In a rapidly

changing energy landscape, FLNG's capacity for quick and timely deployments enables operators to respond to fluctuations in demand, emerging market trends, and geopolitical factors. The modular nature of FLNG facilities enables operators to scale production based on market demand (Alabi, 2021). Unlike traditional onshore LNG plants with fixed capacities, FLNG units can be designed and deployed to match the specific production requirements of a given project. This optimization ensures that LNG production aligns closely with market needs, preventing overproduction or underutilization of resources. FLNG's adaptability serves as a valuable tool in mitigating market uncertainties. Whether responding to changes in global energy demand, geopolitical shifts, or evolving regulatory landscapes, FLNG facilities provide operators with a versatile solution. The ability to relocate and repurpose these units allows for strategic adjustments, contributing to stability in LNG supply chains (Hohenstein, 2022)

FLNG facilities showcase versatility by being applicable in diverse geographic contexts. From offshore fields in tropical waters to challenging environments with extreme weather conditions, FLNG can be deployed across various regions. This adaptability ensures that different nations and companies can leverage FLNG technology to harness their unique offshore gas resources. FLNG presents an economically suitable option for developing nations with untapped offshore gas reserves. The lower infrastructure costs, faster development timelines, and reduced need for extensive onshore facilities make FLNG a viable solution for nations seeking to monetize their natural gas resources. This economic feasibility empowers developing nations to become active players in the global LNG market. The versatility of FLNG extends to its role in contributing to energy accessibility. By enabling the development of gas reserves in diverse geographic and economic contexts, FLNG facilitates the provision of clean and reliable energy sources. This aligns with global efforts to enhance energy accessibility, especially in regions where traditional onshore infrastructure may be challenging or cost-prohibitive.

In conclusion, the transformative influence of FLNG facilities on global energy dynamics is multifaceted. From unlocking stranded gas reserves to adapting to market demands and showcasing versatility in different contexts, FLNG technology emerges as a pivotal force in shaping the future of the LNG industry. The economic, environmental, and geopolitical benefits associated with FLNG underscore its significance as a catalyst for innovation and progress in the evolving landscape of global energy dynamics. As FLNG technology continues to evolve, its transformative impact is likely to be felt across a broader spectrum of energy markets, contributing to a more resilient, diversified, and sustainable global energy future.

7. Case Studies and Operational Success

The operational success of Floating Liquefied Natural Gas (FLNG) facilities is exemplified through case studies that showcase their successful deployment, regional variations in implementation, and the valuable lessons learned from operational experiences (Ramirez, 2022). These case studies underscore the transformative impact of FLNG technology on the global energy industry. The Prelude FLNG facility, located offshore Australia, stands as a testament to the successful deployment and operation of FLNG on an unprecedented scale. Operated by Shell, Prelude is the world's largest floating facility, capable of producing 3.6 million tonnes per annum (mtpa) of LNG (Mossolly, 2020). Deployed in the Prelude and Concerto gas fields, this FLNG unit overcame engineering challenges associated with its size and the challenging marine environment. Since its start of operations in 2018, Prelude has demonstrated reliability in LNG production and has played a pivotal role in unlocking offshore gas reserves.

The Coral South FLNG project, situated off the coast of Mozambique, showcases the successful collaboration between project stakeholders in deploying FLNG in a region with significant natural gas reserves. Led by Eni, the project involved the construction of a mid-sized FLNG facility with a capacity of 3.4 mtpa. Overcoming regulatory challenges and adhering to environmental standards, the Coral South FLNG project became operational in 2022, contributing to Mozambique's emergence as a key player in the LNG market. The Petronas FLNG Satu, located in the Kanowit gas field offshore Malaysia, represents a successful case of converting stranded gas into a valuable resource. With a production capacity of 1.2 mtpa, FLNG Satu became the world's first operational FLNG facility when it commenced production in 2017. This project demonstrated the adaptability of FLNG in different geographic contexts and showcased its economic viability for monetizing smaller gas reserves (Lorenzato et al., 2022)

African nations, endowed with substantial offshore gas reserves, have embraced FLNG technology to harness their energy potential. Projects like Coral South in Mozambique and Greater Tortue Ahmeyim between Mauritania and Senegal illustrate the regional variations in FLNG implementation. These projects align with Africa's strategy to monetize its natural gas resources, contribute to economic development, and establish the continent as a major player in the global LNG market. Asia, a hub for LNG demand, has witnessed the deployment of FLNG facilities to address energy needs and enhance economic competitiveness. Malaysia, with its Petronas FLNG Satu, has been at the forefront of FLNG adoption (Bahnemann et al., 2022). Asian nations are exploring FLNG as a solution for developing smaller gas fields,

optimizing production, and ensuring a flexible response to market demands. South America, with its emerging role in the LNG market, has seen FLNG projects emerge as strategic solutions. In addition to Coral South in Mozambique, South American nations are exploring FLNG as a means to unlock and export their offshore gas reserves. The successful implementation of FLNG in this region reflects its adaptability to varying geopolitical and economic contexts.

Operational experiences with FLNG facilities emphasize the importance of effective collaboration and stakeholder engagement (Walter, 2023). Successful projects have demonstrated that involving regulatory bodies, local communities, and industry partners from the early stages enhances project acceptance, facilitates smoother regulatory approvals, and contributes to the overall success of FLNG ventures. Lessons learned from operational experiences underscore the necessity of robust environmental management practices. FLNG projects have implemented advanced environmental impact assessments, monitoring programs, and sustainable practices to address concerns related to emissions, marine biodiversity, and local ecosystems. Proactive environmental management contributes to project sustainability and acceptance (Ahmed et al., 2021).

The evolution of FLNG technology is guided by continuous innovation and lessons learned from operational experiences. Engineering challenges encountered in early projects have led to technological advancements, modular construction innovations, and improved safety measures. The adaptability of FLNG technology is a direct result of incorporating lessons learned into subsequent projects, ensuring ongoing improvements in operational efficiency and safety (Ashkanani and Kerbache, 2023).

In conclusion, the case studies and operational success of FLNG facilities illuminate their transformative influence on the global energy landscape. From the monumental Prelude FLNG to regional variations in Africa, Asia, and South America, these case studies underscore the adaptability and versatility of FLNG technology. The lessons learned from operational experiences emphasize the significance of collaboration, robust environmental management, and continuous innovation in shaping the future of FLNG projects. As the industry continues to learn and evolve, FLNG stands as a beacon of innovation, unlocking stranded gas reserves and contributing to a more resilient and sustainable global energy future.

8. Future Trends and Innovations

The development of Floating Liquefied Natural Gas (FLNG) facilities has sparked a wave of ongoing research and development, paving the way for potential improvements and innovations. As the industry looks toward the future, these trends not only promise advancements in technology but also anticipate a significant impact on the future of the Liquefied Natural Gas (LNG) industry (Al-Kuwari, 2023).

Ongoing research focuses on refining and enhancing modular construction techniques for FLNG facilities. The goal is to optimize the construction process, reduce costs, and improve the efficiency of assembling and integrating modular components (Bertram et al., 2019). Innovations in this area may include advanced fabrication methods, automation, and the use of cutting-edge materials to further streamline the construction phase. Research efforts are directed towards developing next-generation liquefaction technologies that enhance the efficiency and environmental performance of FLNG facilities. Advanced processes, such as novel refrigeration cycles and more energy-efficient liquefaction methods, are under exploration. These innovations aim to reduce the carbon footprint of LNG production, aligning with global sustainability goals and environmental considerations. The integration of digitalization and smart technologies is a key focus in ongoing research. Implementing advanced sensors, artificial intelligence, and data analytics can enhance the monitoring, maintenance, and overall performance of FLNG facilities. Real-time data analytics and predictive maintenance systems contribute to operational efficiency, safety, and the longevity of floating LNG assets (Amaechi et al., 2022).

Future trends may witness the development of floating hybrid energy platforms that integrate various energy sources. These platforms could combine LNG production with renewable energy technologies such as floating solar panels or offshore wind turbines. This innovative approach aims to create more sustainable and resilient energy solutions, aligning with the broader shift towards cleaner and greener energy sources. Anticipated innovations include the integration of FLNG facilities with power generation capabilities. Floating LNG-to-Power (FLNGP) projects aim to directly convert LNG into electricity offshore, allowing for decentralized power generation. This concept aligns with the increasing demand for flexible and distributed energy solutions, particularly in regions with limited access to reliable power infrastructure. As global efforts intensify to address climate change, the integration of Carbon Capture and Storage (CCS) technologies into FLNG facilities is gaining traction. This innovation involves capturing CO₂ emissions produced during LNG production and transporting them for secure storage (Al Baroudi et al., 2021). CCS integration

aims to significantly reduce the carbon footprint of FLNG operations, enhancing the environmental sustainability of the entire LNG value chain.

The ongoing advancements and innovations in FLNG technology are expected to increase accessibility to offshore gas reserves. As technology evolves, FLNG facilities may become more adaptable to different water depths, allowing for the development of previously untapped reserves in deeper offshore locations (Crivellari, 2020). This increased accessibility contributes to the diversification of global gas supply sources. Future trends in FLNG technology are anticipated to prioritize environmental sustainability and regulatory compliance. Integrating cleaner technologies, reducing emissions, and adopting carbon-neutral practices will become paramount (Ma et al., 2024). As environmental regulations tighten globally, FLNG facilities that align with stringent environmental standards will gain a competitive edge in the LNG market. Innovations in FLNG technology will likely lead to more flexible and scalable LNG production capabilities. The ability to quickly adapt to market demands, scale production capacities based on project requirements, and optimize resource utilization will be crucial (Reim, 2021). FLNG's flexibility positions it as a key player in shaping the future of the LNG industry, providing a responsive and dynamic solution to evolving market conditions.

In conclusion, the future of Floating LNG Facilities is marked by ongoing research and development, potential improvements, and anticipated innovations. From enhanced modular construction techniques to the integration of smart technologies and the exploration of floating hybrid energy platforms, these trends reflect the industry's commitment to sustainability, adaptability, and technological progress (Ghenai et al., 2022). As FLNG technology continues to evolve, its impact on the LNG industry is poised to be transformative, shaping a future where offshore gas reserves are harnessed efficiently, sustainably, and in alignment with the changing dynamics of the global energy landscape (Evans and Farina, 2013).

9. Conclusion

The development of Floating Liquefied Natural Gas (FLNG) facilities has unfolded as a pioneering chapter in the global energy narrative, leaving an indelible impact on the industry's landscape. As we conclude our review of this transformative journey, we summarize the key aspects of FLNG development, reflect on its implications for the future of energy, and distill key takeaways and recommendations for stakeholders. The evolution of FLNG technology has traversed significant milestones, from early conceptualization to the operational success of large-scale projects such as Prelude, Coral South, and Petronas FLNG Satu. These case studies illuminate the successful deployment of FLNG facilities across diverse geographic regions, unlocking stranded gas reserves, and contributing to the global LNG market's resilience. The triumphs of FLNG development underscore its adaptability, economic viability, and role as a catalyst for innovation in the energy sector.

The global impact of FLNG facilities extends beyond the operational realm. These floating facilities have become instrumental in addressing regional variations in energy demands, promoting sustainability through environmental management practices, and fostering economic development in nations with untapped offshore gas reserves. FLNG's versatility in different contexts, be it in Asia, Africa, or South America, highlights its transformative influence on global energy dynamics.

The implications of FLNG development reverberate through the corridors of the future energy landscape. The unlocking of stranded gas reserves, efficient modular construction techniques, and ongoing research into advanced liquefaction technologies position FLNG as a linchpin in ensuring energy accessibility, adaptability, and environmental sustainability. The integration of smart technologies, potential advancements in floating hybrid energy platforms, and the exploration of Carbon Capture and Storage (CCS) herald a future where FLNG contributes to a cleaner, more resilient energy paradigm. As the energy industry grapples with the imperatives of climate change mitigation, FLNG's potential role in floating LNG-to-Power (FLNGP) projects becomes increasingly significant. The prospect of directly converting LNG into electricity offshore aligns with the growing demand for decentralized and sustainable power solutions, offering a glimpse into a future where FLNG transcends its traditional boundaries.

Effective collaboration and stakeholder engagement emerge as critical factors for the success of FLNG projects. Early involvement of regulatory bodies, local communities, and industry partners enhances project acceptance, facilitates regulatory approvals, and contributes to overall project success. Robust environmental management practices are imperative for the sustainability of FLNG operations. Stakeholders should prioritize the integration of cleaner technologies, emissions reduction strategies, and adherence to stringent environmental standards to enhance the environmental sustainability of FLNG facilities.

Stakeholders in the FLNG sector should prioritize continuous innovation and adaptability. Ongoing research and development, as well as the incorporation of technological advancements, ensure that FLNG facilities remain at the forefront of industry trends, responding dynamically to market demands and regulatory changes. FLNG's role in unlocking stranded gas reserves contributes to global energy accessibility. Stakeholders should explore opportunities for deploying FLNG facilities in regions with untapped offshore gas reserves, particularly in developing nations, to enhance energy accessibility and foster economic development. Stakeholders are encouraged to engage in strategic planning for future trends and innovations in FLNG technology. Anticipating the integration of next-generation liquefaction technologies, digitalization, and potential advancements in floating hybrid energy platforms positions stakeholders to harness the full potential of FLNG in a rapidly evolving energy landscape.

In conclusion, the review of the development of Floating LNG Facilities unveils a narrative of innovation, adaptability, and transformative impact on the global energy industry. As FLNG continues to navigate uncharted waters, it serves as a beacon of progress, offering sustainable solutions to energy challenges and reshaping the contours of a future where floating facilities play a pivotal role in ensuring a resilient, diverse, and cleaner global energy ecosystem.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

- [1] Aczel, M.R., 2022. Technological Revolution in Natural Gas Developments and LNG: Policy Advancements and Their Implications for National and International Markets. In *The Palgrave Handbook of Natural Gas and Global Energy Transitions* (pp. 21-72). Cham: Springer International Publishing.
- [2] Adekoya, O.O., Adefemi, A., Tula, O.A., Nwaobia, N.K. and Gidiagba, J.O., 2024. Technological innovations in the LNG sector: A review: Assessing recent advancements and their impact on LNG production, transportation and usage. *World Journal of Advanced Research and Reviews*, 21(1), pp.040-057.
- [3] Adumene, S. and Ikue-John, H., 2022. Offshore system safety and operational challenges in harsh Arctic operations. *Journal of safety science and resilience*, 3(2), pp.153-168.
- [4] Ahmed, M., Guo, Q., Qureshi, M.A., Raza, S.A., Khan, K.A. and Salam, J., 2021. Do green HR practices enhance green motivation and proactive environmental management maturity in hotel industry?. *International Journal of Hospitality Management*, 94, p.102852.
- [5] Al Baroudi, H., Awoyomi, A., Patchigolla, K., Jonnalagadda, K. and Anthony, E.J., 2021. A review of large-scale CO₂ shipping and marine emissions management for carbon capture, utilisation and storage. *Applied Energy*, 287, p.116510.
- [6] Alabi, F.A., 2021, August. Offshore LNG and Gas Monetization. In *Offshore Technology Conference* (p. D032S085R009). OTC.
- [7] Al-Kuwari, O., 2023. The future of liquified natural gas (LNG) in the energy transition: options and implications for the LNG industry in a decarbonising world (Doctoral dissertation, UCL (University College London)).
- [8] Amaechi, C.V., Reda, A., Kgosiemang, I.M., Ja'e, I.A., Oyetunji, A.K., Olukolajo, M.A. and Igwe, I.B., 2022. Guidelines on asset management of offshore facilities for monitoring, sustainable maintenance, and safety practices. *Sensors*, 22(19), p.7270.
- [9] Arefin, M.A., Nabi, M.N., Akram, M.W., Islam, M.T. and Chowdhury, M.W., 2020. A review on liquefied natural gas as fuels for dual fuel engines: Opportunities, challenges and responses. *Energies*, 13(22), p.6127.
- [10] Ashkanani, S.H. and Kerbache, L., 2023. Enhanced megaproject management systems in the LNG industry: A case study from Qatar. *Energy Reports*, 9, pp.1062-1076.
- [11] Bahnemann, W.O., Pereira, E.G. and de Medeiros Costa, H.K., 2022. Natural Gas and Energy Transition for Large International Oil Companies. In *The Palgrave Handbook of Natural Gas and Global Energy Transitions* (pp. 285-318). Cham: Springer International Publishing.
- [12] Balakrisnan, M., Halim, B.A., Johan, A.L., Ahmad Ani, M.Q., Ismail, A.F., Yap, Y.T., Abd Hakim, H., Abu Bakar, M.A., Lai, B.M.S. and Fariyah, H., 2022, October. Methodological Engineering Approach in Designing Injector and

Observation Wells Incorporating MMV Requirements in Carbonate CCS Project in Offshore Malaysia. In *ADIPEC. OnePetro*.

- [13] Benti, N.E., Woldegiyorgis, T.A., Geffe, C.A., Gurmesa, G.S., Chaka, M.D. and Mekonnen, Y.S., 2023. Overview of geothermal resources utilization in Ethiopia: Potentials, opportunities, and challenges. *Scientific African*, 19, p.e01562.
- [14] Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G. and Woetzel, J., 2019. Modular construction: From projects to products. *McKinsey & Company: Capital Projects & Infrastructure*, pp.1-34.
- [15] Choi, S. and Park, J.S., 2021. Development of augmented reality system for productivity enhancement in offshore plant construction. *Journal of Marine Science and Engineering*, 9(2), p.209.
- [16] Christofilos, P., 2023. Natural gas and LNG and its transportation: environmental applications and European regulatory framework (Master's thesis, Πανεπιστήμιο Πειραιώς).
- [17] Čović, M., BACALJA, B., KRČUM, M. and MRČELIĆ, G.J., 2021. From ballast water to harmful air emissions: how to reduce the impact of shipping on the pollution of the marine environment—a review. *Urban and Maritime Transport*, 27, pp.105-116.
- [18] Crivellari, A., 2020. Development of methodologies supporting the sustainable and safe integration of offshore conventional and renewable energy production.
- [19] da Silva, V.O., Relva, S.G., Mondragon, M., Mendes, A.B., Nishimoto, K. and Peyerl, D., 2023. Building Options for the Brazilian Pre-salt: A technical-economic and infrastructure analysis of offshore integration between energy generation and natural gas exploration. *Resources Policy*, 81, p.103305.
- [20] Dewan, R., Yadav, U.K., Nayyar, A., Verma, N. and Kumar, A., 2022, November. Advancement and Evolution of LNG Terminals: A Review. In
- [21] Dezi, M., 2023. Floating Liquefied Natural Gas (FLNG) vs. conventional Natural Gas (NG) supply chains: energy and environmental sustainability perspectives (Doctoral dissertation, Politecnico di Torino).
- [22] Evans, P.C. and Farina, M.F., 2013. The age of gas & the power of networks. *General Electric Company, Fairfield*.
- [23] Farr, M., Davies, P., Andrews, H., Bagnall, D., Brangan, E. and Davies, R., 2021. Co-producing knowledge in health and social care research: reflections on the challenges and ways to enable more equal relationships. *Humanities and Social Sciences Communications*, 8(1).
- [24] Ghenai, C., Husein, L.A., Al Nahlawi, M., Hamid, A.K. and Bettayeb, M., 2022. Recent trends of digital twin technologies in the energy sector: A comprehensive review. *Sustainable Energy Technologies and Assessments*, 54, p.102837.
- [25] Guseynov, C.S., 2020. In Arctic-new technical means and technologies for the development of oil and gas fields in long-term freezing deepwater areas. In *IOP Conference Series: Materials Science and Engineering* (Vol. 734, No. 1, p. 012174). IOP Publishing.
- [26] Hohenstein, N.O., 2022. Supply chain risk management in the COVID-19 pandemic: strategies and empirical lessons for improving global logistics service providers' performance. *The International Journal of Logistics Management*, 33(4), pp.1336-1365.
- [27] Hu, J., Khan, F. and Zhang, L., 2021. Dynamic resilience assessment of the Marine LNG offloading system. *Reliability Engineering & System Safety*, 208, p.107368.
- [28] JOHNSON, N., 2023. Strategic Mastery: Uncleashing the Power of LNG Program Development through Advanced Techniques.
- [29] Krol, M., Bruckhaus, N. and Weidner, P., 2019. Prime role forecast for LNG with plant investment of \$35 Bln a year.
- [30] Lee, H.J., Yoo, S.H. and Huh, S.Y., 2020. Economic benefits of introducing LNG-fuelled ships for imported flour in South Korea. *Transportation Research Part D: Transport and Environment*, 78, p.102220.
- [31] Lorenzato, G., Tordo, S., Howells, H.M. and van den Berg, B., 2022. *Financing solutions to reduce natural gas flaring and methane emissions*. World Bank Publications.
- [32] Ma, J., Yang, L., Wang, D., Li, Y., Xie, Z., Lv, H. and Woo, D., 2024. Digitalization in response to carbon neutrality: Mechanisms, effects and prospects. *Renewable and Sustainable Energy Reviews*, 191, p.114138.

- [33] Markou, F., 2020. Exemption Regime for new gas infrastructures under European & National law-The case of Alexandroupolis Floating Storage and Regasification Unit (FSRU)–An Energy Gateway to Europe.
- [34] Max, M.D., Johnson, A.H., Max, M.D. and Johnson, A.H., 2019. Leveraging Technology for NGH Development and Production. *Exploration and Production of Oceanic Natural Gas Hydrate: Critical Factors for Commercialization*, pp.227-279.
- [35] Mossoly, M., Bustos, E. and Messineo, D., 2020, May. Prelude’s Remarkable Turbomachinery-The Story From Selection To First Drop Of LNG. In *Offshore Technology Conference* (p. D041S045R006). OTC.
- [36] Oberthür, S., Khandekar, G. and Wyns, T., 2021. Global governance for the decarbonization of energy-intensive industries: Great potential underexploited. *Earth System Governance*, 8, p.100072.
- [37] Olsen, A.A., 2023. *Merchant Ship Types*. Taylor & Francis.
- [38] Paca, E., 2023. Assessing the technical feasibility of converting US salt caverns used for natural gas storage into hydrogen storage facilities (Doctoral dissertation, Massachusetts Institute of Technology).
- [39] Pym, J.G., 2021. Managing Innovation Under Nationalisation: the British Gas industry and the first trans-oceanic transportation of Liquefied Natural Gas: 1954-1959 (Doctoral dissertation, University of Leicester).
- [40] Ramirez, A.F., 2022. Negotiating power over oil and gas resources in Senegal: The political economy of oil and gas in a ‘new producer’ country (Doctoral dissertation, University of Cambridge).
- [41] Rane, N., 2023. Potential Role and Challenges of ChatGPT and Similar Generative Artificial Intelligence in Architectural Engineering. *Available at SSRN 4607767*.
- [42] Rehbein, J.A., Watson, J.E., Lane, J.L., Sonter, L.J., Venter, O., Atkinson, S.C. and Allan, J.R., 2020. Renewable energy development threatens many globally important biodiversity areas. *Global change biology*, 26(5), pp.3040-3051.
- [43] Reim, W., Sjödin, D. and Parida, V., 2021. Circular business model implementation: A capability development case study from the manufacturing industry. *Business Strategy and the Environment*, 30(6), pp.2745-2757.
- [44] Van Biert, L., Mrozewski, K. and Hart, P., 2021. Public final report: Inventory of the application of Fuel Cells in the MARitime sector (FCMAR). *Maritime Knowledge Centre (MKC): London, UK*.
- [45] Venegas, F.G., Petit, M. and Perez, Y., 2021. Active integration of electric vehicles into distribution grids: Barriers and frameworks for flexibility services. *Renewable and Sustainable Energy Reviews*, 145, p.111060.
- [46] Walter, M., 2023. Accelerating LNG developments in Germany-bringing participation to a standstill? (Doctoral dissertation).