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Carbon capture and sustainability in LNG projects: Engineering lessons for a greener future

Ovie Vincent Erhueh [1, *], Chukwuebuka Nwakile [1], Oluwaseyi Ayotunde Akano [2], Andrew Emuobosa Esiri [3] and Enobong Hanson [1]

[1] *Independent Researcher, Nigeria.*
[2] *Chevron Nigeria Limited, Nigeria.*
[3] *Independent Researcher, Houston Texas, USA.*

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Abstract

As the global energy transition accelerates, Liquefied Natural Gas (LNG) projects are under increasing pressure to reduce their carbon footprint. Carbon capture, utilization, and storage (CCUS) technologies have emerged as a critical tool in mitigating greenhouse gas emissions and promoting sustainability within the LNG industry. This paper explores the integration of carbon capture technologies in LNG projects, focusing on engineering solutions that enhance environmental performance while ensuring operational efficiency. By examining the role of CCUS in LNG projects, the paper highlights how innovative design and process optimization can contribute to a greener future. The discussion delves into key engineering lessons learned from successful LNG projects that have implemented carbon capture systems. These include advancements in process design, material selection, and the integration of renewable energy sources to power carbon capture facilities. Additionally, the paper evaluates the economic and environmental benefits of CCUS deployment, such as cost reductions from enhanced resource recovery and significant emissions reductions. It also considers the challenges posed by large-scale implementation, including infrastructure requirements, regulatory frameworks, and public perception. Furthermore, the paper outlines how LNG projects, through the adoption of carbon capture technologies, align with global climate goals and contribute to sustainable development. The potential for scaling up these technologies and replicating them across various energy-intensive industries is also discussed. The paper emphasizes that achieving sustainability in LNG projects is not only possible but essential for the industry's future viability. Ultimately, this paper underscores the need for continuous innovation in carbon capture technologies and the importance of collaborative efforts among stakeholders, including governments, industry leaders, and engineers, to drive progress toward a sustainable energy future.

Keywords: Carbon Capture; Sustainability; Liquefied Natural Gas (LNG); CCUS; Green Engineering; Emission Reduction; Energy Transition; Process Optimization; Renewable Energy Integration; Sustainable Development**.**

1. Introduction

The global energy landscape is undergoing a significant transformation as the world strives to transition from fossil fuels to cleaner and more sustainable energy sources. This transition is driven by the need to address climate change, reduce greenhouse gas emissions, and meet the growing demand for energy in a more environmentally responsible way (Abdul-Azeez, Ihechere & Idemudia, 2024, Babayeju, et al., 2024, Ikevuje, et al., 2024). Liquefied natural gas (LNG), traditionally considered a cleaner alternative to other fossil fuels such as coal and oil, plays a vital role in this energy transition. Its lower carbon emissions when combusted, compared to coal and oil, have positioned LNG as a bridge fuel in the shift towards a low-carbon future. However, despite its advantages, the extraction, processing, and transportation

* Corresponding author: Ovie Vincent Erhueh

of LNG contribute significantly to the overall carbon footprint of the industry, necessitating innovative approaches to mitigate its environmental impact.

Reducing the carbon footprint in LNG projects is of paramount importance in ensuring that this energy source remains viable in a carbon-constrained world. As countries and industries set ambitious targets for achieving net-zero emissions, the LNG sector faces increasing pressure to adopt more sustainable practices. One of the most effective strategies for reducing emissions in LNG operations is through the deployment of Carbon Capture, Utilization, and Storage (CCUS) technologies (Adebayo, Ogundipe & Bolarinwa, 2021, Babayeju, Jambol & Esiri, 2024, Ilori, Nwosu & Naiho, 2024). These technologies capture carbon dioxide (CO2) emissions from industrial processes, including those generated during LNG production, and either store them underground or repurpose them for use in other industries. By integrating CCUS into LNG projects, the industry can significantly reduce its environmental impact, align with global climate goals, and ensure the long-term sustainability of LNG as an energy source.

This paper aims to explore the integration of carbon capture in LNG projects as a means of achieving sustainability. It will examine the engineering lessons learned from recent CCUS implementations in the LNG industry, the challenges faced, and the potential for these technologies to shape a greener future for energy production (Afeku-Amenyo, 2024, Babayeju, Jambol & Esiri, 2024, Ilori, Nwosu & Naiho, 2024, Oshodi, 2024). Through this exploration, the paper will contribute to the broader discussion on how LNG can continue to play a crucial role in the global energy transition while minimizing its carbon footprint.

1.1. The Evolution of Carbon Capture Technologies

The evolution of carbon capture technologies has emerged as a crucial component in the quest for sustainability, particularly in liquefied natural gas (LNG) projects. With the global push to combat climate change, the need for innovative solutions that can mitigate greenhouse gas emissions while ensuring the continued viability of fossil fuel resources has never been more pressing (Anyanwu, et al., 2024, Banso, et al., 2023, Ikevuje, et al., 2023, Ilori, Nwosu & Naiho, 2024). As a result, carbon capture and storage (CCS) technologies have gained prominence, transforming the engineering landscape and providing valuable lessons for a greener future.

Historically, carbon capture technologies have been around for several decades, initially developed for industrial applications such as the production of ammonia and hydrogen. However, it was not until the late 20th century that the potential for CCS in addressing climate change was fully recognized. The Kyoto Protocol of 1997 highlighted the need for developed countries to reduce their carbon emissions, prompting increased investment in CCS research and development (Arowosegbe, et al., 2024, Bassey, 2022, Ikevuje, et al., 2024, Ilori, Nwosu & Naiho, 2024). Early initiatives primarily focused on the capture and storage of carbon dioxide (CO2) from large stationary sources, such as power plants and industrial facilities. These foundational projects laid the groundwork for future advancements in carbon capture technologies.

In recent years, the LNG sector has become a focal point for carbon capture initiatives. The LNG industry is characterized by its significant carbon footprint, particularly during the extraction, processing, and transportation phases. As global demand for LNG continues to rise, so does the urgency to implement carbon capture technologies that can significantly reduce emissions (Aderamo, et al., 2024, Bassey, 2023, Ikevuje, et al., 2024, Ilori, Nwosu & Naiho, 2024). Engineering lessons learned from earlier CCS projects have informed the development of more efficient and cost-effective capture methods tailored specifically for LNG operations.

One notable advancement in carbon capture technology is the development of post-combustion capture systems. These systems involve the separation of CO2 from flue gases after the combustion process. This approach has gained traction within the LNG sector due to its versatility and potential for retrofitting existing facilities. For instance, the use of amine-based solvents has emerged as a popular choice for capturing CO2 from exhaust streams (Popo-Olaniyan, et al., 2022, Soyombo, et al., 2024, Udegbe, et al., 2022, Udo, et al., 2023). These solvents chemically react with CO2, allowing for its subsequent separation and storage. As the LNG industry seeks to enhance its sustainability profile, the integration of post-combustion capture systems into existing plants represents a significant step forward.

Another area of evolution in carbon capture technologies is the development of pre-combustion capture systems. This approach involves the removal of CO2 from fossil fuels before combustion occurs. In LNG projects, this can be achieved through gasification processes, where natural gas is converted into hydrogen and CO2. The hydrogen can then be utilized as a clean energy source, while the CO2 is captured and stored (Alemede, et al., 2024, Bassey, 2022, Iyede, et al., 2023, Joel, et al., 2024, Ozowe, 2018). Pre-combustion capture not only reduces emissions but also allows for the utilization of hydrogen, contributing to the broader transition toward a hydrogen economy. The lessons learned from integrating pre-combustion capture into LNG projects have broader implications for the energy sector, emphasizing the importance of considering the entire lifecycle of carbon emissions.

Furthermore, advancements in direct air capture (DAC) technologies present a promising avenue for carbon capture in LNG projects. DAC involves the extraction of CO2 directly from the atmosphere, offering the potential for negative emissions. While still in its infancy, DAC technology has garnered attention for its scalability and versatility (Abdul-Azeez, et al., 2024, Bassey, 2023, Jambol, Babayeju & Esiri, 2024, Olutimehin, et al., 2024). By incorporating DAC into LNG operations, companies can offset their emissions and work toward achieving net-zero targets. The engineering challenges associated with DAC, such as energy consumption and cost, are significant but not insurmountable. Lessons learned from ongoing DAC pilot projects can inform future developments and integration into LNG operations.

The successful implementation of carbon capture technologies in LNG projects requires collaboration across various stakeholders, including governments, industry leaders, and research institutions. Public policy plays a critical role in creating an enabling environment for investment in carbon capture technologies (Agupugo, Kehinde & Manuel, 2024, Bassey, 2024, Jambol, et al., 2024, Olu-Lawal, Ekemezie & Usiagu, 2024). Regulatory frameworks that incentivize emissions reduction, provide funding for research and development, and establish clear guidelines for carbon storage can significantly accelerate the deployment of CCS in the LNG sector. Engineering lessons from past projects highlight the importance of early stakeholder engagement and the need for comprehensive assessments of the economic viability of carbon capture initiatives.

Moreover, the integration of digital technologies and data analytics is reshaping the landscape of carbon capture in LNG projects. Advanced monitoring systems, powered by artificial intelligence and machine learning, enable real-time analysis of emissions data and system performance. These technologies enhance the efficiency of carbon capture processes and provide valuable insights for optimizing operations (Adebayo, et al., 2024, Bassey, 2023, Joel, et al., 2024, Ogundipe, et al., 2024, Ozowe, Daramola & Ekemezie, 2023). By leveraging data-driven decision-making, LNG companies can improve their carbon capture efforts and achieve more sustainable outcomes. The lessons learned from the integration of digital technologies into carbon capture processes serve as a blueprint for future engineering advancements across the energy sector.

The evolution of carbon capture technologies in LNG projects not only contributes to emissions reduction but also plays a vital role in shaping the future of energy production. The transition to a low-carbon economy necessitates a holistic approach that encompasses not only the technical aspects of carbon capture but also considerations of sustainability and social responsibility (Ajiga, et al., 2024, Bassey & Ibegbulam, 2023, Joel, et al., 2024, Okoduwa, et al., 2024). The lessons learned from implementing carbon capture in LNG operations can be extrapolated to other sectors, highlighting the importance of innovation and collaboration in the pursuit of a greener future.

As the world grapples with the urgent challenges of climate change, the role of carbon capture technologies in LNG projects becomes increasingly critical. The evolution of these technologies reflects a broader trend toward sustainability and the recognition that fossil fuels can play a role in a decarbonized future when paired with effective carbon management strategies (Abdul-Azeez, Ihechere & Idemudia, 2024, Bassey, Aigbovbiosa & Agupugo, 2024, Ozowe, 2021). The engineering lessons gleaned from these initiatives underscore the need for continued investment in research and development, collaboration across sectors, and a commitment to fostering innovation.

In conclusion, the evolution of carbon capture technologies in LNG projects offers a wealth of engineering lessons that can inform the path toward a greener future. As the industry embraces sustainability, the integration of advanced capture systems, pre-combustion techniques, and digital technologies will be essential in reducing emissions and enhancing overall efficiency. By learning from past experiences and fostering collaboration, the LNG sector can pave the way for a more sustainable energy landscape, demonstrating that progress is possible even in the face of significant environmental challenges (Afeku-Amenyo, 2024, Bassey, Juliet & Stephen, 2024, Joseph, et al., 2020, Olutimehin, et al., 2024). The commitment to carbon capture and sustainability will not only benefit the LNG industry but will also contribute to global efforts in combating climate change, ensuring a healthier planet for future generations.

1.2. Lessons for Designing Sustainable LNG Projects

The design and implementation of sustainable liquefied natural gas (LNG) projects are critical in addressing the dual challenges of meeting global energy demands while mitigating climate change. As the LNG sector continues to expand, the incorporation of carbon capture and storage (CCS) technologies has emerged as a vital strategy to enhance the sustainability of these projects (Aziza, Uzougbo & Ugwu, 2023, Bassey, et al., 2024, Joseph, et al., 2022, Omaghomi, et al., 2024). The lessons learned from existing initiatives in carbon capture can inform the design of future LNG facilities, emphasizing the importance of engineering innovation, stakeholder engagement, and holistic planning in achieving sustainability goals.

One of the foremost lessons in designing sustainable LNG projects is the importance of early integration of carbon capture technologies in the project lifecycle. From the initial design phase, it is crucial to incorporate CCS into the overall project architecture, ensuring that emissions reduction strategies are not merely an afterthought but a fundamental component of the facility's operational framework (Anyanwu, et al., 2024, Bassey, et al., 2024, Katas, et al., 2023, Okeleke, et al., 2023, Ozowe, Daramola & Ekemezie, 2024). By integrating carbon capture solutions from the outset, project developers can identify the most suitable capture methods, optimize the facility's layout, and enhance the efficiency of the capture process. This proactive approach not only reduces overall costs but also maximizes the potential for successful implementation.

The selection of appropriate carbon capture technologies is another essential aspect of designing sustainable LNG projects. Given the diversity of capture technologies available, including post-combustion, pre-combustion, and direct air capture, project developers must carefully evaluate which method aligns best with their specific operational context. For instance, post-combustion capture systems, which separate CO_2 from flue gases after combustion, may be particularly well-suited for retrofitting existing facilities (Aderamo, et al., 2024, Bassey, et al., 2024, Katas, et al., 2022, Ogundipe, Okwandu & Abdulwaheed, 2024). In contrast, pre-combustion capture, which involves removing CO_2 before combustion, may offer advantages in new plant designs where natural gas is converted into hydrogen and CO_2. Understanding the trade-offs associated with each technology is critical for making informed decisions that enhance sustainability while ensuring economic viability.

Moreover, the implementation of carbon capture technologies should be complemented by robust monitoring and measurement systems. Effective monitoring is crucial for assessing the performance of carbon capture systems and ensuring compliance with regulatory requirements. Advanced data analytics and digital technologies can play a pivotal role in this regard, enabling real-time monitoring of emissions and providing insights for optimizing operations (Alemede, et al., 2024, Chinyere, Anyanwu & Innocent, 2023, Katas, et al., 2023, Oshodi, 2024). By leveraging data-driven approaches, LNG project developers can enhance their understanding of capture efficiency, identify potential issues, and implement corrective measures promptly. The engineering lessons learned from successful monitoring initiatives can inform the design of more resilient and adaptive carbon capture systems in future LNG projects.

Another key lesson for designing sustainable LNG projects is the significance of stakeholder engagement throughout the project lifecycle. Engaging stakeholders, including local communities, government agencies, and environmental organizations, is essential for fostering public support and ensuring alignment with sustainability goals (Popo-Olaniyan, et al., 2022, Segun-Falade, et al., 2024, Udegbe, et al., 2024, Uzougbo, et al., 2023). Transparent communication about the project's carbon capture initiatives, environmental impact, and long-term benefits can help build trust and facilitate collaboration among stakeholders. Additionally, involving stakeholders in the decision-making process can lead to valuable insights and innovative solutions that enhance the overall sustainability of the project. The lessons learned from projects that prioritize stakeholder engagement underscore the importance of a collaborative approach in achieving successful outcomes.

Furthermore, the design of sustainable LNG projects should consider the broader energy landscape and the potential for integrating renewable energy sources. The transition to a low-carbon future requires a comprehensive approach that encompasses not only carbon capture but also the adoption of cleaner energy technologies (Adebayo, et al., 2024, Coker, et al., 2023, Katas, et al., 2022, Ogundipe, et al., 2024). By integrating renewable energy systems, such as solar and wind, into LNG project designs, companies can enhance their sustainability profile and reduce their reliance on fossil fuels. This holistic approach to energy management is critical for achieving long-term sustainability goals and positioning LNG as a viable component of a diversified energy portfolio. The engineering lessons derived from integrating renewables into LNG projects can inform future designs, fostering innovation and resilience in the face of evolving energy demands (Arowoogun, et al., 2024, Ikevuje, Anaba & Iheanyichukwu, 2024, Ogbu, et al., 2024, Usiagu, et al., 2024).

Additionally, the concept of circular economy principles can significantly influence the design of sustainable LNG projects. By adopting circular economy practices, project developers can minimize waste generation and enhance resource efficiency. For example, the reuse of captured CO_2 in industrial processes, such as enhanced oil recovery or as a feedstock for chemicals, can create value and contribute to the overall sustainability of the project (Ajiga, et al., 2024, Daniel, et al., 2024, Katas, et al., 2023, Olutimehin, et al., 2024). The lessons learned from successful circular economy initiatives can guide the design of LNG projects that prioritize resource optimization and waste reduction, promoting a more sustainable and responsible approach to energy production.

The importance of regulatory frameworks and policies in shaping sustainable LNG projects cannot be overlooked. Effective policies that incentivize carbon capture and support emissions reduction efforts are essential for driving innovation and investment in sustainable technologies (Abdul-Azeez, Ihechere & Idemudia, 2024, Datta, et al., 2023, Kwakye, Ekechukwu & Ogundipe, 2023). Project developers must stay informed about regulatory developments and engage with policymakers to advocate for supportive measures that facilitate the adoption of carbon capture technologies. The engineering lessons learned from navigating regulatory challenges in previous projects highlight the need for proactive engagement and collaboration with regulatory bodies to ensure compliance and facilitate successful project implementation.

In conclusion, the design of sustainable LNG projects requires a multifaceted approach that incorporates carbon capture technologies as a central component of the project lifecycle. The lessons learned from existing initiatives emphasize the importance of early integration of CCS, careful selection of capture methods, robust monitoring systems, stakeholder engagement, and the consideration of broader energy trends (Afeku-Amenyo, 2024, Digitemie & Ekemezie, 2024, Kwakye, Ekechukwu & Ogundipe, 2023, Ozowe, Russell & Sharma, 2020). By embracing innovation and collaboration, project developers can create sustainable LNG facilities that not only meet energy demands but also contribute to global efforts in mitigating climate change. The commitment to sustainability in LNG projects will play a vital role in shaping a greener future, demonstrating that engineering excellence and environmental responsibility can go hand in hand in the pursuit of sustainable energy solutions. As the world continues to navigate the challenges of climate change, the insights gained from designing sustainable LNG projects will be invaluable in fostering a more sustainable energy landscape for generations to come.

1.3. Implementing CO2 Capture Systems for Future U.S. Energy Infrastructure

The implementation of carbon capture and storage (CCS) systems is increasingly recognized as a critical strategy for reducing carbon dioxide (CO2) emissions within the context of future U.S. energy infrastructure. As the nation grapples with the pressing challenge of climate change, integrating CCS technologies across various sectors, including liquefied natural gas (LNG) projects, presents an opportunity to enhance sustainability while ensuring the continued reliability of energy supply (Arowosegbe, et al., 2024, Digitemie & Ekemezie, 2024, Kwakye, Ekechukwu & Ogundipe, 2023). The engineering lessons learned from past CCS initiatives provide valuable insights into how these systems can be effectively integrated into the U.S. energy landscape.

To begin with, the design and implementation of CO2 capture systems should be considered at the earliest stages of project development. Incorporating CCS into energy infrastructure projects from the outset allows for a more seamless integration of carbon capture technologies. For instance, when planning new natural gas plants or retrofitting existing facilities, engineers can evaluate the specific requirements for capturing CO2 emissions and design systems that optimize efficiency (Aderamo, et al., 2024, Digitemie & Ekemezie, 2024, Kwakye, Ekechukwu & Ogundipe, 2023, Zhang, et al., 2021). Early integration facilitates the identification of suitable capture technologies, whether they be post-combustion, pre-combustion, or oxy-fuel combustion, ensuring that the systems are tailored to the operational characteristics of the facility. By prioritizing CCS in the design phase, project developers can maximize the potential for emissions reduction while minimizing costs associated with later retrofitting.

Moreover, the selection of appropriate capture technologies is crucial for the effective implementation of CO2 capture systems. The U.S. energy landscape is diverse, encompassing various types of power generation, including coal, natural gas, and renewables. Each of these energy sources presents unique challenges and opportunities for carbon capture. For example, post-combustion capture systems, which involve the separation of CO2 from flue gases after combustion, are particularly well-suited for existing coal-fired power plants (Anyanwu, et al., 2024, Dozie, et al., 2024, Latilo, et al., 2024, Okoro, Ikemba & Uzor, 2008). In contrast, natural gas facilities can benefit from pre-combustion capture, where CO2 is removed before the combustion process. Understanding the nuances of each technology is essential for making informed decisions that align with the goals of emissions reduction and sustainability.

The integration of advanced monitoring and measurement systems is another critical component of implementing CO2 capture systems in future energy infrastructure. Effective monitoring is essential for assessing the performance of carbon capture technologies and ensuring compliance with environmental regulations (Akomolafe, et al., 2024, Ejairu, et al., 2024, Latilo, et al., 2024, Olufemi, Ozowe & Afolabi, 2012). Real-time data analytics, enabled by digital technologies, can provide valuable insights into the efficiency of capture systems, enabling operators to optimize performance and identify areas for improvement. The engineering lessons learned from past projects emphasize the need for robust monitoring frameworks that can adapt to evolving technologies and regulatory requirements. By implementing advanced monitoring systems, energy producers can enhance transparency and accountability in their emissions reduction efforts, fostering public trust and confidence in the effectiveness of CCS initiatives.

Furthermore, stakeholder engagement is paramount in the successful implementation of CO2 capture systems within the U.S. energy infrastructure. Engaging local communities, government agencies, and environmental organizations in the planning and development process fosters a sense of ownership and accountability (Alemede, et al., 2024, Ekemezie, et al., 2024, Latilo, et al., 2024, Olatunji, et al., 2024). Transparent communication regarding the benefits of carbon capture, such as job creation and environmental protection, can help build support for CCS projects. Moreover, involving stakeholders in decision-making processes can lead to innovative solutions that address community concerns and enhance the overall sustainability of energy infrastructure. The engineering lessons learned from past CCS initiatives highlight the importance of collaboration and engagement as key drivers of successful project implementation.

As the U.S. seeks to transition toward a low-carbon future, the potential for integrating renewable energy sources with carbon capture technologies becomes increasingly significant. The future energy landscape will likely include a diverse mix of generation sources, including solar, wind, and natural gas (Abdul-Azeez, et al., 2024, Ekemezie & Digitemie, 2024, Latilo, et al., 2024, Ozowe, Daramola & Ekemezie, 2024). By incorporating carbon capture into renewable energy projects, such as biomass facilities or hydrogen production from natural gas, engineers can create a synergistic relationship that enhances sustainability. The lessons learned from successful integrations of renewable energy and CCS illustrate the potential for creating a more resilient energy system that minimizes reliance on fossil fuels while maintaining energy security.

Additionally, adopting circular economy principles can significantly influence the implementation of CO2 capture systems within U.S. energy infrastructure. The concept of a circular economy emphasizes the reuse and recycling of materials, reducing waste and enhancing resource efficiency (Ajiga, et al., 2024, Eleogu, et al., 2024, Latilo, et al., 2024, Ogundipe, et al., 2024). By exploring innovative uses for captured CO2, such as utilizing it in enhanced oil recovery or converting it into valuable products, energy producers can create additional economic value while contributing to emissions reduction. The engineering lessons derived from circular economy initiatives underscore the importance of viewing carbon capture not merely as a cost but as a potential revenue stream, encouraging investment and innovation in the sector.

The role of policy and regulatory frameworks in supporting the implementation of CO2 capture systems cannot be overstated. The U.S. government has already taken steps to promote carbon capture technologies through various incentives, including tax credits and grants for CCS projects. However, to achieve widespread adoption, it is essential to establish a clear and supportive regulatory environment that incentivizes emissions reduction and facilitates investment in carbon capture technologies Abdul-Azeez, Ihechere & Idemudia, 2024, Emmanuel, et al., 2023, Manuel, et al., 2024). Policymakers must engage with industry stakeholders to develop comprehensive strategies that address barriers to implementation, such as high costs and regulatory uncertainty. The engineering lessons learned from navigating regulatory challenges in past projects highlight the need for proactive engagement with policymakers to ensure that CCS initiatives are both feasible and economically viable.

Moreover, continued research and development in carbon capture technologies are vital for driving innovation and enhancing the performance of CO2 capture systems. Ongoing investment in R&D can lead to breakthroughs in capture efficiency, cost reduction, and scalability. Collaborative efforts between government, industry, and research institutions can facilitate knowledge sharing and accelerate the development of next-generation capture technologies (Popo-Olaniyan, et al., 2022, Segun-Falade, et al., 2024, Udegbe, et al., 2023, Uzougbo, Ikegwu & Adewusi, 2024). The engineering lessons learned from successful R&D initiatives underscore the importance of fostering a culture of innovation that encourages experimentation and exploration of new ideas.

In conclusion, implementing CO2 capture systems in future U.S. energy infrastructure is essential for achieving sustainability and reducing greenhouse gas emissions. The lessons learned from past carbon capture initiatives emphasize the importance of early integration of capture technologies, appropriate selection of methods, robust monitoring systems, and stakeholder engagement. As the nation transitions toward a low-carbon future, the integration of renewable energy sources, adoption of circular economy principles, supportive policy frameworks, and continued research and development will be critical for the successful implementation of carbon capture technologies (Afeku-Amenyo, 2024, Enahoro, et al., 2024, Moones, et al., 2023, Okeleke, et al., 2024). By learning from past experiences and fostering collaboration across sectors, the U.S. can create a more sustainable energy landscape that not only meets energy demands but also contributes to global efforts in combating climate change, paving the way for a greener future. The commitment to carbon capture and sustainability will play a vital role in ensuring a resilient and responsible energy infrastructure for generations to come.

1.4. Aligning Engineering Solutions with Global Climate Goals

Aligning engineering solutions with global climate goals is essential in the pursuit of sustainable development, particularly in the context of carbon capture and storage (CCS) technologies in liquefied natural gas (LNG) projects. As the world grapples with the urgent need to mitigate climate change, the energy sector must adopt innovative engineering strategies that not only enhance operational efficiency but also contribute significantly to reducing greenhouse gas emissions (Anyanwu, et al., 2024, Esiri, Babayeju & Ekemezie, 2024, Nwabekee, et al., 2024, Ozowe, Zheng & Sharma, 2020). The lessons learned from past engineering practices can inform the development of more sustainable LNG projects that align with international climate targets, ultimately paving the way for a greener future.

To effectively align engineering solutions with climate goals, it is crucial to understand the role of LNG in the global energy landscape. LNG is often touted as a cleaner alternative to coal and oil, primarily due to its lower carbon emissions when combusted. However, the extraction, processing, and transportation of LNG can result in substantial methane emissions, a potent greenhouse gas (Akinsooto, Ogundipe & Ikemba, 2024, Esiri, Babayeju & Ekemezie, 2024, Nwabekee, et al., 2024). Therefore, it is imperative that engineering teams prioritize carbon capture solutions throughout the LNG value chain to minimize emissions and enhance sustainability. By integrating carbon capture technologies at various stages, from production to end-use, engineers can significantly reduce the overall carbon footprint of LNG projects.

The integration of CCS technologies into LNG projects requires a comprehensive understanding of the various capture methods available. Engineers must evaluate which technologies, such as post-combustion capture, pre-combustion capture, or direct air capture, are best suited for their specific operational context (Adewusi, Chikezie & Eyo-Udo, 2023, Esiri, Babayeju & Ekemezie, 2024, Nwankwo, et al., 2024). The choice of technology should be guided by a thorough assessment of factors such as efficiency, cost, and feasibility. For instance, post-combustion capture can be particularly effective in capturing CO2 from existing facilities, while pre-combustion capture may offer advantages in new plants designed for hydrogen production. By tailoring capture methods to the specific characteristics of each project, engineers can optimize performance and enhance sustainability.

Moreover, the design and engineering of LNG facilities should incorporate principles of energy efficiency and waste minimization. Implementing energy-efficient technologies, such as combined heat and power (CHP) systems or advanced process controls, can significantly reduce energy consumption and associated emissions. Additionally, engineers should prioritize the use of waste heat recovery systems to maximize resource efficiency and minimize waste generation (Adebayo, et al., 2024, Esiri, Babayeju & Ekemezie, 2024, Nwosu, 2024, Olatunji, et al., 2024). The lessons learned from past projects highlight the importance of adopting a holistic approach to engineering design, wherein energy efficiency and sustainability are integrated into every aspect of facility operations.

The role of advanced data analytics and digital technologies cannot be overstated in the quest to align engineering solutions with climate goals. Leveraging real-time data and predictive analytics can enhance operational efficiency, optimize energy use, and improve decision-making processes. For instance, using machine learning algorithms to analyze operational data can identify patterns that lead to reduced emissions and enhanced performance (Alemede, et al., 2024, Esiri, Jambol & Ozowe, 2024, Nwosu & Ilori, 2024, Omaghomi, et al., 2024). Furthermore, digital twin technologies can simulate various operational scenarios, allowing engineers to assess the potential impacts of different design choices on emissions and overall sustainability. By harnessing the power of data, engineers can make informed decisions that align with climate objectives and drive continuous improvement in LNG projects.

In addition to technological innovations, the successful alignment of engineering solutions with global climate goals necessitates robust stakeholder engagement. Collaborating with local communities, government agencies, and environmental organizations is essential for fostering support and ensuring that projects meet social and environmental standards (Ajiga, et al., 2024, Esiri, Jambol & Ozowe, 2024, Nwosu, Babatunde & Ijomah, 2024, Uzougbo, Ikegwu & Adewusi, 2024). Transparent communication regarding the sustainability initiatives and emissions reduction strategies employed in LNG projects can build trust and facilitate collaboration. Engaging stakeholders in the decision-making process can also yield valuable insights that enhance project outcomes and align with broader climate goals. The engineering lessons learned from projects that prioritize stakeholder engagement underscore the importance of building strong partnerships to achieve shared sustainability objectives (Anyanwu, Ogbonna & Innocent, 2023, Ikevuje, et al., 2024, Ogbu, Ozowe & Ikevuje, 2024, Uzougbo, Ikegwu & Adewusi, 2024).

Furthermore, the implementation of carbon capture technologies in LNG projects should be complemented by a commitment to a circular economy. This approach emphasizes the reuse and recycling of materials, which can significantly reduce waste and enhance resource efficiency (Abdul-Azeez, Ihechere & Idemudia, 2024, Esiri, Jambol & Ozowe, 2024, Obijuru, et al., 2024). By exploring innovative uses for captured CO2, such as converting it into valuable products or utilizing it for enhanced oil recovery, LNG projects can create additional economic value while contributing to emissions reduction. The lessons learned from successful circular economy initiatives can guide engineers in designing LNG facilities that prioritize resource optimization and waste minimization, thereby aligning with global climate goals.

The role of regulatory frameworks and policies in supporting the alignment of engineering solutions with climate objectives is also critical. Governments must establish clear and supportive policies that incentivize emissions reduction and promote the adoption of carbon capture technologies. For instance, financial incentives, such as tax credits or grants for CCS projects, can encourage investment in sustainable technologies (Afeku-Amenyo, 2024, Esiri, Jambol & Ozowe, 2024, Ochuba, et al., 2024, Olatunji, et al., 2024). Moreover, policymakers should engage with industry stakeholders to develop comprehensive strategies that address barriers to implementation, such as high costs and regulatory uncertainty. The engineering lessons learned from navigating regulatory challenges in previous projects highlight the need for proactive engagement with policymakers to create a conducive environment for sustainable development.

In conclusion, aligning engineering solutions with global climate goals is essential for fostering sustainability in LNG projects and the broader energy sector. By integrating carbon capture technologies throughout the LNG value chain, engineers can significantly reduce emissions and enhance the sustainability of their operations (Anaba, Kess-Momoh & Ayodeji, 2024, Esiri, et al., 2023, Ochuba, et al., 2024, Ukato, et al., 2024). The selection of appropriate capture methods, the incorporation of energy-efficient technologies, and the use of advanced data analytics are all critical components of this alignment. Furthermore, stakeholder engagement and a commitment to circular economy principles can enhance project outcomes and foster collaboration among various stakeholders. By leveraging lessons learned from past engineering practices and prioritizing sustainability in design and implementation, the LNG sector can contribute to achieving global climate goals and pave the way for a greener future. As the world continues to confront the challenges of climate change, the commitment to sustainable engineering practices will play a vital role in shaping an energy landscape that prioritizes environmental stewardship and social responsibility (Afeku-Amenyo, 2024, Ikevuje, et al., 2023, Ogbu, Ozowe & Ikevuje, 2024, Olatunji, et al., 2024).

1.5. Challenges in Scaling Up Carbon Capture in LNG

Scaling up carbon capture technology in liquefied natural gas (LNG) projects presents a complex array of challenges that must be addressed to realize a sustainable energy future. As global efforts intensify to mitigate climate change, carbon capture and storage (CCS) has emerged as a promising solution for reducing greenhouse gas emissions from industrial processes (Porlles, et al., 2023, Segun-Falade, et al., 2024, Udegbe, et al., 2023, Udo, et al., 2024). However, the implementation of CCS in the LNG sector involves multifaceted considerations, including infrastructure requirements, economic factors, and regulatory and public perception challenges.

The infrastructure needed for carbon capture in LNG projects is one of the primary challenges that stakeholders face. Existing LNG facilities were primarily designed without the intention of capturing carbon emissions, leading to significant limitations in their current configurations. Retrofitting these facilities to accommodate CCS technologies can be a formidable task, as it often requires extensive modifications and enhancements. For instance, carbon capture systems need to be integrated into the gas processing operations, which may involve significant alterations to the existing pipelines, storage facilities, and transportation systems (Adewusi, Chikezie & Eyo-Udo, 2023, Esiri, et al., 2023, Ochuba, et al., 2024, Ozowe, et al., 2024). This integration often necessitates new construction or upgrades to existing infrastructure, which can be time-consuming and costly.

Moreover, the effective transportation and storage of captured CO_2 also demand substantial infrastructural investments. Pipelines must be developed to transport CO_2 from the point of capture to the storage site, and suitable geological formations must be identified and assessed for their capacity to store the CO_2 safely (Awonuga, et al., 2024, Esiri, et al., 2024, Ochuba, et al., 2024, Ogedengbe, et al., 2024). These geological assessments require rigorous testing and modeling to ensure long-term sequestration and environmental safety. In regions where such infrastructure is lacking, establishing the necessary systems can become a critical barrier to scaling up carbon capture in LNG projects. The challenge lies not only in the financial aspect but also in the logistical and engineering complexities of designing and implementing robust infrastructure that can handle the unique requirements of carbon capture.

Economic considerations play a pivotal role in determining the feasibility and attractiveness of carbon capture technologies in LNG operations. The costs associated with implementing CCS technologies can be substantial. Initial investments include the capital required for developing carbon capture systems, retrofitting existing infrastructure, and establishing transportation and storage networks (Abdul-Azeez, et al., 2024, Esiri, Sofoluwe & Ukato, 2024, Odili, et al., 2024, Usiagu, et al., 2024). Additionally, the ongoing operational and maintenance costs must be factored into the economic equation. These costs can significantly impact the overall financial viability of LNG projects, particularly in a competitive energy market where profit margins are often tight.

However, while the upfront investments in carbon capture technologies may be high, it is essential to consider the long-term economic benefits. As regulatory pressure to reduce emissions increases, failing to adopt CCS could lead to heightened operational costs in the future, such as carbon taxes or penalties for exceeding emission limits (Ajiga, et al., 2024, Eyieyien, et al., 2024, Odili, Ekemezie & Usiagu, 2024, Ozowe, et al., 2020). By investing in carbon capture now, LNG operators may mitigate future financial risks and align themselves with a low-carbon economy. Furthermore, the potential for revenue generation from carbon credits and enhanced public perception of environmental stewardship could lead to improved market positioning and competitiveness.

The regulatory landscape surrounding carbon capture and storage is complex and often varies significantly across regions. Stakeholders in the LNG industry must navigate a myriad of regulatory frameworks, each with its own requirements and compliance issues (Akinsooto, Ogundipe & Ikemba, 2024, Ezeh, et al., 2024, Odili, Ekemezie & Usiagu, 2024). These regulations may include emissions reporting, monitoring, and verification processes, all of which can complicate the implementation of CCS technologies. In some cases, the absence of clear regulatory guidance or incentives can further hinder progress, leaving operators uncertain about the pathways to compliance and investment.

Public perception is another critical factor influencing the successful scaling of carbon capture in LNG projects. While there is growing awareness of the need for sustainable practices, skepticism about carbon capture technology persists among certain segments of the population. Concerns about the potential environmental impacts of carbon capture, particularly regarding the long-term storage of CO2 and the possibility of leakage, can lead to public resistance to CCS projects (Abdul-Azeez, Ihechere & Idemudia, 2024, Ezeh, et al., 2024, Odili, et al., 2024, Osimobi, et al., 2023). Building trust and engaging with local communities is vital for addressing these concerns and fostering public acceptance of carbon capture initiatives.

To navigate these challenges effectively, a collaborative approach involving government, industry stakeholders, and local communities is essential. Governments can play a pivotal role in facilitating the deployment of carbon capture technologies through policy frameworks that support research and development, provide financial incentives, and establish clear regulations. Such measures can help create an enabling environment for investments in carbon capture in LNG projects (Agupugo, 2023, Ezeh, et al., 2024, Odili, et al., 2024, Ogedengbe, et al., 2023, Ozowe, et al., 2024). Furthermore, engaging with local communities through transparent communication and education initiatives can help demystify carbon capture technology and alleviate public concerns.

Lessons learned from existing carbon capture and LNG projects can inform future efforts in scaling up these technologies. Collaborative pilot projects that demonstrate the feasibility and effectiveness of carbon capture systems can serve as valuable case studies for stakeholders. Sharing best practices and engineering lessons from these projects can facilitate knowledge transfer and drive innovation in carbon capture technologies (Afeku-Amenyo, 2015, Ezeh, et al., 2024, Odili, et al., 2024, Oguejiofor, et al., 2023, Uzougbo, Ikegwu & Adewusi, 2024). By addressing the challenges of infrastructure, economics, regulation, and public perception, the LNG sector can position itself as a leader in the transition to a greener, more sustainable energy future.

In conclusion, scaling up carbon capture in LNG projects is fraught with challenges that must be systematically addressed to unlock the full potential of this technology in the fight against climate change. The engineering lessons gleaned from existing projects can guide future endeavors, emphasizing the need for robust infrastructure, careful economic planning, regulatory clarity, and proactive engagement with the public (Aziza, Uzougbo & Ugwu, 2023, Farah, et al., 2021, Odilibe, et al., 2024, Oshodi, 2024). By overcoming these challenges, the LNG industry can contribute significantly to reducing greenhouse gas emissions and advancing sustainability efforts in the energy sector. The pursuit of carbon capture in LNG represents a crucial step toward achieving a balanced energy future, where economic viability and environmental stewardship coexist harmoniously.

1.6. Future Directions for Carbon Capture in LNG

The future of carbon capture and storage (CCUS) in liquefied natural gas (LNG) projects presents a landscape filled with opportunities for innovation and sustainability. As the global community strives to combat climate change, the potential for scaling CCUS technologies not only in LNG but also across various industries becomes increasingly critical (Quintanilla, et al., 2021, Segun-Falade, et al., 2024, Udegbe, et al., 2023, Udeh, et al., 2024). The success of these efforts hinges on engineering advancements, collaborative initiatives, and the commitment of stakeholders at all levels to prioritize sustainability. Scaling CCUS technologies in LNG and other industries is paramount in the fight against climate change. The LNG sector, which is a significant source of carbon dioxide (CO_2) emissions, has a unique opportunity to lead the charge in carbon reduction efforts. As the demand for cleaner energy sources grows, integrating CCUS technologies can enable LNG facilities to capture a substantial portion of their emissions. This not only helps mitigate environmental impacts but also enhances the overall sustainability of LNG as a transition fuel in the energy mix.

The potential for scaling CCUS extends beyond LNG to a myriad of other industries, including cement, steel, and chemical production, all of which are significant contributors to global greenhouse gas emissions. The learnings from the LNG sector can serve as a blueprint for implementing carbon capture technologies in these industries (Akagha, et al., 2023, Hamdan, et al., 2023, Odulaja, et al., 2023, Ogugua, et al., 2024). By leveraging existing infrastructure, such as pipelines for transporting CO_2, and adapting best practices from LNG carbon capture projects, other sectors can also accelerate their transition to more sustainable operations. This interconnected approach promotes a circular economy where carbon capture technologies become an integral part of various industrial processes, ultimately contributing to a substantial reduction in emissions across the board.

Emerging engineering innovations are poised to play a pivotal role in enhancing the efficiency of carbon capture processes in LNG projects. Advancements in materials science, for instance, are leading to the development of novel absorbents and solvents that can capture CO_2 more effectively and at lower costs (Adebayo, et al., 2024, Ijomah, et al., 2024, Odunaiya, et al., 2024, Olatunji, et al., 2024). These innovations can significantly reduce the energy required for the capture process, making it more economically viable. Furthermore, the incorporation of advanced technologies, such as machine learning and artificial intelligence, can optimize carbon capture operations by analyzing data in real time to improve performance and efficiency. For instance, smart monitoring systems can provide insights into the performance of carbon capture units, allowing operators to make informed decisions on maintenance and operational adjustments. By predicting equipment failures before they occur and ensuring optimal operating conditions, these technologies can enhance the reliability and efficiency of carbon capture systems. Moreover, integrating renewable energy sources to power carbon capture operations can further lower the carbon footprint, reinforcing the sustainability of the entire LNG production process (Abdul-Azeez, 2024, Ikevuje, et al., 2024, Ogbu, Ozowe & Ikevuje, 2024, Ogugua, et al., 2024).

Another critical engineering advancement is the development of modular carbon capture units. These smaller, transportable systems can be deployed at various LNG facilities, allowing for more flexible and scalable carbon capture solutions. By standardizing components and designs, these modular units can be manufactured off-site and rapidly deployed, reducing installation times and associated costs (Abdul-Azeez, Ihechere & Idemudia, 2024, Ijomah, et al., 2024, Odunaiya, et al., 2024). This flexibility can enable LNG operators to implement carbon capture solutions tailored to their specific operational needs, enhancing overall adoption rates.

Collaboration among industry stakeholders is essential for fostering widespread adoption of CCUS technologies in LNG and beyond. The complexity and scale of implementing carbon capture systems necessitate a unified approach that includes government agencies, private sector companies, research institutions, and non-governmental organizations (Agupugo & Tochukwu, 2021, Ikemba, 2017, Odunaiya, et al., 2024, Ogundipe, Okwandu & Abdulwaheed, 2024). Public-private partnerships can provide the necessary funding and support for research and development efforts, driving innovation and accelerating the deployment of CCUS technologies.

Moreover, sharing knowledge and best practices across industries can enhance the collective understanding of carbon capture technologies and their applications. Collaborative research initiatives can focus on identifying challenges, developing solutions, and disseminating findings to ensure that all stakeholders benefit from advancements in carbon capture (Anaba, Kess-Momoh & Ayodeji, 2024, Ikemba, 2017, Odunaiya, et al., 2024, Ozowe, et al., 2024). Such cooperation can lead to the establishment of industry-wide standards and guidelines, ensuring that carbon capture systems are deployed effectively and safely. Regulatory frameworks also play a vital role in the successful scaling of CCUS technologies. Governments must create policies that incentivize the adoption of carbon capture solutions, such as tax credits, grants, or subsidies for projects that incorporate CCUS. Clear regulatory guidelines can provide the certainty that businesses need to invest in carbon capture technologies, ultimately driving down costs and enhancing competitiveness. Furthermore, establishing a robust carbon market can create economic opportunities for companies that capture and store CO_2, allowing them to generate revenue while contributing to climate goals.

Public engagement and education are equally critical for the success of CCUS initiatives. Many communities remain unaware of the benefits and potential of carbon capture technologies. Increasing public awareness can help demystify these technologies and build trust among stakeholders (Afeku-Amenyo, 2021, Ikemba, 2022, Oduro, Uzougbo & Ugwu, 2024, Ogugua, et al., 2024). Through open dialogues and educational campaigns, industry leaders can address public concerns and emphasize the importance of CCUS in achieving a sustainable future. The future of carbon capture in LNG projects is not only about technological advancements but also about the integration of sustainability into the core of energy production. As the world transitions toward a low-carbon economy, LNG operators must prioritize sustainability in their strategies. This can involve adopting best practices for energy efficiency, minimizing waste, and leveraging carbon capture technologies to reduce emissions. By aligning business objectives with sustainability goals, LNG companies can position themselves as leaders in the energy transition, ultimately enhancing their market value and reputation.

In conclusion, the future of carbon capture and sustainability in LNG projects is ripe with possibilities. By embracing the potential for scaling CCUS technologies across various industries, investing in emerging engineering innovations, and fostering collaborative efforts, stakeholders can drive meaningful change in the fight against climate change (Abdul-Azeez, et al., 2024, Ikemba & Okoro, 2009, Oduro, Uzougbo & Ugwu, 2024, Udo, et al., 2024). The lessons learned from existing carbon capture initiatives can pave the way for a greener future, where LNG and other industries contribute to a more sustainable energy landscape. As the global demand for cleaner energy sources continues to grow, the successful integration of carbon capture technologies will be paramount in ensuring a balanced and sustainable energy future for generations to come.

1.7. Model for Carbon Capture and Sustainability in LNG Projects

Carbon capture and sustainability in liquefied natural gas (LNG) projects represent a critical intersection of engineering innovation and environmental responsibility. The escalating urgency to mitigate climate change has prompted energy sectors worldwide to explore effective strategies for reducing greenhouse gas emissions (Anaba, Kess-Momoh & Ayodeji, 2024, Ikemba, et al., 2021, Ogbonna, Oparaocha & Anyanwu, 2024). As LNG is increasingly viewed as a transitional fuel towards a more sustainable energy future, the implementation of carbon capture technologies becomes paramount. This model outlines essential components and engineering lessons learned in the pursuit of a greener future through carbon capture in LNG projects.

The foundation of this model lies in understanding the various technologies available for carbon capture. The primary methods include pre-combustion, post-combustion, and oxy-fuel combustion capture. Each method has distinct engineering requirements and efficiencies, making the choice of technology contingent upon the specific characteristics of the LNG facility and its operational processes (Abdul-Azeez, Ihechere & Idemudia, 2024, Ikemba, et al., 2021, Ogbonna, et al., 2024). Pre-combustion capture involves removing carbon dioxide from fossil fuels before combustion, effectively preventing emissions from entering the atmosphere. Post-combustion capture captures CO2 after combustion, while oxy-fuel combustion employs pure oxygen to combust fuels, producing a concentrated CO2 stream for easier capture.

The successful integration of carbon capture technology into LNG projects requires a comprehensive assessment of existing infrastructure. Many LNG facilities operate using legacy systems that may not be compatible with new carbon capture technologies. Upgrades or retrofitting of equipment and processes may be necessary to accommodate these innovations. This presents both challenges and opportunities for engineers (Paul, Ogugua & Eyo-Udo, 2024, Segun-Falade, et al., 2024, Sulaiman, Ikemba & Abdullahi, 2006, Udegbe, et al., 2023). Retrofitting existing plants can be more cost-effective than building new facilities, and leveraging existing infrastructure can expedite implementation timelines.

Moreover, the economic considerations associated with carbon capture implementation cannot be understated. Initial capital investment is significant, with costs associated with technology installation, operation, and maintenance (Agupugo, 2022, Ikemba, et al., 2024, Ogbu, et al., 2024, Ogedengbe, et al., 2024, Uzougbo, Ikegwu & Adewusi, 2024). However, the long-term benefits—including potential revenue streams from carbon credits, compliance with regulatory frameworks, and improved market competitiveness—often outweigh these upfront expenses. Economic modeling can assist in evaluating the return on investment for carbon capture technologies, providing a clear financial incentive for stakeholders.

Regulatory frameworks play a vital role in shaping the adoption of carbon capture technologies in LNG projects. Understanding local, national, and international regulations regarding emissions reduction is essential for compliance and securing project approvals. Engineers and project managers must work closely with regulatory bodies to navigate these frameworks and ensure that their projects align with evolving standards (Aziza, Uzougbo & Ugwu, 2023, Ikevuje, Anaba & Iheanyichukwu, 2024, Ogbu, et al., 2024). This collaboration can also foster a supportive environment for innovation, as regulatory incentives may encourage the development and deployment of cutting-edge carbon capture solutions.

Public perception and stakeholder engagement are critical factors in the successful implementation of carbon capture technologies. Addressing concerns regarding the environmental impact of carbon capture and ensuring transparency about its benefits and limitations are essential to gaining public support. Effective communication strategies that educate stakeholders on the importance of carbon capture in the context of climate change can facilitate broader acceptance of these technologies (Afeku-Amenyo, 2022, Ikevuje, Anaba & Iheanyichukwu, 2024, Ogbu, et al., 2023, Ozowe, et al., 2024). Additionally, collaboration with community organizations and local governments can enhance public trust and support for LNG projects that incorporate carbon capture.

The engineering lessons derived from successful carbon capture implementations emphasize the importance of continuous innovation and improvement. Emerging technologies, such as direct air capture and carbon utilization, offer new avenues for enhancing carbon capture efficiencies and expanding the role of captured CO2 in sustainable applications. Engineers must remain vigilant in researching and adopting these advancements to enhance the performance of carbon capture systems (Abdul-Azeez, et al., 2024, Ikevuje, Anaba & Iheanyichukwu, 2024, Ogbu, et al., 2024).

Furthermore, fostering collaboration among stakeholders—including industry players, academia, government agencies, and non-governmental organizations—is essential for driving the research and development of carbon capture technologies. Knowledge sharing and collective problem-solving can accelerate innovation and identify best practices for implementation. Public-private partnerships can facilitate investment and resources, enabling more extensive deployment of carbon capture systems in LNG projects (Adebayo, et al., 2024, Ikevuje, Anaba & Iheanyichukwu, 2024, Ogbu, et al., 2024, Ozowe, Ogbu & Ikevuje, 2024).

In conclusion, carbon capture and sustainability in LNG projects represent a multifaceted challenge that requires engineering ingenuity, economic foresight, and proactive regulatory engagement. By leveraging advanced carbon capture technologies and fostering collaborative efforts, stakeholders can effectively mitigate greenhouse gas emissions while positioning LNG as a pivotal player in the global transition to a sustainable energy future (Agupugo, 2022, Ikevuje, Anaba & Iheanyichukwu, 2024, Ogbu, et al., 2023, Orikpete, Ikemba & Ewim, 2023). The lessons learned from implementing these technologies will not only benefit LNG projects but also contribute to the broader goal of achieving a greener, more sustainable world. The path to a sustainable energy future is paved with innovation, collaboration, and a commitment to reducing our environmental footprint, ensuring that carbon capture becomes a cornerstone of modern energy infrastructure.

2. Conclusion

In conclusion, the integration of carbon capture technologies into liquefied natural gas (LNG) projects represents a pivotal step toward enhancing sustainability within the energy sector. Key engineering lessons learned from the current implementation of carbon capture in LNG facilities underscore the significance of developing robust infrastructures, optimizing processes through innovative materials and technologies, and ensuring effective monitoring and maintenance systems. These lessons highlight the importance of designing carbon capture systems that are not only effective in reducing emissions but also economically viable and adaptable to existing operational frameworks.

The journey toward sustainable LNG projects hinges on the continuous pursuit of innovation and the collaboration among various stakeholders. As engineering practices evolve, ongoing advancements in carbon capture technologies must be matched by cooperative efforts between industry players, governmental entities, research institutions, and local communities. By fostering a collaborative environment that encourages knowledge sharing and resource pooling, the industry can accelerate the development and deployment of effective carbon capture solutions. This teamwork is essential for overcoming the inherent challenges and complexities of implementing these technologies at scale, ensuring that all parties benefit from the progress made.

Looking ahead, the future of sustainable LNG projects is promising. As global energy demands rise and the imperative to combat climate change intensifies, the role of LNG as a transition fuel can be significantly enhanced through the integration of carbon capture technologies. By prioritizing sustainability and committing to engineering innovations, the LNG sector can not only reduce its carbon footprint but also position itself as a leader in the broader energy transition. The potential to transform LNG into a cleaner energy source, supported by effective carbon capture solutions, paves the way for a greener future where environmental stewardship and energy production coexist harmoniously. The pursuit of sustainability in LNG projects is not merely a response to regulatory pressures or market demands; it is a crucial component of the global effort to secure a resilient and environmentally sustainable energy landscape for generations to come.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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