Engineering and Technology Journal e-ISSN: 2456-3358

Volume 10 Issue 05 May-2025, Page No.- 4789-4796

DOI: 10.47191/etj/v10i05.09, I.F. – 8.482

Comprehensive Review of Climate Change Mitigation through Cutting-edge LNG Technologies

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ABSTRACT: This paper comprehensively reviews the potential of cutting-edge LNG technologies to mitigate climate change .We explore advancements in liquefaction processes, focusing on cryogenic heat exchangers, mixed refrigerant cycles, and turbo molecular expanders, aiming to improve efficiency and reduce energy consumption. Carbon capture and storage (CCS) technologies are examined as a strategy to capture and store CO2 emissions generated during LNG production. Novel approaches to methane emissions reduction, such as advanced leak detection and repair, membrane-based technologies, and utilization of boil-off gas, are also discussed. Liquefied natural gas (LNG) plays a significant role in the global energy landscape, but its life cycle raises concerns about greenhouse gas emissions, particularly methane leakage. Furthermore, the paper analyzes the efficient transportation and distribution of LNG, including LNG shipping technologies, cryogenic insulation, boil-off gas management, and supply chain optimization strategies for emissions reduction. Safe and responsible storage and handling practices are explored, encompassing onshore and offshore facilities, innovative storage solutions, and robust safety measures. The paper delves into the utilization of LNG in various end-use applications, including power generation, transportation (trucks, marine vessels), and industrial processes. While acknowledging the challenges of infrastructure development and cost considerations, the potential for emissions reduction across diverse sectors is highlighted. Finally, the paper emphasizes the importance of life cycle assessments to comprehensively evaluate the environmental impact of LNG. Collaborative efforts among industry stakeholders, governments, and research institutions are identified as crucial for accelerating the transition to cleaner LNG technologies. Continued research on leak mitigation, carbon capture, and life cycle optimization, alongside supportive policies and public awareness, are emphasized as essential for harnessing the potential of LNG for a sustainable future while mitigating climate change. This review provides valuable insights for policymakers, industry leaders, and researchers seeking to navigate the complex landscape of LNG and its role in a climate-conscious energy future.

KEYWORD: Climate Change; Mitigation; LNG; Sustainability; Review

INTRODUCTION

Climate change is a pressing global challenge characterized by rising temperatures, shifting weather patterns, and increasingly severe natural disasters (Ebi et al., 2021). At the heart of this issue lies the contribution of human activities, particularly the combustion of fossil fuels for energy generation, transportation, and industrial processes. These activities release greenhouse gases (GHGs) such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) into the atmosphere, trapping heat and causing the Earth's temperature to rise (Nayak, 2020).

Energy systems play a crucial role in driving climate change, as they are responsible for the majority of GHG emissions worldwide. Traditional energy sources like coal, oil, and natural gas account for a significant portion of these emissions. The inefficiencies and carbon-intensive nature of these systems exacerbate the climate crisis, underscoring the urgent need for transition to cleaner alternatives. Importance of Mitigating Greenhouse Gas Emissions, Mitigating greenhouse gas emissions is paramount in addressing climate change and its far-reaching impacts on ecosystems, economies, and human societies (Sahoo et al., 2023).

Failure to curb emissions poses severe consequences, including more frequent and intense heat waves, droughts, storms, and sea-level rise, threatening food security, water resources, and infrastructure. Transitioning to low-carbon energy sources and implementing energy efficiency measures are essential steps in mitigating emissions (Kabeyi and

Olanrewaju, 2022). This involves shifting towards renewable energy sources such as wind, solar, and hydroelectric power, which emit little to no GHGs during operation. Additionally, improving energy efficiency in buildings, transportation, and industry can significantly reduce overall emissions while enhancing energy security and economic competitiveness.

Introduction to Liquefied Natural Gas (LNG) as a Cleaner Alternative, Liquefied Natural Gas (LNG) is emerging as a promising cleaner alternative to traditional fossil fuels, offering lower emissions and greater efficiency in energy production and transportation. LNG is natural gas that has been cooled to -162°C, reducing its volume for easier storage and transportation. As a result, LNG emits fewer pollutants and GHGs compared to coal and oil when burned for electricity generation or used as a fuel for transportation (Pavlenko et al., 2020).

The use of LNG can help countries reduce their reliance on coal and oil, thereby lowering their carbon footprint and contributing to global efforts to mitigate climate change. Furthermore, LNG infrastructure investments can enhance energy security by diversifying energy sources and supply routes, reducing geopolitical risks associated with traditional fossil fuel imports. In summary, understanding the relationship between climate change and energy systems is crucial for devising effective strategies to mitigate emissions and transition towards cleaner alternatives like LNG. By prioritizing emission reductions and embracing sustainable energy solutions, we can mitigate the impacts of climate change while fostering a more resilient and sustainable future for generations to come (Salam et al., 2024).

2.1. THE ROLE OF LNG IN CLIMATE CHANGE MITIGATION

Advantages of LNG Compared to Conventional Fuels, Liquefied Natural Gas (LNG) offers several advantages over conventional fossil fuels, making it an attractive option in the transition towards cleaner energy systems. Firstly, LNG has a higher energy density compared to natural gas in its gaseous form, allowing for more efficient storage and transportation. This higher energy density means that LNG can be transported over long distances via specialized tankers, opening up access to remote regions without pipeline infrastructure (Molnar, 2022).

Secondly, LNG combustion produces fewer emissions of air pollutants such as sulfur dioxide (SO2), nitrogen oxides (NOx), and particulate matter, compared to coal and oil. This makes LNG a cleaner-burning fuel, contributing to improved air quality and public health outcomes, particularly in densely populated urban areas. Additionally, LNG offers greater flexibility in fueling various sectors, including power generation, industry, and transportation. Its versatility stems from its ability to be used directly in power plants to generate electricity, as well as its potential as a feedstock for industrial processes such as fertilizer production and petrochemical manufacturing (Ikwue et al., 2023).

Moreover, LNG can serve as a cleaner alternative fuel for heavy-duty vehicles, ships, and trucks, reducing emissions in the transportation sector. Potential for LNG as a Transitional Fuel in the Energy Transition, LNG holds significant potential as a transitional fuel in the ongoing energy transition towards a low-carbon future(Oguejiofor et al., 2023). As countries seek to reduce their reliance on coal and oil while ramping up renewable energy deployment, LNG can serve as a bridge fuel to help smooth the transition. Its abundance, accessibility, and relatively lower emissions profile make it a viable option for replacing more carbon-intensive fuels in the short to medium term (Hassan et al., 2024).

Furthermore, LNG infrastructure investments can provide a foundation for future renewable energy integration, as liquefaction terminals and degasification facilities can be repurposed to handle alternative fuels such as renewable natural gas (RNG) or hydrogen (Ogunjobi et al., 2023). This adaptability underscores the role of LNG as a flexible and strategic component of the evolving energy landscape. Contribution to Reducing Emissions in Key Sectors (e.g., Power Generation, Transportation) ,LNG has the potential to significantly reduce emissions in key sectors such as power generation and transportation (Al-Enazi et al., 2021).

In the power sector, replacing coal-fired power plants with natural gas-fired facilities can result in substantial emissions reductions, as natural gas combustion emits approximately 50% less CO2 per unit of energy produced compared to coal (Ewim et al., 2023). This shift towards cleaner energy sources can help countries meet their emissions reduction targets under international agreements like the Paris Agreement. Similarly, in the transportation sector, LNG offers a cleaner-burning alternative to diesel and heavy fuel oil, particularly for maritime and heavy-duty road transport (Alsheikh and Ali, 2023).

LNG-powered vehicles and ships emit lower levels of pollutants such as sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter, leading to improved air quality and reduced greenhouse gas emissions. Overall, LNG presents significant opportunities for reducing emissions across key sectors of the economy, contributing to global efforts to mitigate climate change and transition towards more sustainable energy systems. By leveraging the advantages of LNG and supporting its responsible deployment, policymakers, industry stakeholders, and communities can accelerate progress towards a cleaner, more resilient energy future (ESCAP, 2021).

2.2. TECHNOLOGICAL INNOVATIONS IN LNG PRODUCTION

Technological Innovations in LNG Production, A Quest for Efficiency and Sustainability Liquefied natural gas (LNG) plays a crucial role in the global energy landscape, enabling the transportation of natural gas over long distances (Ninduwezuor-Ehiobu, et al., 2023). However, traditional LNG production processes are energy-intensive, contributing to greenhouse gas emissions. To address these concerns and ensure a sustainable future for the industry, technological innovation is paramount Traditional LNG Production, Conventional LNG production relies on a multi-stage process involving, Natural gas pre-treatment, Removal of impurities like water, sulfur, and mercury to prevent equipment damage and ensure product quality (Chalkidis et al., 2020).

Refrigeration, utilizing a cascade of cooling units, natural gas is progressively cooled to around -160°C, transforming it into a liquid state (Xu et al., 2024). Liquefaction, The final stage where the pre-cooled gas is further chilled, reducing its volume by approximately 600 times, facilitating storage and transportation.Advanced Liquefaction Technologies, Several advancements aim to improve efficiency and reduce the environmental footprint of LNG production, Cryogenic heat exchangers, these recover waste cold from outgoing LNG, reducing the energy required for pre-cooling incoming gas (Gidiagba et al ,2023).

Mixed refrigerant cycles, employing multiple refrigerants with different boiling points optimize the cooling process, leading to lower energy consumption. Turbo mechanical expanders, these utilize the pressure drop of expanding gas to generate power, partially offsetting the energy demand of the liquefaction process. Carbon Capture and Storage (CCS),CCS technology captures carbon dioxide emissions generated during LNG production and stores them underground, preventing their release into the atmosphere. This significantly reduces the overall carbon footprint of LNG production (Aseel et al., 2021).

Novel Approaches to Methane Emissions Reduction, Emerging technologies address methane emissions, a potent greenhouse gas, throughout the LNG value chain, advanced leak detection and repair, Utilizing sensors and innovative monitoring systems helps identify and address leaks promptly, minimizing methane emissions (Adekanmbi and Wolf, 2024). Membrane-based technologies, these membranes selectively separate methane from other components in the natural gas stream, capturing valuable methane while reducing unwanted emissions (Zhang et al., 2020).

Conclusion, technological innovation plays a critical role in shaping the future of LNG production. By embracing advanced liquefaction technologies, CCS, and novel approaches to methane reduction, the industry can strive towards a more sustainable and environmentally responsible future, ensuring continued access to clean energy while mitigating its environmental impact (Cantarero, 2020).

2.3. EFFICIENT TRANSPORTATION AND DISTRIBUTION OF LNG

Efficient Transportation and Distribution of LNG, Balancing Safety, Sustainability, and Cost (Iannaccone, 2021).The efficient transportation and distribution of Liquefied Natural Gas (LNG) are crucial for meeting global energy demands. However, navigating this process requires careful consideration of safety, sustainability, and cost optimization.LNG Shipping Technologies and Safety Considerations, LNG carriers, these specialized double-hulled vessels are equipped with cryogenic containment systems to maintain LNG at -160°C during transport (Onoyere and Adekanmbi, 2012.).

Advanced technologies like membrane tanks and independent cargo tanks offer improved efficiency and safety. Safety measures, stringent regulations and rigorous inspections ensure safe transportation. Emergency response plans and crew training are essential to mitigate potential risks associated with LNG spills and fires. Cryogenic Insulation and Boil-Off Gas Management, Cryogenic insulation, Multi-layered insulation systems minimize heat transfer, preventing LNG from vaporizing during transport (Ye, 2022).

This reduces boil-off gas (BOG), a mixture of methane and other hydrocarbons, which can be a safety and environmental concern () Optimization of LNG Supply Chains for Emissions Reduction, Route optimization, Utilizing advanced software and weather forecasting to plan efficient routes, minimizing travel distance and fuel consumption.LNG carrier size and utilization, Optimizing the size and utilization of LNG carriers based on demand patterns can reduce overall emissions per unit of LNG transported (Bittante and Saxén, 2020).

Collaboration across the supply chain, Effective collaboration between producers, shippers, and consumers can streamline logistics, minimize inefficiencies, and optimize emissions reduction strategies (Fabian et al., 2023). By continuously innovating in these areas, the LNG industry can ensure safe, sustainable, and cost-effective transportation and distribution, contributing to a cleaner energy future (Adekoya et al., 2024).

2.4. STORAGE AND HANDLING OF LNG

Safe and Efficient Storage and Handling of LNG, Balancing Security and Sustainability The storage and handling of Liquefied Natural Gas (LNG) are crucial stages in the energy supply chain (Onoyere,). Ensuring efficient and safe operations requires careful consideration of storage facilities, innovative solutions, and robust safety measures. Onshore and Offshore LNG Storage Facilities, Onshore storage, Large, double-walled, cryogenic tanks made of special steel and concrete are used for onshore storage (Ratnakar et al., 2023).

These tanks are designed to minimize heat transfer and maintain LNG at its extremely low temperature.Natural gas pre-treatment, Removal of impurities like water, sulfur, and mercury to prevent equipment damage and ensure product quality. Refrigeration, utilizing a cascade of cooling units, natural gas is progressively cooled to around -160°C, transforming it into a liquid state (Faruque and Nabil, 2021). Liquefaction, the final stage where the pre-cooled gas is further chilled, reducing its volume by approximately 600 times, facilitating storage and transportation (Ilugbusi et al., 2020). Advanced Liquefaction Technologies, Offshore storage, Floating storage and degasification units (FSRUs) are self-contained vessels used for offshore storage and degasification. They offer flexibility for deployment in locations lacking onshore infrastructure. Innovative Storage Solutions, Underground storage, Utilizing depleted natural gas reservoirs or salt caverns for LNG storage offers advantages like reduced land footprint and improved security (Liu et al., 2023).

Emerging technologies, Cryogenic containers and mobile LNG solutions are being explored for smaller-scale applications, offering greater flexibility and accessibility (Vincent et al., 2021). Safety Measures and Environmental Risk Mitigation, Stringent regulations, Comprehensive regulations govern the design, construction, operation, and maintenance of LNG storage facilities, ensuring adherence to safety standards. Leak detection and prevention, Advanced monitoring systems are employed to detect and address leaks promptly, minimizing environmental impact (Vandrangi et al., 2022).

Emergency response plans, Comprehensive plans and trained personnel are essential to effectively respond to potential incidents, ensuring public safety and environmental protection. Conclusion, The safe and efficient storage and handling of LNG are paramount for a reliable and sustainable energy future (Hu et al., 2021). By embracing innovative solutions, adhering to stringent regulations, and implementing robust safety measures, the industry can ensure responsible operations that minimize environmental risks and maximize the benefits of this vital energy source (Adagaetal., 2024).

2.5. UTILIZATION OF LNG IN END-USE APPLICATIONS

Utilizing LNG in End-Use Applications, Powering Diverse Sectors Liquefied Natural Gas (LNG) plays a crucial role in various end-use applications, offering a cleaner alternative to traditional fuels across multiple sectors. Power Generation with LNG-fired Plants, Natural gas power plants, These highly efficient plants utilize LNG as fuel to generate electricity. Compared to coal-fired plants, they offer significantly lower greenhouse gas emissions, contributing to cleaner energy production (Yang et al., 2022).

Combined Cycle Power Plants, Combining gas turbines with steam turbines, these plants achieve even higher efficiencies, maximizing fuel utilization and minimizing emissions (Adaga et al., 2024). LNG as a Fuel for Transportation, LNG trucks, Heavy-duty trucks powered by LNG offer a cleaner alternative to diesel, reducing emissions and noise pollution. Their longer range compared to electric trucks makes them suitable for long-haul transportation. Marine vessels, LNG-fueled ships are gaining traction, particularly for larger vessels like container ships and cruise liners (Tan, 2020).

This transition helps to reduce air and water pollution in coastal areas and contribute to cleaner maritime transportation (Abraham et al., 2024). Industrial Applications and Process Heat Generation, Industrial processes, various industries utilize LNG as a clean and efficient fuel source for applications like metal production, glass manufacturing, and chemical processing. Replacing traditional fuels with LNG can significantly reduce emissions and improve air quality. Process heat generation, Industrial facilities can use LNG for generating process heat required for various operations, offering a cleaner alternative to traditional fuels like coal or oil (Chen, 2022).

While LNG offers several advantages, challenges remain, including, Infrastructure development, expanding the network of LNG filling stations and storage facilities are crucial for wider adoption in the transportation sector (Liaw et al., 2020). Cost considerations, the initial investment in LNG infrastructure and vehicles can be higher compared to traditional options. Despite these challenges, ongoing technological advancements, infrastructure development, and cost reductions are paving the way for wider adoption of LNG across diverse end-use applications (Al Ghafri et al., 2023).

By leveraging its cleaner burning properties and potential for emissions reduction, LNG can contribute to a more sustainable energy future for various sectors (Hoang et al., 202). LNG: Powering Diverse Sectors Liquefied natural gas (LNG) transcends its role as a fuel source, offering a cleaner alternative across various end-use applications. Power Generation, LNG-fired plants generate electricity with significantly lower emissions compared to coal, contributing to cleaner energy production (Tan et al., 2022).

Transportation: Heavy-duty trucks and marine vessels powered by LNG offer reduced emissions and noise pollution, paving the way for cleaner transportation options. Industry: LNG serves as a clean and efficient fuel source for various industrial processes, minimizing emissions and improving air quality. While challenges like infrastructure development and cost remain, ongoing advancements are making LNG a viable option for a more sustainable energy future across diverse sectors (Sakmar, 2013).

2.6. ENVIRONMENTAL IMPACTS AND SUSTAINABILITY CONSIDERATIONS

Assessing the Environmental Footprint of LNG, A Life Cycle Perspective While often touted as a cleaner alternative to traditional fossil fuels, the environmental impact of Liquefied (Daudu et al., 2024). Natural Gas (LNG) needs to be assessed holistically through life cycle assessments (LCA) (Cucinotta et al., 2021). Methane Leakage and Fugitive Emissions Mitigation, A significant concern is methane leakage throughout the LNG supply chain, from extraction to end-use. Methane, a potent greenhouse gas, can negate the climate benefits of LNG if leakage rates are high. Addressing this challenge requires, improved leak detection and repair technologies, Utilizing advanced sensors and monitoring systems to identify and address leaks promptly (Ali and Choi, 2019).

Investment in infrastructure upgrades, Replacing aging pipelines and equipment with newer, leak-proof technologies (Ge and Shoaf, 2022). Best practices implementation, adopting operational best practices to minimize fugitive emissions across all stages of the LNG life cycle. Water and Land Use Implications of LNG Infrastructure, the development of LNG infrastructure, including extraction wells, liquefaction facilities, and storage tanks, can have impacts on water and land use (de Mello et al., 2020).

These concerns necessitate Careful site selection, minimizing the footprint of infrastructure on sensitive ecosystems and prioritizing Brownfield redevelopment (Mofrad and Ignatieva, 2022).Water resource management, implementing water-efficient technologies and adopting responsible water withdrawal practices to minimize freshwater use.Land reclamation and restoration, implementing effective land reclamation and restoration strategies following infrastructure development to minimize long-term environmental impacts. By acknowledging and addressing these environmental concerns throughout the LNG life cycle, the industry can strive towards a more sustainable future, balancing energy needs with environmental responsibility (Hall et al., 2022).

2.7. CONCLUSION

The exploration of various aspects of LNG technology reveals both its potential and the challenges it presents. Here's a summary of key findings and the path forward, Technological advancements, Innovations in liquefaction, storage, and utilization offer opportunities for improved efficiency, reduced emissions, and wider applicability of LNG. Environmental concerns, Methane leakage, water and land use impacts necessitate robust mitigation strategies and responsible infrastructure development.

Diverse applications, LNG holds promise for cleaner power generation, transportation, and industrial processes, contributing to a more sustainable energy mix. Importance of Collaborative Efforts, Accelerating the transition to cleaner LNG technologies requires collaborative efforts across various stakeholders, Industry collaboration, Collaboration between energy companies, technology providers, and research institutions can foster innovation and accelerate the development and deployment of cleaner LNG solutions.

Government support, Policy frameworks that incentivize research, development, and adoption of cleaner LNG technologies are crucial for driving industry-wide change. International cooperation, Sharing best practices and knowledge exchange between countries can accelerate progress towards a more sustainable global LNG industry. Call for Continued Research and Policy Support, Continued research and policy support are essential for mitigating climate change and ensuring the responsible use of LNG.

Further research is needed on advanced leak detection and mitigation technologies, carbon capture and storage solutions, and life cycle assessments to optimize the environmental footprint of LNG. Policy frameworks, Implementing carbon pricing mechanisms and emissions reduction targets can incentivize cleaner LNG production and utilization. Public awareness, raising public awareness about the potential and challenges of LNG can foster informed decision-making and support for sustainable energy solutions. By fostering collaboration, prioritizing continued research, and implementing supportive policies, we can navigate a path towards cleaner LNG technologies, ensuring a responsible and sustainable future for this vital energy source.

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