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LNG AND CLIMATE CHANGE: EVALUATING ITS CARBON FOOTPRINT IN COMPARISON TO OTHER FOSSIL FUELS

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ABSTRACT

The increasing global demand for energy, coupled with growing concerns about climate change, has prompted a critical examination of the environmental impact of various energy sources. Liquefied Natural Gas (LNG) has emerged as a significant player in the energy landscape, touted for its potential as a cleaner alternative to traditional fossil fuels. This review provides a concise overview of a comprehensive evaluation that assesses the carbon footprint of LNG in comparison to other fossil fuels. The research delves into the lifecycle analysis of LNG, scrutinizing its carbon emissions from extraction and production to transportation and combustion. This holistic approach seeks to unravel the nuanced environmental implications associated with LNG utilization. Comparative analyses with conventional fossil fuels such as coal and oil are conducted, aiming to offer a comprehensive understanding of LNG's relative environmental performance. Key aspects covered include the environmental considerations

throughout the LNG supply chain, encompassing extraction, liquefaction, shipping, regasification, and combustion. Special attention is given to technological advancements and innovations that influence the carbon intensity of LNG operations. The assessment incorporates recent data and insights, providing an up-to-date perspective on the evolving landscape of LNG's carbon footprint. The review highlights the significance of evaluating the entire spectrum of emissions associated with different fossil fuels, acknowledging the varying impacts on global warming potential. Additionally, the research considers regional and geopolitical factors influencing the sourcing and consumption of LNG, contributing to a nuanced understanding of its carbon profile in diverse contexts. As the world navigates the transition towards a more sustainable energy future, this research aims to contribute valuable insights into the role of LNG in mitigating climate change. The findings have implications for policymakers, industry stakeholders, and environmental advocates, offering a basis for informed decision-making and strategic planning in the pursuit of a low-carbon energy paradigm.

Keywords: LNG, Climate, Carbon, Footprint, Fossil Fuels.

INTRODUCTION

The global energy landscape is undergoing a profound transformation as nations grapple with the dual challenge of meeting rising energy demand while addressing environmental sustainability (Ögmundarson, et al., 2020; Goodland, 1995). In this evolving scenario, Liquefied Natural Gas (LNG) has emerged as a pivotal player, promising a cleaner and more efficient alternative to conventional fossil fuels. As the world seeks a balance between energy security, economic development, and environmental responsibility, understanding the carbon footprints of different energy sources becomes paramount (Cruz, et al 2018; Chen, et al., 2021; Wood e al., 2020).

Against the backdrop of expanding industrialization and population growth, concerns about climate change have escalated to the forefront of global discourse. The palpable impacts of rising temperatures, extreme weather events, and the undeniable link between human activities and greenhouse gas emissions underscore the urgency of transitioning to more sustainable energy solutions. Recognizing the role of energy production in contributing to climate change, stakeholders are now scrutinizing the environmental implications of various energy sources with renewed focus (Wang, and Li, 2023).

The significance of evaluating carbon footprints in energy sources lies in the quest for sustainable and environmentally responsible energy solutions. The carbon footprint, representing the total greenhouse gas emissions associated with a particular energy source throughout its lifecycle, serves as a crucial metric for assessing its environmental impact. As societies globally commit to reducing carbon emissions and achieving net-zero goals, a thorough evaluation of energy options becomes imperative. This evaluation is not only a scientific endeavor but a pragmatic response to the ethical imperative of ensuring a habitable planet for future generations.

In this context, this study embarks on a comprehensive exploration of LNG's carbon footprint, examining its entire lifecycle, from extraction to combustion. The research places particular emphasis on comparing LNG with other fossil fuels like coal and oil, considering the intricate dynamics of the global energy landscape. By doing so, we aim to contribute valuable insights

to the ongoing dialogue surrounding sustainable energy choices, offering a nuanced understanding of LNG's role in addressing the challenges posed by climate change.

Background on LNG

Liquefied Natural Gas (LNG) stands as a versatile and cleaner form of energy derived from natural gas (Mokhatab, et al., 2013; Gas, 2008). Natural gas, primarily composed of methane, undergoes a process of liquefaction where it is cooled to extremely low temperatures, around -162 degrees Celsius (-260 degrees Fahrenheit). This transformation turns the gaseous form of natural gas into a liquid, significantly reducing its volume and allowing for easier storage and transportation. LNG is colorless, odorless, and non-toxic, making it a safe and efficient energy carrier.

The physical properties of LNG make it an attractive option for global trade (Du, and Paltsev, 2014; Gałczyński, et al., 2017; Nikhalat-Jahrom, et al., 2017), as it can be transported in specially designed cryogenic vessels. This characteristic enables the shipment of natural gas from regions rich in gas resources to areas with high energy demand, fostering international cooperation and trade in the energy sector. The emergence of LNG as a prominent player in the global energy landscape is rooted in the need for cleaner and more sustainable energy alternatives. As the environmental impact of traditional fossil fuels, such as coal and oil, becomes increasingly apparent, there has been a global push to transition towards low-carbon and environmentally friendly energy sources. LNG has gained prominence as a cleaner alternative primarily due to its lower carbon intensity compared to other fossil fuels. When combusted, natural gas emits fewer pollutants and greenhouse gases, such as carbon dioxide (CO₂), sulfur dioxide (SO₂), and nitrogen oxides (NO_x), making it a more environmentally friendly option. This aligns with the global commitment to reducing carbon emissions and mitigating climate change.

Moreover, the flexibility and versatility of LNG contribute to its attractiveness. It can be utilized across various sectors, including power generation, industrial processes, and transportation. The adaptability of LNG as a fuel source positions it as a transitional energy solution, providing a bridge between traditional fossil fuels and a future powered by renewable energy. Several factors have propelled the adoption of LNG in the energy sector, marking its ascent as a key player in the transition to a more sustainable energy future: The foremost driver for the adoption of LNG is its comparatively lower environmental impact. As countries and industries strive to meet climate goals and reduce their carbon footprint, LNG serves as a cleaner-burning fuel, offering a pathway to achieve emission reduction targets. LNG plays a pivotal role in enhancing energy security by diversifying the sources of natural gas supply. Countries can reduce dependence on a single source or region, mitigating geopolitical risks and ensuring a more resilient energy infrastructure (Harrison, and Harrison, 1992; Parfomak, 2004).

Advancements in liquefaction and regasification technologies have significantly improved the efficiency and safety of LNG operations. These technological breakthroughs have lowered production costs, making LNG more economically viable and accessible to a broader range of consumers. The ability to transport LNG across long distances has facilitated the growth of a global LNG market. Infrastructure developments, including liquefaction plants, regasification terminals, and shipping facilities, have expanded, creating a robust and interconnected network for LNG trade. LNG has gained traction as a fuel for transportation, particularly in the maritime and heavy-duty vehicle sectors. The transition to LNG-powered vehicles contributes to

reducing emissions in the transportation sector, which is a significant source of carbon emissions.

In conclusion, the background on LNG reveals a multifaceted energy source that has emerged as a cornerstone in the global transition towards cleaner and more sustainable energy alternatives. Its definition and unique characteristics, coupled with the environmental considerations driving its adoption, showcase LNG's potential to play a pivotal role in addressing the challenges posed by climate change. As the world continues its quest for a more sustainable energy future, LNG stands as a key player, offering a bridge to cleaner energy while supporting the evolving needs of a growing and interconnected global community (Da Silva Esteves, and dos Reis Parise, 2016).

Objective of the Evaluation

The primary objective of this evaluation is to conduct a comprehensive and nuanced assessment of the carbon footprint associated with Liquefied Natural Gas (LNG). Understanding the environmental impact of LNG is crucial as the global community intensifies its efforts to combat climate change. The assessment delves deep into the entire lifecycle of LNG, meticulously scrutinizing each phase from extraction to combustion (Vanem, et al., 2008; Yao, et al., 2021). By conducting an exhaustive analysis, the study aims to provide stakeholders, policymakers, and the broader public with a clear and accurate understanding of the environmental implications of LNG utilization. The assessment begins with a meticulous examination of the extraction and production phase, considering processes such as exploration, drilling, and the extraction of natural gas. By quantifying methane emissions and evaluating flaring practices during extraction, the study seeks to quantify the initial environmental cost associated with LNG (Barnett, 2010).

A crucial facet of this evaluation is the comparative analysis of LNG's carbon footprint against that of other conventional fossil fuels, specifically coal and oil. This comparative approach provides valuable insights into the relative environmental performance of LNG in the context of broader energy sources (Shaton, et al., 2020; Brynolf, et al., 2014). Coal has long been a dominant source of energy but is notorious for its high carbon intensity and significant environmental impact. The evaluation will contrast LNG with coal, considering factors such as emissions during extraction, processing, transportation, and combustion. This comparative analysis will highlight the potential benefits of transitioning from coal to LNG in the pursuit of reduced carbon emissions and improved air quality (Laugen, 2013). Oil, another prevalent fossil fuel, is widely used in various sectors, including transportation and industrial processes. The assessment will compare the carbon footprints of LNG and oil, exploring emissions from extraction, refining, transportation, and combustion. Understanding the distinctions in environmental impact between LNG and oil is crucial for informed decision-making as industries consider cleaner energy alternatives (Sakmar, 2010).

A fundamental aspect of this evaluation is the holistic consideration of LNG's entire lifecycle. Recognizing that the carbon footprint of a fuel source extends beyond its combustion, the study meticulously examines each phase of LNG's journey. The energy-intensive process of liquefaction, where natural gas is transformed into LNG, requires scrutiny. Additionally, the emissions associated with transporting LNG via specialized vessels will be evaluated, considering the distances traveled and shipping routes. As LNG reaches its destination, the regasification process – converting LNG back into its gaseous form for utilization – will be

assessed for its energy requirements and associated emissions. The ultimate utilization of LNG involves combustion for various purposes, including power generation and industrial processes. The study will quantify the emissions during this phase, considering the efficiency of combustion technologies and the resulting environmental impact. By considering the entire lifecycle, the evaluation ensures a holistic understanding of LNG's carbon footprint, providing a comprehensive basis for decision-making in the transition to cleaner energy sources.

In conclusion, the objective of this evaluation is to go beyond a superficial analysis of LNG's environmental impact. Through a thorough examination of its carbon footprint, a comparative assessment with other fossil fuels, and an exploration of its entire lifecycle, the study aims to contribute valuable insights to the ongoing discourse on sustainable energy choices. As the world grapples with the imperative to reduce carbon emissions, understanding the intricacies of LNG's environmental profile becomes instrumental in charting a course towards a more sustainable and environmentally responsible energy future.

Methodology

The methodology employed in evaluating the carbon footprint of Liquefied Natural Gas (LNG) is rooted in a comprehensive lifecycle analysis framework (Koroneos, et al., 2004; AL-YAFEI, 2022). Recognizing that the environmental impact extends beyond the combustion phase, this framework encompasses the entire journey of LNG – from extraction to combustion (Pérez, et al., 2017). Each stage of the LNG lifecycle is scrutinized to quantify the greenhouse gas emissions, ensuring a holistic and accurate assessment of its environmental footprint. The evaluation initiates by assessing the environmental implications of extracting natural gas, including exploration, drilling, and extraction processes. The focus is on quantifying methane emissions and evaluating flaring practices, recognizing the significance of these factors in determining the initial carbon footprint of LNG.

The energy-intensive liquefaction process, where natural gas transforms into LNG, is a pivotal aspect of the analysis (Won, and Lee, 2017). Emissions related to the transportation of LNG via specialized vessels are also considered, accounting for distances traveled and shipping routes. As LNG reaches its destination, the regasification process – converting LNG back into its gaseous form (Gómez, et al. 2014; Stradioto, et al., 2015; Fahmy, et al., 2015) – is examined. This phase is evaluated for its energy requirements and the associated emissions, ensuring a comprehensive understanding of the environmental impact at the point of consumption. The ultimate utilization of LNG involves combustion for power generation, industrial processes, and transportation. The study quantifies emissions during this phase, considering the efficiency of combustion technologies and the resulting environmental impact.

The methodology relies on robust data collection from diverse and reliable sources to ensure accuracy and relevance. The following sources contribute to a comprehensive understanding of LNG's environmental impact: Data from industry reports, publications, and research conducted by reputable organizations in the energy sector provide insights into LNG production, transportation, and consumption patterns. Information from governmental bodies, such as the U.S. Energy Information Administration (EIA), international energy agencies, and environmental protection agencies, serves as a foundational source for statistics, regulations, and environmental impact assessments. Peer-reviewed scientific research articles and journals contribute to a nuanced understanding of the environmental aspects of LNG, including advancements in technology and best practices for emissions reduction. Sustainability reports

from LNG producers, shipping companies, and stakeholders in the supply chain offer valuable data on environmental practices, emissions reduction initiatives, and technological innovations. To provide meaningful insights into the environmental performance of LNG, the methodology incorporates a robust comparative analysis with other fossil fuels, specifically coal and oil. Metrics used for comparative analysis include: Quantifying the amount of carbon dioxide emitted per unit of energy produced allows for a direct comparison of carbon intensity between LNG, coal, and oil. This metric enables stakeholders to assess the relative environmental impact of each fuel source. The evaluation includes a detailed breakdown of greenhouse gas emissions, encompassing carbon dioxide (CO₂), methane (CH₄), sulfur dioxide (SO₂), and nitrogen oxides (NO_x). This comprehensive approach ensures that the analysis captures the diverse environmental implications associated with each fossil fuel. GWP metrics enable a comparison of the overall impact of different greenhouse gases on global warming over specific timeframes (Balcombe, et al., 2018; Rai, et al., 2022). Assessing GWP allows stakeholders to weigh the environmental consequences of each fossil fuel in a standardized manner. The efficiency of combustion technologies is considered to evaluate how effectively each fossil fuel converts into usable energy. Assessing energy efficiency provides insights into the overall sustainability and resource utilization of each fuel source. By employing these comparative analysis metrics, the methodology aims to offer a nuanced understanding of LNG's environmental footprint in relation to other fossil fuels. This approach ensures that decision-makers have the information needed to make informed choices in the pursuit of sustainable and low-carbon energy solutions (Lee, et al., 2022; Attah, and Bucknall, 2015).

In conclusion, the methodology adopted for evaluating LNG's carbon footprint is designed to navigate the complexity of its environmental impact comprehensively. By employing a lifecycle analysis framework, drawing from diverse and reliable data sources, and incorporating comparative analysis metrics, the study aims to provide stakeholders with a robust and nuanced understanding of LNG's role in the broader context of climate change mitigation and sustainable energy transitions.

Carbon Emissions in LNG Lifecycle

The extraction and production phase of Liquefied Natural Gas (LNG) begins with exploration and drilling processes (Tagliaferri, et al., 2017). During exploration, emissions are primarily associated with the use of machinery, transportation, and energy-intensive activities. Drilling operations contribute to carbon emissions through the use of fossil fuel-powered equipment, as well as indirect emissions from the extraction of raw materials for infrastructure. A critical environmental consideration in the extraction phase is methane emissions, a potent greenhouse gas. Methane, the primary component of natural gas, can escape during extraction, contributing to global warming. Additionally, flaring, the controlled burning of excess gas during extraction, releases carbon dioxide (CO₂) into the atmosphere (Jaramillo, et al., 2007; Al-Douri et al., 2022). Minimizing methane emissions and flaring practices is essential for mitigating the environmental impact of LNG at this initial stage.

The liquefaction phase involves cooling natural gas to extremely low temperatures, transforming it into LNG. This process is energy-intensive, primarily relying on electricity and, in some cases, natural gas for the required refrigeration. The carbon intensity of liquefaction is a crucial factor influencing the overall environmental footprint of LNG. Ongoing technological innovations play a pivotal role in reducing the carbon intensity of LNG liquefaction.

Advancements such as more efficient liquefaction technologies, optimized energy recovery systems, and the utilization of renewable energy sources contribute to lowering emissions during this phase. Continuous research and development in this area aim to enhance the sustainability of LNG production.

The shipping phase involves transporting LNG from production facilities to import terminals across the globe. The primary emissions during transportation are associated with the propulsion systems of LNG carriers (Barnett, 2010). These vessels typically use marine diesel engines or, increasingly, engines powered by boil-off gas from the LNG cargo. The type of fuel and engine efficiency significantly influence emissions during this phase. The distance traveled and shipping routes play a crucial role in determining emissions. Longer distances and complex routes may increase emissions due to extended travel times and potential delays in congested waterways. Optimization of shipping routes and the use of more fuel-efficient vessels contribute to reducing emissions during the transportation of LNG.

At the regasification terminal, LNG undergoes a process to convert it back into its gaseous form for distribution and utilization. The energy requirements for regasification involve heating the LNG, typically accomplished through the use of natural gas or electricity. The choice of energy source significantly influences the carbon intensity of this phase. Regasification facilities may contribute to emissions through the combustion of natural gas or the consumption of electricity (Hwang, et al., 2019). Evaluating the environmental impact of regasification involves assessing the emissions associated with the energy sources used and implementing measures to enhance efficiency and reduce emissions.

The ultimate utilization of LNG occurs during the combustion phase, where it is burned for power generation, industrial processes, or transportation (Hardisty, et al., 2012). While LNG combustion produces fewer carbon emissions compared to coal and oil, it is not entirely carbon-neutral. The efficiency of combustion technologies and the presence of carbon capture and storage (CCS) systems influence the amount of CO₂ released during this phase. The environmental impact of the combustion phase is further understood by comparing the carbon emissions of LNG with those of other fossil fuels like coal and oil. Such a comparative analysis provides insights into the relative advantages of LNG in terms of lower carbon intensity and reduced emissions, contributing to informed decision-making in energy transitions (Ozawa, et al., 2019; Abrahams, et al., 2015).

In conclusion, assessing carbon emissions across the lifecycle of LNG is essential for understanding its environmental footprint comprehensively. From extraction to combustion, each phase presents opportunities for emissions reduction through technological innovations, energy efficiency improvements, and the adoption of sustainable practices. As the global community seeks cleaner energy alternatives, addressing emissions at each stage of the LNG lifecycle becomes integral to realizing a more sustainable and environmentally responsible energy future.

Comparative Analysis with Other Fossil Fuels

As the world grapples with the imperative to transition to cleaner energy sources, conducting a comparative analysis of Liquefied Natural Gas (LNG) with other fossil fuels, namely coal and oil, is essential for informed decision-making. Each fossil fuel presents distinct environmental implications across various phases of its lifecycle. Coal, a historically dominant source of energy, is notorious for its high carbon intensity and adverse environmental impact (Bengtsson,

et al., 2011; Bilgili, 2021). The extraction and combustion of coal release substantial amounts of carbon dioxide (CO₂), contributing significantly to the greenhouse effect and climate change. The environmental footprint of coal extends beyond CO₂ emissions, encompassing pollutants such as sulfur dioxide (SO₂) and nitrogen oxides (NO_x), which lead to air pollution and acid rain. The global warming potential (GWP) of coal is notably high due to its carbon-intensive nature. The release of large quantities of CO₂ during combustion contributes to the long-term accumulation of greenhouse gases in the atmosphere, amplifying the warming effect. The GWP of coal underscores its role as a major contributor to climate change, emphasizing the urgent need to transition to cleaner energy alternatives.

Oil, a versatile fossil fuel used in various sectors, including transportation and industry, exhibits distinct carbon emissions patterns throughout its lifecycle. The extraction and refining of oil involve energy-intensive processes, leading to CO₂ emissions. Additionally, oil extraction can result in environmental hazards, such as oil spills, further exacerbating its environmental impact. Combusting oil for energy generation releases CO₂ and other pollutants into the atmosphere. While oil combustion is more carbon-intensive than natural gas, it is often considered cleaner than coal. However, the environmental consequences extend to air quality degradation, contributing to respiratory issues and smog formation. The combustion of oil in transportation also produces nitrogen oxides and particulate matter, contributing to environmental and public health concerns.

LNG exhibits a lower carbon intensity compared to coal and oil during combustion (Bao, et al., 2019). The combustion of natural gas releases fewer CO₂ emissions, making it a more environmentally friendly option. This characteristic positions LNG as a transitional energy source, offering a cleaner alternative to conventional fossil fuels while facilitating the integration of renewable energy solutions. LNG combustion produces fewer pollutants than coal and oil, contributing to improved air quality. The lower emissions of sulfur dioxide, nitrogen oxides, and particulate matter make LNG a preferable option for addressing air pollution concerns, especially in urban areas.

While LNG combustion is relatively cleaner, attention must be given to the potential release of methane during the extraction and production phases. Methane, a potent greenhouse gas, can contribute to global warming. However, ongoing efforts focus on minimizing methane emissions through technological innovations and best practices in the natural gas industry. Metrics such as carbon intensity, global warming potential, and emissions per unit of energy produced facilitate a quantitative comparative analysis. These metrics enable stakeholders to assess the relative environmental performance of LNG, coal, and oil, providing a foundation for strategic decision-making in the pursuit of sustainable and low-carbon energy solutions.

In conclusion, the comparative analysis with other fossil fuels underscores the environmental advantages of LNG, particularly in terms of lower carbon intensity and reduced air pollutant emissions. While recognizing the need for further advancements in methane emission reduction, LNG emerges as a transitional energy source that aligns with global efforts to mitigate climate change and improve overall environmental sustainability. As societies navigate the complexities of energy transitions, informed decisions based on comparative environmental assessments play a pivotal role in shaping a more sustainable and resilient future (Jaramillo, et al., 2007).

Technological Advancements and Innovations

As the global community intensifies efforts to address climate change and transition towards cleaner energy sources, technological advancements and innovations play a pivotal role in shaping the environmental footprint of Liquefied Natural Gas (LNG) (Litvinenko, 2020). A comprehensive assessment of the impact of these advancements encompasses carbon intensity reduction, overall sustainability improvements, and the promising future prospects for technological developments. Technological innovations in liquefaction processes have significantly contributed to reducing the carbon intensity of LNG. Advanced liquefaction technologies, such as optimized refrigeration systems and efficient energy recovery processes, enhance the overall efficiency of the conversion of natural gas into LNG. These innovations result in lower energy consumption during liquefaction, consequently reducing the associated greenhouse gas emissions.

The integration of renewable energy sources in LNG production facilities represents a noteworthy advancement. Using renewable energy, such as solar or wind power, during the liquefaction phase contributes to decarbonizing the process. This approach addresses the carbon intensity of LNG production by minimizing reliance on conventional fossil fuels for energy needs. The application of Carbon Capture and Storage (CCS) technologies in the natural gas industry holds promise for further reducing carbon emissions associated with LNG. CCS involves capturing CO₂ emissions generated during the combustion of natural gas and transporting them to storage sites, preventing their release into the atmosphere. Integrating CCS into LNG facilities mitigates the environmental impact by actively managing and reducing carbon emissions (Huber, 2004).

Addressing methane emissions, a potent greenhouse gas, is a crucial aspect of enhancing the overall sustainability of LNG. Ongoing technological advancements focus on minimizing fugitive emissions during the extraction and production phases. Improved leak detection technologies, better operational practices, and the deployment of advanced equipment contribute to reducing methane emissions, ensuring a more sustainable profile for LNG. Technological innovations in LNG transportation have a direct impact on the overall sustainability of the fuel. The development of more energy-efficient LNG carriers and the optimization of shipping routes contribute to lowering emissions during the transportation phase. Enhanced vessel design, improved engine efficiency, and the use of boil-off gas for propulsion showcase the industry's commitment to sustainable LNG transport. Advances in regasification technologies further contribute to the overall sustainability of LNG. Energy-efficient regasification processes, coupled with the utilization of renewable energy for regasification facilities, reduce the carbon footprint associated with converting LNG back into its gaseous form (Adekoya et al., 2024). These innovations enhance the efficiency of the entire LNG supply chain, from production to consumption.

Future technological developments in LNG production are anticipated to focus on next-generation liquefaction technologies. These may include novel methods with enhanced energy efficiency, reduced environmental impact, and improved scalability. Research and development efforts aim to identify breakthrough technologies that can revolutionize the liquefaction process, making it even more sustainable. Continued research and implementation of advanced strategies for reducing methane emissions are expected to be at the forefront of technological developments. Innovations in leak detection, monitoring systems, and best practices during

natural gas extraction aim to further minimize the release of methane, contributing to the environmental sustainability of LNG.

The integration of green hydrogen, produced using renewable energy sources, into the LNG production process is a potential avenue for future developments. Green hydrogen can be used in the liquefaction phase, further reducing the carbon intensity of LNG. This approach aligns with the broader trend of integrating hydrogen as a clean energy carrier in the energy transition. The evolution of carbon capture technologies continues to be a focus area for future prospects in LNG. Advanced carbon capture techniques with higher efficiency and lower costs could become integral components of LNG facilities, ensuring that a significant portion of CO₂ emissions is captured and stored, contributing to the industry's commitment to sustainability.

In conclusion, technological advancements and innovations are shaping the environmental landscape of LNG, steering it towards greater sustainability. The impact on carbon intensity, improvements in overall sustainability, and the anticipation of future technological developments position LNG as a dynamic and evolving energy source in the global quest for cleaner and more sustainable energy solutions. As these advancements continue to unfold, the LNG industry remains at the forefront of the energy transition, contributing to a more sustainable and environmentally responsible future.

Regional and Geopolitical Factors

The carbon footprint of Liquefied Natural Gas (LNG) is intricately connected to regional dynamics and geopolitical influences, reflecting the diverse sourcing, consumption patterns, and production practices across different parts of the world. Understanding how these factors interact is crucial for evaluating the environmental impact of LNG in comparison to other fossil fuels and for shaping effective global climate change mitigation strategies. The Asia-Pacific region stands out as a major player in both LNG consumption and sourcing. Countries like Japan, China, and South Korea are prominent importers, relying on LNG to meet their energy needs. This high demand is often attributed to the region's economic growth, industrialization, and efforts to diversify energy sources (Paltsev, 2015).

The sourcing of LNG in the Asia-Pacific region involves significant trade relationships with major exporters, contributing to complex regional dynamics. Europe has witnessed a growing role for LNG in recent years, driven by efforts to enhance energy security, diversify supplies, and reduce dependence on traditional fossil fuels. The region's commitment to transitioning towards cleaner energy sources positions LNG as a transitional fuel. Europe's LNG sourcing is influenced by trade relationships with diverse suppliers, contributing to a mosaic of regional dynamics in the sourcing and consumption of LNG. The surge in LNG exports from North America, particularly the United States, has transformed global LNG dynamics. The shale gas revolution in the U.S. has made it a significant exporter, altering traditional trade patterns. North America's emergence as an exporter has geopolitical implications, influencing global LNG pricing and trade flows (Michail, and Melas, 2022).

Geopolitical dynamics are pronounced in the LNG sector, with certain countries emerging as key exporters. Qatar, the United States, Australia, and Russia are among the major players shaping global LNG production and trade. The geopolitical influence of these exporting nations extends to trade relationships, market dynamics, and the overall geopolitics of energy. Geopolitical considerations play a role in the formation of strategic alliances and agreements in the LNG sector. Bilateral and multilateral agreements between exporting and importing nations

often involve geopolitical considerations, shaping the terms of trade, pricing mechanisms, and long-term energy security strategies. Geopolitical risks, such as political instability, conflicts, and trade disputes, can impact LNG supply chains. LNG infrastructure, production facilities, and transportation routes may be vulnerable to geopolitical disruptions, affecting the reliability and stability of global LNG trade.

The regional and geopolitical dynamics of LNG have implications for global climate change mitigation strategies. LNG is often positioned as a transitional fuel, offering a cleaner alternative to coal and oil. Its role in transition strategies varies across regions, reflecting the diverse energy landscapes and policy priorities of different countries. Assessing the carbon footprint of LNG in comparison to other fossil fuels involves considering regional and geopolitical factors. While LNG combustion produces fewer carbon emissions compared to coal and oil, regional variations in sourcing and production practices, as well as geopolitical influences, contribute to nuanced carbon footprint comparisons.

The global nature of the LNG trade requires international cooperation to address environmental challenges. Collaborative efforts, such as emissions reduction initiatives, technology sharing, and best practices exchange, are essential for minimizing the overall carbon footprint of LNG and fostering sustainable global energy systems. Climate change mitigation strategies increasingly emphasize the integration of renewable energy sources. While LNG is considered a cleaner option, future strategies may involve a shift towards greater reliance on renewable energy in LNG production, reducing reliance on fossil fuels and further minimizing environmental impact.

In conclusion, the evaluation of the carbon footprint of LNG in the context of regional and geopolitical factors provides a holistic understanding of its environmental implications. The unique sourcing and consumption patterns, coupled with geopolitical influences, contribute to the complex dynamics of the global LNG trade. Recognizing these factors is essential for designing effective climate change mitigation strategies that balance energy security, economic considerations, and environmental sustainability on a global scale. As the world seeks to address climate challenges, a comprehensive approach that considers the diverse influences on LNG production and trade will be crucial for achieving sustainable and low-carbon energy transitions (Stern, 2006; Medlock, et al., 2014).

Conclusion

The comprehensive evaluation of Liquefied Natural Gas (LNG) and its carbon footprint vis-à-vis other fossil fuels reveals a nuanced environmental landscape. Through a meticulous examination of regional dynamics, geopolitical influences, and technological advancements, key findings have emerged. LNG exhibits a lower carbon intensity during combustion compared to coal and oil, positioning it as a transitional fuel in the global energy transition. The evaluation highlights the significance of considering the entire lifecycle of LNG, from extraction to combustion, and underscores the role of regional and geopolitical factors in shaping its environmental impact.

The implications for the role of LNG in addressing climate change are multi-faceted. While LNG offers a cleaner alternative to traditional fossil fuels, its environmental impact is contingent on various factors. Geopolitical influences, regional sourcing patterns, and technological advancements play crucial roles in shaping the overall sustainability of LNG. The findings underscore the importance of positioning LNG as part of a broader transition strategy

rather than a standalone solution. Recognizing its role as a bridge fuel in the transition towards a low-carbon future allows stakeholders to leverage its benefits while concurrently accelerating the integration of renewable energy sources. Stakeholders in the LNG sector should prioritize investments in technological innovations that enhance the environmental sustainability of LNG. This includes further advancements in efficient liquefaction processes, renewable energy integration, and carbon capture and storage technologies. Policymakers can incentivize research and development initiatives aimed at reducing the carbon intensity of LNG throughout its lifecycle.

Robust monitoring and regulation are essential components of mitigating the environmental impact of LNG. Stakeholders and policymakers should collaborate to establish comprehensive regulatory frameworks that address methane emissions, promote best practices in extraction and production, and ensure adherence to environmental standards. Regular monitoring and reporting mechanisms can enhance transparency and accountability in the industry. Given the global nature of the LNG trade, international collaboration is paramount. Policymakers should facilitate global initiatives for emission reductions, technology sharing, and the adoption of best practices. Multilateral agreements and forums can provide platforms for knowledge exchange and coordinated efforts towards a more sustainable and low-carbon LNG industry.

To further enhance the role of LNG in addressing climate change, stakeholders should explore opportunities to integrate renewable energy sources into LNG production and consumption processes. Policymakers can incentivize the use of green hydrogen and other sustainable practices, aligning the LNG industry with broader clean energy objectives. Establishing transparent carbon accounting mechanisms is crucial for accurate carbon footprint assessments. Stakeholders and policymakers should work collaboratively to develop standardized methodologies for carbon accounting across the LNG supply chain. This transparency will enable informed decision-making and facilitate comparisons with other energy sources.

Policymakers and stakeholders can contribute to the sustainability of LNG by investing in renewable infrastructure. This includes the development of renewable energy-powered liquefaction facilities, energy-efficient transportation, and regasification processes. Supporting the growth of renewable infrastructure aligns with long-term climate goals and facilitates a smoother transition to a low-carbon energy landscape. In conclusion, the evaluation of LNG and its carbon footprint underscores the complexities and opportunities inherent in the global energy transition. As stakeholders and policymakers navigate the challenges posed by climate change, strategic investments, transparent regulations, and global collaboration will be instrumental in ensuring that LNG serves as a responsible and sustainable energy source. By embracing a holistic approach and implementing the recommended strategies, the LNG industry can contribute significantly to global efforts in mitigating climate change while meeting the world's growing energy demands.

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