



(REVIEW ARTICLE)



LNG as a bridge fuel in the transition to renewable energy: A global perspective

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Abstract

The global energy landscape stands at the precipice of transformation, with a growing consensus on the imperative to shift towards sustainable and renewable sources. Amidst this transition, Liquefied Natural Gas (LNG) emerges as a pivotal bridge fuel, strategically positioned to facilitate the journey towards renewable energy. This review encapsulates the essence of the comprehensive review, delving into the global perspective on LNG's role as a bridge fuel in the renewable energy transition. The narrative unfolds with a contextualization of the pressing need for a renewable energy transition, acknowledging the escalating environmental concerns and the imperative to reduce carbon footprints. It then seamlessly transitions to the concept of LNG as a bridge fuel, elucidating its capacity to serve as a cleaner alternative to traditional fossil fuels and its role in mitigating the challenges associated with intermittent renewable energy sources. Examining LNG's significance on a global scale, the review navigates through key aspects. It scrutinizes the environmental considerations and carbon reduction goals that position LNG as a pragmatic choice in the decarbonization journey. The analysis extends to policy factors influencing LNG demand, unraveling the intricate tapestry of governmental initiatives supporting its adoption and the dynamic interplay with renewable energy policies. Economic drivers take center stage in the exploration of LNG's role as a bridge fuel. The review investigates the cost competitiveness, market dynamics, and the industrial demand propelling its consumption. The comprehensive examination encompasses the expansion of global LNG production capacity, featuring key exporting nations and the technological innovations transforming LNG production processes. Regional dynamics further enrich the narrative, providing insights into LNG's impact on major economies across Asia-Pacific, Europe, and North America. The review culminates in a nuanced exploration of the geopolitical implications surrounding LNG trade, emphasizing its role in geopolitical events, trade agreements, and potential risks for stakeholders. In essence, this review serves as a guide to stakeholders, policymakers, and industry players navigating the complex interplay between LNG and renewable energy in the global quest for a sustainable energy future.

Keywords: LNG; Bridge Fuel; Transition; Renewable Energy; Review

1. Introduction

The world is at the crossroads of a transformative journey in the energy landscape, marked by an escalating global consensus on the imperative to shift towards sustainable and renewable energy sources. The urgency is fueled by environmental concerns, climate change realities, and a collective commitment to reduce carbon footprints. As nations grapple with the challenges of embracing renewables at scale, a critical juncture emerges in the form of a transitional fuel poised to bridge the gap between the present and the renewable energy future.

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In the pursuit of a cleaner and more sustainable energy future, the transition from traditional fossil fuels to renewables presents a formidable challenge. The intermittent nature of renewable energy sources, coupled with the existing infrastructure and economic dependencies on conventional fuels, necessitates a pragmatic and flexible approach. Recognizing this need for an intermediary step becomes paramount, calling for a fuel that can serve as a bridge, facilitating a smoother transition without compromising environmental goals.

Liquefied Natural Gas (LNG) emerges as a key player in this transitional phase, strategically positioned to navigate the complexities of the global move towards renewable energy (Mokhatab, et al., 2013; Lim, et al., 2013). This section of the review seeks to elucidate the role of LNG as a bridge fuel. LNG, with its cleaner combustion profile and relative abundance, presents itself as an intermediary solution, offering a stepping stone towards a future dominated by renewable energy. It balances the immediate need for energy security, economic stability, and reduced emissions, aligning with the evolving goals of sustainability and climate resilience.

As we delve into the intricate dynamics of LNG's role in this transition, the subsequent sections will unravel its environmental impact, policy implications, economic drivers, and geopolitical significance, providing a holistic view of LNG as a bridge fuel in the global pursuit of a renewable energy future (Animah, and Shafiee, 2020; Gas, 2008).

2. Environmental Considerations and Carbon Reduction Goals

The global imperative to address climate change has propelled the exploration of cleaner energy alternatives, and in this landscape, Liquefied Natural Gas (LNG) emerges as a bridge fuel, strategically positioned to navigate the complexities of the transition to renewable energy (Diabat, and Al-Salem, 2015; Honegger, et al., 2021). This section delves into the environmental considerations and carbon reduction goals that underscore LNG's significance in the global pursuit of a greener future (Wang, 2023; Mahapatra, et al., 2021).

LNG, in its liquefied form, offers a cleaner alternative to traditional fossil fuels, particularly coal and oil. When combusted, natural gas produces fewer greenhouse gas emissions, notably lower levels of carbon dioxide (CO₂) and pollutants such as sulfur dioxide and nitrogen oxides (Chaabane et al., 2011). This cleaner combustion profile aligns with the escalating global awareness of the need to reduce air pollution and mitigate the impacts of climate change. As the world transitions away from more carbon-intensive energy sources, the cleaner nature of LNG positions it as a crucial intermediary in meeting energy demands while concurrently reducing the environmental footprint (Honegger, et al., 2021; Wang, et al., 2023).

Governments and international bodies have set ambitious carbon reduction goals as part of broader initiatives to combat climate change (Mahapatra et al., 2021). LNG, as a bridge fuel, plays a pivotal role in achieving these targets. Its cleaner combustion contributes to immediate reductions in carbon emissions compared to traditional fossil fuels, aligning with the carbon reduction aspirations outlined in international agreements such as the Paris Agreement. LNG's role extends beyond its immediate environmental impact; it serves as a catalyst in fostering the development and integration of renewable energy sources by providing a reliable and lower-emission alternative during the transitional phase (Stern, 2022; Ahmed, et al., 2023; Prontera, 2017).

One of the inherent challenges of renewable energy sources, such as solar and wind, is their intermittency. LNG addresses this challenge by offering a reliable and flexible energy source that can complement intermittent renewables. LNG-fired power plants can quickly respond to fluctuations in renewable energy generation, providing a stable and continuous energy supply. This capacity to act as a dependable backup mitigates the intermittency challenges associated with renewables, ensuring a steady energy flow and enhancing the overall reliability of the energy grid.

In essence, the examination of LNG as a cleaner alternative, its contribution to achieving carbon reduction goals, and its role in addressing the challenges of intermittent renewables collectively position LNG as a vital player in the global energy transition. As we progress towards a sustainable future, understanding these environmental considerations becomes imperative, guiding policymakers and industry stakeholders in making informed decisions that balance immediate energy needs with long-term environmental objectives.

3. Policy Factors Influencing LNG Demand

As the world steers towards a renewable energy future, Liquefied Natural Gas (LNG) emerges as a pivotal bridge fuel, strategically positioned to play a transformative role (Foo, 2015; Wang, and Wang, 2021). This section delves into the intricate interplay between policy factors and LNG demand, shedding light on government initiatives, the impact of

renewable energy policies, and the dynamic landscape that shapes the utilization of LNG in the global transition to cleaner energy.

Governments worldwide are championing the adoption of LNG as part of broader energy strategies. Many nations are investing in infrastructure development, incentivizing the construction of LNG terminals, and fostering partnerships to secure a stable supply chain. Financial incentives, tax breaks, and regulatory support are becoming commonplace, encouraging industries to transition towards LNG-based solutions. Furthermore, governments are recognizing the environmental benefits of LNG, promoting its use in transportation and industries as a cleaner alternative to traditional fossil fuels (Aboltinš, 2021; Shaikh, et al., 2016). These initiatives not only bolster the economic viability of LNG but also position it as a crucial component in achieving national energy security objectives (Wan, et al., 2019; Geng, et al., 2017).

The global push towards renewable energy sources introduces a new dimension to energy policies. Governments are implementing ambitious renewable energy targets, often accompanied by supportive policies that promote the integration of renewables into the energy mix (Xia, 2017). While this shift is commendable for environmental sustainability, it introduces challenges related to the intermittency of renewable sources. In this context, LNG assumes a complementary role, offering a flexible and reliable energy source that aligns with the goals of a cleaner energy mix. Policies that encourage a balanced approach, acknowledging the role of LNG in supporting renewable energy integration, become pivotal in driving LNG demand (Rogers, 2015; Yusuf, et al., 2023).

The landscape of energy policies is dynamic, and the interplay between governmental strategies and LNG demand is nuanced. As governments prioritize reducing carbon emissions and diversifying their energy portfolios, the demand for LNG evolves. Striking a delicate balance between promoting renewables and acknowledging the immediate need for a transitional fuel, governments are shaping policies that foster a harmonious coexistence of LNG and renewables. The dynamic nature of this interplay is evident in instances where LNG is positioned not just as a stopgap but as a strategic component, enhancing energy security and contributing to a more sustainable energy future.

In conclusion, the trajectory of LNG demand is intricately linked to the policies enacted by governments globally. The support and incentives provided, the alignment with renewable energy goals, and the adaptability of policies to the evolving energy landscape collectively influence the demand for LNG. Understanding this dynamic interplay is essential for policymakers, industry stakeholders, and environmental advocates as they collaboratively navigate the complex path towards a cleaner and more sustainable energy future.

4. Economic Drivers Shaping Global LNG Consumption

As Liquefied Natural Gas (LNG) assumes a central role as a bridge fuel in the transition to renewable energy, its consumption is significantly influenced by a complex web of economic drivers. This section delves into the economic dynamics shaping the global consumption of LNG, analyzing price trends, industrial demand, and the cost competitiveness that positions LNG as a strategic player in the evolving energy landscape.

The economic viability of LNG is closely linked to its price trends and the broader market dynamics. Historically, LNG prices have exhibited volatility, influenced by factors such as supply-demand imbalances, geopolitical events, and changes in production capacities. A comprehensive analysis of these price trends is essential for understanding the cost dynamics of LNG and its attractiveness in comparison to other fuels. Additionally, market dynamics, including the growth of LNG trading hubs and the emergence of spot markets, contribute to the economic considerations that drive global LNG consumption. The adaptability of LNG pricing strategies to these dynamic market conditions plays a crucial role in its sustained economic appeal.

The economic growth of nations and the industrial sector's demand for energy are pivotal factors influencing global LNG consumption. As economies expand, so does the need for reliable and scalable energy sources. LNG, with its flexibility and relatively lower environmental impact, becomes an attractive solution for meeting the growing energy demands of industrial sectors such as manufacturing, power generation, and transportation. The economic synergies between LNG consumption and industrial growth underscore its role as a catalyst for economic development, creating a mutually reinforcing relationship that supports the transition to renewable energy (Pavlenko, et al., 2020).

A key driver behind the increasing adoption of LNG is its cost competitiveness relative to traditional fossil fuels. The economic feasibility of LNG becomes particularly evident when compared to coal and oil. The cleaner combustion profile of LNG (Blanton, and Mosis, 2021; Balcombe, et al., 2019) translates into fewer emissions, aligning with global efforts to reduce environmental impact. This environmental advantage, combined with its cost-effectiveness, positions LNG as a preferred choice for industries seeking to balance economic considerations with sustainability goals. The cost

competitiveness of LNG not only impacts its consumption in energy-intensive industries but also influences the decisions of policymakers and investors looking for economically viable pathways in the transition to renewable energy (Adekoya, et al., 2024).

In conclusion, the economic drivers shaping global LNG consumption are multifaceted, encompassing price trends, industrial demand, and the cost competitiveness of LNG in comparison to traditional fuels. The economic growth of nations, coupled with the expanding needs of industries, propels the demand for this versatile bridge fuel. As the world navigates the intricate path towards renewable energy, understanding and leveraging these economic drivers are critical for optimizing the role of LNG in the evolving energy landscape.

5. Expansion of Global LNG Production Capacity

As the world undergoes a paradigm shift towards renewable energy, Liquefied Natural Gas (LNG) stands as a linchpin in the transitional phase, ensuring energy stability and security. This section delves into the expansion of global LNG production capacity (Gałczyński, et al., 2017; Zou, et al., 2022), exploring key exporting nations, technological advancements, and the pivotal role of LNG in maintaining global energy stability.

Several nations play a central role in the global LNG market, serving as major exporters and contributing significantly to the expansion of LNG production capacity. Among these key players, Qatar consistently ranks as the world's leading LNG exporter, boasting substantial reserves and advanced liquefaction infrastructure. Australia follows closely, capitalizing on its abundant natural gas resources and robust export infrastructure. The United States has emerged as a formidable contender, propelled by the shale gas revolution and ongoing investments in LNG terminals. Other notable contributors include Russia, Malaysia, and Indonesia. This diverse group of exporting nations collectively forms the backbone of global LNG supply, meeting the burgeoning demand for this versatile fuel (Merkulov, et al., 2020; Nikhalat-Jahromi, et al., 2017).

The expansion of global LNG production capacity is intricately linked to technological advancements that enhance the efficiency and viability of LNG production processes. Traditional liquefaction methods involve cooling natural gas to extremely low temperatures, transforming it into a liquid state for easier storage and transportation. Recent innovations have focused on optimizing this liquefaction process, reducing energy consumption, and improving overall plant efficiency. Modular and floating LNG facilities represent cutting-edge developments, offering greater flexibility and accessibility to remote gas reserves. Advancements in cryogenic technologies and liquefaction plant designs contribute to the scalability of LNG production, allowing for tailored solutions that align with the evolving needs of the global energy landscape (Vazhenina, 2018).

The expansion of global LNG production capacity is not merely a matter of meeting current demand but is intricately tied to ensuring global energy stability and security. LNG's versatility enables its use in various sectors, including power generation, transportation, and industries, contributing to a diversified and resilient energy portfolio. As a bridge fuel, LNG provides a reliable source of energy during the transition to renewable sources, offering a stable supply that complements intermittent renewables. The ability to transport LNG globally through advanced shipping infrastructure further enhances its role in addressing regional energy deficits and promoting energy security. In times of geopolitical uncertainties or disruptions in traditional energy supply chains, the widespread availability of LNG offers a strategic buffer, mitigating risks and enhancing the resilience of the global energy system (Du, and Paltsev, 2014).

In conclusion, the expansion of global LNG production capacity is a multifaceted process driven by key exporting nations, technological innovations, and the overarching goal of ensuring global energy stability and security. As the world charts its course towards a renewable energy future, the strategic positioning of LNG as a transitional fuel is pivotal, providing a reliable and flexible energy solution that underpins the dynamic and evolving energy landscape.

6. Regional Dynamics

In the global pursuit of a transition to renewable energy, Liquefied Natural Gas (LNG) emerges as a crucial bridge fuel, with regional dynamics shaping its role and impact. This section explores the distinctive features and trends in the Asia-Pacific, Europe, and North America, reflecting the diverse landscape of LNG as a bridge fuel in the transition to renewable energy (Kovacevic, 2017; Winter, et al., 2018). The Asia-Pacific region stands as a powerhouse in the global LNG landscape, driven by the increasing demand from major economies such as China, Japan, and South Korea. Rapid industrialization, coupled with policies promoting cleaner energy sources, has fueled a surge in LNG consumption. China, in particular, has demonstrated a robust appetite for LNG as it strives to meet growing energy needs while

reducing carbon emissions. The region's commitment to environmental sustainability and the transition to renewable energy positions LNG as a critical component in the energy mix.

Asia-Pacific's LNG landscape is characterized by significant infrastructure developments, including the construction of new LNG terminals and pipelines. These developments facilitate the efficient distribution and utilization of LNG across the region. Furthermore, regional LNG trends showcase the evolution of pricing mechanisms, with the emergence of spot markets and flexible contracts. The Asia-Pacific region, being a key driver of global LNG demand, plays a pivotal role in shaping the future trajectory of LNG as a bridge fuel. Europe, with its commitment to reducing carbon emissions and ensuring energy security, has increasingly embraced LNG. LNG plays a strategic role in diversifying Europe's energy sources and enhancing energy security by reducing dependence on traditional suppliers. The flexibility of LNG allows European nations to adapt to changing energy dynamics, contributing to a more resilient and sustainable energy infrastructure.

Europe's LNG market is influenced by stringent environmental regulations and a dynamic regulatory framework (Christofilos, 2023; Stern, 2006). The region emphasizes the development of a competitive and transparent LNG market, fostering innovation and investment. Market dynamics in Europe reflect a growing interest in small-scale LNG applications, such as LNG bunkering for maritime transport. These initiatives align with the broader goal of transitioning to renewable energy while strategically utilizing LNG as a bridge fuel. North America, particularly the United States, has witnessed a transformative impact on LNG dynamics due to the shale gas revolution. Abundant shale gas reserves have positioned the U.S. as a major LNG exporter. The flexibility of shale gas extraction and LNG production has contributed to North America's role in meeting global LNG demand, especially from Asia. This evolution highlights the interconnected nature of global LNG trade and the strategic role of North America in the transition to renewable energy (Zyuzev, and Ayed, 2008).

Market trends in North America reflect a dynamic LNG landscape characterized by expanding liquefaction capacities and evolving export infrastructure. The region's commitment to innovation in LNG technologies, including modular and floating LNG facilities, showcases a proactive approach to meeting global demand. Developments in the North American LNG sector contribute not only to regional economic growth but also to the global sustainability agenda. In conclusion, the regional dynamics of LNG in the Asia-Pacific, Europe, and North America underscore the varied roles and contributions of LNG as a bridge fuel in the transition to renewable energy. While Asia-Pacific drives demand, Europe emphasizes energy security through LNG, and North America emerges as a significant player in the global LNG trade. These regional nuances collectively shape the evolving narrative of LNG in a renewable energy future.

7. Geopolitical Implications on LNG Trade

In the evolving landscape of global energy, Liquefied Natural Gas (LNG) emerges not only as a bridge fuel but also as a geopolitical player, influencing and being influenced by geopolitical events, trade agreements, and associated risks (Michail, and Melas, 2022; Snijder, 2008). This section delves into the geopolitical implications on LNG trade as the world navigates the transition to renewable energy. Recent geopolitical events have significantly impacted LNG markets, shaping the dynamics of supply and demand. One notable event is the geopolitical tension in the Middle East, a region crucial to global LNG trade. The geopolitical instability in traditional LNG exporting nations has the potential to disrupt supply chains, leading to uncertainties in the market. Additionally, the global response to energy security concerns in the wake of geopolitical events influences strategic decisions by both LNG-producing and -consuming nations (Medlock, et al., 2014; Salameh, and Chedid, 2020).

The emergence of new geopolitical players also adds complexity to the LNG trade. The Arctic region, rich in natural gas reserves, has become a focal point for geopolitical discussions. The opening of Arctic shipping routes due to melting ice presents opportunities for LNG trade but also raises geopolitical considerations related to territorial claims and environmental concerns. Analyzing and understanding these geopolitical events is crucial for stakeholders in the LNG trade to navigate potential disruptions and seize opportunities (Karachalios, 2021; Stähr, et al., 2015; Meza, and Koç, 2021; Hryniewiecki, and Giordano, 2013).

Trade agreements play a pivotal role in shaping the landscape of LNG trade, affecting the flow of liquefied natural gas across borders. The United States, for instance, has actively engaged in LNG trade agreements, fostering relationships with key importing nations. Bilateral and multilateral agreements not only facilitate the flow of LNG but also strengthen geopolitical alliances. The geopolitical dimension of trade agreements is particularly evident in the context of LNG, where nations strategically align their energy interests, fostering economic cooperation and geopolitical stability. The influence of trade agreements extends beyond the economic realm. It is intertwined with geopolitical considerations, where LNG becomes a tool for diplomatic leverage. Nations engaging in LNG trade agreements aim not only to secure

reliable energy sources but also to strengthen geopolitical ties, creating a complex interplay between economic interests and geopolitical strategies. Assessing geopolitical risks is imperative for LNG stakeholders to anticipate potential consequences and devise risk mitigation strategies. Geopolitical risks include not only direct threats to the physical infrastructure of LNG facilities but also disruptions to supply chains due to geopolitical events. For example, tensions between major LNG-producing and -consuming nations can result in policy changes, affecting the terms and conditions of LNG trade (Wood, 2012).

Navigating geopolitical risks requires a comprehensive understanding of the geopolitical landscape, including factors such as political stability, regulatory frameworks, and regional conflicts. LNG stakeholders must monitor geopolitical developments, anticipate potential risks, and develop contingency plans to ensure the resilience of the LNG supply chain.

In conclusion, the geopolitical implications on LNG trade in the transition to renewable energy are multifaceted, encompassing recent geopolitical events, the influence of trade agreements, and the assessment of geopolitical risks. As the global energy landscape evolves, stakeholders in the LNG trade must navigate geopolitical complexities to ensure the stability and sustainability of LNG as a bridge fuel. Geopolitical considerations will continue to shape the future of LNG trade, highlighting the need for a nuanced and adaptive approach in the dynamic intersection of energy and geopolitics.

8. Conclusion

As the global energy landscape undergoes a transformative shift towards renewable sources, Liquefied Natural Gas (LNG) emerges as a crucial bridge fuel, playing a pivotal role in the intricate dance between traditional energy and the promise of renewables. This conclusion synthesizes the multifaceted role of LNG, reflects on its implications for the global energy panorama, and contemplates the future prospects and challenges inherent in the transition to renewable energy.

LNG, with its cleaner burning properties and flexibility, has assumed the role of a bridge fuel, facilitating the transition from conventional fossil fuels to renewable energy sources. Its versatility allows nations to address immediate energy needs while simultaneously paving the way for a sustainable future. Acting as a transitional element, LNG bridges the gap between the existing energy infrastructure and the evolving landscape of renewables, providing a reliable and comparatively cleaner alternative.

The unique characteristics of LNG, such as its transportability and storage capabilities, make it a valuable asset in the global energy portfolio. From meeting the demands of burgeoning economies to complementing intermittent renewable sources, LNG serves as a bridge that harmonizes the present energy requirements with the aspirations of a cleaner, more sustainable future. The adoption of LNG as a bridge fuel carries profound implications for the global energy landscape. Its integration allows for enhanced energy security, providing nations with diversified sources and reducing dependence on traditional fossil fuels. Additionally, LNG trade fosters economic cooperation, as nations engage in strategic alliances through trade agreements, influencing geopolitical dynamics. The environmental implications are significant, as LNG helps reduce carbon emissions compared to traditional fuels. It aligns with global climate goals and supports efforts to transition towards a low-carbon energy future. LNG's impact on air quality, coupled with advancements in cleaner production technologies, positions it as a vital component in achieving a sustainable and environmentally conscious energy mix. Looking ahead, the future of LNG as a bridge fuel is intricately linked to the broader transition to renewable energy. As renewable technologies mature and become more economically viable, the need for LNG may gradually diminish. However, the path to a fully renewable energy landscape is fraught with challenges, ranging from intermittency issues to the scalability of technologies. The continued development of renewable energy sources, energy storage solutions, and advancements in grid infrastructure will shape the trajectory of the transition. Challenges such as the geopolitical complexities surrounding LNG trade, the need for robust regulatory frameworks, and the imperative to address environmental concerns will require concerted efforts from stakeholders.

In navigating these future prospects and challenges, collaboration among nations, industries, and policymakers will be crucial. The transition to renewable energy is a collective endeavor, and LNG, as a bridge fuel, contributes to this ongoing journey towards a sustainable, resilient, and cleaner global energy landscape. In conclusion, the role of LNG as a bridge fuel is not only significant but also dynamic, adapting to the evolving needs of a world in transition. As the energy sector embraces renewables, LNG stands as a testament to the possibilities of harmonizing immediate energy needs with long-term sustainability goals. The journey towards renewable energy is underway, and LNG plays a central role in guiding us across the bridge to a cleaner and more sustainable future.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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