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Liquefied Natural Gas as a Sustainable Energy Carrier for Medium and Heavy-Duty Vehicles: Potential, Challenges, and Policy Implications

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Abstract: The ongoing depletion of conventional fossil fuel reserves, coupled with escalating environmental concerns and the volatility of global oil markets, has intensified the search for cleaner and more sustainable energy alternatives for transportation. Among various low-emission fuels—such as biodiesel, ethanol, methanol, ammonia, hydrogen, and Compressed Natural Gas (CNG)—Liquefied Natural Gas (LNG) has emerged as a particularly viable option for Medium- and Heavy-Duty Vehicles (M&HDVs). LNG offers several advantages, including higher volumetric energy density, reduced tailpipe emissions, and compatibility with high-efficiency engine technologies. Its adoption is of strategic relevance to countries such as India, where transportation remains one of the largest contributors to Greenhouse Gas (GHG) emissions and is predominantly dependent on imported crude oil. The utilisation of LNG in M&HDVs has been identified as a means to simultaneously reduce GHG emissions and enhance national energy security. In this context, a comprehensive assessment is presented, encompassing LNG production pathways, distribution logistics, cryogenic storage technologies, and economic feasibility, as well as supportive government policies and international best practices. Key challenges, such as Boil-off gas (BOG) management, refuelling infrastructure gaps, cost parity with diesel, and engine retrofitting, have also been critically evaluated. Particular attention has been given to recent technological advancements and their potential to improve lifecycle emissions performance and cost-effectiveness. It is suggested that the integration of LNG into national energy and transportation strategies may yield substantial environmental and economic benefits, especially when supported by policy instruments, public–private investment models, and standardised regulatory frameworks. The findings indicate that LNG is poised to play a pivotal role in the decarbonisation of the freight and commercial transport sector, both in India and globally, thereby contributing to long-term sustainability objectives.

Keywords: Liquefied Natural Gas (LNG); Sustainable transportation; Medium- and Heavy-Duty Vehicles (M&HDVs); Greenhouse gas (GHG) emissions; Boil-off gas (BOG); Energy security; Cost parity; Policy support

1 Introduction

The pressing problem of pollution has prompted the implementation of increasingly stringent emissions regulations for automotive vehicles, thereby making compliance with established emission limits more challenging [1]. At the national level, the major part of the fuel demand is met through the import of crude oil from Gulf countries [2]. Conventional fuels, which generate higher carbon emissions, require the incorporation of advanced emission control technologies to meet government standards. Considering environmental concerns and technological advancements, there has been a notable shift away from petroleum and diesel vehicles toward an increase in alternative fuel-fired vehicles, particularly those powered by natural gas. In recent years, nations have intensified efforts to fulfill their commitments to achieve net-zero emissions, thereby elevating the significance of natural gas as a cleaner fuel option [3–5]. Natural gas is abundantly available from fossil sources and plays a crucial role not only in the automotive sector but also in mitigating high levels of urban pollution in metropolitan areas across India. This is largely attributable to the conversion of passenger cars, buses, and auto-rickshaws to CNG [6]. The primary challenge associated with natural gas pertains to its storage methodology, as there exist differing viewpoints regarding the advantages of natural gas storage for practical applications [7]. In the subsequent sections of this paper, the challenges associated with LNG storage, including safety and environmental considerations, are critically examined. Additionally, the behaviour of LNG in internal combustion engines (ICEs) and a comprehensive life-cycle analysis of LNG, with a particular focus on its demand and production dynamics within the Indian context, has been analyzed.

1.1 Global Energy Demand

The overall trajectory of global electricity demand reflects a complex interplay between economic conditions and energy policy. The current global energy landscape is characterized by record high energy consumption levels [8]. In 2023, global primary energy consumption reached unprecedented levels, and it was driven largely by fossil fuels. Despite a gradual decline in their share of the energy mix, fossil fuels still account for approximately 82% of total energy use. Notably, oil and coal consumption has reached all-time highs due to increasing demand across various sectors [9].

Wind and solar power have emerged as significant contributors to new energy generation; together, they added approximately 4.9 exajoules of new energy in 2023, representing about 40% of the overall increase in global demand [10]. This is a historic moment, as wind and solar energy outpaced fossil fuels for the first time as sources of new energy supply. However, despite advancements in renewable energy capacity, fossil fuels remain dominant in the global energy system [11].

The International Energy Agency (IEA) forecasts that global electricity demand will increase at an accelerated pace, averaging 3.4% annually from 2024 through 2026. This growth is underpinned by an improved economic outlook that will boost demand across advanced and emerging economies. Emerging markets are expected to drive approximately 85% of the additional electricity demand through 2026, with China continuing to play a pivotal role despite its economic transition away from heavy industry. For instance, China's electricity consumption rose by 6.4% in 2023, primarily driven by growth in the services and industrial sectors. However, as China's economy evolves, its electricity demand growth is expected to moderate gradually over the coming years. Electricity demand in the United States fell by 1.6% in 2023, after increasing by 2.6% in 2022, but it is expected to recover in the 2024-26 outlook period [12].

1.2 Energy Demand in India

India's energy scenario has undergone significant transformations over the past few decades. Historically reliant on traditional biomass and coal, the country has progressively diversified its energy portfolio [13]. The liberalization of the economy in the early 1990s catalyzed investments in infrastructure and technology, paving the way for enhanced energy production capabilities. The introduction of various policies aimed at promoting renewable energy sources began in earnest in the early 2000s, leading to a gradual increase in the share of renewable energy within the energy mix. From 2000 to 2023, India made substantial advancements in electricity generation and access. Approximately 700 million people have gained access to electricity since 2000, reflecting a concerted effort by the government to eradicate energy poverty. Furthermore, about 80 million new Liquified Petroleum Gas (LPG) connections have been established for clean cooking, demonstrating progress in improving health outcomes and reducing reliance on polluting fuels [14].

Currently, India's energy demand is projected to continue its upward trajectory, with expectations that it will account for 25% of global energy demand growth over the next two decades. The country's GDP growth rate reached 7.8% in 2023, making it the fastest-growing major economy globally [15]. This economic expansion is accompanied by urbanization and an increase in built environments, which are anticipated to drive energy demand growth at rates that surpass those of other regions by 2050. The integration of renewable energy into India's power system has seen significant progress; between 2016 and 2018, the share of solar photovoltaic (PV) and wind power in electricity generation doubled from 4% to 8%. Investments in clean energy have surged recently, reaching approximately $68 billion in 2023—an increase of nearly 40% from the average during 2016-2020. Nearly half of this investment has been directed toward low-emission power generation technologies, including solar PVs. Energy efficiency initiatives have also played a critical role; between 2000 and 2018, these measures helped to avoid an additional 15% of energy demand and reduced carbon dioxide emissions by approximately 300 million tons [14].

The energy distribution in India is illustrated in Figure 1 and characterized by its diverse sources, which has significantly contributed to the increasing energy demand within the country. From generation to end-use, each sector benefiting from this distribution has had a profound impact on both the Indian energy landscape and its economy [16]. Non-renewable sources have historically played a dominant role in meeting national energy needs, with coal serving as the primary energy source. While coal remains crucial to energy production, it comes with environmental and economic costs that India must address. The majority of the country's energy demand is satisfied through the production and imports of coal, with other non-renewable and renewable sources contributing a smaller share to the overall energy distribution [17–19]. Natural gas and crude oil are other significant non-renewable resources that help fulfil India's energy requirements. Crude oil, primarily imported from foreign nations, does not foster energy independence, whereas natural gas benefits from several domestic terminals and refineries [20]. The government's initiatives to reduce import duties and promote domestic production through the "Make in India" campaign have made natural gas a more cost-effective option than imported alternatives [21]. Using natural gas can substantially benefit both the environment and public health because it produces fewer emissions than coal and crude oil. This shift toward natural gas can improve air quality and mitigate the adverse effects associated with increased coal and crude oil consumption [20].

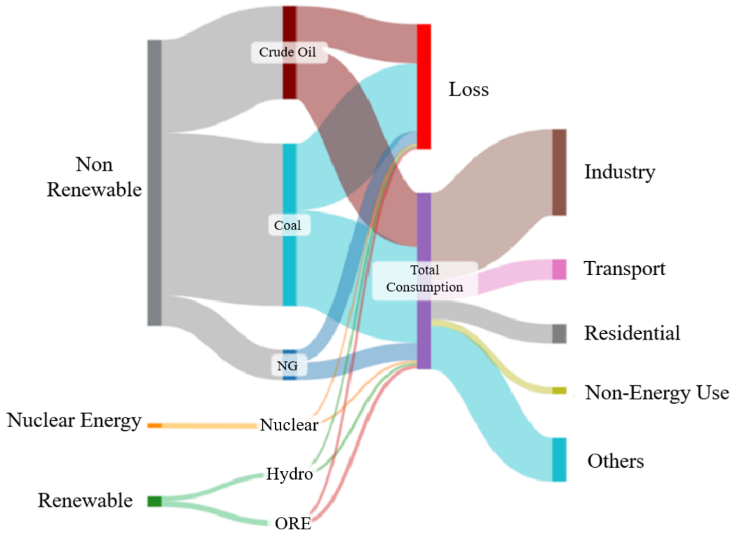

Figure 1. India's energy distribution - flow and losses [22]

Natural gas is not only environmentally friendly but also economically advantageous, making it a viable choice for addressing India's growing energy demand. As the country continues to urbanize and industrialize, the transition toward cleaner energy sources will become essential for sustainable development. By prioritizing natural gas and renewable energy sources, India can enhance its energy security while simultaneously reducing its carbon footprint.

1.3 History of LNG

The journey of LNG as an energy source begins with the extraction of natural gas, which is often found during the crude oil extraction process. This natural gas is subsequently stored and utilized for energy generation. The origins of LNG production can be traced back to Algeria, where the first LNG generation plant was established in 1964 [23]. This was a significant milestone in the energy market, as LNG was introduced as a new energy source capable of being transported over long distances. The advent of LNG created substantial trading opportunities among countries, fundamentally transforming the industry by allowing for larger quantities to be stored and transported due to its liquid state, in contrast to natural gas [24]. Over the past decade, the LNG sector has seen considerable expansion, particularly with major projects emerging in the Middle East, Australia, South Asia, and the broader Asian subcontinent. These developments have significantly contributed to the global supply of LNG, enhancing energy security and diversification for many nations [25].

The exploration and production (E&P) of oil and gas in India has a rich history that dates back to the 19th century. The journey began in 1866 when the first well was drilled, leading to a significant milestone in 1889 with the first commercial discovery in 1889 in Digboi, Assam. Initially, E&P efforts were primarily concentrated within the Assam Oil Company and Attock Oil [26]. However, the real transformation of the oil and gas sector occurred after India gained independence in the 1950s and 1960s. In 1948, the Indian government recognized the potential of the petroleum industry and enacted an Industrial Policy Statement aimed at its development [26]. Up until 1955, exploration was largely in the hands of private companies like the Burmah Oil Company and the Assam Oil Company, but vast areas, especially offshore regions, remained largely untouched [27]. In response, the government established the Oil and Natural Gas Directorate (ONGD) in 1955 to spearhead resource development under the Ministry of Natural Resources and Scientific Research. A pivotal change occurred in 1956 when the government adopted an Industrial Policy Resolution that placed oil industry development under state control, transforming the ONGD into the Oil and Natural Gas Commission (ONGC) [28]. The Commission's authority grew over time as it took on more responsibilities. In 1959, Oil India Limited (OIL) was formed, with the Burmah Oil Company holding a two-thirds stake and the government owning one-third; this arrangement evolved into a joint venture by 1961 [29].

Gas production began in Assam with OIL in 1959, followed by ONGC's operations in Gujarat starting in 1964. Although gas demand was initially low, it surged after ONGC began production from the Bombay High in 1974.

By 1981, the OIL had become fully state-owned. The increasing gas production necessitated advancements in infrastructure, leading to the establishment of GAIL in 1984 to enhance gas usage and develop midstream and downstream infrastructure. The liberalization of India's economy in 1991 marked another turning point for the gas sector, as it began deregulating markets and reducing reliance on public enterprises. In 1993, the Directorate General of Hydrocarbons (DGH) was created to oversee upstream activities [30]. Subsequent years saw ONGC transitioning into a public company with share divestments occurring through competitive bidding. The late 1990s introduced private and foreign investments into the upstream sector via the New Exploration Licensing Policy (NELP), allowing full project ownership for investor. Between 1997 and 2009, several licensing rounds were conducted to attract exploration efforts. GAIL also significantly expanded its transmission network during this period, completing major pipelines like Hazira-Vijaipur-Jagdishpur (HVJ) in 1991. Today, various private players and international firms are active across different segments of India's gas market—upstream exploration, transmission, LNG terminals, and distribution—with Reliance Industries Limited (RIL) being a prominent example known for its extensive involvement across these areas [29].

1.4 Advantages and Feasibility of LNG

The nation's increasing energy demand necessitates the use of non-renewable sources for power generation, with coal and heavy fuels playing a major role. Conventional sources generate substantial amounts of energy; however, they are not environmentally friendly and contribute to GHG emissions, which are associated with carcinogenic illnesses. In contrast, LNG and natural gas provide a viable transition from dirtier energy sources to cleaner alternatives. Power generators operating on LNG and/or natural gas emit 45% to 55% lower GHG than conventional fuels used for energy generation [31]. In industrial applications, LNG and natural gas also offer a clean solution for the demand for high-calorific fuels in production processes. Household energy consumption has increasingly shifted to natural gas in the form of Piped Natural Gas (PNG), which reduces the health impacts associated with emissions from other fuel sources, such as coal and kerosene [32]. In the automobile industry, significant emissions are produced from petrol and diesel, adversely affecting the environment and human health [33–35]. LNG presents a substantial solution for emission reduction in the transport sector, aiding fuel diversification and minimizing air pollution for heavy-duty road transport as well as shipping vessels. These factors underscore LNG's central role in the transition of energy sources, with predictions indicating a major increase in natural gas usage by 45% in the upcoming decades, positively impacting growth in developing countries.

Natural gas can be utilized in three distinct forms, each exhibiting variation in its physical and chemical properties. Initially, CNG was the primary form of natural gas; however, other forms have since been adopted for various applications. The two additional forms of LNG and PNG are both fuel sources. PNG has traditionally been employed as a cooking fuel in residential settings, whereas LNG, produced by refrigerating natural gas to convert it into a liquid state, has found application as a transportation fuel. The introduction of LNG into the transportation sector has provided a significant enhancement globally, primarily due to the limitations of the energy storage associated with CNG in this domain. The utilization of LNG as a transport fuel is largely analogous to that of CNG, with the primary distinction arising from differences in composition; specifically, LNG contains a higher concentration of methane and employs different storage methods. LNG is stored at cryogenic temperatures under relative pressure, optimizing its energy density for transport applications. LNG offers enhanced feasibility for the transportation sector by extending the operational range of vehicles without necessitating major modifications to existing natural gas engines [36]. This adaptability positions LNG as a promising solution for improving urban air quality while supporting the transition toward cleaner fuel alternatives [37]. Additionally, LNG is a more effective option when the battery technology of electric vehicles falls short of the range needed for HDVs [38]. It can decrease harmful air pollutants released from vehicle exhaust, making it a cleaner energy alternative than conventional fuels [39]. For instance, LNG can lower Nitrogen Oxides (NOx) emissions by around 70% and Non-Methane Volatile Organic Compounds (NMVOCs) by 45% compared with conventional fuels [39, 40]. Notably, the reduction in Sulphur Oxides (SOx) and Particulate Matter (PM) can exceed 90% compared with conventional fuels.

1.5 Disadvantages of Adapting LNG

The adaptation of LNG as a fuel presents several challenges for both M&HDVs and passenger cars. A primary concern is the high degree of import dependence, which exposes the industry to fluctuations in global prices and potential supply disruptions, thereby affecting the stability of fuel costs for consumers [41]. Additionally, existing infrastructure limitations, particularly the inadequacy of pipelines and storage facilities, hinder the widespread adoption of LNG across the transportation sector [31]. The requirement for large insulated tanks to maintain LNG's low temperature renders it unsuitable for passenger vehicles, whereas its efficiency is primarily realized in vehicles that are frequently used, such as long-haul trucks [42, 43]. Also, to maintain a certain temperature in an LNG fuel tank, special materials are required to ensure minimum or no temperature transfer across the tank wall and the surrounding area, which influences the cost of manufacturing an LNG fuel tank. The approximate cost of a 500-liter WC LNG tank is listed around 15 lakhs (17,570 USD). If LNG is not used regularly, it gradually warms and evaporates, a phenomenon known as the boil-off phenomenon, leading to raw methane emissions. Environmental concerns regarding methane leakage during extraction and transportation also challenge the sustainability of LNG, as methane is a potent GHG that can contribute to a greater overall GHG footprint than conventional fuels. Although LNG can achieve a reduction in GHG emissions by up to 25% relative to diesel, it remains classified as a fossil fuel and thus falls short of providing substantial environmental benefits [44]. Furthermore, the high upfront costs associated with adopting LNG vehicles and establishing the necessary infrastructure—including specialized refueling stations and vehicle modifications—pose significant barriers to entry. Natural Gas (NG) liquefaction requires a significant amount of energy. Although the advantages of LNG transportation offset this energy expenditure, the LNG supply chain's balance needs to be improved. Collectively, these challenges may deter companies and local government services from transitioning their fleets to LNG, as the high initial investment and specialized infrastructure requirements could limit accessibility and convenience for refueling, while the environmental implications of methane leakage could negatively impact the reputation of organizations committed to sustainability [45].

1.6 Properties of LNG Fuel

LNG refers to natural gas that has been cooled to approximately -259.6°F (-162°C), transforming it into a liquid state for efficient shipping and storage. This liquefaction process reduces the volume of natural gas to approximately 600 times smaller than its gaseous form, making it highly advantageous for transportation [46]. Consequently, LNG enables the delivery of natural gas to regions that are not accessible via pipelines. The ability to liquefy natural gas is crucial for its transport over long distances, where pipeline infrastructure is impractical. Markets that are geographically distant from production areas can still access this vital energy source. In its condensed liquid form, natural gas is transported in specialized tankers to various terminals around the world. At these facilities, LNG is converted back into its gaseous state and subsequently distributed through pipelines to consumers, including distribution companies, industrial users, and power generation plants. LNG represents a significant advancement in energy logistics, facilitating global trade and enhancing energy security for countries lacking direct pipeline connections. The versatility and efficiency of LNG position it as a key player in the transition toward cleaner energy solutions, allowing nations to diversify their energy sources while meeting growing demand.

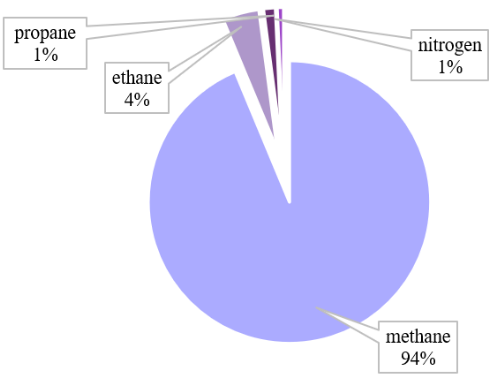

Figure 2. Various constituents of LNG [47, 48]

The various constituents of LNG are illustrated in Figure 2. The primary component of LNG is methane, which typically constitutes about 85-95% of its composition. Alongside methane, LNG contains small percentages of other hydrocarbons such as propane, ethane, and butane, as well as trace amounts of nitrogen. An essential parameter to consider in the LNG industry is the Wobbe Index, which ranges from approximately 48 to 52 MJ/m^3. This index serves as a critical indicator of the interchangeability of gases in combustion systems, ensuring that different types of fuel gases can be utilized without significant adjustments to the combustion equipment. The Wobbe Index significantly impacts the LNG industry by facilitating the seamless integration of various gas types into existing infrastructure. A consistent Wobbe Index allows for efficient operation across different fuel sources, enhancing safety and performance in combustion systems. Moreover, understanding the Wobbe Index aids operators in managing fuel quality effectively and ensures that variations in gas composition do not adversely affect combustion efficiency or emissions [49]. The composition of LNG can vary depending on the production method, processing history, and end-use requirements. Despite these variations, LNG shares similar properties with methane: it is colorless, odorless, non-toxic, and noncorrosive. Table 1 represents the desired specifications of LNG as per IS standard 15959:2023.

Table 1. Characteristics of LNG fuel [50, 51]

Serial Number	Characteristics	Required Value
1	Wobbe Index	48.8-51.0 $\mathrm{MJ/m^3}$
2	Boiling Point	-259.6°F (-162°C)
3	Flash-Point	< -306.4°F (< -188°C)
4	Heat of Vaporization:	511 kJ/kg
5	Relative Density/Specific Gravity:	0.43 at -260°F(H_2O = 1)
6	Auto-Ignition Temperature	998.6°F (537°C)
7	Freezing Point:	-295.96°F(-182.2°C, 91.0°K)
8	Critical Temperature:	-115.96°F(-82.2°C, 191.0°K)
9	Water Content	5.0 $\mathrm{mg/m^3}$
10	Methane	90.0% of total organic carbon
11	Ethane	6.0%
12	Propane and higher HC levels	3.0%
13	Hexane and higher HC content	0.5%
14	Total Unsaturated HCs	0.5%
15	Sulphur	10 $\mathrm{mg/m^3}$
16	Oxygen	0.5% Vol
17	Carbon-Dioxide and Nitrogen	0.4% Vol
18	Hydrogen	0.1% mole
19	Carbon Monoxide	0.1% mole
20	Methane number	90
21	Gross-Calorific-Value	44 $\mathrm{MJ/m^3}$

1.7 LNG Production Methods

The transformation from natural gas to LNG not only enhances the energy density of natural gas but also facilitates its transportation by trucks and cargo ships from production sites to consumers. The liquefaction process (Figure 3) is energy-intensive, necessitating improvements in efficiency to reduce the overall energy consumption. There are several prominent methods for LNG production, each with distinct characteristics and advantages.

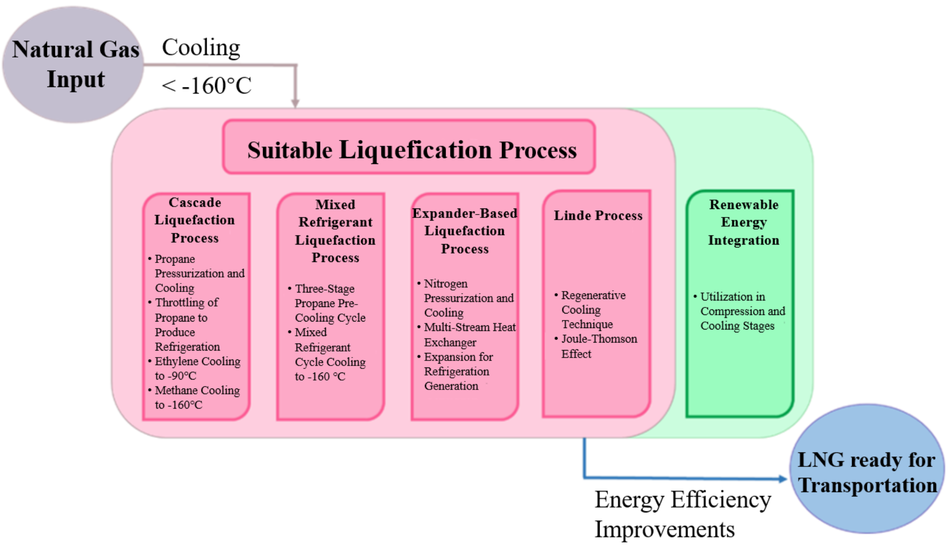

Figure 3. Overview of LNG liquefaction processes: Cascade, mixed refrigerant, expander-based techniques and Linde process

One of the most established methods is the cascade liquefaction process, which uses three independent refrigeration cycles with different refrigerants. Typically, these refrigerants include propane, ethylene, and methane. In this process, propane is first pressurized and cooled using air- or water-cooling systems. The condensed propane then undergoes a throttling process to produce refrigeration capacity, cooling the natural gas and the other two refrigerants to approximately -30°C. Following this, ethylene further cools the mixture down to -90°C before methane is used to achieve the final liquefaction at -162°C [52]. Despite its complexity and high capital costs due to multiple equipment requirements, the cascade process offers superior thermal efficiency compared to other methods. The mixed refrigerant liquefaction process is another significant approach that aims to reduce equipment needs while maintaining efficiency. This method employs a mixture of hydrocarbons and nitrogen as refrigerants, which are carefully selected to minimize temperature gaps in heat exchangers [53]. The most recognized variant of this approach is the propane pre-cooled mixed refrigerant (C3MR) process developed by Air Products and Chemicals Inc., which has become dominant in caseload LNG plants. The C3MR cycle combines a three-stage propane pre-cooling cycle with a mixed refrigerant cycle that cools natural gas down to -162°C in multi-stream heat exchangers. This dual-cycle system effectively minimizes the energy consumption while simplifying the overall liquefaction process [54]. Another innovative technique is the expander-based liquefaction process, which operates on the principle of a reverse Brayton refrigeration cycle. This method typically uses nitrogen or methane as the working fluid and involves nitrogen being pressurized through a compressor before being cooled using a water cooler. The high-pressure nitrogen is then passed through a multi-stream heat exchanger, where it cools naturally before entering an expander that further reduces its pressure and temperature, generating refrigeration for liquefying natural gas. This method allows for efficient energy recovery and is particularly advantageous in specific operational contexts [55].

In addition to these prominent methods, several other techniques are also employed for LNG production globally. The Linde process, often used in conjunction with variations such as the Claude process, uses regenerative cooling techniques in which natural gas is continually passed through an orifice until it reaches liquefaction temperatures. This method leverages the Joule-Thomson effect for efficient cooling and has been widely adopted due to its effectiveness [56]. Furthermore, advancements in compact LNG technologies have emerged in response to growing demands for smaller-scale LNG production facilities. These technologies aim to optimize space and reduce capital costs while maintaining operational efficiency. Compact systems often integrate multiple processes into single units, thereby enhancing overall productivity without compromising performance. The integration of renewable energy sources into LNG production processes also represents a promising avenue for future development. By using renewable power for certain operational stages, such as compression and cooling, facilities can significantly reduce their carbon footprint while contributing to sustainability goals within the energy sector [57]. The landscape of LNG production encompasses various methods that cater to different operational needs and market conditions. Each method presents unique advantages and challenges, highlighting the ongoing evolution of technology aimed at improving efficiency and reducing environmental impacts on the liquefaction of natural gas. As the global demand for cleaner energy sources continues to rise, innovations in LNG production will play a crucial role in meeting both economic and environmental objectives across various markets worldwide [58].

1.8 Exergy of LNG Processes

Exergy, which represents the maximum useful work obtainable from a system, is a crucial concept for understanding and optimizing processes related to LNG, particularly during regasification where significant cold energy is released. Exergy is the maximum amount of work that can be obtained from a system as it reaches equilibrium with its surroundings, considering both the energy content and the quality of that energy. It is a measure of the "usefulness" or "quality" of energy, as it accounts for the limitations imposed by the second law of thermodynamics [59]. In the context of LNG, the cryogenic temperatures of LNG indicate that it has high exergy potential even though its internal energy is low. During the liquefaction of NG to form LNG, a significant amount of energy is required to cool the gas to cryogenic temperatures. During regasification, the cold energy of LNG is released, which can be harnessed for various applications. The cold exergy of LNG, especially during regasification, can be used for power generation, refrigeration, or other cooling applications. Exergy analysis helps identify inefficiencies and opportunities for energy recovery in LNG processes. The data presented in Table 2 shows the gasification process's considerable potential for optimization. If all processes are reversible, a vaporization unit operating at 1 bar of pressure can produce 1082.6 kJ of external work per kg of LNG. The practical use of the phase change exergy only enables the recovery of 853.8 kJ entropy-free energy per kg of LNG.

Table 2. Physical and vaporization exergy of LNG stored under various pressures [60]

Pressure of Vaporization (Bar)	Exergy of LNG (KJ/kg LNG)	Exergy of LNG Vaporization (KJ/kg LNG)
1	1082.6	853.8
2	1032.1	725.5
5	962.2	550.7
10	906.3	415.0

1.9 LNG Material Compatibility

The LNG industry relies on advanced materials to address extreme cryogenic conditions (-150°C to -195.8°C), high pressures, and thermal cycling across production, storage, and transportation phases as compiled in Figure 4. During production, cryogenic refrigeration cycles require materials such as PTFE (Polytetrafluoroethylene) and PCTFE (Polychlorotrifluoroethylene) for seals and valves because of their chemical inertness, low friction, and dimensional stability at ultra-low temperatures [61]. Storage systems employ flexible graphite and impregnated PTFE asbestos ropes for gaskets and seals, ensuring leak-proof containment despite LNG's high liquid-to-gas expansion ratio (1:694) and pressure fluctuations. Transportation infrastructure, including Fleet-LNG vessels and road tankers, utilizes Ultra-High-Molecular-Weight Polyethylene (UHMWPE) and modified Polytetrafluorethylene (TFM) for wear-resistant components, such as valve stem seals and butterfly seat seals, which resist extrusion and mechanical stress under vibration. Material compatibility is critical, as LNG's cryogenic nature and methane-rich composition necessitate polymers with low thermal expansion coefficients, resistance to embrittlement, and chemical stability. PTFE and PCTFE excel in cryogenic valves and pumps due to their non-reactivity and self-lubricating properties, while graphite composites effectively manage thermal cycling in storage tanks. Challenges include balancing the spring force and friction in seals to prevent leakage, managing thermal contraction and expansion mismatches, and ensuring flammability resistance [62]. Advanced manufacturing processes such as precision CNC machining and injection molding ensure components meet stringent safety standards, particularly for fugitive emissions control. Overall, the industry prioritizes materials that combine cryogenic resilience, mechanical durability and chemical compatibility to maintain operational integrity across the LNG lifecycle [63].

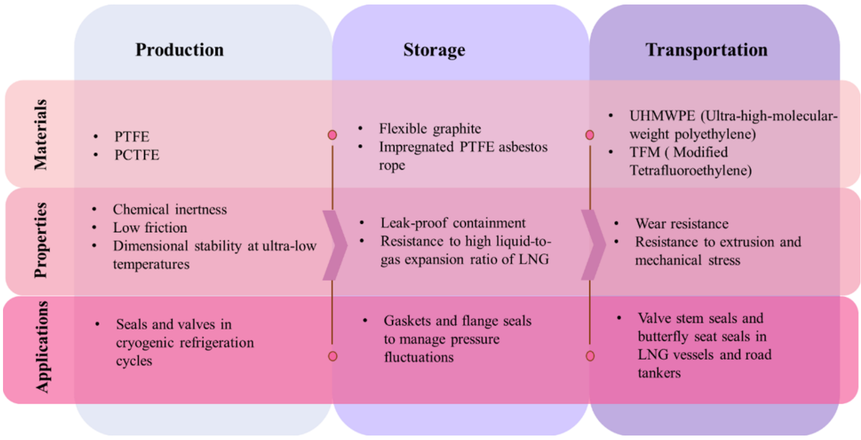

Figure 4. Key advanced materials for LNG production, storage, and transportation

1.10 LNG Storage and Transportation

LNG storage and transportation systems are engineered to maintain the fuel's cryogenic state (-162°C) and ensure safety throughout its lifecycle. At production facilities, LNG is stored in specialized tanks categorized by containment design. Single containment systems feature an inner liquid-tight tank paired with an outer vapor-retaining shell, making them ideal for low-risk environments. Double containment adds a secondary liquid-tight layer around the primary tank, thereby enhancing leak protection. The most robust option, full containment, incorporates dual independent tanks (both liquid and vapor-tight) with Thermal Corner Protection (TCP) to shield structural joints from cryogenic stress during leaks. Onshore storage often employs double-walled tanks: an inner nickel-steel alloy tank for cryogenic resistance, surrounded by an outer concrete or steel shell, with insulation sandwiched between them to minimize heat ingress. Offshore, Floating Storage Units (FSUs) serve as temporary or supplementary solutions in locations where land-based infrastructure is impractical [64–66].

For transportation, LNG carriers use advanced tank designs to balance capacity, safety, and thermal efficiency. Spherical tanks, which are self-supporting and pressure-resistant, are commonly used because of their structural integrity. Prismatic tanks adopt angular geometries to maximize the cargo space while resisting mechanical stress. Membrane tanks employ thin, flexible layers of stainless steel or low-expansion alloys, often with waffle-like patterns, to absorb thermal contraction during cooling. These are paired with insulation materials such as perlite (a lightweight volcanic glass) and nitrogen flushing to reduce heat transfer. Smaller-scale Type C pressure vessels, which are cylindrical or bi-lobe in shape, handle higher pressures for niche applications. Additionally, pipelines constructed with cryogenic-grade materials transport LNG over land, although their use is geographically limited. Collectively, these systems prioritize thermal stability, vapor containment, and insulation efficiency to mitigate BOG and ensure safe transit. From production to end-use, the integration of robust storage designs and specialized transport infrastructure underscores the balance between engineering innovation and operational reliability in global LNG logistics [65].

1.11 Global LNG Scenario

The global landscape of natural gas production has exhibited a nuanced evolution in 2023, which is influenced by geopolitical dynamics and market shifts. The global exports and imports of LNG are illustrated in Figure 5 and Figure 6, respectively. From an Indian perspective, the data present challenges and opportunities for the country's energy strategy. In 2023, global natural gas production reached approximately 4.05 trillion cubic meters, reflecting a slight increase from 4.04 trillion cubic meters in 2022. The United States emerged as the leading producer, registering a notable growth of 4.2%, which aligns closely with its historical averages from 2010 to 2019. Meanwhile, Russia experienced a significant decline of 5.2% in its production, primarily due to reduced exports to Europe amid ongoing geopolitical tensions stemming from the war in Ukraine. In contrast, the country's This shift has seen Russia's share of the European market plummet from 45% in 2021 to just 14% in 2023, prompting the EU to seek alternatives and phase out its reliance on Russian gas by 2027.

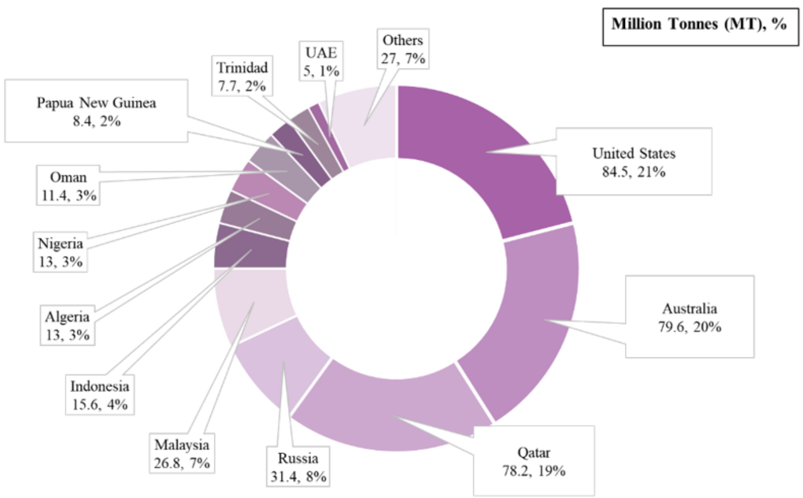

Figure 5. Global leading LNG exporters for 2023 [67]

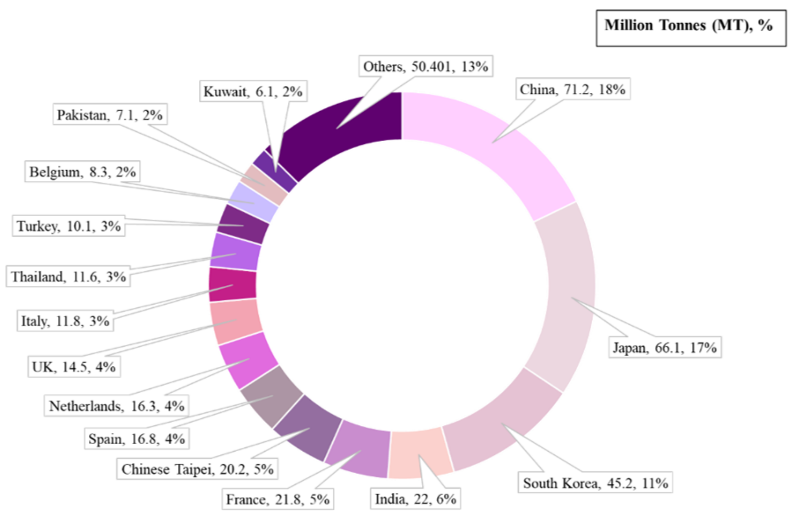

Figure 6. Global leading LNG importers for 2023 [67]

In Asia, where India is strategically positioned, there was a robust increase in production, with growth rates of around 6% in both China and India. This trend is crucial for India as it seeks to enhance its energy security and reduce its dependence on imported energy. The overall demand for natural gas has risen by a modest 0.5% globally, buoyed by increases in regions such as China and North America, whereas Europe faced a stark decline of 6.9%, reaching its lowest consumption levels since 1994. This decline can be attributed to the rapid adoption of renewable energy sources and increased nuclear power generation. These global developments underscore the importance of diversifying energy sources and enhancing domestic production capabilities in India. As the country continues to ramp up its LNG imports—evidenced by a year-on-year increase of nearly 9.7%—it must also focus on fostering sustainable production practices to align with global energy transitions toward lower carbon emissions. The evolving dynamics of natural gas production not only highlight the shifting geopolitical landscape but also present an opportunity for India to position itself as a significant player in the LNG market while ensuring energy security for its growing economy [67].

In 2023, the global LNG export landscape experienced a remarkable shift, with the United States solidifying its position as the leading exporter. The U.S. accounted for approximately 84.5 million tonnes, representing 21% of global exports, followed closely by Australia at 79.6 million tonnes (20%) and Qatar at 78.2 million tonnes (19%). This trio of nations collectively dominated the market, highlighting their pivotal roles in meeting international energy demands. Russia's exports, while still significant at 31.4 million tonnes (8%), faced challenges due to geopolitical tensions and declining production capabilities. Other notable exporters included Malaysia and Indonesia, which contributed 26.8 million tonnes (7%) and 15.6 million tonnes (4%), respectively. The African nations of Algeria and Nigeria each provided 13 million tonnes (3%), while Oman and Papua New Guinea contributed smaller volumes of 11.4 million tonnes (3%) and 8.4 million tonnes (2%). Overall, the global LNG export volume reached approximately 400 million tonnes, with various countries adapting to shifting market dynamics and increasing competition in the sector. This evolving scenario underscores the importance of strategic partnerships and infrastructure investments to enhance export capabilities in a rapidly changing energy landscape [67].

In 2023, the global LNG import landscape underwent significant shifts, with China reclaiming its position as the largest importer, accounting for 71.2 million tonnes or 18% of total imports. Japan and South Korea were closely followed, with imports of 66.1 million tonnes (16%) and 45.2 million tonnes (11%), respectively. The data indicate a diverse array of importing nations, with India emerging as a notable player, importing 22 million tonnes (5%), reflecting India's growing energy needs and commitment to diversifying its energy sources. France and Chinese Taipei each imported approximately 21.8 million tonnes and 20.2 million tonnes, respectively, while several European countries, such as Spain and the Netherlands, contributed 16.8 million tonnes and 16.3 million tonnes, respectively. The United Kingdom, Italy, and Turkey also played significant roles in the LNG import market, while other nations collectively accounted for approximately 50.4 million tonnes. India's position in the global LNG market is particularly noteworthy; as it continues to enhance its energy security through increased LNG imports, the nation is poised to leverage its growing demand to negotiate better terms with exporting countries. This strategic focus on LNG is vital for India as it aims to reduce its reliance on coal and other fossil fuels, aligning with its broader objectives of sustainable development and energy transition. The increase in India's LNG imports underscores India's commitment to meeting rising energy demands while fostering economic growth, thus solidifying its role in the evolving global LNG landscape [67].

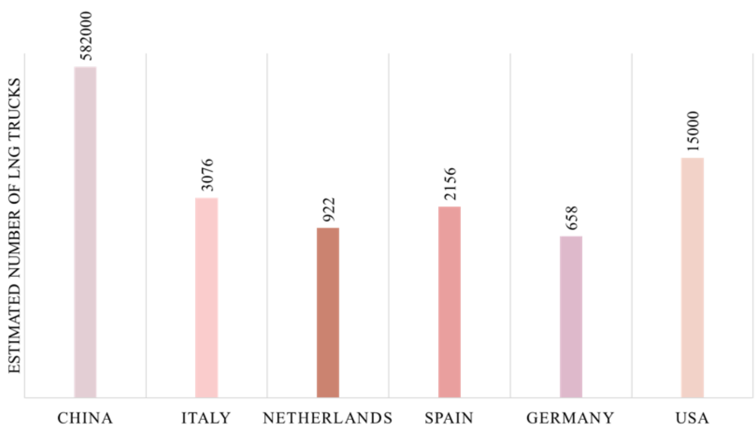

Figure 7. LNG trucks plying worldwide [68, 69]

The global landscape for LNG as a fuel for HDVs is rapidly evolving, driven by the increasing demand for cleaner transportation solutions. The methodology outlined in NITI Aayog's 2024 LNG report employs stakeholder engagement, historical data analysis, and key assumptions of HDVs running 60,000 km/year, with diesel mileage at 3 km/liter and LNG at 3 km/kg, alongside a 7% annual freight growth rate to estimate the LNG vehicle adoption. As shown in Figure 7and Figure 8, China leads the way with 582,000 LNG HDVs and 4,800 LNG stations, showcasing its commitment to transitioning from conventional fuels. Italy followed with 3076 vehicles and 103 stations, while the Netherlands, Spain, and Germany made notable contributions as well, with respective figures of 922, 2156, and 658 vehicles. The United States has also established a significant presence with 15,000 LNG HDVs and 50 stations. These figures indicate the growing acceptance of LNG as an effective alternative to traditional fuels such as petrol and diesel. As a cleaner-burning fuel, LNG significantly reduces GHG emissions and other pollutants, making it an attractive option for medium- and heavy-duty transportation. The establishment of LNG infrastructure is crucial in facilitating this transition; the European Union (EU) has reported a total of 7342 LNG stations across its member states, highlighting the region's commitment to sustainable transport solutions. The data suggest that the LNG market is poised for substantial growth in the coming years. With increasing regulatory pressures for lower emissions and rising fuel prices pushing fleets toward more sustainable options, demand for LNG as a transportation fuel is expected to surge. As countries worldwide recognize the environmental benefits of LNG, its adoption in M&HDVs will accelerate, contributing to a greener future in transportation. This transformation underscores LNG's potential to play a pivotal role in achieving global sustainability goals while meeting the energy needs of an expanding economy [68].

Figure 8. LNG filling stations worldwide [68, 69]

The global LNG market has faced considerable volatility due to recent geopolitical disruptions, particularly the Russia–Ukraine conflict and the intensifying trade tensions between China and the United States. The ongoing war in Ukraine has resulted in a significant decrease in Russian pipeline gas supplies to Europe, compelling European nations to strategically diversify their energy portfolios by substantially increasing their LNG imports. As a result, European LNG imports surged by more than 60% in 2022. Notably, countries like Germany have reacted swiftly by commissioning new Floating Storage Regasification Units (FSRUs) in Wilhelmshaven and Lubmin within remarkably short timeframes, highlighting the urgency with which nations are adapting to the evolving energy landscape [70]. This sudden increase in demand from Europe has tightened global LNG supply chains, driving up spot prices and diverting cargoes from South Asia and Africa. This shift undermines energy affordability in price-sensitive economies like India and Bangladesh [71].

The trade tensions between the United States and China have significantly influenced LNG flows. During the height of the trade conflict from 2018 to 2019, China implemented tariffs on U.S. LNG, leading to a considerable decline in bilateral trade. However, following the Phase I trade agreement in 2020, China resumed large-scale LNG purchases from the United States. By 2021, the U.S. had emerged as one of China's largest suppliers of LNG [72]. The resumption of trade emphasizes the strategic adjustments made by both countries to maintain energy security in the face of global supply disruptions. In early 2025, escalating tensions between China and the U.S. prompted China to re-impose tariffs on U.S. imports of LNG, disrupting the previously stable energy exchanges between the two nations. Consequently, Chinese importers reduced their spot cargo purchases from the U.S. and redirected their procurement efforts toward Qatar, Russia, and Australia under existing long-term agreements. This shift led to a temporary decline in the market share of U.S. LNG in China and contributed to short-term price volatility in the Asia-Pacific region, highlighting the geopolitical sensitivity surrounding LNG trade [73].

In response to these developments, the EU has established a joint LNG procurement framework through the EU Energy Platform. This initiative aims to strengthen collective bargaining power and diminish price competition among member states. Concurrently, the United States has been enhancing its LNG export infrastructure, adding new liquefaction capacity at terminals such as Calcasieu Pass. Meanwhile, China has secured long-term LNG deals with QatarEnergy and other producers, ensuring supply availability beyond 2035, while also expanding its regasification infrastructure along its coastal provinces [74]. These actions demonstrate a strategic shift among major economies to safeguard their LNG policies from geopolitical instability.

1.12 Current Scenario of LNG in India

The rising demand for fuels free from pollutants has led to significant interest in alternative fuels, with natural gas emerging as a reliable and sustainable option. This shift is particularly relevant given the increasing levels of pollutants associated with conventional fossil fuels, which have been used for decades [75]. Among the various forms of natural gas, CNG is the most commonly used, offering an accessible solution for reducing emissions. Another variant, LNG, is gaining traction due to its enhanced compatibility and lower emissions. LNG is essentially a purified form of methane that is effective for powering M&HDVs. Its long-range capabilities and clean-burning characteristics make it a more competitive choice than CNG.

The increase in LNG imports reflects India's commitment to transitioning toward cleaner energy sources as it strives to achieve its sustainability objectives. The nation has set an ambitious target of reaching a 15% share of natural gas in its energy mix by 2030, as showcased in Figure 9, this will necessitate significant expansion and enhancement of its LNG infrastructure. At present, India operates a limited number of LNG terminals, with a regasification capacity of 42 million tonnes per annum (MTPA), which falls short of the projected demand of 70 MTPA by 2030 [76]. The current scenario of LNG imports in India indicates the progressive use of LNG, leading to a steady increase in the country's LNG imports. July 2024 is projected to be the month with the maximum number of LNG imports, valued at 2.8 million metric tonnes (MMT), while the total average for FY 2024-25 is approximately 2.4 MMT [76]. These data illuminate the anticipated usage of LNG as a transportation fuel in the coming years. As India pursues sustainable development and economic progress, the role of LNG in its energy landscape has become increasingly important. Recognized for its potential to lower carbon emissions and diversify energy supply, LNG is crucial for advancing a more environmentally friendly future. However, to fully capitalize on the benefits of LNG, India must address the pressing need to improve its LNG infrastructure. In India, a developing nation, there is a growing adoption of LNG as an alternative fuel, particularly for M&HDVs involved in goods transportation. As shown in Figure 10, the country is rapidly advancing its LNG import capabilities and developing technologies for LNG production and supply [6].

This transition signifies India's readiness to move away from traditional fossil fuels toward greener mobility solutions by integrating alternative fuels like LNG into its transportation sector. As the nation progresses in this direction, LNG is poised to become a primary fuel source for heavy commercial vehicles, reflecting a broader commitment to reducing environmental impact and promoting sustainable energy practices while nearing the target of achieving net zero, as it is evident from Figure 11. India has firmly established itself as the world's fourth-largest importer of LNG, with imports reaching approximately 22 MMT in the last financial year. This surge in imports has significantly enhanced the share of natural gas in India's overall energy consumption, reflecting the country's robust economic growth and commitment to transitioning toward cleaner energy sources. Projections indicate that India's LNG imports are expected to rise from 8.5% to 20% in the upcoming financial year, driven by ongoing investments in LNG infrastructure and production capabilities as seen in Figure 12. Currently, India boasts a regasification capacity of 30 MMT per annum, which is anticipated to expand to 55 MMT by 2025. Additionally, the country's gas pipeline network is expected to grow to 27,000 kilometers, facilitating better distribution of natural gas across various regions. The increasing reliance on LNG aligns with India's strategic objectives to reduce its dependence on conventional fossil fuels while promoting sustainable energy practices. Notably, LNG's role as a cleaner alternative to petrol and diesel is becoming increasingly recognized, particularly for HDVs, which are crucial for transportation and logistics. With the global LNG market witnessing a decline in prices—falling below $10 per MMBtu—Indian importers have been incentivized to engage more actively in spot market purchases, further bolstering demand as seen from Figure 13. As India continues its journey toward energy diversification, these developments will position the country on a trajectory to potentially become the third-largest LNG importer globally within the next five years. The government's initiatives to enhance domestic production alongside increasing imports underscore its commitment to achieving zero-emissions objectives while ensuring energy security for its growing economy. With LNG as a pivotal component of this strategy, it not only supports India's environmental goals but also strengthens its position in the global energy landscape [77, 78]. There are plans by both government and private entities to establish a total of 1000 stations nationwide. Currently, Indian Oil Corporation Ltd is setting up 20 LNG stations, with additional stations being constructed by Bharat Petroleum and Hindustan Petroleum. This initiative, which involves collaboration between the government and private sector, aims to replace diesel in long-haul vehicles and promote the use of cleaner fuel. Blue Energy Motors also participates in the establishment of these stations. The proposed 1000 stations are strategically located along key routes, including the Golden Quadrilateral and other major highways [79]. In addition, approximately 645–700 LNG-powered trucks are operating in India, reflecting the early stage of this sector. The Indian government aims to convert about one-third of its heavy truck fleet, which exceeds 7 million vehicles, to LNG within the next five to seven years, indicating ambitious growth projections for LNG trucks in the country [80].

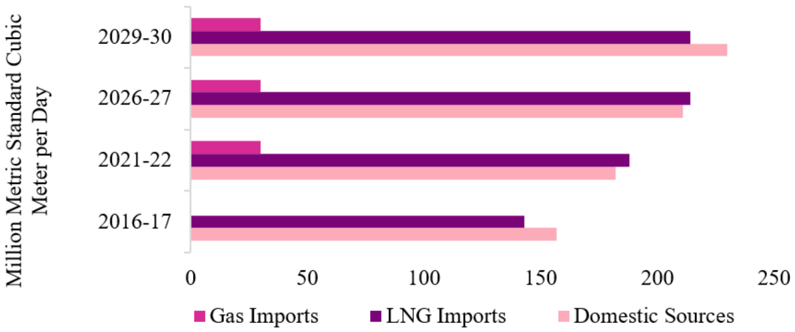

Figure 9. Natural gas forecast for the MMSCMD in India

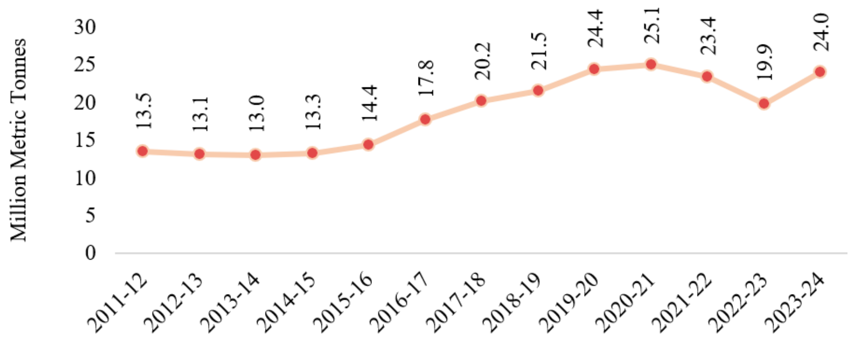

Figure 10. Total LNG imports (long term, spot) in MMT [81]

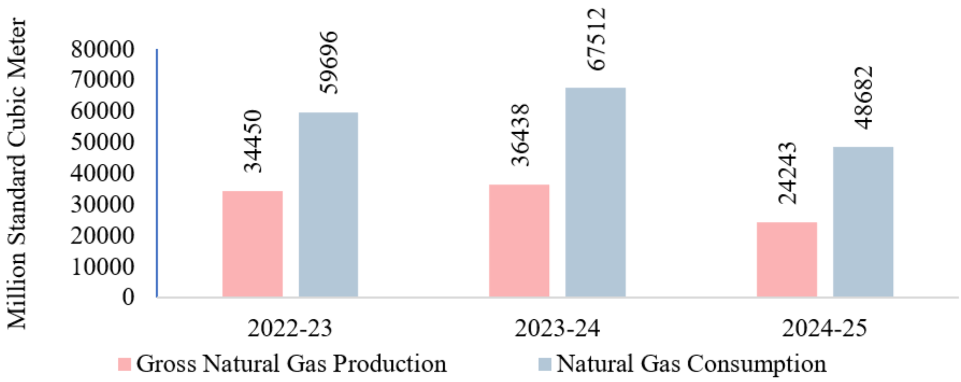

Figure 11. India's natural gas scenario for the past three years in MMSCM [82, 83]

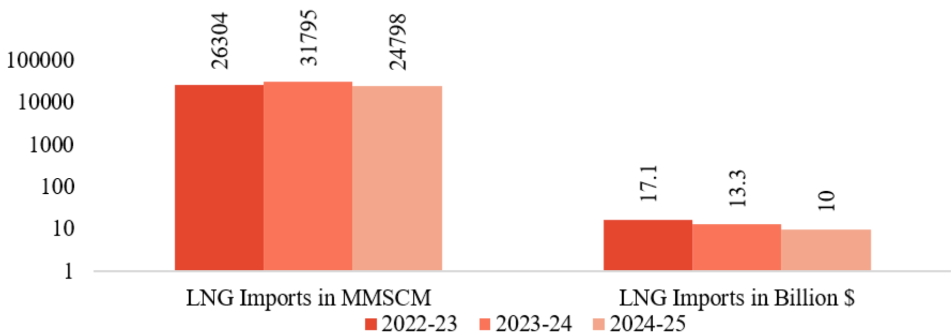

Figure 12. LNG imports in India [81, 84]

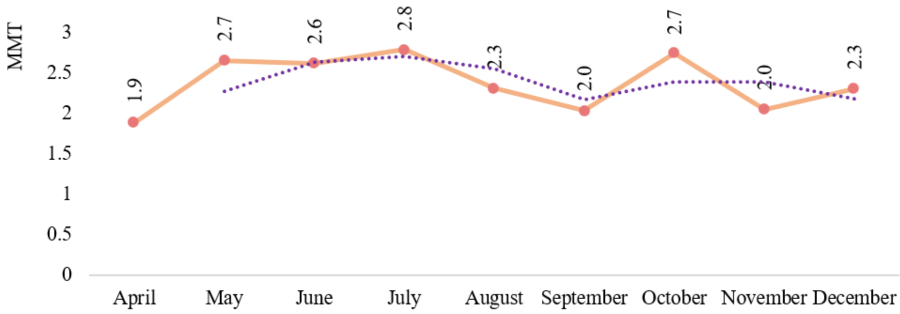

Figure 13. Total LNG imports in FY 2024-25 (in MMT) upto December 2024 [81]

1.13 Natural Gas Production

India is the third-largest emitter of GHGs on a global scale, and the transportation sector is the foremost contributor to these emissions. The capital city exemplifies the ecological harm caused by vehicles using petrol and diesel. According to a report from The Energy and Resources Institute [85], the transportation sector accounts for 47% of GHG emissions in the city. Furthermore, the power sector plays a notable role, contributing 8% of total emissions, as stated in the same report. Natural gas has emerged as a feasible, sustainable alternative. Although it is not entirely environmentally benign, it can significantly mitigate GHG emissions. The combination of domestic production and imported LNG has fulfilled the demand across various sectors for several years. However, there appears to be a decline in domestic natural gas production, leading to an increased reliance on imports for most supply.

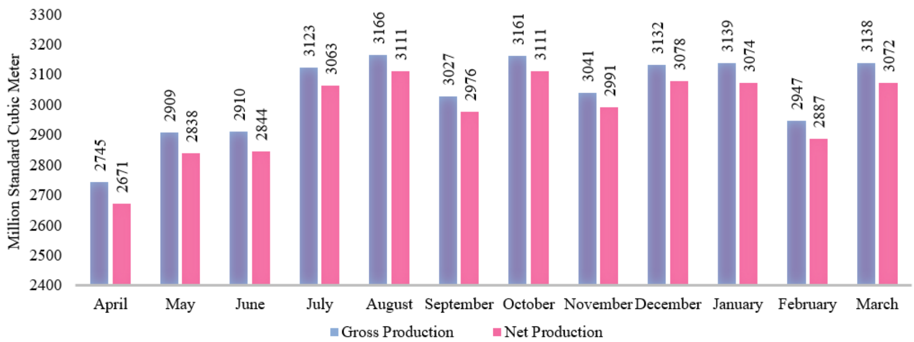

Figure 14. Natural gas production in India, 2023-24 (MMSCM) [83]

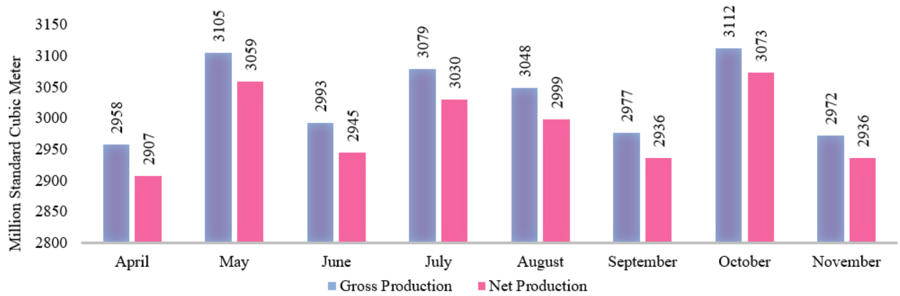

Figure 15. Natural gas production in India, 2024-25 (MMSCM) [83]

In October 2024, total LNG imports rose by 10.8%, reaching 2941 million standard cubic meters (MMSCM) compared with the same month the previous year. In contrast, domestic LNG production declined by 1.6% year on year (YoY), amounting to 3,111 MMSCM, according to provisional figures released by the Petroleum Planning & Analysis Cell (PPAC) and can be seen from Figure 14 and Figure 15. India's LNG import expenses have increased sharply recently. Imports for FY24 have nearly doubled from the levels seen in FY14, while domestic production has remained largely stagnant. Over the last decade, daily gas production has increased by only about 5%. In

September, natural gas production was reported at 2936 MMSCM, which is 8.4% lower than the government's target for that month based on official data. In the first quarter of FY25, imports satisfied up to 49% of India's gas demand. Furthermore, India was ranked as the fourth-largest LNG importer globally in 2023, with forecasts indicating continued growth in its imports over the next decade [77].

India's gas consumption, which faced challenges in FY 2023 due to rising LNG prices, experienced a significant recovery, reaching 187.9 million metric standard cubic meters per day in FY 2024, marking a 17% increase compared to the previous year. Looking ahead, consumption is projected to rise by 6-8% in FY 2025, supported by lower LNG prices and an increase in domestic gas production [86].

1.14 LNG Terminals in India

India's natural gas landscape has undergone significant transformation in recent years, driven by a marked increase in demand from the power and fertilizer sectors, which together account for over 75% of the country's gas consumption [20]. The growing reliance on natural gas is attributed to its availability, cost-effectiveness compared to alternative fuels, and its environmentally friendly characteristics. As domestic production struggles to keep pace with demand, India is increasingly turning to Re-Gasified Liquefied Natural Gas (R-LNG) to bridge the supply gap. Currently, India is witnessing a surge in LNG import terminal projects along its western and eastern coasts. The development of these terminals is crucial, as they are expected to triple the country's regasification capacity from current levels to over 80 MTPA within the next decade with the upcoming terminals as shown in Figure 16 and listed in Table 3. This expansion will facilitate greater access to LNG, enabling India to meet its growing energy needs while reducing its dependence on conventional fossil fuels.

Figure 16. LNG terminals in India

Table 3. Upcoming LNG terminals in India [87]

Proposed LNG Terminals	Capacity (MMPTA)	Operator
Jaffrabad, Gujarat	5.0	Swan LNG
Chhara, Gujarat	5.0	HPCL
Jaigarh, Maharashtra	6.0	WPCL
Karaikal, Puducherry	1.0	AG&P
Gopalpur, Odisha	5.0	Petronet LNG Limited
Kakinada, Andhra Pradesh	7.2	Crown LNG

As of now, the operational R-LNG terminals listed in Table 3 and Table 4 include significant facilities such as the Dahej Terminal in Gujarat, which has a capacity of 15 MTPA, and the Hazira Terminal, also in Gujarat, with a capacity of 5 MTPA. Additionally, the Dabhol Terminal in Maharashtra contributes another 5 MTPA. The government's strategic push for LNG infrastructure development aligns with its goal of increasing the share of natural gas in India's energy mix from approximately 6% to 15% by 2030 [88].This shift not only supports India's energy security but also positions natural gas as a pivotal transition fuel in the nation's journey toward a greener economy. The anticipated increase in LNG imports and infrastructure development reflects India's commitment to fostering a sustainable energy future while addressing the challenges posed by limited domestic supply. As such, LNG is poised to play a vital role in meeting India's energy demand and achieving its environmental objectives in the coming years.

Table 4. LNG terminals in India [87]

Operational LNG Terminals	Present Capacity (MMTPA)	Current Utilization (2023-24)	Operator
Dahej, Gujarat	17.5	95.10%	Petronet LNG Limited, a subsidiary of Petronet
Kochi, Kerala	5.0	20.60%	Petronet LNG Limited, a subsidiary of Petronet
Hazira, Gujarat	5.2	30.30%	Hazira LNG Private Limited (Hazira)
Dabhol Maharashtra	5.0	42.7%	Konkan-LNG, Ltd.
Ennore, Tamilnadu	5.0	18.30%	Indian Oil-LNG Private Limited
Mundra, Gujarat	5.0	14.60%	Gujarat State Petroleum Corporation Limited and Adani Enterprises Limited
Dhamra, Odisha	5.0	27.40%	Adani-Total-Gas Limited

2 Government Policies and Regulations for LNG Worldwide

2.1 China

China's experience with LNG adoption in the M&HDVs sector offers a clear example of how targeted subsidies and regulations can drive market transformation. To promote cleaner fuels and reduce urban air pollution, the government implemented a range of monetary incentives. For instance, in Beijing, a subsidy of ¥25,000 was offered to scrap older HDVs, while provincial governments provided up to 15% of the vehicle cost as financial support for purchasing LNG trucks. These measures significantly boosted adoption, particularly between 2012 and 2014, when LNG HDV sales surged alongside rapid expansion of refueling infrastructure. Policy actions were not limited to subsidies. In 2017, China banned diesel HDVs in the Beijing-Tianjin-Hebei region and promoted LNG alternatives by exempting them from excise tax. Despite higher upfront vehicle costs, LNG trucks became attractive to buyers due to their lower fuel costs, especially when global oil prices were high—as seen during 2017–2019, when Brent crude averaged $65 per barrel. These conditions allowed the payback period for LNG HDVs to fall to around 1.5 years, well within the average 4–5-year lifespan of such vehicles. By 2023, China had over 582,000 LNG HDVs and 4,800 LNG stations, making it the global leader. This case shows how financial incentives, infrastructure development, and regulatory push can work together to accelerate clean fuel adoption [69, 89].

2.2 EU

The EU's approach to promoting LNG in the HDV sector stands out for its structured policy framework and targeted funding mechanisms. Between 2011 and 2014, a total of €117.2 million—with up to 50% EU co-funding—was invested in early infrastructure and vehicle deployment projects. Landmark initiatives such as the LNG Blue Corridor (2014–2018) and LNG Motion (2016–2020) were instrumental in building the market ecosystem. The Blue Corridor funded 140 LNG HDVs and 12 refueling stations, while LNG Motion supported 200 HDVs and 42 LNG stations along TEN-T corridors. These projects were not only infrastructure-oriented but also focused on real-world feasibility studies, commercial and environmental assessments, and standardization. A critical policy driver was the Directive on Alternative Fuel Infrastructure (DAFI, 2014), which mandated member states to establish national frameworks for alternative fuels and required LNG stations at every 400 km on core transport corridors by 2025. Additionally, the 2019 Zero and Low Emission Vehicle (ZLEV) regulations enforced stricter CO_2 standards and incentivized manufacturers to produce cleaner vehicles by offering regulatory credits. By 2020, 93% of Europe's LNG HDV fleet was concentrated in Italy, Spain, Germany, and the Netherlands—highlighting these nations' effective implementation of EU-wide policy. This case illustrates the importance of cohesive policy design, financial support, and regional cooperation in enabling clean fuel transitions [69, 90].

2.3 United States of America

The U.S. government has implemented a series of policies and regulations to facilitate the growth of LNG exports, reflecting its strategic importance in global energy markets and environmental considerations. The 2024 LNG Export Study by the Department of Energy (DOE) highlights the significant increase in U.S. LNG exports since 2016, with current export authorizations totaling approximately 48.45 billion cubic feet per day (Bcf/d). This study employs advanced modeling techniques to assess the economic and GHG implications of varying export levels, revealing that unconstrained LNG exports could raise domestic natural gas prices by 30% and residential prices by 4% by 2050. The study also emphasizes the potential for increased GHG emissions, estimating an additional 711 million metric tons of CO_2 equivalent emissions under higher export scenarios. Key initiatives, such as the Directive on Alternative Fuel Infrastructure, aim to standardize LNG infrastructure and promote its use, while financial incentives for LNG projects have been crucial in attracting investments. The U.S. has positioned itself as a leading global LNG supplier, particularly to Europe, which has seen its share of imports rise significantly since the onset of the Ukraine crisis. However, the future demand for U.S. LNG remains uncertain because of shifting global energy policies that prioritize decarbonization and alternative energy sources. The DOE's analysis suggests that while U.S. LNG can displace higher-emission fuels globally, it may also lead to increased overall natural gas consumption, complicating its role in the energy transition. Overall, U.S. LNG policies reflect a balance between enhancing energy security and addressing environmental impacts, with ongoing evaluations needed to align export strategies with climate goals [91]. The United States has adopted a market-driven approach to the adoption of LNG in the HDVs sector, primarily supported by tax incentives and emissions regulations. Significant federal incentives include the Alternative Fuel Excise Tax Credit and grants available through the DOE's Clean Cities Program. Furthermore, the U.S. has made investments in expanding LNG infrastructure via the American Recovery and Reinvestment Act (ARRA), fostering public-private partnerships. In contrast to the EU's coordinated corridor strategy, LNG adoption in the U.S. has been regionally concentrated, particularly in states such as California and Texas, guided by local air quality mandates and economic considerations for fleets. The use of Renewable LNG (RLNG) is also on the rise, bolstered by Low Carbon Fuel Standard (LCFS) credits. However, national uptake of LNG remains modest in comparison to diesel and CNG fleets.

2.4 Australia

The current scenario for LNG in Australia reflects the complex interplay of economic growth, government policies, and market dynamics. Following a peak in LNG investment around 2013, the sector has transitioned toward ramping up production and exports, contributing significantly to Australia's GDP—estimated at around 0.75 percentage pointst in 2016/17. As LNG is projected to become Australia's second-largest commodity export by 2018, its value is intricately linked to global oil prices, which directly influence terms of trade and domestic income levels. The Australian government has implemented various policies to support the LNG sector, including tax incentives and regulatory frameworks that facilitate investment and production. These measures aim to enhance LNG export competitiveness while addressing environmental impacts. However, the capital-intensive nature of LNG production means that while household incomes may benefit from employment in the investment phase, the production phase relies less on labor, potentially limiting broader economic benefits. In addition, government revenues from corporate taxes and royalties are expected to rise with increased LNG production, although fluctuations in oil prices can significantly impact revenue generation. The government continues to encourage exploration and development through Strategic Basin Plans, aiming to capitalize on the growing global demand for LNG. Despite these positive trends, challenges remain, including the need for sustainable practices and managing foreign ownership stakes in the industry, which can affect domestic economic benefits. Overall, while the Australian LNG sector presents substantial opportunities for economic growth and energy security, careful management of its development and integration into the broader economy will be crucial for maximizing its benefits to Australian consumers and communities [92, 93].

Key Learnings: India can draw valuable lessons from the global adoption of LNG as a transportation fuel, particularly in the context of government incentives and private initiatives. A key takeaway is the importance of implementing non-fiscal incentives to change public perception and encourage the adoption of alternative fuel-fired vehicles. For instance, India could consider establishing priority lanes for LNG vehicles or granting them access to urban areas during high pollution days, similar to successful models observed elsewhere. Additionally, introducing eco-labelling for LNG vehicles could enhance visibility and consumer awareness, fostering a sustainable mindset among the public. The establishment of low-emission zones in heavily polluted cities would further support the transition to cleaner fuels by restricting access to higher-emission vehicles. Moreover, India could benefit from creating a demand aggregator for LNG trucks to streamline procurement and reduce costs, akin to existing models in the electric vehicle sector. Fiscal measures such as reducing the Value-added Tax (VAT) on LNG sales and providing subsidies for LNG vehicle purchases can significantly lower operating costs and stimulate market growth.

Furthermore, setting quotas for public sector fleets to include a percentage of LNG vehicles can drive demand and encourage manufacturers to invest in this space. Overall, adopting a multifaceted approach that combines regulatory frameworks, fiscal incentives, and innovative non-fiscal measures will be crucial for India to successfully promote LNG as a viable alternative fuel in its rapidly expanding transportation sector.

2.5 India

The global LNG market is rapidly evolving to address the needs of market participants and to adapt to changing conditions as summarized in Figure 17. Increasing demand for gas in emerging markets, a broader range of market players, and advancements in LNG infrastructure and technology are key trends shaping the industry. However, challenges such as regulatory issues, geopolitical tensions, infrastructure limitations, and environmental concerns may hinder LNG sector growth and create uncertainty. To navigate these opportunities and challenges, innovative project planning is essential for ensuring the long-term sustainability of LNG. The Indian government has undertaken significant initiatives to promote LNG as a viable alternative fuel in the transportation sector. As supportive regulations and policies are essential for the successful adoption of alternative fuels, these measures aim to foster infrastructure development and mitigate market uncertainties associated with new technologies. The government's commitment is particularly critical for enhancing the use of LNG in M&HDVs, which is expected to contribute to emission reductions and decrease reliance on oil imports. India has set ambitious targets for reducing emissions and oil import dependency over the next decade, with the transportation sector being a major contributor to national emissions. By focusing on LNG in HDVs, the government addresses both environmental concerns and energy security, aligning with its long-term sustainable strategy. To promote the usage and distribution of LNG, the government has placed LNG imports under the Open General Licensing (OGL) category, and the establishment of LNG infrastructure, including LNG terminals, is also permitted under 100% Foreign Direct Investment (FDI) through the automatic route. The government is also promoting the usage of natural gas in gaseous/liquid (LNG) forms through the expansion of gas infrastructure, including City Gas Distribution, gas grid networks, and the development/retrofit of LNG-based vehicles [94]. In April 2018, the Petroleum and Explosives Safety Organization (PESO) issued updated guidelines that established specific safety protocols for LNG storage at dispensing stations. These regulations require compliance with the ASME Boiler and Pressure Vessel Code and EN13458, with pressure limits of 20 kg/m^2. Additionally, safety relief valves are mandated on inner vessels to prevent overpressure, while transport vessels must adhere to stringent safety standards to ensure that no aluminium valves or fittings are used externally [94].

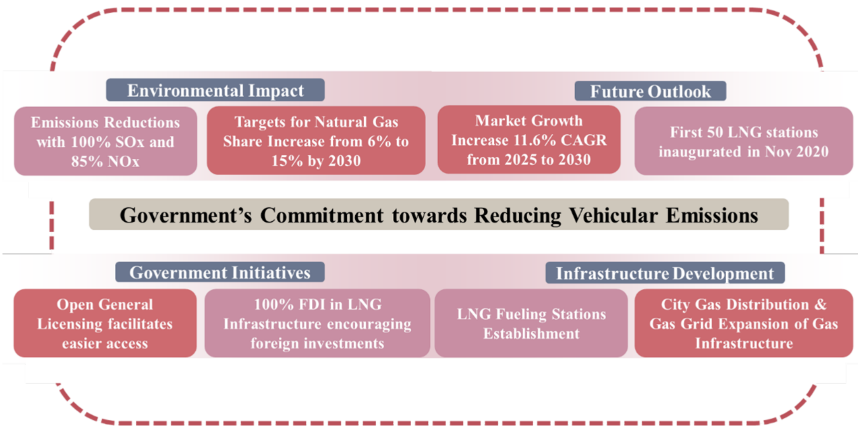

Figure 17. Government initiatives and future pathway for emission reduction using LNG [94]

Comprehensive operating procedures and emergency preparedness plans are also required to maintain high safety standards at LNG facilities. Further regulatory measures include the Ministry of Road Transport and Highways (MoRTH) rule GSR 1151(E), which mandates that retrofitted diesel engines using LNG or dual-fuel systems comply with existing diesel emission norms. Type approval certificates for dual-fuel kits are valid for three years and can be renewed, ensuring that new original equipment manufacturer (OEM) engines or converted gasoline engines fitted with LNG systems meet the same mass emission standards as CNG vehicles. The Petroleum and Natural Gas Regulatory Board (PNGRB) has clarified regulations regarding the establishment of standalone LNG stations, allowing any entity to set up an LNG station without needing authorization for a City or Local Gas Distribution Network (CGD). This regulatory clarity is expected to encourage investments in LNG infrastructure.

In 2021, the Ministry of Petroleum & Natural Gas (MoPNG) released a draft policy emphasizing the development of LNG terminals and pipelines to facilitate importation and distribution across India, particularly targeting the transportation and mining sectors. The MoRTH rule GSR 336(E) aims to promote LNG usage in agriculture, specifically in tractors, power tillers, and harvesters. The Indian government's proactive stance includes various strategies designed to enhance the adoption of LNG as an alternative fuel. By implementing favourable policies for fleet operators and fueling infrastructure owners, India seeks to transform its energy landscape. The establishment of LNG stations is anticipated to significantly reduce vehicular emissions while simultaneously supporting economic growth through a transition to cleaner energy sources. These initiatives underscore India's commitment to transitioning toward a gas-based economy by increasing the share of natural gas in its energy mix from 6% to 15% by 2030. The strategic emphasis on developing LNG infrastructure not only addresses current energy demands but also aligns with broader environmental objectives aimed at minimizing carbon emissions from the transportation sector. Through these comprehensive policies and regulations, India is laying the groundwork for a sustainable future powered by LNG. The Indian government's recent regulatory framework reflects a concerted effort to promote LNG as an alternative fuel in the transportation sector. By establishing necessary safety protocols, emission norms, and facilitating infrastructure development, these measures aim to enhance the adoption of LNG among M&HDVs while simultaneously addressing pressing environmental concerns related to emissions and energy security. The government's ambitious targets for increasing natural gas's share in the primary energy mix further demonstrate its commitment to fostering a sustainable energy future through strategic investments in LNG infrastructure.

The Government of India has facilitated the adoption of LNG as a transportation fuel by amending the Central Motor Vehicle Rules of 1989, thereby officially recognizing LNG in this capacity. In addition, initiatives have been developed to establish LNG fueling infrastructure throughout the nation. The global LNG market is expected to witness a compound annual growth rate of 11.6% from 2025 to 2030, reaching USD 226.97 billion by 203. A significant milestone was achieved in November 2020, with the inauguration of the first 50 LNG fueling stations. The Ministry of Petroleum and Natural Gas asserts that utilizing LNG in HDVs results in a substantial reduction in exhaust emissions, achieving a complete elimination of SOx and an 85% decrease in NOx emissions [95].

3 LNG as Fuel for IC Engines

3.1 Performance and Emission

As the global use of natural gas increases across various sectors, including transportation, the adoption of LNG as a fuel for M&HDVs is gaining interest. Consequently, studying the advantages and challenges of LNG as a dedicated fuel source for Internal Combustion (IC) engines is essential (Figure 18). LNG can be utilized in three distinct forms within IC engines: first, as the primary fuel source in dedicated LNG engines operating on spark ignition; second, as a secondary fuel source through direct gas injection in compression ignition engines; and third, in power generation plants utilizing dual-fuel capability engines [96].

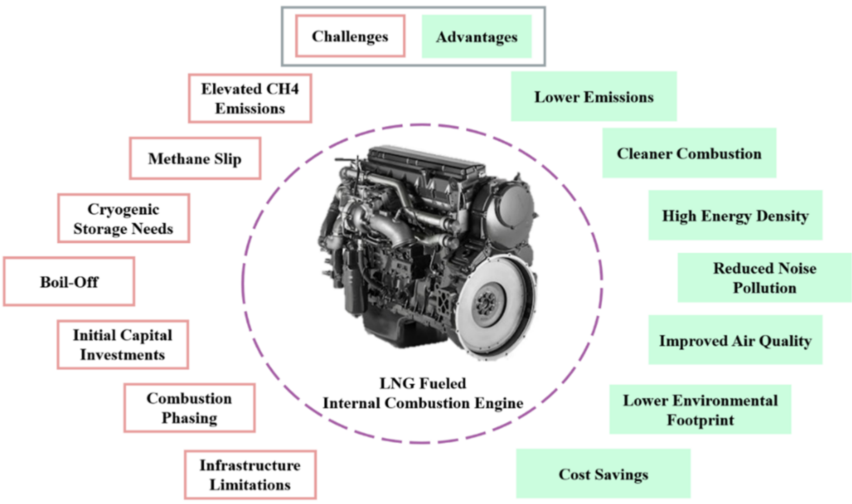

Figure 18. Challenges and advantages of LNG as an automotive fuel

The study by Singh et al. [37] significantly advances the understanding of LNG as a sustainable fuel option for heavy-duty engines adhering to BS VI standards. Their research established a comprehensive procedure for LNG engine testing, which included the creation of a dedicated LNG fuel storage and dispensing system, as well as a specialized testing facility. The successful storage, dispensing, and use of LNG were demonstrated while adhering to stringent safety protocols. A novel forced convection heating method was introduced to mitigate icing issues in the LCNG line, and a dedicated engine oil (SAE 15W-40, API CG4) was developed specifically for LNG applications.

The study included extensive endurance testing over 1500 hours and field trials covering 30,000 km to confirm the engine's performance and the oil's suitability for long drain intervals. The results indicate significant emission reductions compared with CNG, with notable decreases in CO, NMHC, and CH_4, and a slight increase in NOx. Overall, these findings underscore the practical viability of LNG buses and the effectiveness of the newly developed engine oil, providing a valuable framework for future LNG projects.

Boretti [97] described a detailed procedure for LNG engine testing, highlighting the advantages of using LNG as a fuel in dual-fuel diesel-LNG ICEs. His research emphasizes the implementation of two high-pressure injectors per cylinder—one for diesel and one for LNG—coupled with super-turbocharging, which enhances fuel energy conversion efficiencies while significantly reducing emissions of CO_2, PM, and NOx. The study indicates that diesel-LNG ICEs not only improve air quality in polluted regions but also offer a better carbon-to-hydrogen (C/H) ratio, further decreasing CO_2 emissions. The findings suggest that LNG, which is derived from methane rather than oil, allows for the diversification of fossil fuel supplies, which is particularly beneficial for countries rich in natural gas. Additionally, the paper discusses the critical role of high-performance LNG injectors in achieving superior combustion characteristics, thereby minimizing the reliance on diesel fuel and enhancing the overall engine performance. The results indicate that diesel-LNG engines can match or exceed the performance and emissions profiles of traditional diesel-only engines, paving the way for further advancements in injection and combustion technologies.

The use of LNG as a supplementary or alternative fuel in dual-fuel diesel engines presents significant opportunities to enhance efficiency and reduce emissions, particularly under low-to-medium-load conditions. Research on diesel-LNG dual-fuel combustion highlights the critical role of combustion phasing, quantified through the centroid angle of combustion duration α, in optimizing Brake Thermal Efficiency (BTE) and NOx emissions. By adjusting the diesel injection timing, the combustion centroid angle can be strategically positioned relative to the Top Dead Center (TDC), directly influencing the performance outcomes. At low loads, retarding α to 1–2°CA after TDC (ATDC) improves BTE by up to 16.7% compared to later phasing, while simultaneously mitigating NOx emissions, which remain below 500 ppm due to lower in-cylinder temperatures. However, this adjustment increases unburned Total Hydrocarbons (THC) and Carbon Monoxide (CO) emissions, underscoring a trade-off between efficiency and incomplete combustion by-products. At medium loads, advancing α near TDC initially elevates BTE but risks efficiency losses if combustion shifts excessively before TDC, alongside a sharp rise in NOx due to higher peak temperatures. These findings emphasize LNG's potential to decouple efficiency and NOx trends when combustion phasing is optimized, particularly in dual-fuel mode. By prioritizing precise control over injection timing to maintain α within 1–2°CA ATDC, LNG-diesel systems can achieve a favourable balance—sustaining thermal efficiency while curbing NOx, even as challenges like THC and CO emissions necessitate further combustion strategy refinements. This positions LNG as a viable transitional fuel, enabling emission reduction without compromising the energy conversion efficacy of conventional diesel architectures [98].

A study conducted by Lee et al. [99] investigates various factors that affect NOx emissions and the performance of LNG ICEs, with a particular emphasis on the use of Exhaust Gas Recirculation (EGR) as an emission control strategy. Key parameters influencing NOx emissions include spark timing, equivalence ratio, and boost pressure. The formation of NOx is predominantly governed by the concentration of oxygen and the temperature within the cylinder. At equivalence ratios below 0.9, reduced heat release leads to a decrease in cylinder temperature, which in turn slows the rate of NOx formation, resulting in lower emissions. Optimal spark timing is essential, as it directly influences NOx formation by affecting the peak pressure in the combustion chamber. Delaying the spark timing correlates with a reduction in engine pressure, which consequently lowers cylinder temperature. Since the rate of NOx formation depends on temperature, a decrease in temperature results in a slower reaction rate, thereby reducing NOx emissions. Additionally, effective management of boost pressure is critical; exceeding 15 kPa can lead to a significant increase in HC emissions. The implementation of EGR proves to be a successful strategy for mitigating NOx emissions, as the high specific heat of recirculated gases contributes to lowering peak temperatures. Increasing the EGR rate from 0% to 20% can lead to an impressive 96% reduction in NOx emissions, though this may also increase HC emissions and Indicated Specific Fuel Consumption (ISFC). Consequently, the authors recommend an optimal EGR rate of 15%, which achieves an 86% reduction in NOx emissions while maintaining acceptable levels of engine efficiency.

The adoption of LNG as a fuel in spark-ignition engines, particularly when integrated with Reformed Exhaust Gas Recirculation (REGR), offers a pathway to reduce emissions while enhancing combustion efficiency, albeit with nuanced trade-offs. REGR, which generates hydrogen-rich reformates via the catalytic conversion of exhaust and fuel, improves methane (CH_4) oxidation in LNG engines by elevating the concentrations of reactive radicals (OH, O, H), thereby reducing total CH_4 emissions by up to 12% at high loads as the reformate addition ratio (Rref) increases. However, this strategy introduces challenges: CO emissions rise significantly with higher Rref, primarily due to unburned CO from the reformate itself, which becomes the dominant source (over 9% of total CO) at Rref = 10%. Furthermore, valve timing adjustments, such as delaying exhaust valve closure (EVC), exacerbate hydrocarbon (HC) and CO emissions due to increased leakage during overlap periods, despite marginal reductions in unburned in-cylinder residues [100]. These findings underscore the dual role of LNG—its high hydrogen content and clean-burning potential can be leveraged to mitigate CH_4 slip through REGR-optimized combustion, yet its efficacy critically depends on reformate composition and valve timing precision. To minimize emissions, low-CO reformate and shorter valve durations are recommended to balance radical-driven CH_4 oxidation with CO containment. Thus, while LNG presents inherent advantages in decarbonizing engine systems, its synergy with REGR demands careful calibration to address co-emission risks, positioning it as a viable but complex solution for sustainable combustion strategies. The adoption of LNG in M&HDVs offers significant environmental advantages, particularly in reducing SOx, NOx, and PM emissions, compared to conventional diesel fuels like Marine Gas Oil (MGO). Studies on dual-fuel LNG engines have demonstrated a 136-fold reduction in ultrafine particulate emissions (PN23) at high loads, which is aligned with urban air quality [101].

Several advanced technologies have been implemented in natural gas ICEs, including Homogeneous Charge Compression Ignition (HCCI), dual fuel combustion, the Miller Cycle, long stroke technology, and EGR, as well as various combinations of these methodologies. HCCI technology in natural gas engines utilizes direct injection of gas to facilitate autoignition and diffusion combustion, thereby enhancing thermal efficiency and performance by eliminating intake throttling losses and enabling higher compression ratios. Similarly, dual-fuel technology employs natural gas as the primary fuel, with diesel injected for ignition, which serves to enhance efficiency and reduce emissions. Miller Cycle technology involves the strategic early or late closure of the intake valve, resulting in a reduced effective compression ratio and lower cylinder temperatures. This approach not only enhances combustion efficiency but also lowers emissions while using high supercharging to compensate for the diminished air intake volume. The long stroke technology extends both the compression and expansion strokes, allowing for improved mixing of natural gas and air, further enhancing the combustion efficiency. This methodology effectively reduces engine speed and friction loss while also incorporating EGR to lower combustion temperatures and mitigate the production of harmful NOx emissions, thereby improving overall engine performance [102]. Selective Catalytic Reduction (SCR) in LNG ICEs dramatically reduces NOx emissions, achieving reductions of over 90%. Additionally, it enhances fuel efficiency by 5% to 7% and supports compliance with strict environmental regulations. The SCR technology operates by injecting a urea-water solution into the exhaust stream, where it reacts with NOx in the presence of a catalyst, converting harmful emissions into harmless nitrogen and water vapor [103].

Currently, high-power ICEs predominantly use fuels such as HFO, Very Low Sulphur Fuel Oil (VLSFO), diesel oil, or LNG. To comply with stringent emissions regulations, there is an urgent need for alternative fuels, with liquid hydrogen (H_2) emerging as a promising option, particularly when produced from renewable energy sources. Kang-Ki Lee et al. investigated the potential of hydrogen-enriched slush LNG ($CH_4(H_2)_4$) as a transitional fuel, emphasizing its advantages over liquid hydrogen, including its higher density and the capability to utilize methane as a carrier for hydrogen. Experiments conducted on a medium 5-speed single-cylinder engine demonstrated that the admixing of hydrogen with natural gas can significantly reduce CO_2 emissions; for instance, a 30% hydrogen blend resulted in approximately a 10% reduction in CO_2 emissions, while an 80% blend achieved over a 50% reduction. Notably, a 100% hydrogen mixture resulted in zero CO_2 emissions, albeit with significant derating, which raises questions regarding the maintenance of stable combustion. This research underscores the viability of hydrogen-enriched slush LNG as a fuel source, paving the way for future advancements in hydrogen fuel technology [104].

An experiment examining the impact of methane content in natural gas has demonstrated that LNG containing 99% methane significantly outperforms LNG with 93% methane content. The higher methane concentration delivers superior antiknock performance, enhanced power output, and improved fuel economy. Notably, when the compression ratio is increased from 11.6 to 14, the LNG with 99% methane is able to sustain maximum loads across all tested speeds, achieving a maximum reduction of 6.4% in BSFC. In contrast, the LNG with lower methane content experiences limited maximum load capabilities at high speeds due to knocking combustion. Furthermore, the increased methane content allows for a larger knock-limited spark advance angle, enabling earlier ignition and further contributing to reduced BSFC. These findings highlight the critical role of methane content in optimizing the performance and emissions characteristics of LNG-fuelled engines, emphasizing the potential of LNG as a cleaner and more efficient alternative fuel source [105].

The performance and emission characteristics of LNG in ICEs present significant advantages, as demonstrated by various studies. Utilizing LNG consistently leads to enhanced fuel efficiency and a reduction in CO_2 and NOx emissions, while producing minimal PM and SOx emissions. This is achieved without compromising power output, acceleration, or range when compared to CNG vehicles. Furthermore, the implementation of emission control strategies, such as SCR and EGR, effectively mitigates harmful emissions, ensuring adherence to stringent environmental regulations.

3.2 Real Driving Emissions (RDE)

Recent real-world studies using portable emission measurement systems (PEMS) have highlighted the complex emissions profile of LNG in M&HDVs. Compared to diesel engines, LNG-powered vehicles emit significantly fewer Particle Numbers (PN), thereby reducing reliance on Diesel Particulate Filters (DPFs). However, higher THC levels, primarily from unburned methane—a potent GHG—pose substantial challenges, necessitating targeted mitigation approaches. Testing has revealed that NOx emissions spike under real driving conditions, particularly during stop-and-go traffic, where SCR systems underperform due to inconsistent exhaust temperatures [106]. Although LNG vehicles meet China's IV and V emission standards, methane leakage undermines their climate advantages, highlighting a critical area for improvement. The diesel counterparts produce lower THC but substantially higher PN emissions, underscoring the need for retrofitting with DPFs. Advancements in combustion optimization and adaptive after-treatment technologies are crucial to maximizing LNG's potential as a transitional fuel, ensuring its environmental benefits translate effectively in real-world use.

LNG-powered buses exhibit distinct real-world emission characteristics compared to CNG and hybrid-CNG alternatives, presenting both challenges and niche applications. Real-driving tests reveal that LNG buses emit the highest levels of CO, NOx, PM, and black carbon (BC), with BC/PM ratios ($\sim 40\%$) far exceeding those of CNG (7.6%) and hybrid-CNG (33%), indicating inefficient combustion and higher soot production. Although LNG's NOx emissions (23.56 g/km) are elevated, its NO2 contribution (0.82 g/km) is lower than that of CNG (1.58 g/km), suggesting potential benefits in urban areas sensitive to NO2 pollution. However, methane slip and incomplete combustion drive elevated the THC, a critical gap given methane's high global warming potential (GWP). Key parameters requiring industry attention include optimizing combustion efficiency to reduce PM/BC, enhancing after-treatment systems (e.g., SCR) for NOx control under low-speed, stop-start conditions, and addressing methane leakage through advanced fuel injection technologies. While LNG buses are less favourable than CNG in terms of fuel efficiency and emissions, their application could be optimized on routes with steady speeds to minimize acceleration-linked emissions. For urban zones with traffic congestion, hybrid-CNG buses, despite their higher BC emissions, offer lower PN emissions, making them preferable. The LNG industry must prioritize real-world emission mitigation strategies, including adaptive engine calibration and hybrid integration, to align with sustainability goals [107].

LNG has also proven to be a promising source of fuel for the marine industry. Recent regulations such as the FuelEU maritime aim to lower GHG emissions from vessels in the EU and the EEA by advocating for the use of renewable and low-carbon fuels. This has increased the focus on employing low-carbon, high-density fuels like LNG for marine applications, and hence, a lot of research has been done on LNG's implications for performance and emissions. N. Kuittinen et al. in his study investigated the methane slip and emissions from a 4-stroke low-pressure dual-fuel LNG engine aboard a new cruise ship, emphasizing real-world operational impacts. Results revealed that methane slip escalated sharply at low engine loads (21 g/kWh at 12% load) but remained moderate at higher loads (2.3–3.0 g/kWh at 54% to 80% loads). LNG reduced PM and BC emissions by 87% to 99% compared to MGO, although PN > 10nm rose by 26% at minimal loads. Formaldehyde emissions from LNG combustion were passively mitigated by the SCR system, even without urea injection. Weighted methane slip, accounting for the vessel's 8-month Mediterranean operation (90% above 40% load), averaged 1.7% of fuel use—below FuelEU Maritime's 3.1% default. This aligns with prior real-driving studies showing methane slip's load dependency and underscores the need for engine load profiling to refine fleet-level GHG assessments. The findings reinforce that LNG's climate benefits hinge on minimizing low-load operation and optimizing after-treatment systems, which are critical for maritime decarbonization strategies [108].

LNG demonstrates significant potential as a transitional fuel for ICEs, offering reduced emissions of CO, NMHC, PM, and CO_2 compared to diesel and CNG, alongside improved efficiency in dual-fuel configurations with optimized combustion phasing. However, challenges such as methane slip (unburned CH_4), elevated NOx under real-world conditions, and trade-offs between THC/CO emissions and efficiency persist. To advance LNG technology, developments in combustion optimization (e.g., precise injection timing, high-pressure injectors), adaptive after-treatment systems (e.g., SCR for NOx, low-CO reformate integration), and methane slip mitigation (e.g., load management, hybrid architectures) are critical. Additionally, infrastructure enhancements (specialized storage, engine oils) and regulatory frameworks promoting real-world emission monitoring and lifecycle methane leakage control are essential. By addressing these challenges, LNG can solidify its role in decarbonizing medium- and heavy-duty transport and maritime sectors, balancing environmental benefits with operational practicality.

3.3 Life Cycle Analysis (LCA)

Understanding LCA is crucial for evaluating the environmental impacts and sustainability of LNG throughout its entire supply chain. As stricter emission regulations emerge globally, LCA has become an essential tool for measuring GHG emissions from LNG production to its final consumption. A thorough assessment of LNG's ecological footprint encompasses several stages: raw material extraction, production, transportation, and consumption, an overview of which is shown in Figure 19. By analyzing each phase, stakeholders can identify significant sources of GHG emissions and other environmental burdens, facilitating informed decisions regarding energy sources and technologies. This process not only emphasizes LNG's lower emissions than traditional fossil fuels but also promotes operational efficiency and strategies for emission reduction. Customized LCAs can provide insights into specific emission intensities from different suppliers, enabling better comparisons and fostering innovation in cleaner practices [109]. As the global energy landscape increasingly shifts toward lower-carbon alternatives, LCAs are vital for policymakers and industry leaders advocating for LNG as a cleaner energy option. They help identify opportunities for technological advancements that can further reduce environmental impacts, such as investments in more efficient processing methods or enhanced recovery systems. Ultimately, comprehensive LCA studies enhance transparency and accountability within the LNG sector, guiding the transition to a more sustainable energy future while effectively addressing climate change challenges [110].

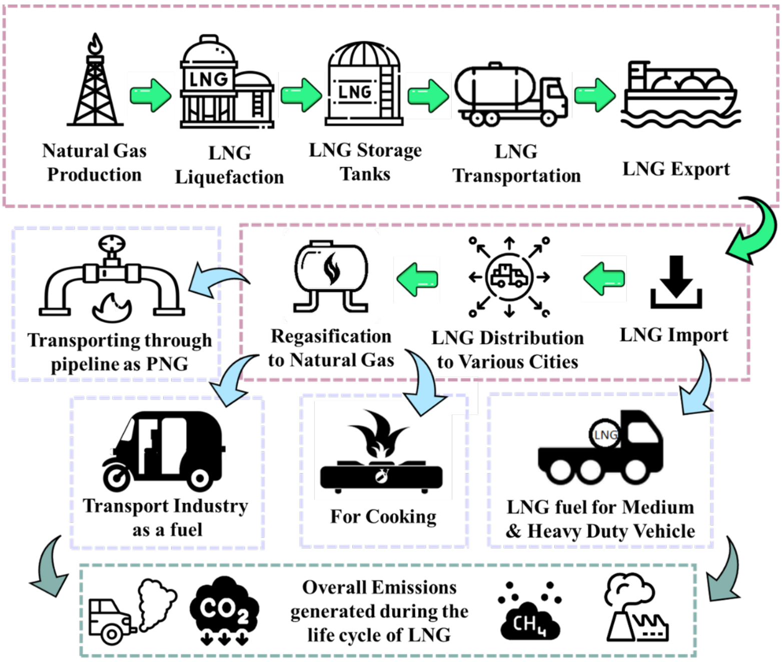

Figure 19. Life cycle of LNG fuel

The emissions associated with the LNG life cycle start at the production stage, specifically during the natural gas extraction process, which occurs at wells designated for this purpose. At this stage, emissions are primarily generated by the fuel consumption of the driving turbines and drivers required to operate the necessary equipment for extracting natural gas. Additionally, emissions are released through the flames produced by the combustion of waste gases, as well as through the venting of gas and a phenomenon known as methane leakage, which occurs during the extraction of natural gas. CO_2 is emitted from the combustion of natural gas, a fuel used for gas turbines that drive compressors to deliver natural gas. The amount of CO_2 emitted in this process varies according to the flow pressure of the gas [111]. The magnitude of these emissions is contingent on the type, method, and quantity of natural gas being extracted at the facility. Purge gas, which is used during emergencies or during start-up phases, is typically burned and emitted from the flare stack as CO_2. Under normal operational conditions, certain gas fields do not generate any CO_2 because of flare combustion. To ensure the removal of water vapor, natural gas undergoes dehydration using glycol as a solvent. During the process of regenerating the solvent, liquid is flushed out, resulting in the release of methane (CH_4) along with other dissolved hydrocarbons. Hydrocarbons can also escape from the venting system. In addition to these emissions, BOG generation is another important aspect of the LNG life cycle that contributes to the overall emissions. BOG refers to the natural vaporization of LNG due to heat ingress during storage and transportation. As LNG is stored at cryogenic temperatures, any increase in temperature can lead to the formation of vapor, which must be managed to maintain the integrity of the storage system. Currently, methods are employed to manage these emissions; hydrocarbons are either incinerated through flaring before release or redirected back into the fuel line to minimize atmospheric discharge. Research has indicated that the volume of gas leaking from compressors is negligible, so it can be regarded as insignificant.

However, in another study made with the shale-based LNG produced and exported in the United States, the carbon dioxide (CO_2) emissions from end-use combustion represents only about 34% of the total LNG GHG footprint. In contrast, upstream and midstream methane emissions account for 38% of total emissions. Consequently, the overall GHG footprint of LNG is 33% greater than that of coal, with average emissions of 160 g CO_2-equivalent/MJ compared to coal's 120 g CO_2-equivalent/MJ. This result raises substantial environmental concerns [112]. Another study reviewed systematically, the Well-to-Wheel lifecycle emissions of LNG compared to diesel for the entire supply chain. Key factors influencing emissions include natural gas engine fuel efficiency and methane leakage, which varies significantly from 0.3% to 20%. While LNG trucks may achieve up to a 10% reduction in efficiency and also a 10% higher emission relative to diesel, achieving net-zero emissions by 2050 remains challenging. Utilizing biomethane can further decrease emissions by 34–66%, emphasizing the importance of managing methane leakage in the supply chain [113]. In 2024, A report by ICCT presented that 55-tonne tractor-trailer that runs on LNG emits approximately the same level of emissions as its diesel version, a natural gas-fueled [114].

Following extraction, natural gas must be liquefied and transformed into LNG to facilitate transportation over long distances, a process that produces another set of emissions. Specifically, the liquefaction process, which involves converting natural gas into liquid form, also generates gases and results in carbon emissions, thereby contributing to the overall environmental impact of LNG production. When natural gas is used as fuel for gas turbines at liquefaction plants, CO_2 is emitted. The amount of fuel consumed is influenced by the plants' operational capacity and efficiency. Before the liquefaction process, CO_2 is extracted from natural gas using solvents like amines. During the regeneration of these solvents, the dissolved CO_2 and small amounts of CH_4 are released into the atmosphere as BOG. In addition, a small quantity of gas may escape from the compressors used for liquefaction. Nevertheless, leaks from valves and flanges can be considered trivial and can be disregarded. At the wellheads, Liquefied Petroleum Gas (LPG) and other substances are produced alongside natural gas. CO_2 and CH_4 emissions from the various stages are distributed according to the heat values of the heavy hydrocarbons produced from natural gas extraction, heavy hydrocarbons generated from the liquefaction process, as well as LNG. CO_2 emissions from fuel consumption in the liquefaction stage account for as high as 1.4 g-C/MJ (5.9 g-C/Mcal) [111]. CH_4 emissions from production and liquefaction together summed up to 0.2 g-C/MJ (0.9 g-C/Mcal), which is substantially low compared to global macroscopic statistical data [115].

After natural gas extraction, liquefaction converts it into a liquid for efficient long-distance transport. However, during this process, significant methane leakage occurs, resulting in substantial fugitive emissions. This leakage was mainly due to transfer pipes, inadequate sealing, and minor cracks in the tank and transfer equipment materials. The severity of these fugitive emissions is exacerbated by the hazardous effects on human health and the significant contribution to global warming, particularly due to methane's 25-fold GWP over a 100-year period compared to CO_2 [116]. The transportation and shipping of LNG thus becomes a critical stage in which methane leakage needs to be minimized, making this stage a pivotal area for emission reduction efforts. Effective strategies must be implemented to reduce leakage from transfer pipes, ensure proper sealing, and inspect transfer equipment to mitigate fugitive emissions. Moreover, advanced technologies and best practices should be adopted to minimize the loss of methane during transportation, thereby reducing its impact on the environment and human health. By focusing on this critical stage of the LNG supply chain, it is possible to make substantial progress in lowering methane emissions and contributing to a cleaner and more sustainable energy future.

The Well-to-Wheel LCA of LNG was considered by evaluating each stage as depicted in Figure 20. The Well-to-Pump (WTP) phase is a critical component in LNG LCA, covering the entire journey from natural gas extraction to its end distribution for refueling. Assessing emissions during this phase is vital for understanding LNG's environmental impact, especially as it gains traction as a transport fuel. Numerous studies have examined the significant supply chain emissions associated with natural gas, highlighting the variability in methane emissions across different stages of the WTP process [113, 117–119]. One major challenge is the lack of standardized reporting and estimation methods, which leads to inconsistencies in emissions reporting. Methane emissions as a percentage of total gas throughput can vary widely, from 0.2% to 10%, contributing to uncertainties regarding LNG's climate implications [113, 120]. The study utilized a systems analysis approach, dividing the Well-to-Wheel lifecycle into three distinct stages: well-to-pump, pump-to-tank (PTT), and tank-to-wheel (TTW). It incorporates region-specific emission factors, sensitivity analyses, and deterministic mathematical modelling to precisely quantify CO_2 and methane emissions. Key metrics analyzed include energy consumption (MJ/km), the percentage of methane leakage, and material transport. The processes examined encompass natural gas extraction, liquefaction, distribution, refuelling with BOG management, and vehicle operation, including engine-specific emissions controls. To provide a clear overview of the processes and focus areas and the structure of LCA at each stage, which is represented in Table 5. This variability often stems from whether emissions are measured using a bottom-up approach—focusing on direct observations at different points in the supply chain—or a top-down approach that looks at total production and consumption volumes. The presence of super-emitters—locations with disproportionately high emissions—also plays a critical role in these figures, as addressing these sources can lead to significant improvements. The IEA Methane Tracker reveals a considerable increase in methane emissions following COVID-19, fuelled by a growing demand for fossil fuels. Understanding WTP emissions is essential for stakeholders and policymakers to enhance LNG sustainability, inform policy, and promote more efficient natural gas supply chains. Ultimately, WTP analysis provides crucial insights as the role of LNG evolves in promoting sustainable energy transitions.

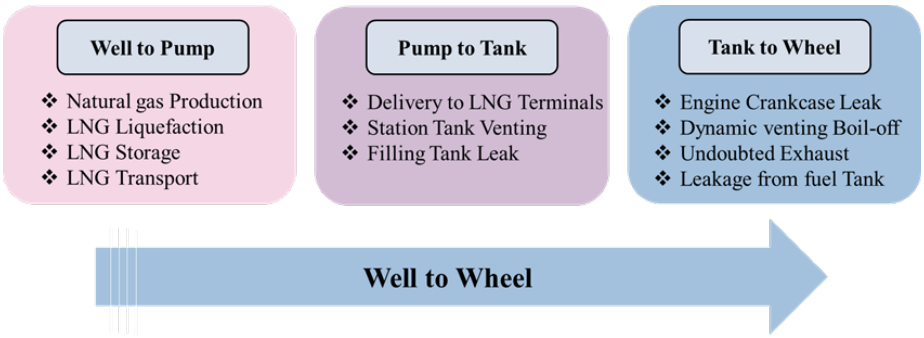

Figure 20. Important considerations for LNG Well-to-Wheel journey

Table 5. Summary table of the LCA stages and key processes involved [108]

Stage	Key Processes	Focus Areas
Well-to-Pump (WTP)	Extraction, processing, transmission, storage, distribution, liquefaction	Methane leakage, energy use
Pump-to-Tank (PTT)	Storage, delivery, offloading, refuelling, BOG management	Methane leaks during refuelling
Tank-to-Wheel (TTW)	Vehicle operation, combustion, emission control technologies	Tailpipe emissions, methane slip

Following the WTP phase, the LCA of LNG continues with the PTT phase, which encompasses the storage of LNG at refuelling stations and its subsequent delivery into vehicle tanks. Although the published literature on methane emissions during this phase is relatively scarce, research suggests that significant leakages can occur, potentially accounting for up to 21% of total Pump-to-Wheel (PTW) emissions [121]. The primary mechanisms contributing to these emissions at refueling stations include continuous, unintentional leaks from fuel nozzles and other components of the fuel delivery system, which can arise due to imperfect seals that allow pressurized natural gas to escape into the atmosphere. Additionally, methane emissions can occur during the coupling and decoupling of the hose to the vehicle at the beginning and end of each refuelling event, highlighting the need for improved sealing technologies and leak detection measures to mitigate these losses [113]. As the LCA of LNG progresses, understanding and addressing emissions during the PTT phase is crucial for accurately assessing the overall environmental footprint of LNG as a transport fuel and identifying opportunities for emissions reduction and efficiency gains.

The next phase of LNG moves toward the ICEs, where it is injected as fuel for combustion to drive a vehicle, thereby leading to fuel emissions from TTW. The TTW phase focuses on the emissions produced by vehicles during operation, particularly LNG HDVs. Various natural gas engine technologies, including the stoichiometric ignition system (SIS) and High-Pressure Direct Injection (HPDI) engines, exhibit different fuel efficiencies and emission profiles compared to traditional diesel engines [121]. Although LNG is associated with lower CO_2 emissions, it is crucial to also address methane emissions, which can significantly impact the overall GHG footprint. During the TTW phase, emissions can arise from several mechanisms. Tailpipe emissions can include unburned methane due to incomplete combustion, which is typically managed by catalysts. Additionally, if not properly contained, methane can escape from the engine crankcase, and HPDI engines may experience dynamic venting, releasing small amounts of gas during operation. Studies have indicated that Spark-Ignited (SI) engines generally produce lower tailpipe methane emissions due to their use of three-way catalysts, whereas HPDI engines show a decrease in methane emissions as the average speed increases. Nitrous oxide (N_2O), a potent GHG with a high GWP, is also emitted during combustion and emissions control processes. Natural gas SI engines tend to produce the lowest N_2O emissions, whereas HPDI engines may emit higher levels compared to both SI and diesel engines. The variability in emissions is influenced by factors such as engine type, driving conditions, and the use of after-treatment systems [113, 121]. Overall, although LNG HGVs demonstrate significant reductions in CO_2 emissions, particularly in regional and long-haul duty cycles, attention must be paid to methane and N_2O emissions to fully understand their environmental impact. Comprehensive assessments of these emissions are essential for evaluating the sustainability of LNG as a cleaner energy alternative.

3.4 BOG

LNG has experienced significant demand over the years, which has led to the emergence of various scenarios and challenges associated with the transportation, production, and shipment of LNG over long distances. In the global natural gas industry, LNG has gained importance as a key energy source. It is stored in specialized tanks and transported by ship. During LNG unloading and storage, a portion evaporates and transforms into gas, which is commonly referred to as BOG, where Figure 21 shows the different parameters influenced by BOG. The BOG can be used as fuel, reliquefied, compressed for inclusion in the gas transportation network, or incinerated in a flare. The efficient management of BOG during the LNG storage process, as well as the assessment of its thermodynamic properties, are essential components in the technical evaluation of energy systems at LNG storage terminals [122].

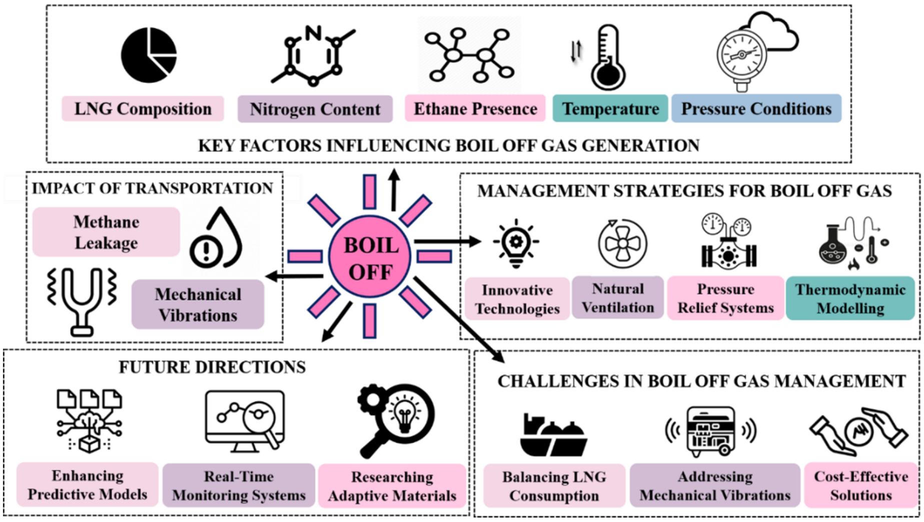

Figure 21. Impact, factors, challenges, and future directions for LNG BOG

In this research investigation, an evaluation was performed to assess the BOG scenario of LNG using three different mixtures: pure methane, methane-ethane, and methane-nitrogen. The examination considered LNG compositions at various ambient temperatures with a storage tank filled to 75% and an operational pressure of 0.2 bar. The Peng-Robinson cubic equation of state was used to calculate key parameters such as boiling temperature and density. The findings revealed that nitrogen content significantly affects the boiling temperature, resulting in lower boiling points for LNG containing nitrogen. Consequently, LNG with nitrogen exhibited the highest boil-off rate, whereas heavy LNG exhibited the lowest. At a temperature of 17°C (290 K), the boil-off rates were measured as 0.02792% vol/day for light LNG, 0.02669% vol/day for heavy LNG, and 0.02882% vol/day for LNG with nitrogen [122]. The elevated boil-off rate in nitrogen-rich LNG was attributed to its lower boiling temperature and increased heat transfer within the storage tank. Additionally, the analysis of ethane's impact showed that as the molar fraction of ethane increased, the evaporation rate as a percentage of LNG volume decreased. However, in terms of mass, the boil-off rate increased slightly with increasing ethane content. Conversely, higher nitrogen concentrations led to a significant rise in both the evaporation and mass boil-off rates, underscoring the critical role of nitrogen in enhancing safety and stability during the storage process. Overall, Włodek's analysis highlights the complex interactions between LNG composition and BOG dynamics, providing valuable insights for optimizing LNG storage systems.

A comprehensive examination was undertaken to assess the risks of methane emissions from LNG-fueled trucks during prolonged parking, focusing on the pressure build-up in small tanks and the subsequent release of flammable gas via pressure relief valves (PRVs). This research combined a simplified pressure build-up model using pure methane as a reference with experimental validation through a custom test facility. Results showed that a tank filled with 73 kg of LNG (40% capacity) experienced pressure build-up for 57 hours before PRV activation, which is consistent with the empirical rules (2.3 days vs. 6 days for full tanks), confirming the model's applicability to small tanks where stratification effects are negligible. The study highlighted that gas release occurs in periodic spikes, exceeding theoretical flow rates by two orders of magnitude, emphasizing the risk of explosive atmospheres in confined spaces like workshops. To mitigate this, the authors calculated a minimum natural ventilation requirement of 0.14 m^3/s and a combined upper/lower ventilation area of 0.59 m^2 under buoyancy-driven airflow assumptions. While adsorption systems (e.g., zeolites) were explored for gas containment, their impracticality was evident due to the excessive sorbent mass (200 kg) and volume (160 L) needed to store 0.64 kg of methane over 8 hours. The work validated the model's accuracy in predicting thermal input, pressure trends, and PRV behavior, underscoring natural ventilation as a viable safety measure. Improvements could involve refining the adsorption material efficiency, exploring alternative storage solutions (e.g., cryogenic re-liquefaction), or integrating real-time monitoring systems to optimize ventilation strategies. Additionally, extending the model to account for variable environmental conditions or mixed LNG compositions could enhance its predictive robustness for diverse operational scenarios [123].

This research was performed to explore BOG generation in LNG road tankers, emphasizing the combined effects of heat leakage and mechanical vibrations during transportation—an aspect often overlooked in prior studies. By integrating computational fluid dynamics (CFD) and process dynamic simulations, a multiphase LNG model was developed to quantify BOG generation under real-world conditions. A dynamic mesh algorithm with User-Defined Functions (UDFs) was employed in CFD to simulate vibration-induced thermal energy, while process modelling accounted for heat leakage from tank insulation. Results revealed that vibration contributed over 10% of the total BOG generation, with its share increasing significantly at higher transportation speeds (e.g., 40–60 km/h), despite heat leakage remaining the dominant factor. This highlights the necessity of incorporating vibration effects, particularly for high-speed transport, to accurately predict BOG and design mitigation strategies. This study pioneers a dual-analysis approach, bridging CFD and process simulations to address both root causes of BOG, offering a foundation for optimizing BOG management in LNG logistics. For improvement, future work could validate simulations with experimental data under varied operational conditions, refine vibration modelling to account for road surface variability, and explore adaptive insulation materials or vibration-damping technologies to reduce BOG. Additionally, extending the framework to other LNG storage and transport scenarios (e.g., maritime) could enhance its applicability [124]. Effectively managing BOG in LNG storage and transportation requires addressing thermodynamic, compositional, and operational challenges. Technologies such as thermodynamic modeling.

4 Total Cost of Ownership (TCO) and Financial Analysis

The economic feasibility of adopting LNG for M&HDVs in markets such as India necessitates a detailed evaluation of ownership costs compared to traditional diesel as put up in Figure 22. A TCO analysis—factoring in upfront expenses, fuel prices, maintenance, tolls, and financing—highlights the balance between higher initial investments and potential long-term savings. In India, LNG trucks, although more expensive upfront (₹42 lakh compared to diesel's ₹30 lakh), benefit from lower fuel costs (₹73/kg versus ₹91/liter for diesel), resulting in a slightly lower TCO (₹34.88/km versus ₹35.61/km) [69]. However, the ₹12–16 lakh premium for LNG vehicles necessitates policy measures, such as subsidies or toll waivers, to shorten the 36-month payback period anticipated by fleet operators. Studies indicate that eliminating toll fees could reduce TCO by 11% to 13%, whereas 50% to 75% subsidies on the capital cost gap could enhance affordability. Sustaining LNG's 20% to 22.5% price advantage over diesel and favourable loan rates (8%to 10%) is crucial for adoption. Despite the environmental benefits, India's infrastructure limitations and fluctuating fuel costs pose threats to LNG's fragile TCO advantage. Emulating strategies such as Germany's toll exemptions, combined with stable policies and financial incentives, could enhance LNG uptake. However, achieving the required annual mileage (80,000–100,000 km) remains challenging, underscoring the need for consistent regulatory support to ensure long-term viability for operators [69].

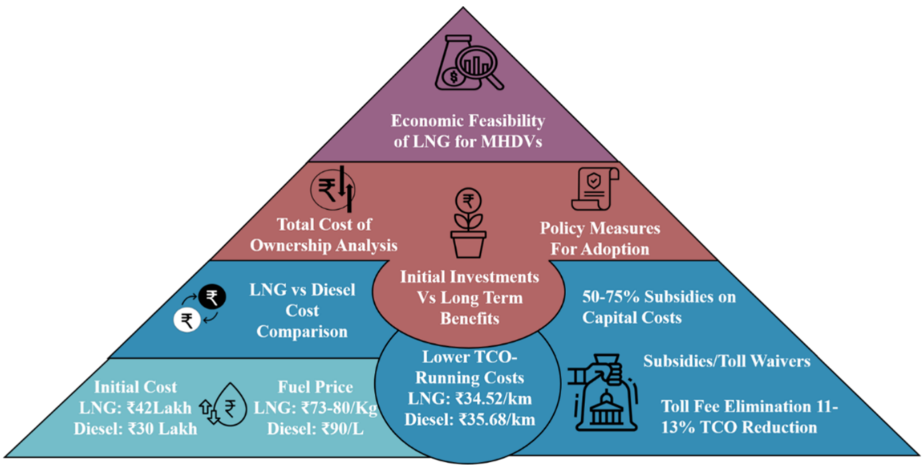

Figure 22. Economic feasibility of LNG for M&HDV in India

The economic viability of adopting LNG for HDVs in the United Kingdom hinges on balancing upfront costs, fuel price differentials, and infrastructure investments. LNG trucks typically incur higher capital costs than their diesel counterparts due to specialized fuel tanks and engine modifications. However, lower LNG fuel prices—driven by abundant domestic natural gas reserves—can offset these initial expenses over time. In the U.S., where diesel prices fluctuate with global oil markets, LNG's price stability offers a potential advantage. For instance, if LNG maintains a 20%–30% price discount per energy equivalent unit compared to diesel, operators could achieve significant fuel cost savings, particularly for high-mileage fleets.

However, the TCO is highly sensitive to refueling infrastructure. Public LNG stations, though sparse outside major corridors, reduce operators' capital risks, while private infrastructure (e.g., depot-based stations) demands substantial upfront investment, often negating long-term savings unless subsidized. The maintenance costs of LNG vehicles are comparable to those of diesel vehicles, but lower particulate emissions may extend engine life. Policy incentives, such as federal tax credits for alternative fuels or state-level grants for infrastructure, could further narrow the TCO gap. However, economic feasibility is threatened by the lack of LNG vehicle efficiency gaps; if LNG HDVs lag behind diesel in energy efficiency (as observed in UK studies), increased fuel consumption will erode cost benefits. In addition, volatile natural gas prices and potential regulatory shifts (e.g., carbon taxes) introduce financial uncertainty. For U.S. operators, the payback period for LNG adoption depends on annual mileage, with high-utilization fleets (100,000+ miles/year) more likely to recoup costs. Strategic alignment with public refueling networks and policy support is critical for realizing LNG's economic promise in the freight sector [125].

A comprehensive review of LNG's economic dynamics highlights its cost sensitivity to interconnected variables such as natural gas prices, Geopolitical Risks (GPR), and carbon markets, with freight rates exhibiting pronounced short-term volatility driven by these factors. GPR—particularly from importers (short-term demand shocks) and exporters (medium-term supply disruptions)—significantly influence regional shipping costs, while carbon pricing mechanisms, notably the EU Emissions Trading System (ETS), increasingly dictate freight economics post-2024, especially on routes like Australia-Japan. Multi-month freight rate trends emerge as critical stability indicators, necessitating close monitoring during supply chain disruptions. Methodologically, advanced models (e.g., time-varying parameter vector autoregression [TVP-VAR]) reveal LNG's exposure to energy market fluctuations and regulatory shifts, although data gaps—such as limited GPR metrics for key routes (e.g., Qatar-Asia)—constrain granular analysis. Regionally, carbon costs directly impact certain corridors, whereas others, like the US-Europe route, face indirect effects [126]. For stakeholders, integrating carbon price trends, geopolitical hedging, and adaptive pricing models is essential to navigate evolving costs, particularly as EU ETS inclusion amplifies compliance expenses. This synthesis underscores the need for robust, region-specific risk assessments and dynamic pricing strategies to optimize LNG's economic viability during global energy transitions [126].

5 Benefits of LNG to the Consumer End

LNG is increasingly recognized as a versatile and cleaner energy source, providing significant advantages across residential, industrial, and transportation sectors. For consumers, LNG offers dependable heating and cooking solutions, particularly in regions with limited access to traditional energy infrastructure. In industrial applications, LNG fuels essential processes such as steel production, medical equipment manufacturing, and fertilizer synthesis. Sectors that interact directly with the public, including hospitality, food services, and retail, benefit from LNG's capabilities in heating, dehumidification, and power generation. Utility companies view LNG as a cleaner alternative for electricity generation, contributing to a reduction in overall emissions. Furthermore, advancements in engine technologies and fuel systems have facilitated the development of natural gas vehicles (NGVs), especially in medium- and heavy-duty categories. These vehicles now provide extended driving ranges—approaching 1,000 kilometres on a single tank—while innovations in tank design and fuelling infrastructure enhance the convenience of LNG refuelling, making it comparable to traditional diesel fuelling. For operators in remote or underserved regions, LNG represents an accessible, reliable, and low-emission energy solution that can effectively bridge energy gaps, manage seasonal demand fluctuations, and offer backup during supply disruptions. Nevertheless, the adoption of LNG—particularly in the transportation sector—faces certain challenges. A prominent barrier is the substantial initial capital investment. For instance, in India, LNG trucks are priced at approximately ₹40–42 lakhs, which is nearly 33% higher than conventional diesel trucks that average around ₹30 lakhs.

When evaluating the TCO, LNG trucks exhibit a slightly lower operating cost of ₹34.38 per kilometre, in comparison to ₹35.18 per kilometre for diesel, resulting in a projected payback period ranging from 36 to 40 months. Similar trends have been observed globally; a study conducted by the International Council on Clean Transportation (ICCT) found that while LNG trucks in Europe have an upfront cost approximately 40% higher, their fuel costs are approximately €0.12 lower per kilometre than those of diesel, yielding an estimated payback period of 4.2 years for long-haul operations [127]. In the United States, where natural gas prices are comparatively lower and tax incentives more favourable, the payback period is even shorter, typically less than three years [128].

In contrast, CNG trucks offer a lower upfront investment but have their own limitations. The retrofitting cost of approximately USD 15,000 makes them more affordable than LNG vehicles, although they are initially costlier than diesel vehicles. Operational savings with CNG are present, but the payback period remains in a similar range, typically between 30 and 36 months, depending on usage patterns [129]. A case study in Shenzhen, China, using Monte Carlo simulations, revealed annual operating cost savings of 11%–22% for LNG trucks compared to diesel trucks across different truck types [36], further supporting the economic feasibility of LNG under high-utilization conditions.

A further comparative assessment of LNG, diesel, and CNG for heavy-duty transportation highlights key differences in cost dynamics and operational feasibility. In India, LNG-powered trucks are approximately 40% more expensive than their diesel counterparts; however, fleet operators covering over 80,000 km annually can recover the additional cost in approximately 1.5 years due to lower fuel expenses [130]. TCO of LNG trucks is estimated at ₹34.88/km, which is slightly less than that of diesel trucks, which is ₹35.61/km [131]. Despite these advantages, the growth of LNG trucks is hindered by insufficient infrastructure—only about 20 LNG refuelling stations were operational as of early 2025 [2].

In contrast, the cost competitiveness of CNG has declined sharply due to a 70% surge in prices over the past year. This has led to a 20% increase in operating costs, with CNG truck operations becoming 5–20% more expensive than diesel alternatives in metropolitan areas such as Delhi and Mumbai [86]. As a result, monthly CNG commercial vehicle sales dropped from 11,000–12,000 units to 6,000–7,000 units, demonstrating reduced market confidence in CNG viability.

In the European context, LNG trucks provide a 20%–30% reduction in operational costs compared to diesel vehicles for fleets traveling over 1,00,000 km per year [4]. However, due to high vehicle costs, the average payback period is approximately 4.2 years [4]. The adoption of LNG is further supported by the EU's carbon regulations, given that LNG combustion emits 22% less CO_2 than diesel [4].

6 SWOT Analysis for Transition to LNG Fuel

The SWOT analysis of the LNG sector revealed a complex landscape characterized by various strengths, weaknesses, opportunities, and threats, as shown in Figure 23. The key strengths of this model include a growing demand within the automotive sector, government support, established infrastructure, and diverse supply sources. However, challenges such as high import dependence, infrastructure limitations, and fluctuations in global prices pose significant weaknesses. Opportunities for expansion and technological advancements exist, yet threats from enviro Figurenmental concerns and geopolitical instability must be addressed to ensure sustainable growth.

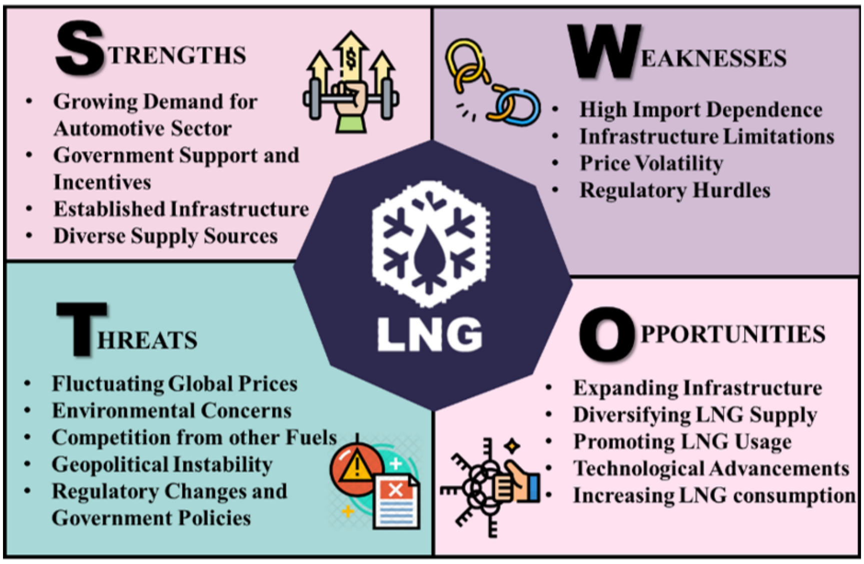

Figure 23. SWOT analysis of the LNG fuel transition

7 Future Perspective of LNG

LNG is positioned to play a pivotal role in the transportation sector of India as the nation endeavors to achieve net-zero carbon emissions by 2070. Given that transportation accounts for one-third of the country's CO_2 emissions and projections indicate that emissions from trucks could reach 800 million tonnes by 2050, the urgency for cleaner alternatives is pronounced. LNG presents a sustainable and cost-effective solution with the potential to reduce total carbon emissions by 1 billion tonnes by 2030 and to decrease the carbon intensity of the economy by 45%. By specifically targeting the transportation sector, which is a major contributor to air pollution, LNG aligns with India's strategic objectives for environmental sustainability. This transition not only supports the reduction of GHG emissions, but also contributes to improved air quality and public health outcomes. As per the MGL data, as depicted in Figure 24, there will be a cost benefit of ₹10-15 for using LNG over diesel. The cost break-up is illustrated in Figure 23. The LNG industry is positioned for robust growth in the coming years, fueled by the rising global demand for cleaner energy sources and the continuous evolution of liquefaction technologies. As the market navigates the aftermath of fluctuating oil and gas prices, a pronounced shift toward advanced liquefaction methods, particularly mixed refrigerant technologies, underscores the sector's adaptability and resilience. Offshore applications increasingly embrace nonflammable refrigerant-based expander technologies stemming from enhanced safety profiles and efficient space utilization. The strategic integration of deterministic and stochastic optimization approaches has emerged as a focal point for enhancing operational efficiency and minimizing compression energy in LNG facilities. Importantly, the industry's trajectory is anticipated to be guided by a holistic emphasis on multi-objective optimization that accounts for economic, technical, and safety considerations, thereby facilitating the deployment of knowledge-based optimization algorithms. As the LNG sector actively addresses the evolving dynamics of feed-gas compositions and environmental conditions, its commitment to sustainable practices and innovation bodes well for its future prosperity on the global stage. The future of LNG is poised for significant transformation, driven by increasing global demand and a transition toward cleaner energy sources. As countries like China shift from coal to natural gas and Europe reorients their supply chains during geopolitical tensions, LNG is becoming a crucial bridging fuel. With substantial increases in production and liquefaction capacities in key regions like the United States and Qatar, global LNG supply is projected to rise by approximately 35% by 2027. The order book for new LNG vessels reflects a more predictable and stable market, with over 133 vessels ordered in 2023 and expectations for continued growth in 2024.

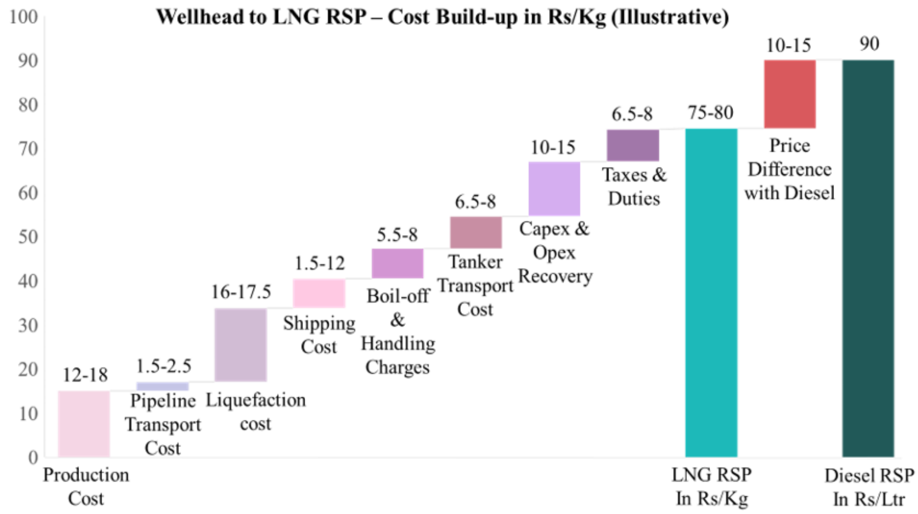

Figure 24. Price parity between LNG and diesel fuel at MGL dispenser end

Notably, advancements in propulsion technologies and modular designs indicate a shift toward greener solutions, focusing on minimizing emissions and improving cargo capacity. Innovations such as methane slip reduction, fuel cells, and carbon capture are on the horizon, suggesting that the next generation of LNG carriers can substantially enhance environmental performance. Additionally, the potential integration of bio-LNG and hydrogen as alternative fuels represents a forward-thinking approach to meeting future energy needs. While challenges remain regarding supply and cost, the evolving LNG landscape underscores a commitment to both energy security and sustainability in the coming years. The future of the LNG market in India looks promising, with a projected growth from USD 8.9 billion in 2024 to USD 27.36 billion by 2030, reflecting a robust Compound Annual Growth Rate of 13.2%. This expansion is primarily fueled by rising energy demand driven by economic growth and urbanization, alongside India's commitment to adopt clean energy sources. As the nation pivots toward a "gas-based economy" supported by government initiatives like the National Gas Grid project, LNG is becoming increasingly attractive due to its lower emissions relative to conventional fuels like coal and oil. The development of new infrastructure, including terminals and storage facilities, is enhancing LNG accessibility across the country, which is essential for meeting the needs of key sectors such as fertilizers, petrochemicals, and power generation. With India importing 22.59 million metric tons of LNG—accounting for 6% of global trade—its position in the LNG market is steadily strengthening. Moreover, emerging markets in transportation and initiatives for LNG fueling stations are set to further drive demand, solidifying LNG's role as a vital component in India's pursuit of a sustainable energy future [132].

To meet India's objective of increasing the share of natural gas to 15% in the primary energy mix by 2030, a more cohesive and pragmatic policy approach is essential [133]. This approach must address regulatory, financial, technological, and infrastructural challenges. Streamlining regulations through mechanisms such as single-window clearances and enhancing collaboration between central and state authorities can significantly reduce procedural delays in the development of LNG infrastructure. To tackle the underutilization of existing LNG terminals, it is crucial to improve regional planning and demand forecasting. From the perspective of end-users, particularly fleet operators, customized incentives such as capital subsidies, concessional loans, and accelerated depreciation can enhance the economic viability of LNG vehicle adoption. Similarly, implementing price stabilization frameworks and long-term procurement strategies will protect stakeholders from global market volatility. Establishing LNG corridors along major freight routes will ensure accessibility to refuelling stations and mitigate operational uncertainties. Leveraging public-private partnerships can expedite infrastructure development, while targeted policy support for domestic manufacturing and research and development can effectively address technical challenges, including methane slip and cold-start issues. Moreover, creating a resale and retrofitting ecosystem will contribute to a circular market, thereby minimizing investment risks. A centralized, transparent monitoring platform will facilitate progress evaluation and allow for real-time policy adjustments. This comprehensive, human-centred strategy can transform LNG into a reliable transitional fuel, advancing India's clean energy and economic aspirations.

Looking ahead, LNG is poised to play a pivotal role in India's transition toward a cleaner and more secure energy future. The government has articulated a bold vision to increase the share of natural gas in the primary energy mix from 6.2% in 2025 to 15% by 2030, aligning with the broader national objective of achieving net-zero emissions by 2070 [29, 134]. Realizing this vision will require sustained investment in infrastructure. India's current regasification capacity of 47.7 MTPA, spread across seven terminals, is expected to expand to 87 MTPA by 2030 [135]. Government-led programs such as the "LNG for Transport" scheme and state-level efforts like Maharashtra's LNG bus retrofitting initiative signal a positive policy direction [136].

However, underutilization of terminals like Kochi and Ennore [137], and the slow pace in achieving targets for CNG and PNG infrastructure [138], highlight the need for accelerated implementation. As several long-term LNG contracts approach expiry between 2028 and 2030, proactive strategies will be essential to secure future supply and reduce exposure to spot market volatility [139]. The proposed allocation of 0.5 million cubic meters per day for LNG retailing could catalyze market growth. To drive adoption, especially in the transport sector, bridging the economic viability gap will be critical. While LNG trucks offer significant long-term cost savings and 20–25% lower CO_2 emissions compared to diesel [134], high initial vehicle costs, infrastructure limitations, and operational uncertainties remain deterrents for small and medium fleet operators [6]. Future policy measures—such as tax breaks, capital subsidies, and corridor-based infrastructure—will be key to mainstreaming LNG as a reliable transition fuel [140, 141].

8 Conclusions

LNG is positioned as a viable alternative fuel for HDVs in India over the next 10-15 years, particularly as the country seeks to reduce its GHG emissions and reliance on diesel. The coexistence of LNG and CNG in the medium- and heavy-duty transport sectors is anticipated, with CNG serving urban good carriers due to its established refueling infrastructure. In contrast, LNG is better suited for long-haul applications, offering a significant range of more than a thousand kilometers before refueling.

India's LNG transition thus hinges on more than infrastructure—it demands an integrated strategy. While the government's target of increasing natural gas's share to 15% by 2030 signals strong intent, uneven terminal utilization and sluggish CNG/PNG rollouts reflect deeper systemic inefficiencies. Merely expanding regasification capacity and promoting pilot schemes will not suffice. LNG adoption, especially in transport, is hindered by high vehicle costs, limited refuelling networks, and uncertain resale value—factors particularly critical for small fleet operators. Moving forward, a shift in focus is needed: from physical infrastructure to market ecosystem. Policies must prioritize affordability, domestic technical capability, and investor confidence. Without cohesive action, LNG risks being a missed opportunity rather than a reliable transitional fuel in India's decarbonization roadmap.

Technically, LNG is a feasible alternative for ICEs, especially in the heavy-duty sector. Its principal component, methane, has a high-octane rating ($\sim$ 130), allowing efficient combustion in spark-ignition engines and enabling dual-fuel strategies in compression-ignition engines. Dual-fuel LNG-diesel systems have demonstrated improved BTE and lower NO_x and PM emissions. However, challenges such as cold-start issues, incomplete combustion at low loads, and methane slip, due to unburned methane, need to be addressed through improved engine calibration and after-treatment solutions. Additionally, the cryogenic nature of LNG necessitates specialized storage and injection systems, making it less viable for smaller engines but suitable for large-scale, heavy-duty applications. Also, considering the fact that Electric Vehicles (EVs) and fuel-cell electric vehicles (FCEVs) are gaining traction, their widespread adoption is contingent upon advancements in infrastructure and cost reductions. Currently, the high initial costs of EVs and FCEVs, which can be four to five times those of diesel vehicles, present significant barriers to entry. To facilitate a successful transition to a multifuel strategy, prioritizing the development of LNG infrastructure and promoting its adoption among fleet operators is essential. This approach will not only enhance the sustainability of the heavy-duty transport sector but also contribute to a diversified fuel mix, including diesel, CNG, LNG, hydrogen, and electric vehicles. By focusing on LNG in the coming decade, India can achieve its decarbonization goals and ensure a more resilient and efficient transport sector.

The authors of this review aimed to examine literature published in the past four years or more recent, focusing on critical topics related to LCA, cost benefits, and BOG. However, due to the dynamic nature of the current market and external factors such as fluctuating oil prices, the ongoing effects of COVID-19, and geopolitical conflicts, shipping, export, and import costs are changing rapidly. These external influences may result in significant deviations from the figures discussed in the review. Furthermore, this analysis only considers technologies that were available prior to the study. Any breakthroughs in technology or unexpected advancements in fields not directly related to LNG could diminish the relevance of the recommendations for future readers. Another limitation of this study is the absence of validation for the studies included. Nonetheless, the authors have thoroughly evaluated and only incorporated studies that have undergone proper validation of their findings, thereby enhancing their credibility.

It is essential to recognize that certain figures, such as the total number of trucks in various countries and boil-off rates, should be regarded as indicators rather than precise values due to the dynamic nature of the market. Nonetheless, the authors strongly believe that the overall integrity of the data trend is upheld even when accounting for these external influences.

Additionally, this study could be expanded to include emissions forecasts based on current data extending to 2075, the target year for India to achieve net-zero emissions. The foundational methodology of this study can also be applied to formulate generalized policy recommendations for other middle- or low-income countries, ultimately leading to a comprehensive assessment of LNG feasibility.

Data Availability

The data used to support the research findings are available from the corresponding author on request.

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Conflicts of Interest

The authors declare no conflict of interest.

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