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Review

A Review on Liquefied Natural Gas as Fuels for Dual Fuel Engines: Opportunities, Challenges and Responses

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Abstract: Climate change and severe emission regulations in many countries demand fuel and engine researchers to explore sustainable fuels for internal combustion engines. Natural gas could be a source of sustainable fuels, which can be produced from renewable sources. This article presents a complete overview of the liquefied natural gas (LNG) as a potential fuel for diesel engines. An interesting finding from this review is that engine modification and proper utilization of LNG significantly improve system efficiency and reduce greenhouse gas (GHG) emissions, which is extremely helpful to sustainable development. Moreover, some major recent researches are also analyzed to find out drawbacks, advancement and future research potential of the technology. One of the major challenges of LNG is its higher flammability that causes different fatal hazards and when using in dual-fuel engine causes knock. Though researchers have been successful to find out some ways to overcome some challenges, further research is necessary to reduce the hazards and make the fuel more effective and environment-friendly when using as a fuel for a diesel engine.

Keywords: liquefied natural gas; diesel engine; greenhouse gas emissions; sustainable development

1. Introduction

Recently, it is projected that global energy demand has been increasing day by day [1,2]. The increased amount of energy demand produces a large amount of greenhouse gases (GHGs) by the burning of fossil fuels, which ultimately causes global warming. Currently, in the industrial and transportation sectors, diesel is mainly used as fossil fuel. The consumption of diesel fuel is increasing day by day unexpectedly because of the dramatic increase in vehicles, mostly in Asian countries like Bangladesh, Korea, India and China [3]. Currently, researchers all over the world are concerned about the way of mitigating this large amount of energy demand and at the same time, carbon dioxide (CO_2) emission reduction, which is one of the major components of GHGs [4,5]. In this regards, other sources of fuel may be a feasible alternative to conventional fuels. Natural gas would be a promising alternative fuel source in the transportation sector because of some of its remarkable advantages. Though natural gas is also derived from fissile resources, it can be converted from renewable sources, i.e., it can be produced through the biomass conversion process (biomethane, which is also known as biogas, is a pipeline-quality gas made from organic matter), attractive cost, better combustion efficiency and greenhouse gas reduction, which are the significant advantages as alternative fuel [3].

Besides, the interest in alternative fuels is rapidly growing because of the energy security concern all over the world. Among the candidates of alternative fuel, biofuels, liquefied petroleum gas (LPG) and liquefied natural gas (LNG) are the potential ones. Nevertheless, the economic aspects and availability make LPG and LNG more realistic solutions compared to biofuels. Additionally, natural gas can be considered as one of the solutions to control engine emissions at present as compared to traditional fuels. In a homogenous charge compression ignition engine (HCCI), the after-treatment technique combined with natural gas present an outstanding potential to meet strict requirements for reducing the emissions [6]. In the transportation sector, both forms of natural gas, i.e., liquefied natural gas (LNG) and compressed natural gas (CNG) can be used as an alternative fuel. However, CNG has already gained popularity in the automobile sector due to its lower cost.

LNG is mainly used for electricity production and transportation. The main advantages offered by LNG are higher safety, easier transportation and storage capacity compared to CNG [3]. LNG is cleaner than coal and oil, therefore, it has got a plethora of recognition in the global market [7]. Since LNG is clean, it is a promising alternative to diesel vehicles and is capable of compensating some of the severe drawbacks of natural gas vehicles; for instance, LNG fuelled trucks have a higher range (up to 700–1000 km) due to higher energy density [8]. However, while considering LNG as an alternative, the economic viability should also be taken into consideration. The cost of an LNG fuel tank and the engine is approximately twice as high as a diesel engine and tank [9]. Consequently, during this decade, the main contributors to LNG supply growth will be Australia and USA, though 18 other countries have already joined and others have a short and long term goal to join the industry [10]. Besides, among various alternatives of natural gas, LNG is the most preferred mode for long distance transportation as because of its liquefaction attribute, its volume reduces by a factor of 600 [11]. Compared to piped natural gas (PNG), the annual growth of LNG trade is two times higher, which accounts for 10% and 31% of global natural gas consumption and trade respectively [8]. According to recent study reports, from 2005 to 2015, Europe, Asia and Oceania were the primary recipients of LNG imports consisted of 90% of global imports [12].

1.1. Economics and Life Cycle of LNG

Figure 1 shows the worldwide LNG price as of June 2019. South Korea and China had the highest landed price of LNG in the world. The price received at the regasification plant is referred to as the landed price. Netback price is taken into consideration for the determination of these prices, which is based on the effective price for a seller and producer at a definite location.

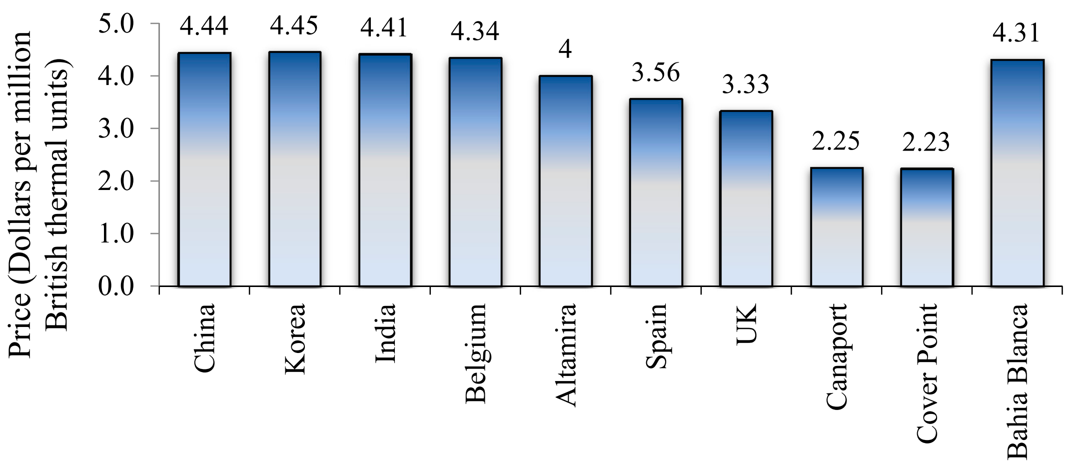

Figure 1. Worldwide landed price of liquefied natural gas (LNG) [13].

It is also required to make an economic calculation of the LNG liquefaction plant because fuel imposes the second highest operational cost after labor. There are some reasons behind the cost of

LNG not being as straight forward as diesel, which are: (1) distribution costs are not included in LNG fuel price, which is dissimilar to diesel fuel price; (2) generally state tax rates for LNG is different from other fuels, and it also varies state-wise; (3) federal tax rates for LNG fuel are also different and (4) energy content of different fuels are different [14]. Table 1 shows the national average cost for LNG and diesel fuel. Equivalent fuel cost is calculated in dollars per diesel equivalent liter by using the energy content of the fuel. Diesel equivalent liter refers to the amount of energy, which is equivalent to one-liter diesel fuel. Since the distribution cost is not included in LNG fuel price, thus, it is more competitive. Based on the distribution costs and state taxes, the costs of LNG fuel will vary radically by location to location. According to the Taxpayer Relief Act of 1997, based on the energy content of transportation fuel it has been taxed, such as the federal tax rate on LNG is changed from $0.0503 (unit conversion) per liter to USD 0.0317 (unit conversion) per liter [14].

Table 1. Average LNG as well as diesel fuel cost worldwide (unit conversion) [14].

Fuel Type	Fuel Cost ($/L)	Distribution Cost ($/L)	State Tax ($/L)	Federal Tax ($/L)	Total Fuel Cost ($/L)	Equivalent Fuel Cost ($/Diesel Equivalent Liter)
Diesel	0.1717		0.0634	0.0555	0.2906	0.2906
LNG	0.0925	0.0264	0.0476	0.0660	0.2325	0.3936

Note: Permission granted from National Renewable Energy Laboratory.

Figure 2 depicts a schematic diagram of the LNG life cycle. With the help of the pipeline extracted raw natural gas is sent to the plant for liquefaction, where LNG is obtained as a byproduct. Mainly, the ship is used to carry LNG to the regasification terminal. Meanwhile, a small amount of liquid is drawn off and carried by small tanker trucks to the service station for fuelling LNG trucks. On the other hand, in each transport and storage, phase boil-off gas is produced, which can be fully recovered for the purpose of using as a gaseous fuel [15].

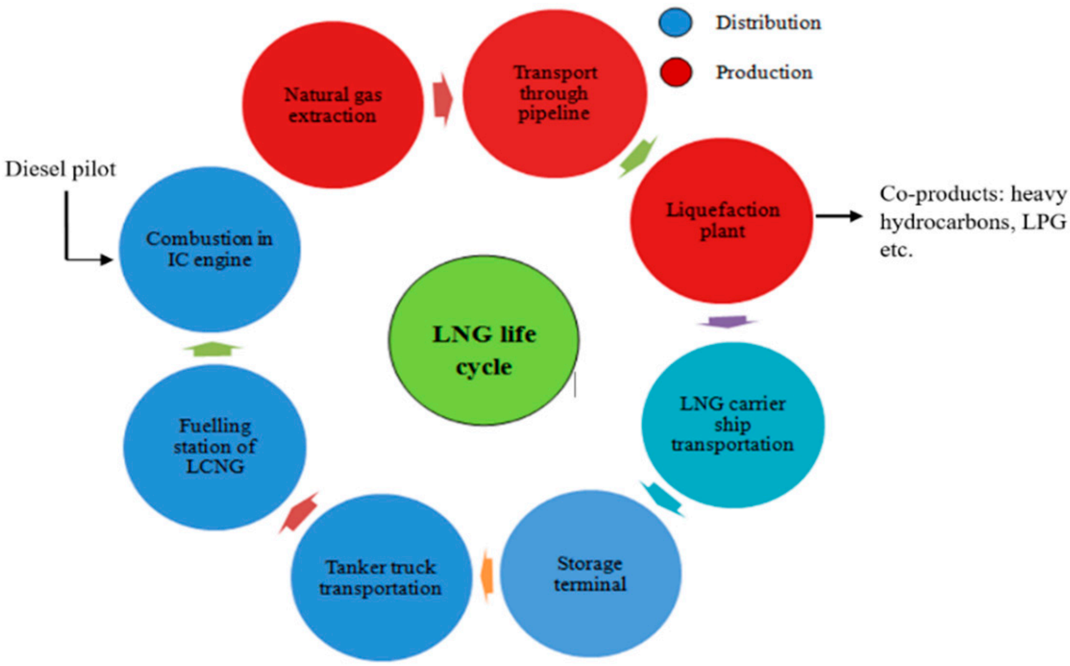

Figure 2. LNG life cycle (adapted from [15]). Note: Permission granted from the publisher (Elsevier-Applied Energy).

Although natural gas is benign and available in nature, it is hardly used in a large diesel engine and still limited to a small engine i.e., spark ignition (SI) engine. Natural gas is mainly used in heavy diesel operated transportation fleets [3]. It is reported that fuelling natural gas with diesel fuel as compared to fuelling diesel only causes a less lean mixture and a lower the efficiency. This is because when natural gas is fuelled it tends to mix with air and could move into the cylinder. Hence, this induced less air leads to an increase in equivalence ratio. Again, when the load is decreased, it causes lesser inducing of natural gas, which results in reducing the efficiency in fixed load speed condition and, thus, more natural gas is needed to be aspirated [16]. Besides, knocking is one of the severe problems of dual-fuel engines [17–19]. According to previous study reports, though advancing the injection timing in the dual-fuel engine reduces emissions [20], may increase the tendency of noise due to fast pressure rise [21,22]. Thus, natural gas is always used as minor fuel in most of the dual-fuel engine operations [3]. One of the key initiatives to utilize LNG as a fuel in a diesel engine is to alleviate the knocking problem and take adequate precautions when knocking resistance is low [23]. In terms of emissions, LNG provides far better results compared to conventional fuels. For instance, an experiment in the Netherlands showed that for trucks GHG emission will be reduced by 10–15% if LNG is used [24]. With the increase in power, the smoke density of diesel increases sharply while LNG-duel fuel increases slightly. Under high loads, the smoke density of LNG duel fuel decreases by a huge amount when compared with diesel [25].

From the above discussion, it can be said that with the increasing demand for natural gas vehicles, the demand for higher performance, environment-friendly and more efficient engines have also been increased. The perspective of this review is to bring attention to the current position of LNG and the use of it in the diesel engine. Engine performances and emission characteristics by using LNG are also discussed in this study. The consciousness of using environmentally viable and economical energy source is attracting researchers and environmental scientists to concentrate on LNG as fuels to fulfill both energy crisis and to control environmental abnormalities.

1.2. Properties of LNG

LNG is a mixture of gases, and its liquefaction is done by reducing the temperature below the boiling point. The amount of methane in LNG is about 87–99 mole%, and the remaining portion is ethane, propane and other heavier hydrocarbons depending on different LNG sources [26,27]. For instance, the LNG imported from Belgium contains 90% (by mass) methane and 10% (by mass) ethane [28]. The lower calorific value of LNG is 21 MJ/L, and the higher calorific value is 24 MJ/L at −164 °C [29]. To produce LNG, natural gas is refrigerated at −162 °C at atmospheric pressure; thus, LNG is known as a cryogenic liquid [30,31]. During liquefaction of natural gas, the primary component, i.e., methane, is cooled below its boiling point. At the same time, the concentrations of oxygen, carbon dioxide, water, hydrocarbons and some sulphur compounds are either removed or reduced in some small extent [32]. Normally, LNG is stored and handled below 1.586 MPa (unit conversion) pressure in extremely cold temperature in the tank [33]. The density of LNG is between 410 and 500 kg/m^3 [29], hence, it is lighter than water [28] and will float if it spilled on water. Per unit volume combustion heat production of LNG is much higher compared to natural gas. At atmospheric conditions, to produce equal energy, natural gas requires 600 times larger volume compared to LNG [28]. Besides, both LNG and its vapor are not explosive when exposed to the unconfined environment [32]. Moreover, LNG is more efficient and feasible for transportation compared to pipeline gases [7,29,34]. Well purified and condensed LNG can be easily transported over the sea [35]. While transporting, to handle the low temperature of LNG, specifically designed double-hulled ships are used [32].

LNG is a non-toxic, non-corrosive, colorless, odorless, safe and clean form of natural gas [7,36]. LNG is non-flammable; therefore, the liquid itself will not burn. However, the vapor of LNG is highly flammable with air, which causes flash fire. The flashpoint of LNG is −187.8 °C, but the autoignition temperature is 537 °C [37]. The specific gravity of LNG is 0.45 and 0.6 of gas [37] and 2.7488 liters of LNG has 100% of the energy of 3.7854 liters (unit conversion) of diesel [38]. The burning speed of LNG is 0.38 m/s in the stoichiometric mixture. This burning speed is comparatively lower for using only LNG in a diesel engine [37]. Due to the requirement of thermal shield and the lower density of

LNG compared to heavy fuel oil (HFO), the fuel tank required for LNG is 2.5–3 times bigger than HFO tank [39]. During combustion, LNG has almost no SO_2 and particulate matter emission [40]. Furthermore, the life cycle CO_2 emissions of LNG are 18% less than its counterpart gasoline vehicle model [41]. These advantages enable LNG as a potential fuel for the transportation sector. Depending on the liquefaction process and the plant where LNG is produced, the chemical components of LNG vary slightly, i.e., Europe, America and Asia, shown in Table 2 [42]. During designing LNG power plant, the regasification and liquefaction processes are controlled by the phase behavior and thermodynamic properties of LNG. Mokhatab et al. [26] have summarized the multiphase equilibrium of LNG using numerical methods.

Table 2. Chemical compositions of LNG imported from various countries all over the world [42].

Terminal	Methane	Ethane	Propane	Butane	Nitrogen
Abu Dhabi	87.07	11.41	1.27	0.14	0.11
Alaska	99.8	0.10	NA	NA	NA
Algeria	91.40	7.87	0.44	0.00	0.28
Australia	87.82	8.30	2.98	0.88	0.01
Brunei	89.40	6.30	2.80	1.30	0.00
Indonesia	90.60	6.00	2.48	0.82	0.09
Malaysia	91.15	4.28	2.87	1.36	0.32
Oman	87.66	9.72	2.04	0.69	0.00
Qatar	89.87	6.65	2.30	0.98	0.19
Trinidad	92.26	6.39	0.91	0.43	0.00
Nigeria	91.60	4.60	2.40	1.30	0.10

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LNG is not explosive; therefore, to be ignited, first, it must be vaporized and then mixed with air at a proper portion [43]. Nevertheless, in the LNG transportation sector, there are some possibilities of accident, for example, the leakage of LNG into ground and sea, and rollover of the LNG tank [35]. However, LNG vapor only burns when it is mixed in a concentration of 5%–15% with air [7,32]. All these factors make LNG a safe alternative fuel for the transportation sector.

LNG makes two distinct types of gases, depending on the extraction procedure. They are natural boil-off gas and forced boil-off gas. From the top of the fuel tank, natural boil-off gas is collected, which contains a higher amount of methane and a lower amount of nitrogen; thus, its knocking resistance is very high. Investigation predicts the value of methane number (MN) is around 100 and the lower calorific value between 33 and 35 MJ/nm^3 [44].

On the other hand, from the down in the tank, forced boil-off gas is extracted and evaporated separately. Forced boil-off gas contains the mixture of all hydrocarbons of the liquid. The knocking resistance of the derived gas varies from load to load and even from origin to origin with the methane number ranging between 70 and 80. The calorific value of forced boil-off gas is about 38–39 MJ/nm^3, which is quite high compared to the natural boil-off gas [44]. Besides, the forced boil-off gas is quite stable than the natural boil-off gas. Thus, for general shipping forced boil-off gas is becoming very popular [44]. After LNG being heated by ambient air, boil-off gas is generated from the tank at the lowest boiling point of the constituents. Thus, it is very difficult to keep the LNG compositions unchanged for a long time once it started to boil-off. Since heavy trucks are operated in the same routes thus, LNG is more suitable as the fuel of those engines. Furthermore, the cruising distance will be tripled if LNG is used as a fuel in the vehicle instead of CNG because the energy density of CNG is three times lower than LNG [45].

Table 3 depicts the comparison of the physical properties of LNG, CNG, diesel and gasoline. With the change of chemical compositions, the physical properties of LNG vary like diesel and gasoline. In some cases, like the pump octane number and lower heating value, CNG and LNG show somewhat similar results. It is important to understand the cryogenic property of LNG during using it as a vehicle fuel. The phenomenon "weathering" or "enrichment" arises because natural gas is a chemical mixture of ethane, nitrogen and methane. LNG contents vary in the percentage of methane as well as other hydrocarbons. Generally, methane content may vary from 92% to 99% [14]. Besides, other hydrocarbon contents in natural gas are ethane 1%–6%, butane 0% to 2%, propane 1%–4% and other compounds [14]. The boiling point of each of the chemical compounds is methane, ethane, propane and butane is −162, −88, −42 and −0.5 °C respectively [45]. This is the reason why the chemical compounds in the liquid vaporize at its unique boiling point. Since the boiling point of LNG components are different and it vaporizes at its unique boiling point, the concentration of heavier hydrocarbons of LNG is increased. Therefore, premature ignition occurs, which tends to "knock" due to the higher concentrations of heavier hydrocarbons. To relieve this uncontrolled knocking tendency, it is required to use LNG before it becomes weathered. To distinguish this potential difficulty, during the manufacture of LNG, it should be ensured that the amount of methane is 99.4% or higher [14]. The higher amount of methane reduces the detrimental constituents thus weathering cannot create harmful fuel mixtures in LNG [14].

Table 3. Comparison of different properties of LNG with CNG, diesel and gasoline.

Property	LNG	CNG	Diesel	Gasoline
Phase	Cryogenic liquid [14]	Gas [45]	Liquid [45]	Liquid [46]
Fuel Material	Underground reserves and renewable biogas [38]	Underground reserves and renewable biogas [38]	Crude Oil [38]	Crude Oil [38]
Composition	CH_4 (vol.) 99.80% [3] C_2H_6 (vol.) 0.10% [3] N_2 (vol.) 0.10% [3]	CH_4 (mole) 84.5% [47] C_2H_6 (mole) 7.70% [47] C_3H_8 (mole) 2.40% [47] C_4H_{10} (mole) 0.58 [47] C_5H_{12} (mole) 0.37 [47]	Typically, alkanes, polyaromatics, cycloalkanes or naphthenes [48]	Alkanes (vol.) 4–8% [46] Alkenes (vol.) 2–5% [46] Iso-alkanes (vol.) 25–40% [46] Cycloalkanes (vol.) 3–7% [46] Cycloalkenes (vol.) 1–4% [46] Total Aromatics (vol.) 20–50% [46]
Density (kg/m^3)	435 at 20 MPa [7]	175 at 20 MPa [7]	850.4 at 15 °C [3]	742.92(unit conversion) [14]
Pump Octane Number	120+ [38]	120+ [38]		84–93 [38]
Lower heating value (kJ/kg)	49,244 [3]	46,892.16 (unit conversion) [38]	43,400 [3]	44,500 [46]
Cetane Number	NA [38]	NA [38]	40–55 [38]	NA [38]
Toxic	No [7]	No [7]	Yes [7]	Yes [7]
Health hazards	None [7]		None [7]	Eye irritant [7]

2. LNG Fuel System

There are mainly three types of the engine that burns LNG as combustion fuel in the marine industry. First one is the "spark ignited" engine, which uses only LNG as fuel with major requirements, simplicity and good overall performance at the lowest total emissions. This engine is generally used in the marine industry for short-distance ferries [44]. The second one has the dual-fuel capability and mainly used for land power plant because of higher specific power production capacity. The third one is the "direct gas injection diesel engine", which was firstly used in the offshore industry because of its high fuel flexibility and power density [44]. The updated concept of this type of engine in the marine industry has made it too flexible but the use of this type is still limited. The multifuel capability, flexibility in fuel mixing and high-pressure gas injection (300–350 bar) made this engine very promising. This type of engine is unique in terms of having no distinct requirements for stabilization of self-ignition of fuel gas. In addition, its operating principle for diesel provides a complete combustion of the gas fuel, though the NOx emission occurred higher than other gas engine types.

2.1. Descriptions of the Additional Components

Generally, diesel fuel containers are a low-pressure tank and kept uninsulated. However, LNG must be kept in a very well insulated and pressurized tank to minimize vapor loss and weathering because of its cryogenic nature [49]. To utilize LNG in a vehicle, a fuel control system is required, which consists of a pressure management system, vaporizer, fill and vent connections and a cryogenic tank. These devices are pre-plumbed and often integral to the tank. Tank pressure depends on fuel temperature and corresponding vapor pressure. Primarily, the saturated vapor pressure is lower than the fill pressure pumped. However, for a given fuel temperature, the saturation pressure will rapidly drop, and condensation of vapor takes place into the liquid. Most of the systems entirely depend on fuel saturation pressure and temperature, but there are some special devices with systems, which can add heat during lowering the tank pressure [50]. Between the inner and outer shell of the fuel tank, there is a perlite insulation to reduce the heat leakages in the vacuum and to maintain the heat in-between the tanks [51].

All the fuel lines, fittings and valves between LNG fuel tank and the vaporizer must be capable of providing cryogenic services. The connecting lines from the vaporizer to the engine are required only to carry the fuel vapor to the engine inlet. It is recommended to use corrosion-resistant fittings to avoid contamination. Total pressure drops to deliver fuel between the fuel tank and engine inlet must be adequate. The pressure drop testing is necessary to measure the performance and isolate the components if excessive system pressure drop occurs and then, system modification is also necessary [50]. Among various types of vaporizers, the intermediate fluid vaporizer (IFV) shows several advantages over others. For designing the IFV, the heat source must be determined considering the climatic conditions and environmental issues [52].

Besides the cryogenic tank, liquid level and pressure transmitters, venting system, cryogenic filling connector and pressure relief valve are other important components. The main feature of the pressure relief valve is to control the boil-off of the tank. To take the liquid from the tank and then pass it through a pressure regulator and vaporizer to the engine feeding system and injector a withdrawal system is used, which is associated with the cryogenic tank. However, there are some modern engines that are designed to directly inject liquid natural gas in the combustion chamber. Due to having a boil-off valve with a cryogenic container, LNG vehicle should be operated continuously without long parking [53].

2.2. Possible Outcome

From a long time, natural gas has been used as fuel for private cars. Heavy vehicles such as heavy trucks and buses are also using natural gas recently. Pressure vessel stores natural gas at very high pressure of about 20 MPa. In the transport sectors, natural gas shows numerous benefits, especially where heavy fuels are utilized [28]. Almost 25% CO_2 [54], 85% NOx [28], 98% SOx [28] and 90% particulate matters [28] are reduced during combustion of the engine when natural gas is used in place of diesel fuel. Shortly, heavy fuels containing sulphur will be severely restricted; thus, Western Europe has a considerable interest to use LNG for ship propulsion [28]. Worldwide share of ship emissions to total emissions is increasing day by day. Ship emission produces SO_2, CO_2 and NO_X, which contributes 4–8%, 2–4% and 10–20% of global emissions, respectively [55]. In the gas-burning mode, LNG vessels result in the elimination of all SO_2 emission and the production of NO_X, CO_2 and particulate matter are less compared to a vessel driven by marine diesel [55]. Generally, the greenhouse gas emission of a diesel truck is higher than the LNG truck in the wheel to wheel (WTW) analysis. Figure 3 shows a particularity of source of origin of tank to wheel (TTW) emission factors, where DENA extricated the information from German Consultancy-Ludwig Bölkow Systemtechnik (LBST) and the rest of the sources are from North American experiments [34]. From Figure 4, it can be seen that the total WTW emissions of all gas heavy ground vehicles (HGVs) are significantly lower than diesel HGVs and LNG shows way better results in terms of emissions than CNG and diesel. Besides, the reduction of emission, LNG provides other competitive advantages in night-time services through inner-city by reducing the noise level when using LNG Otto-cycle engines [56].

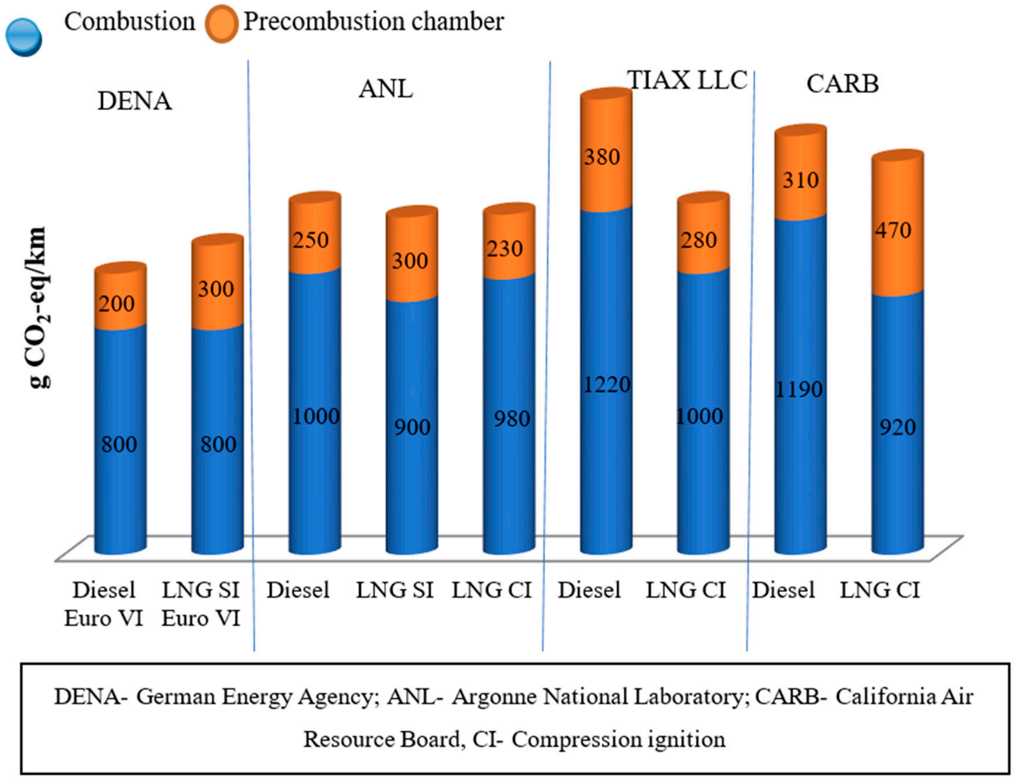

Figure 3. Life cycle greenhouse gas comparison of diesel and LNG heavy-duty vehicle (adapted from [40]). Note: Permission granted from the publisher (Elsevier-Renewable and Sustainable Energy Reviews).

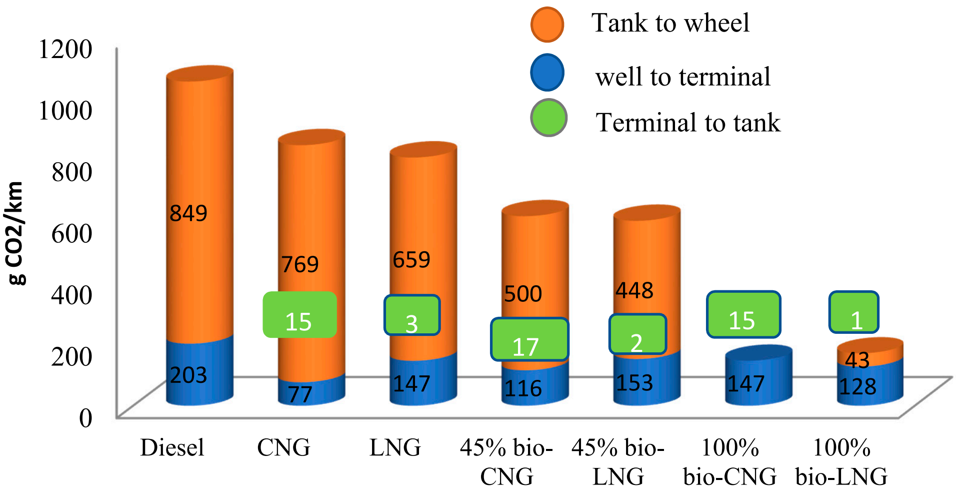

Figure 4. Wheel to Wheel emissions of heavy goods vehicles, adapted from [57].

For many years, the price of LNG depends on the HFO price though often LNG is cheaper. By considering the lower heating value and price of LNG, it can be said that LNG cost is about 60% of HFO [37]. Due to the savings of the reliquefaction process, the cost of produced boil-off gas is decreasing on gas carriers. Due to introducing shale gas in the US market, the natural gas price, including LNG, decreased in 2009 and 2010. Therefore, LNG has become a strong competitive of HFO. The price of HFOIF-0380 in the middle of 2008 was over $1000 per metric ton. In the middle of 2011, it was about $650 and later, the price of HFO further increased. Therefore, it can be said that the price of LNG is more stable compared to the HFO depending on the industry price [37].

Moreover, LNG is a very pure fuel; therefore, the operational costs of the engine are decreasing, the technical states of the engines are better, and the number of emergencies and failures are dropping. The price of LNG in the next 20 years will be equivalent to HFO, but later the LNG price will fall [37].

To make a proper comparison, different performance parameters of LNG-diesel dual-fuel engine such as torque, fuel consumption, smoke density, brake power and different emissions are needed to be measured and compared with a single diesel fuel engine (Table 4). For LNG-diesel dual-fuel engine, the brake specific fuel consumption (BSFC) is lower under light loads. Compared to the diesel engine, the torque and brake power of LNG-diesel dual-fuel engine remain unchanged [58]. Some researchers estimated brake thermal efficiency of the liquid natural gas engine has the same level of the corresponding conventional diesel engine [45]. Moreover, LNG is more preferable for heavy-duty vehicles compared to CNG as the density of LNG is 435 kg/m^3 as compared to 175 kg/m^3 for CNG at 20 MPa [58].

Table 4. Recent research on LNG as a fuel for the diesel engine.

Author	Working Environment	Outcome	Remarks
Kraipat Cheenkachorn et al. [3]	Used liquefied natural gas as primary fuel and small amount of diesel pilot was used as ignition source. Compared the result of dual fuel engine with equivalent diesel engine.	At 1100 rpm the torque obtained in duel fuel engine was around 1780 N-m and in diesel engine 1790 N-m. Additionally, the power output of both engines was equivalent. At lower rpm, thermal efficiency of both the engines is almost same.	LNG and diesel both showed similar power output.
Jiantong Song et al. [25]	Conducted research on LNG dual-fuel engine and conventional diesel engine. Compared the efficiency and emissions of both engines.	The brake specific fuel consumption of dual-fuel increases under <45.63 kW power. However, above this specific value, fuel consumption reduces. The smoke density of dual-fuel engine is significantly low compared to conventional diesel engine.	After a certain speed, the Brake specific fuel consumption (BSFC) of LNG engine reduces compared to diesel engine.
Ahmet Alper Yontar et al. [59]	Authors used Ricardo-Wave software for 1-D wide open throttle modeling of LNG and gasoline spark ignition engine for comparing performance and emissions.	Observed a torque value of 138 N-m and 110 N-m at 3000 and 3500 rpm for both gasoline and LNG respectively. At high speeds, the gasoline fuel consumption is comparatively higher than LNG consumption.	Both the fuels showed similar torque value.
Max Kofod et al. [60]	Conducted research on Well-to Wheel (WTT) Greenhouse Gas emissions of LNG used as a fuel for long haul trucks.	WTT GHG emission for LNG was 37.9 gCO_{2e}/MJ_{out}, whereas, for diesel was 47 gCO_{2e}/MJ_{out}. Total WTW GHG emission for LNG and diesel was 211.7 and 262 gCO_{2e}/MJ_{out}, respectively	GHG emissions of LNG fuel is lower than diesel fuel.
Junli Shi et al. [61]	Did a life cycle assessment to determine energy saving and environmental emission of a remanufactured LNG engine and newly manufactured diesel engine.	For a mileage of 300,000 km the fuel efficiency of diesel and LNG was 25 L/100 km and 26.5 m^3/100 km, respectively.	Both the systems showed almost similar fuel consumption.
Jeong Ok Han et al. [62]	The LNG engine (dual-fuel) was converted from a conventional diesel engine having 12 liter class and compared power, efficiency and emission	Compared to diesel engine, the power of LNG engine was 5% less, also the efficiency was lower. However, the LNG dual-fuel engine showed better results in terms of emissions.	Converted 12 liter class engines are not appropriate for using LNG.
Seokhwan Lee et al. [63]	The authors converted an electronically controlled diesel engine to dual-fuel engine and examined fuel economy, power etc.	Almost 85% of diesel substitution ratio was shown by the developed vehicle. The emission results were satisfactory and met k2006 standard. Moreover, the LNG dual-fuel engine performance was equivalent to the conventional diesel engine.	LNG showed same power output and less emissions compared to diesel.
Chandan Misra et al. [64]	Authors conducted research on two diesels and LNGs with three-way catalyst and one hydraulic hybrid diesel system and compared the NOx formation.	Found that the NOx emissions of LNG were slowest of all the technologies tested and emission from diesel was highest of all the technologies.	NOx emissions of LNG are lower than diesel.
Broynolf et al. [65]	Conducted research on the transportation of 1 t cargo 1 km with a ro-ro vessel and examined different parameters such as emissions, fuel characteristics etc.	CO_2 (fossil origin) (g/MJ fuel) for LNG was 8.3 and HFO was 6.7, CH_4 (g/MJ fuel) for HFO 0.072 and LNG 0.033. C_3H_8 (g/MJ fuel) for HFO 0.0067 and LNG 0.027. In case of emissions of air during tank-to-propeller- CO_2 (fossil origin; g/MJ fuel) for HFO 77 and LNG 54. NO_X (g/MJ fuel) for HFO 1.6 and LNG 0.11.	In terms of emissions, LNG shows better results (except fossil origin) than HFO.

Table 4. *Cont.*

Author	Working Environment	Outcome	Remarks
Jiehui Li et al. [66]	Designed a control system for LNG dual-fuel marine engine and compared different engine parameters with conventional diesel engine.	Calculated fuel flow rate from 600 to 1800 rpm and found that for the same speed, LNG consumption is lower than diesel consumption. Natural gas consumption rate increases with rpm, but decreases sharply once the speed overtakes 1400 rpm. Authors also found that cost of LNG dual-fuel engine is lower than diesel engine with a maximum decrease of 28.7% at 1300 rpm.	LNG engines show way better results than a conventional dual-fuel engine in terms of fuel consumption over 1400 rpm.
Ibrahim S. Seddiek et al. [67]	Conducted research on on-board diesel engine and natural gas (LNG) dual-fuel engine for ships.	Found that fuel consumption and all sorts of emissions (except hydrocarbon) are less for LNG dual-fuel compared to on-board diesel engine.	BSFC and emissions of LNG are less than diesel.
Green Truck Partnership project (report) [52]	Green Truck Partnership evaluates the quality and potential of fuels for heavy duty trucks. The discussed report analyzed LNG dual-fuel trial conducted under the program in 2013.	Throttle body injection LNG dual-fuel system did not produce any benefits regarding emissions. However, cost saving was around 4% compared to the conventional system. Authors recommended using the system in a case where the gas substitution rate could be higher.	Throttle body injection is not effective when using LNG where the gas substitution rate is low.
Harald Schlick [68]	Performed some experiments on LNG dual-fuel engine and compared power and NO_x emission.	Found that NOx and CO_2 emissions of LNG dual-fuel engines are clearly lower than diesel engine. They also recommended some solutions for reducing THC/CH_4/CO emissions: Valve overlap optimization, crevice volume reduction and minimization of flame quenching.	LNG shows better results in terms of emissions.
Dominik Schneiter et al. [69]	Performed an experiment on X-DF (engine model/series) LNG engine and compared with X-DF diesel engine.	GHG, NOx, SOx and particulate matter emission of X-DF LNG engine are less than diesel. SOx emission of LNG engine was found almost zero.	X-DF LNG engines show way better results than diesel in terms of emissions.
Hengbing Zhao et al. [70]	Analyzed emissions and power of class 8 hybrid electric truck technologies electricity, hydrogen, diesel and LNG as fuels for numerous applications.	At part load, the LNG compression ignition engine shows similar efficiency as diesel engine and at full load the efficiency is a bit low.	The efficiency of LNG and diesel are almost equivalent at part load.

2.3. Challenges

Though there are many merits of LNG, it also has some challenges to overcome. Frost burn occurs when LNG comes into contact with human skin because of being a cryogenic fluid. This phenomenon is also known as frostbite or cold burn [27,28]. Structural failure may occur due to metal cracks and metal embrittlement of the LNG storage tank, which rises by LNG spill [28]. Besides, different common usable materials such as plastic, carbon steel and rubber become brittle at an enormously cold temperature [27]. Since methane does not sustain breathing, thus, due to a large concentration of methane dispersed in air and vapor accumulated near the ground may rise to asphyxiation [28]. When LNG is released on water, it becomes less dense, which gives rise to rapid vaporization of liquefied natural gas and known as rapid phase transition (RPT) [37,71–73]. Consequently, due to the accidental release of LNG, a strong pressure wave is developed and causes heat radiation and burning clouds. Besides, higher flammability of LNG causes different fatal hazards [28]. LNG vaporizes readily when it is released from containment. Then, the liquid will be heated by the surroundings, thus, causing it to vaporize. The vapor will be mixed with the surrounding air and carried out downward causing a cloud. Eventually, it will be mixed with additional air and will be further diluted. The vapor cloud may ignite if the flammable portion comes in contact with a fire source. Secondary fires can be generated by the burn-backs of the primary vapor cloud and cause severe damage to the persons caught within the cloud [74].

According to a safety study regarding LNG, the maximum effective distance of LNG transportation with trucks is 230 m [28]. Flash fire of LNG causes truck tank rupture, which is related to the distance effect. Boiling liquid expanding vapor explosion (BLEVE) may occur with lethal effects during rupturing an LNG truck tank with elevated pressure [28]. Sometimes because of BLEVE, the released liquid immediately flashes and atomizes the resulting fireball. Though fireball lasts for only a couple of seconds, its effects can be very dangerous [74]. If LNG truck tank rupture occurs during engulfing fuel firing, then the maximum effect distance would be 190 m [28]. Pool fires occur due to immediate ignition of LNG, which can cause several damages to the surrounding equipment and burns to people caught within the cloud. The surface emissive power of LNG pool fires generally lies in the range of 220 ± 50 kW/m^2. However, a huge amount of smoke is produced during a large fire, which is very dangerous [27].

Due to having different density, LNG has the potential to layer in unstable strata within the tank. These strata have the potential of rolling over to stabilize the liquid in the tank. Due to normal heat leak, the longer LNG layer gets heated and changes density until it becomes lighter than the upper layer. As a result, a liquid rollover may occur with sudden vaporization of LNG. However, if the design of pressure relief systems is not adequate the excess pressure can result in cracks or other structural failures in the tank [71]. Since LNG is extremely cold, it can cause damage to eyes and tissue. Oxygen deficient hazard (ODH) results from the displace of air caused by the release of LNG [75]. Due to the accidental release of flammable liquid from pressurized containment, the leak takes the form of a spray of liquid droplets and vapors and if it is ignited the resulting fire is called torch fire. Torch fire possesses similar types of hazards as a pool fire. In some cases, for similar size pool and torch fire, the radiant heating power of a torch fire is frequently greater than that of a pool fire [74].

In a high pressure dual fuel engine, the combustion is nearly complete when LNG is injected at a pressure of 30–35 MPa with a small amount of diesel. However, when using in low pressure dual-fuel LNG is injected at a low pressure, which is comparable to the Otto cycle. A major disadvantage of the dual fuel diesel engine is the high amount of methane slip compared to the diesel engine. At high and medium loads the air fuel mixture enters the crevices and cylinder wall causes methane slip [76]. Moreover, at low speed the emission problem is more severe because of a low air-fuel ratio. This phenomenon therefore causes high methane slip and fuel consumption as a result of bulk quenching in the coldest areas of the combustion chamber [77]. In an Otto based dual fuel engine, at high power the methane slip is low, however, with the decrease of power, methane slip increases significantly [78].

3. Possible Solutions

Researchers all over the world are trying to find out some ways to face the challenges to use LNG and have already found some techniques as discussed below. The safety barriers, i.e., layers of protections, may have been used for preventing, controlling or mitigating undesired accidents or events. Similarly, for preventing the depth of catastrophic accident, different types of safeguards and protection layers have been used. Currently, the LNG industry uses several layers of protection for minimizing and controlling the consequences connected with vapor dispersions, LNG spills and subsequent fires and explosions [27]. To minimize cryogenic embrittlement, different types of special steels have been developed [28]. Moreover, currently, operators are using LNG rollover models, which can optimize boil-off costs by inducing density stratification and by doing so, converting a dangerous configuration into a potentially operational asset [71].

Basic responses to accidental LNG spills include detecting the spill, securing the origin and taking measures to prevent it from worsening. It is very important to secure the leak and the area, move the people away from the spill, prevent ignition sources and monitoring should be performed carefully until no vapor remains in the flammable limits [79]. A potential technique to reduce the size of the flammable vapor cloud is to increase the vapor dispersion generated by the liquefied gas spill [27]. The cloud generated by the spill of unconfined LNG on water travels at the speed of the wind before dispersion. Since it is denser than air, for land-based facilities, it has some advantages i.e., it can be easily controlled, though sometimes it can be a disadvantage if it takes longer to disperse [80]. Some experimental conditions of LNG spills on the water are summarized in Table 5. To determine low flammability limit (LFL), spill rate, volume, vaporization rate and atmospheric condition are taken into account [80]. However, reducing the pool surface area would be an effective solution to reduce LNG vaporization [27]. Water spray curtains may be used as a promising technique to mitigate many toxic and flammable LNG vapors by reducing the concentration of LNG vapor clouds [80]. A properly designed water curtain is capable of enhancing the dispersion of LNG vapor cloud and reducing the vapor cloud exclusion zone through mechanical effects, dilution and thermal effects. It is considered one of the most economical and efficient cloud control techniques [81]. However, the effectiveness of different water curtains is still widely unknown because of the temperature increase and LNG concentration reduction [80].

Table 5. LNG dispersion test on water [80].

Experiment	Spill Volume (m^3)	Spill Rate (m^3/min)	Pool Radius (m)	Downward Distance to LFL (m; maximum)
ESSO	0.73–10.2	18.9	7–14	442
Shell	27–193	2.7–19.3	NA	2250 (visual)
Maplin Sands	5–20	1.5–4	10	190 ± 20
Avocet (LLNL)	4.2–4.52	4	6.82–7.22	220
Burro (LLNL)	24–39	11.3–18.4	5	420
Coyote (LLNL)	8–28	14–19	Not reported	310
Falcon (LLNL)	20.6–66.4	8.7–30.3	Not reported	380

LLNL—Lawrence Livermore National Laboratory; note: reprinted with permission from the publisher (American Chemical Society—Energy and Fuels).

Three types of thermal coatings are used for exposure protection. For many years, as a thermal protective coating in refineries and petrochemical industries, concrete has been used [82]. To mitigate LNG vapor ignition and pool fire, high expansion foam application would be one of the effective solutions [82]. Additionally, to extinguish LNG fire dry chemicals such as sodium bicarbonate, potassium bicarbonate and urea potassium bicarbonate are a suitable accomplishment [83]. In most cases, for high expansion foam-controlled LNG pool fire dry chemical is useful, where the magnitude of the fire is small, the production of heat is reduced and fire fighters can apply dry chemical competently. To create greater firefighting capabilities, potassium bicarbonate is usually mixed with an aqueous film forming foam (AFFF) to create a dual agent system. However, inducing corrosions of exposed metals, low visibility after discharge, inducing breathing hazards, clogging ventilation filters, etc., are some limitations of dry chemicals [27].

A very effective method in managing LNG fires is the use of the medium (20:1 up to 200:1) and high (200:1 up to 1000:1) expansion foams. For LNG fires the effective ratio for high expansion foam should be at least 500:1. Gaz de France experience has demonstrated that the utilization of high expansion foam on LNG flames can diminish the fire stature by 60% and also the radiant heat can be decreased by around 90% [79]. Moreover, the results of a recent experiment show that exfoliated ZrP nanoplates can stabilize high expansion foam and this foam can increase the duration over which it needs to be replenished, while by exchanging heat with the vapor and foam and makes the vapor lighter, which ensures effective vapor dispersion [84]. Nevertheless, it is very important here to mention that applying water on LNG fire is not effective as it will not extinguish it; rather, the liquid will vaporize more quickly if the water is applied. Moreover, the fire will get hotter and burn faster if the water is applied to it [79]. Moreover, in recent years, some improvements have been done on LNG dual-fuel engine to improve efficiency, reduce pollution and improve sustainability as discussed in Table 6.

Table 6. Recent advancements on LNG dual-fuel engine.

Author	Working Environment	Outcome	Remarks
Koichi Watanabe [85]	A new engine was developed by Niigata, which is called dual fuel engine used two-types of fuel: gas and oil.	The NOx emission of the engine meets International Maritime Organization Tier II and Tier III requirements at diesel operation and gas operation, respectively.	The engine is capable of maintaining Tire II and Tire III emission standards.
GH Choi et al. [86]	Authors conducted some experiments on retrofitted LNG-diesel dual-fuel engine. The design of intake manifold was modified and electronic control system (ECU) was used to control amount of injected diesel fuel.	The modified system narrowed down the cylinder to cylinder variation by almost 60%.	The designed intake manifold was capable of reducing cylinder to cylinder variation.
Zheng Chen et al. [87]	Authors analyzed the effects of high compression ratio with hydrogen enrichment for the efficiency of LNG dual-fuel engine.	Reported that due to the effect of high compression ratio, cylinder pressure rises, ignition advances and shortens the combustion duration. Therefore, the process increases combustion stability and indicated efficiency.	Hydrogen enrichment increases the efficiency of LNG dual-fuel engine.
Jianqin Fu et al. [88]	Authors used a novel approach to improve the performance of LNG engine. LNG was purified into liquefied methane and then it was used as the engine fuel.	Ignition delay period is reduced and start of combustion advances. The torque of the engine increased by 9.5%, while the BSFC was reduced by almost 10.9%.	Since the octane number of methane is higher, the engine shows some better performance. However, since the pressure and temperature of the engine would also be high with high compression ratio, NOx emissions should be taken into consideration.
PA Davies et al. [89]	Authors developed a risk assessment model. The model was developed to determine the release likelihood and also provided guidance for the selection of appropriate safeguards and the prevention of leak.	Authors reported that calculating the likelihood of releases helps to identify where additional safeguards are necessary and would be effective.	The discussed risk assessment model should be implemented in LNG applications.
Qijun Tang et al. [90]	Author investigated the intake air supply system to improve accelerating and climbing performance. Authors designed a set of air supply systems and attached it with a LNG engine, then, its performance was tested.	Reported that at 1000 rpm, the torque was increased by 31% and specific gas consumption decreased by 1.64%. Additionally, the vehicle acceleration time was decreased by around 14.7–30%.	The intake air supply system is very effective for LNG engines.
Gyeung Ho Choi et al. [91]	Tested the performance and emissions of LNG dual-fuel engine with two different gas injectors. The main objective of the research was to gain economic benefits by replacing imported injector by local product.	Reported that the local product can operate satisfyingly with no knocking. The emission and engine performance were not compromised.	Local injectors are cost effective and provide quite similar output like imported ones.
Zunhua Zhang et al. [92]	Authors performed a numerical investigation on exhaust reforming characteristics of hydrogen production on the LNG marine engine.	For methane reforming reaction, inhibition of coke formation and hydrogen yield, higher mass ratio of water to fuel is advantageous. However, carbon monoxide is produced with higher exhaust gas recirculation process.	The developed numerical model is capable of discussing some fundamental parameters of LNG marine engines.
Chunhua Zhang et al. [93]	Authors investigated the effects of combustion duration characteristic on NOx production and brake thermal efficiency of diesel-LNG dual-fuel engine.	Authors reported that at low and medium speeds, the production of NOx is higher, whereas, when the centroid angle of combustion duration is before top dead centre, NOx emission is completely opposite.	In the LNG dual-fuel engine, the NOx emission is less when the centroid angle of combustion duration is before top dead centre.
Seokhwan Lee et al. [63]	Authors converted an electronically operated diesel engine into dual-fuel engine system. Maximum driving distance, fuel economy and emissions were examined. Authors also did an ND 13-mode test.	The engine meets k2006 regulations and the performance of the engine was similar to a conventional diesel engine.	Electronically operated diesel engine can be converted into dual-fuel engine system without having any performance reduction.

Table 6. *Cont.*

Author	Working Environment	Outcome	Remarks
Sinian He et al. [94]	The authors proposed and investigated a combined organic Rankine cycle (ORC) system, where exhaust waste was used as a heat source and LNG as a heat sink to provide alternative power for a LNG fired vehicle. In this study, five types of organic fluids were analyzed such as CF3I, R236EA, R236FA, RC318 and C4F10.	Reported that fluid R236FA provides the highest thermal efficiency (21.6%). These five fluids can improve fuel economy by more than 14.7%.	The study reported five types of fluids, which can increase combined organic Rankine cycle efficiency.
Yifeng Guan et al. [95]	Authors developed a fault tree model to analyze fire and explosions in a dual-fuel ship.	According to the faults found, authors suggested ten fundamental safety measures where authors put great importance on the working humans near accidents.	The study suggested some techniques, which could reduce the tendency of accidents.
Elena Stefana et al. [96]	Authors did a qualitative risk assessment on LNG-diesel dual-fuel engine. First authors developed a reliability block diagram, then performed failure mode analysis, failure effect analysis, likelihood and consequence analysis, fault tree and bow-tie analysis.	Bow tie analysis allowed providing barriers to prevent and mitigate critical events. By applying all the methods, authors were able to identify and design a set of safety measures.	Authors successfully developed some safety measures for the failures of LNG-diesel dual-fuel engine.
Khaled Senary et al. [97]	Authors developed a waste heat recovery system to meet IMO (international maritime organization) regulations onboard LNG carrier.	The developed system meets the requirements and regulations set by IMO for Tier-III. The waste heat recovery system is capable of reducing almost 130 kg NOx per day.	The waste heat recovery system is capable of reducing a huge amount of NOx production.

3.1. Engine Knock Reduction

Knocking is one of the severe problems of the LNG dual-fuel engine. One of the key initiatives to utilize LNG as a fuel in a diesel engine is to alleviate the knocking problem and take adequate precautions when knocking resistance is low. However, there is no specific technique to reduce knocking completely. One of the solutions to improve the knock resistance of LNG is to keep higher methane in LNG. During the manufacture of LNG, it should be ensured that the amount of methane is 99.4% or higher [14]. The knock resistance of LNG is strongly dependent upon the boil-off rate of the cargo container system used and the initial composition of the fuel. The reduction of methane and nitrogen in LNG increases the fraction of butane and propane and results in decrease in the PKI-MN (propane knock index-methane number), which is responsible for knocking [23]. Further, to reduce the knock combustion, leaning combustible mixture and exhaust gas recirculation strategy can be applied as an efficient way [98]. In the case of an SI engine, higher turbulent kinetic energy in the centre of the combustion chamber, lower mean flow velocity in the spark plug region and near the spark plug can produce knock [99]. Therefore, it is necessary to develop combustion chamber, which can provide higher mean flow velocity.

3.2. Future Research Perspective

With the increasing demand and potential of LNG, numerous research has been conducted regarding the use of it in a diesel engine. According to previous discussion and literature, researchers and engineers have successfully used LNG in a diesel engine, where the emissions are less, and the power output is similar to conventional engines. However, more research is necessary regarding fuel consumption, fuel atomization, engine equipment and safety of using LNG. According to research [19], below the power of 45.63 kW, the BSFC of LNG dual-fuel engine is higher, though after this certain limit BSFC tends to reduce. The reason can be that the LNG–air mixture may be too lean to burn under light loads. However, as the power increases, the mixture of fuel in the cylinder enriches, eventually the conditions of combustion are improved, which reduces BSFC. Further research is necessary on how the BSFC of LNG dual-fuel engine can be reduced under light loads. Literature suggest that under a certain load and power output conditions, formation of hydrocarbon is almost double in LNG-dual fuel engine than a conventional on board diesel engine, which also should be a concern for the researchers. Research related to different powertrain such as series and parallel hybrids associated with the use of LNG are very rare. Hengbing Zhao et al. [99] did research, where the authors developed and analyzed some hybrid configurations and according to the simulation results, LNG-CI hybrids showed better results in terms of emissions for Class 8 Hybrid-Electric Truck. Experiments should be conducted in this area to verify the results. Moreover, the hazards and dynamics of LNG spill require more research. Regarding vaporizers, the IFV shows various advantages over other types. In the above discussed literature, finding related to design, configurational variations, working fluids, etc., are discussed. However, it is recommended to develop a three-dimensional unsteady CFD model to evaluate instantaneous flow and heat transfer. As discussed above, in the LNG dual-fuel engine, at low and medium speeds, the production of NOx is higher. Advancing the diesel injection timing, increases the proportion of compression and eventually increases the peak in-cylinder temperature. At medium loads with the increase of temperature, energy in the exhaust gas increases, which eventually increases the intake pressure. This also should be a concern of researchers and further research is necessary to develop a solution to mitigate this problem. For determining hazards, experimental data from large scale experiments are not sufficient. Therefore, it is recommended to consider small scale experiments where large scale is not feasible.

4. Conclusions

All over the world, liquefied natural gas (LNG) would be a clean primary energy source shortly. LNG provides a plethora of potential point of interests as a fuel for a dual fuel engine. It is capable of compensating some of the major drawbacks of natural gas and diesel vehicles. LNG is not only clean, has relatively higher density, has easier transportation and is safe but also the price is reasonable. The indicated thermal efficiency and brake thermal efficiency of an engine using LNG are equivalent to that of diesel and the production of emission is less when using LNG. This paper also reviews successfully the challenges, finds out some responses to overcome those challenges and provides some recommendations for proper utilization of LNG as a fuel for the dual fuel engine. The major challenges of LNG are its higher flammability causes different fatal hazards and when using in dual-fuel engine causes knock. Though researchers have been successful to find out some ways to overcome some challenges, further research is necessary to reduce the hazards and make the fuel more effective and environment-friendly when using as a fuel for a diesel engine.

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