marcogaz

LIQUEFIED NATURAL GAS
AS TRANSPORTATION FUEL

June 2021

Contact

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ABOUT MARCOGAZ

Founded in 1968, MARCOGAZ is the technical association of the European gas industry. It represents 30 member organisations from 20 countries. Its mission encompasses monitoring and policy advisory activities related to the European technical regulation, standardisation and certification with respect to safety and integrity of gas systems and equipment, rational use of energy as well as environment, health and safety issues. It is registered in Brussels under number BE0877 785 464.

DISCLAIMER

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1. INTRODUCTION

EU following Paris Agreement goals to a low-carbon future and preventing some of the worst impacts of climate change has released new initiatives:

- in 2019 The European Green Deal Communication COM (2019)640; and
- in 2020 EU Commission Communication: "EU strategy to reduce methane emissions" COM (2020)663.

Climate action is at the heart of the European Green Deal – an ambitious package of measures ranging from ambitiously cutting greenhouse gas emissions, to investing in cutting-edge research and innovation, to preserving Europe's natural environment.

First climate action initiatives under the Green Deal include:

- European Climate Law to enshrine the 2050 climate-neutrality objective into EU law
- European Climate Pact to engage citizens and all parts of society in climate action
- 2030 Climate Target Plan to further reduce net greenhouse gas emissions by at least 55% by 2030
- New EU Strategy on Climate Adaptation to make Europe a climate-resilient society by 2050, fully adapted to the unavoidable impacts of climate change.

By June 2021, the Commission will also review and, where necessary, propose to revise all relevant policy instruments to deliver additional greenhouse gas emissions reductions.

The clean energy transition will be key, and in particular LNG use in gas value chain will contribute significantly in the GHG reduction.

Methane is a GHG and its release can occur during all stages of the LNG life cycle. The methane emission resulting from internal engine combustion is called "methane slip" induced during incomplete gas combustion. Methane slip can be eliminated with the two-stroke engines technology and the optimized design of the four-stroke dual-fuel engines. LNG engines are put in operation for different uses like road, rail, maritime and aerial transportation.

The vapours created due to the ambient heat input (while maintaining constant pressure

in the storage vessel) are called "boil-off". The boil-off is an LNG physical phenomenon and the gas industry treats it applying processes described herein below.

Other current EU initiatives apart from the Clean energy package (in November 2016) are, the Action against aviation emissions in February 2017, the Support for sustainable transport and energy infrastructure in April 2017, also in April 2017 the Agreement reached on new Security of Gas Supply Regulation, Decarbonisation of the Transport Sector (element of the recast of the RES Directive).

2. LNG AS A TRANSPORTATION FUEL

Natural gas has been used during decades as a fuel for vehicles. In recent years, the concerns on environmental issues (CO_2, NO_x and particle emissions), diversification of fuel sources and high oil prices have promoted the use of natural gas as a fuel for any type of transportation mode.

In this context, LNG is seen as the perfect choice for heavy transport: trucks, trains & ships, because it allows a higher mass based energy density compared to the traditional fuels.

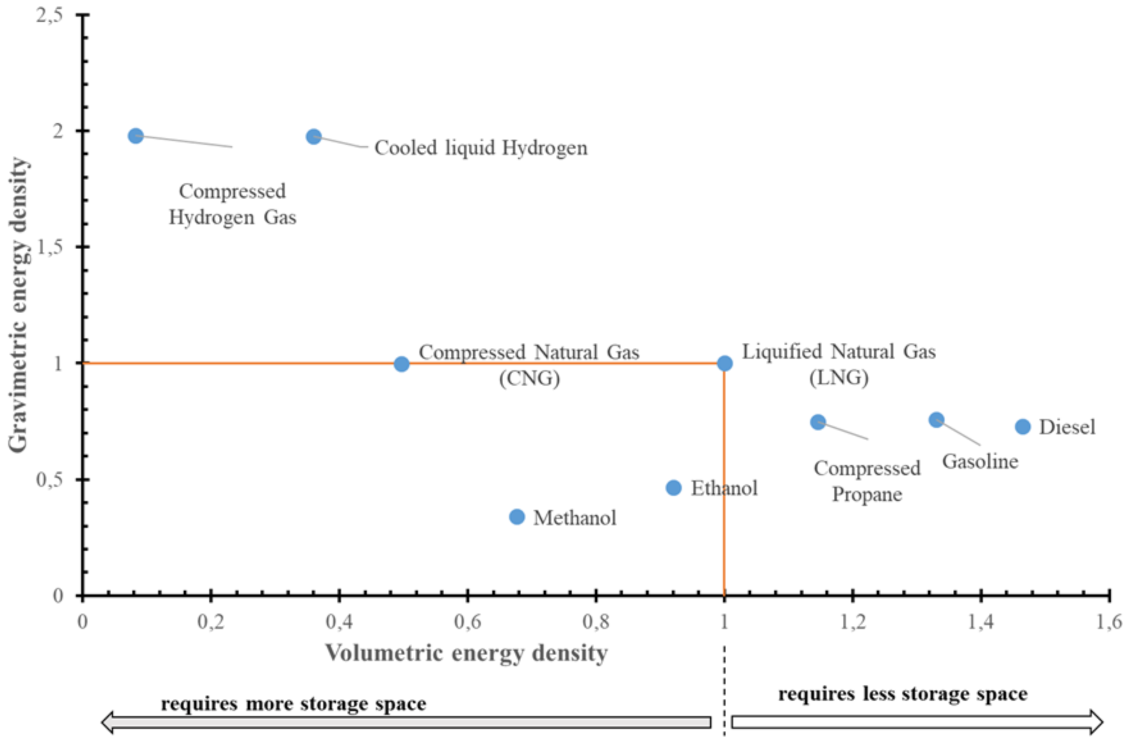

Figure 1 - Energy density comparison of several transportation fuels (gasoline = 1).

Source: US EIA, http://www.eia.gov/todayinenergy/detail.cfm?id=14451.

2.1. LNG as a maritime transportation fuel

2.1.1. Regulation

In maritime transportation air emission and GHE reduction are key issues. Decision from IMO are already addressing the Sulfur emission reduction from January 1st, 2020 sulfur content in the fuel to 0.5% max from 3,5%.

2.1.2. LNG for propulsion

Based on EMSA Guide a report prepared in cooperation with the European Commission (DG MOVE), member states and industry within the context of the European Sustainable Shipping Forum and was released in February 2018 aiming to support port authorities and administrations backing the use of LNG as a ship fuel, as part of a joint effort to increase safety and sustainability.

The benefits from using LNG as fuel are indeed very significant with an almost complete reduction of Sulphur oxide emissions and PM (particulate matter), and with a very significant reduction of NO_x emissions.

Whilst addressing the life cycle approach applied to LNG as fuel for shipping, the following aspects are identified as having the potential to further improve the accuracy of WtW results:

- Upstream methane release estimates (production, liquefaction and distribution), having integrated up-to-date research in the industrial production/processing of LNG.
- Engine Technology – considering new and emerging dual-fuel engine technology on both two stroke and four-stroke diesel engines, focusing on efficiency and methane slip mitigation/reduction.
- Environmental impact of producing low-Sulphur fuel oils (LSFOs) – identifying the relative GHG impact of oil fuel desulphurization, using the results as further evidence of the advantages of LNG.
- Comparative new technologies other than LNG – in particular scrubbers, identifying the additional energy consumption of such systems as an argument for using LNG rather than fuel oils.

The carbon emission factor of LNG (actual CO_2 emissions from burning LNG as fuel) is approximately 25% less than Marine Diesel Oil [MDO] (see table below). This is the result of its lower carbon presence at molecular level.

FUEL	Combustion Emission Factor [gCO_2/MJ LHV]	Percentage reduction [%]
Diesel	75	0
LNG	56.1	-25

Table 1 – Carbon Emission Factor for LNG vs Marine Diesel Oil.

The Well-to-Wake approach takes the analysis onto a more comprehensive scale, looking at each of the fuel's life cycle stages. A rough comparison between WtW values of LNG compared to those of MDO shows mainly that LNG causes approximately 20 per cent less CO_2 emissions than MDO (if methane slip is not considered). A more modest benefit of 10% would result if methane slip were to be considered.

In the particular context of the EMSA Guidance the WtW considerations for CO_2 emissions from LNG as Fuel are relevant as a measure indication on how important are LNG handling, distribution, transfer and bunkering operations in the port area. Having an appropriate production and distribution architecture in place is also very important when considering the environmental footprint of LNG as fuel.

LNG as fuel can, therefore, represent a clear advantage with regards to local air quality improvement, with very significant expression in reduction of pollutant air emissions, but also the potential for methane emissions to the atmosphere, affecting thereon the GHG benefits from direct combustion CO_2 reduction.

2.1.3. Boil-off

Liquefied natural gas (LNG) is becoming an attractive alternative to traditional transportation fuels such as diesel and heavy fuel oil. The major advantages in terms of reduced pollutant emissions and its worldwide availability make it an attractive fuel for powering ships.

The natural boil-off gas (NBOG), which is taken from the top of the tank, can directly be used to power the auxiliary engines and the boilers. The NBOG typically contains large methane fractions and hence has a high knock resistance. During a voyage, the continued “boil-off” of methane can change the composition of the LNG fuel, which slowly lowers its knock resistance. When the power demand is higher than the power that can be generated using NBOG, forced boil-off gas (FBOG, obtained by vaporizing liquid LNG) is mixed with the NBOG to meet the power demand. Given the differences in knock resistance the addition of FBOG to NBOG also reduces the knock resistance of the fuel. It means that the mixing of the FBOG and NBOG and/or switching from natural boil-off to forced boil-off needs to be carefully done.

2.1.4. Other application - electricity production with LNG as fuel in maritime transportation - from cold ironing to green ironing

Although most of the energy used from shipping is for propulsion far away from inhabitants most of the time, however ships are also producing power when at berth, using low sulfur MDO, in the vicinity of dense urban areas where million people are living.

In order to reduce this pollution at berth, electricity could be provided from the shore allowing the ship to shut down its auxiliary engines, making the iron body of the engine (formerly a boiler) cold ("cold ironing"). But this solution is not always effective since the capacity of the electricity grid sometimes doesn’t meet the demand from ships and huge investments are required to face it.

When electricity grid connection is not economic, or not possible due to currency frequency difference (ship at 60 Hz while EU grid at 50 Hz), LNG may provide an efficient and flexible alternative. Power generation from a gas engine using clean LNG fuel can be installed onshore or on a barge and connected to the ship.

To reduce emissions in the air and in the meantime save considerable fuel, one of the solutions is the Cold Ironing that means switching off the engines of the ships while in port in front of an electric support point provided on the dock.

LNG apart from used as fuel in maritime transportation can also be used for power generation for the ships "cold ironing" (making the iron body of the engine cold) from a gas engine which can be installed onshore or on a barge and connected to the ship. Using LNG propulsion, no longer ship to shore connection is need. Mobile power generation equipment can be used which therefore may be repositioned in another quay or exported to another port.

From Cold Ironing to Green Ironing: LNG combustion doesn't emit particles nor sulfur oxides and reduces NOx by more than 80% without any post combustion treatment.

Compared to auxiliary engines in the ship, the purpose designed generator offers higher efficiency and may cut GHG by more than 50%. In the close future, bio LNG produced from the biomass may replace fossil fuel partially or totally for a progressive de-carbonation.

Depending the energy mix of the country (or the island), LNG fueled engines may have a lower carbon density (g CO2/kWh) than average power grids.

Gas engines are generating less noise and are in an acoustic box, avoiding noise trouble.

2.2. LNG for heavy duty vehicles (HDV)

NGVA reports that on top of the continuous engines and powertrains technological evolution, the use of natural gas results in an immediate reduction of CO2 tailpipe emissions, from 7% up to 15% compared to Diesel, thanks to the combination of a high efficient engine and the fuel properties, as Low Carbon fuel.

Current ongoing developments on natural gas engine technologies (cfr. EU H2020 projects "GASON" and "HDGAS") are demonstrating the potential to develop for post 2020 high efficient engines with Diesel-like efficiency capable to take the maximum profit for the fuel characteristics, considering specifically the development of new Direct Injection systems.

Nevertheless, CO2 emissions have to be also assessed looking to the in-use emissions in order to include also the contribution from the fuel production and distribution. This results fundamental in the case of alternative fuels and/or energy carriers where GHG emissions from the production process and distribution can dramatically influence the overall result in terms of real decarbonisation.

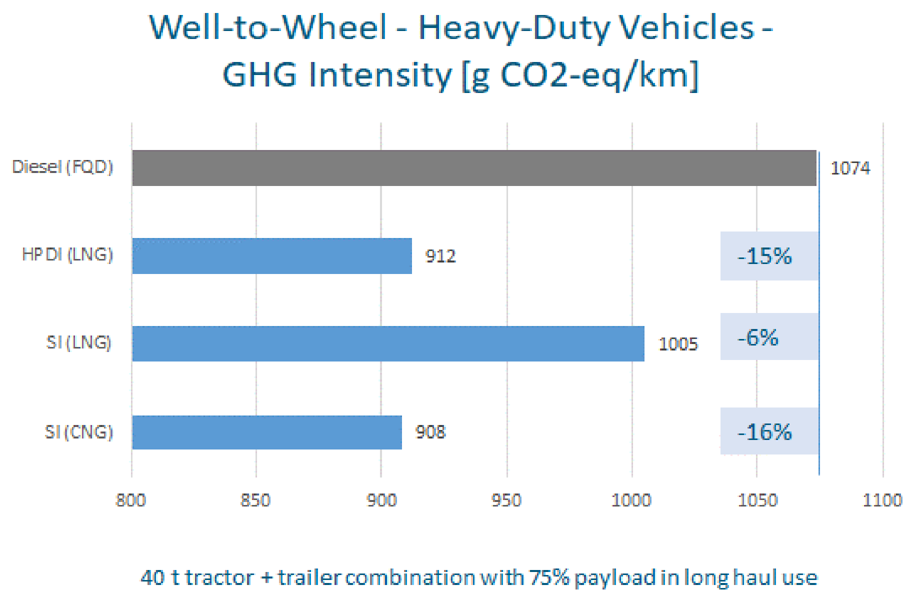

Figure 2 – Well-to-Wheel-Heavy-Duty Vehicle-GHG Intensity (g CO2-eq/km)

Figure 2 shows the result from a recent study on the GHG footprint from the natural gas used as transport fuel; results show a benefit in terms of GHG Well-to-Wheel reduction up to 16% compared to Diesel.

It is also important that the analysis has considered all the GHG emission sources, including CH_4 and N_2O, on both Well-to-Tank and Tank-to-Wheel side.

2.2.1. Regulation

EU's commitments under the Paris Agreement. are one important part of a broader strategy to further decarbonise road transport as all transport modes together are responsible for roughly 25% of EU CO_2 emissions with the Heavy-duty vehicles accounting for one-fifth of this, while trucks also carry more than 70% of all land-based freight. On 17 May 2018, the European Commission published the ‘Third Mobility Package’ including apart from significant measures to improve road safety in the EU, measures completing its agenda for a low-emission mobility system by putting forward the first ever CO_2 emissions standards for heavy-duty vehicles. In 2025, average CO_2 emissions from new trucks will have to be 15% lower than in 2019. For 2030, an indicative reduction target of at least 30% compared to 2019 is proposed.

2.2.2. Boil-off management

Natural gas is directly injected into an HPDI engine at high pressure. Because it is more efficient to pump a liquid (LNG) to high pressure than to compress a gaseous medium, HPDI HDVs currently employ a high-pressure cryogenic pump within the LNG tank. This is similar to the high pressure common rail pump of modern diesel engines. LNG is also attractive for long haul HDVs (both HPDI and SI) because it offers longer range potential than CNG; given that the density of LNG is greater than CNG so more energy can be stored in the same volume. At ambient pressure, LNG remains a cryogenic liquid at about -162°C, depending on the gas composition. LNG tanks are highly insulated to prevent the LNG from warming-up, boiling and exceeding their certified pressure limit. If the pressure of the tank exceeds its certified limit, a pressure relief valve vents methane from the tank for safety reasons. All modern LNG tanks used in Natural Gas HDVs are designed and certified to hold a full tank of LNG for more than five days without venting (BMVI study [16]). Despite the effective insulation, some heat transfer to the LNG is inevitable and will eventually cause boil-off, tank pressure rise and atmospheric venting unless the fuel is consumed and the tank refueled on a regular basis. For an SI HDV, this relatively low-pressure boil-off gas is consumed by the engine when it is operating but cannot be consumed by an HPDI engine. Instead, it remains in the tank.

The rate of tank pressure rise is also dependent on the initial condition of the fuel when the tank is filled. Because SI systems build pressure in the tank to push the fuel to the engine, it is preferred to fill the tank with saturated "warm" LNG. Conversely, because HPDI systems employ a tank in pump method of building pressure, it is preferred to fill the tank with colder fuel at a lower initial pressure. Tanks filled with "cold", lower pressure fuel will have a longer static hold time than tanks filled with saturated "warm", pressurised fuel.

Many studies indicate high boil-off losses result in methane venting to atmosphere to prevent an excessive pressure rise in the tank. The applied method in Europe of managing tank pressure is to transfer the boil-off gas to a refueling station when the vehicle is refueled with LNG. This happens through a vent line to the LNG station. Where the boil-off gas collapses back to liquid because of the temperature and pressure difference Because an HDV is almost permanently in operation, long periods of non-usage greater than the required five day hold time are highly unlikely. This suggests current boil-off losses are relatively low in state-of-the-art LNG powered heavy-duty vehicles. HPDI engines may also vent small quantities of gas from the fuel system during certain engine operating conditions such as high transient load changes (often referred to as "dynamic venting") that require the fuel rail pressure to be reduced quickly. Instead of venting the gas into the atmosphere, both the diesel and the Natural Gas are recaptured in modern engine architectures and returned to their respective tanks, see Westport [2]. As indicated by Table (2) the total amount of methane released to the atmosphere is really low and only represent 1% in CO2 equivalent of the total CO2 emitted by the LNG vehicle.

Parameter	Natural Gas (SI)	Natural Gas (HPDI)	Diesel
Fuel consumption (kg/100 km, l/100 km)	26.7	22.5 (natural gas) 1.8 (diesel pilot)	31.5
Energy consumption (MJ/km)	13.2	11.7	11.3
CO_2 emissions (g CO_2/km)	728	659	(827)
CH_4 emissions (g CH_4/km)	0.349	0.349	-
N_2O emissions (g N_2O/km)	0.019	0.032	-

Table 2 – Heavy Duty Vehicles: fuel consumption, CO2, CH4 and N2O emissions

Notes

(1) Bundesministerium für Verkehr und digitale Infrastruktur (BMVI), „LNG als Alternativkraftstoff für den Antrieb von Schiffen und schweren Nutzfahrzeugen (DE/EN),“ Berlin, Germany, 2014.

(2) Westport Innovation, „Progress in the development of natural gas high pressure direct injection for Euro VI heavy-duty trucks,“ Westport Innovation, Vancouver, Canada, 2016.

2.3. LNG for rail transportation

LNG as automotive fuel has got a great impulse in Europe for heavy road transportation during second decade of 21st century where sales of LNG driven trucks is estimate more than one thousand units per year in 2017, there are signs of the same process to take on in rail transportation in the 3rd decade. LNG fuel on rail pilot projects were started in USA in 1997, LNG driven locomotives pull heavy trains in Florida since 2012 in routine operation. Pilot projects were started in Europe in Spain (passenger train with DMU self-propelled cars in operation – Enagas/Renfe project) and Russia (a locomotive for long speed train drive).

The usual strategy is to modify diesel locomotives that provide service on non-electrified lines where electrification is not economically viable, thus allowing the reduction of polluting and greenhouse gas emissions.

The technologies available for the conversion of traction locomotives by Natural Gas, allow the option of 100% natural gas engines and Dual Gas / Diesel engines (80% / 20%):

- Engine retrofit: The diesel engine is modified by means of a conversion kit that allows the use of LNG. There are currently two types of retrofit:
    - 100% LNG engine retrofit. It is the most efficient option in environmental terms, however it is more expensive than its Dual alternative. It is characterized by its low maintenance, low emissions, with the disadvantage of slightly reducing engine performance. If there is not enough space for the LNG tanks it could reduce autonomy compared to 100% Diesel.
    - Dual Diesel / Gas engine retrofit. This option is more economical and allows to maintain the performance of the engine. However, it is less environmentally efficient. It is easily maintainable. If there is not enough space for the LNG tanks it could reduce autonomy compared to 100% Diesel.
- New engine: New engine that is compatible with the available dimensions, does not involve *modifications to the train frame and is compatible with the electric generator for the original Diesel / electric traction trains. There are currently two options*:
    - New 100% LNG engine. It is optimal option in environmental terms. However, it is the most expensive option compared to a retrofit. Additionally, compared to the alternative of a new dual engine, it has less autonomy if it doesn’t have enough space for LNG tanks.

    - New Dual engine (80% LNG / 20% Diesel). It is a cheaper option than a new 100% LNG engine, but in environmental terms it’s performance is lower.

- Gensets: This option is used to convert Diesel / Electric locomotives, where the diesel engine and electric generator is replaced by a new power installation that includes cascaded natural gas electric generators that operate on demand for acceleration or train power. It is an optimal configuration in terms of environment, consumption, reliability and low maintenance.

In Spain, projects are being developed in the main railway segments (self-propelled, heavy haul and switcher), both in LNG and other alternative fuels such as H2 and BIOGNL, seeking the best technical and economic performance. On-going projects include:

- in the Heavy Haul segment a Dual Diesel / Gas engine retrofit of a S333 locomotive, a 100% New LNG engine for a S1600 locomotive (provided with a tender storage tank).
- in switcher segment Dual Diesel / Gas engine retrofit of S310 locomotives with activity in several Spanish ports.
- In the self-propelled segment a new 100% LNG engine for 4 DMU S2600.

Gazprom announced signing a project with 24 LNG driven locomotives for a 572 km long railway in Yamal region at Northern shore of Siberia in May, 2018.

Besides of important economical savings, because LNG is available for distribution for lower cost than Diesel-equivalent to practically everywhere on European territory, reduction of emissions is another important factor.

Rail transportation is distinguished with a very low fuel consumption compared to road. Because of low friction on rails, low aerodynamic resistance compared to equivalent number of road vehicles and lower variations in the load of the engine, the fuel consumption of rail per unit of load is lower. While a Diesel truck needs energy 4,5 kWh/ton-km, the Diesel rail locomotive needs 1,2 kWh/ton.km only, which is 27%.

Dual fuel LNG truck reduces emission to 87% of CO_2 and 25% of NO_x.

If the same ratio is applied to already reduced consumption of energy on rail, reduction of emission is to 23,5% on CO_2 and 7% on NO_x, compared to Diesel trucks.

Research was done on specific categories of vehicles with large energy consumption. Conversion of refuse trucks working on Diesel reduced NO_x emissions from 0,666 – 1,17 gNO_x/bhp-hr. Conversion on monofuel LNG drive reduced the emission to 0,09 – 0,12 gNO_x/bhp-hr. The ratios are 10 to 14% NO_x. This result can be applied to railway shunter locomotives, which have similar modes of operation: Heavy loads, frequents starts and stops.

These results are very encouraging. movement road-to-rail and simultaneously rail to LNG is a prospect to saving cost of fuel, to diversification of fuels and, at the same time, reduction of emissions.

2.3.1. Regulation

The European directive 2004/26/EC sets the following stages of emission limit values:

- Stage III A covers engines from 19 to 560 kW including constant speed engines, railcars, locomotives and inland waterway vessels.
- Stage III B covers engines from 37 to 560 kW including, railcars and locomotives.
- Stage IV covers engines between 56 and 560 kW.

Stage III A and III B standards have been adopted for engines above 130 kW used for the propulsion of railroad locomotives (categories R, RL, RH) and railcars (RC). There are no upper limits concerning engine power.

Category	Net Power	Market Placement Date	CO	HC	$HC+NO_x$	NO_x	PM
	kW		g/kWh				
RC A	130 < P	2006.01	3.5	–	4.0	–	0.2
RL A	130 ≤ P ≤ 560	2007.01	3.5	–	4.0	–	0.2
RH A	560 < P	2009.01	3.5	0.5*	–	6.0*	0.2

Notes:
* HC = 0.4 g/kWh and NO_x = 7.4 g/kWh for engines of P > 2000 kW and D > 5 liters/cylinder

Table 3 - Stage III A standards for Rail Traction Engines

Category	Net Power	Market Placement Date	CO	HC	$HC+NO_x$	NO_x	PM
	kW		g/kWh				
RC B (railcar)	130 < P	2012.01	3.5	0.19	–	2.0	0.025
R B (locomotive)	130 < P	2012.01	3.5	–	4.0	–	0.025

Table 4 - Stage III B standards for Rail Traction Engines

EU NRMM Stage V Emission Regulation

- REGULATION (EU) 2016/1628 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 September 2016 on requirements relating to emission limits for gaseous and particulate pollutants and to type approval for internal combustion engines to be installed in non-road mobile machinery and amending Regulations (EU) No 1024/2012 and (EU) No 167/2013 and amending and repealing Directive 97/68/EC.
- RLL engines: "RLL category": engines intended exclusively for use in locomotives for their propulsion or intended for this.
- As for EU regulation 2016/1628 for RLL engines, it states the following: Make D2 NRSC Cycle for constant speed engines and F for variable speed engines (UIC ISO 8178-2 D2 CYCLE) Detail ANNEX 8.

This regulation is divided into:

Implementing regulation that there are two rules:

- COMMISSION IMPLEMENTING REGULATION (EU) 2017/656 of 19 December 2016 laying down the administrative requirements relating to emission limits and type-approval of internal combustion engines for non-road mobile machinery in accordance with Regulation (EU) 2016/1628 of the European Parliament and of the Council.
- COMMISSION IMPLEMENTING REGULATION (EU) 2018/988 of 27 April 2018 amending and correcting Implementing Regulation (EU) 2017/656 laying down the administrative requirements relating to emission limits and type-approval of internal combustion engines for non-road mobile machinery in accordance with Regulation (EU) 2016/1628 of the European Parliament and of the Council.

Delegated regulation that there are two rules

- COMMISSION DELEGATED REGULATION (EU) 2017/655 of 19 December 2016 supplementing Regulation (EU) 2016/1628 of the European Parliament and of the Council with regard to monitoring of gaseous pollutant emissions from in-service internal combustion engines installed in non-road mobile machinery.
- COMMISSION DELEGATED REGULATION (EU) 2018/987 of 27 April 2018 amending and correcting Delegated Regulation (EU) 2017/655 supplementing Regulation (EU) 2016/1628 of the European Parliament and of the Council with regard to monitoring of gaseous pollutant emissions from in-service internal combustion engines installed in non-road mobile machinery.

2.3.2. Boil-off

In DMU[1] segments that use standard pressurized tanks, the treatment of the Boil Off gas is similar to that carried out in other mobility applications, taking into account the characteristics of the tank.

In this case, the Boil Off gas serves as a propellant for the LNG from the tank to the vaporizer before the inlet to the engine while it is running. The gas works as a piston on the liquid phase of the cryogenic storage vacuum insulated tank. Boil-off, is managed through a suitable mechanical design of the tank, allowing a wide range of pressures in it. A wide range of pressures is capable of accommodating the Boil-off gas generated for a long period of time without reaching critical pressures in the tank which would need to be, where appropriate, vented either manually or by means of a safety valve.

In cases where ISO-containers are used, the Boil Off gas management possibilities are much broader, allowing systems with higher degrees of complexity. The fact of being able to have a platform for it,

[1] DMU: Diesel Multiple Unit

makes it possible to have enough space in order to develop more complex annexed systems, as well as control systems that allow a more efficient control system for the generated BOG.

In this case, among the different alternatives currently available, are the use of excess Boil Off gas for its compression and use as a source of CNG for consumption in the locomotive itself, or the generation of electricity for the operation of the systems associated with the locomotive, the LNG platform or for storage using battery systems, minimizing energy losses and eliminating atmospheric gas emissions.

3. LNG FOR AVIATION

At first it is to be noted that LNG as fuel is not yet in operational use for any aircrafts. However, the Russian Tupolev Tu-155 flew LNG-fueled during the late 1980's as part of a testing program. During the years 2010-2013 a feasibility study including some bench testing has been carried-out by the companies TGE gas Engineering and Air-LNG. This was part of the project alliance FAIR ("Future Aircraft Research"), also joined by Airbus, EADS, Lufthansa, DLR, MTU, Airport Hamburg and funded by the Federal Ministry of Economics and Technology based on a resolution of the German Bundestag.

The thoroughly positive result of this feasibility study including combustion simulations, supported by combustion chamber tests, shows a clear reduction of several environmentally harmful exhaust gas components. Compared to Jet-Fuel (Kerosene) the following reductions can approximately be expected:

NO_x	-80%
CO_2	-25%
Sulfur, Soot, Aromatics	-100%
Vapor Trail	less, not quantified

Out of these the vapor trail has not yet been considered as environmental damaging so far. The German aerospace center DLR has come to the conclusion during research in the recent years that cirrus clouds caused by worldwide aircraft traffic and vapor trails impact significantly the greenhouse effect. Due to absence of condensation nucleus in the LNG-fueled aircraft exhaust – essentially soot – a considerable reduction in any vapor trail is expected.

The feasibility study targeted the retrofit of existing airbus aircrafts from Kerosene to dual-fuel operation LNG and Kerosene. As no time consuming new EASA ("European Aviation Safety Agency") approval for the whole aircraft is assumed – the fuselage remains unchanged -, the retrofit is considered as realistic within just a few years of development.

A further short-term application could be the LNG-fueling of the aircraft APU ("Auxiliary Power Unit") that supplies the energy demand during taxiing at ground level. If all aircraft APU's fuel would be changed to LNG, the positive impact in the proximity of airports would be remarkable.

3.1. Regulation

Existing and upcoming environmental regulations in the air traffic.

CO_2 Emissions Regulations

In March 2017, a new standard for aircraft CO2 emissions has been adopted by the ICAO (International Civil Aviation Organization).

Its date of entry into force was 1st July 2017; its applicability date is theoretically 1st January 2018. In practice, its embedded applicability date for subsonic jet airplanes is 2020 [17].

The CO2 standard for aircraft:

- Does not apply to in-service aircraft,
- Reduces aircraft CO2 emissions by encouraging the integration of fuel efficient technologies into aircraft design and development,
- Ensures that older aircraft models end production in an appropriate timeframe or that manufacturers invest in technology to improve their efficiency,
- Brings CO2 emissions into the formal certification process that new aircraft need to pass in order to enter service,
- Is part of a "Basket of Measures" to deal with industry's climate impact,
- Covers all commercial jet aircraft (except the smallest business aviation jets),
- Focuses on cruise flight performance.

Details about the standard are available on the ICAO website: https://www.icao.int/Newsroom/Pages/FR/ICAO-Council-adopts-new-CO2-emissions-standard-for-aircraft.aspx

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

After the COP 21 in Paris, the ICAO has taken two important decisions:

- 2% annual fuel efficiency improvement.
- Carbon neutral growth from 2020.

ICAO implemented a global scheme called CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) which will help reaching these goals.

CORSIA will take place in three implementation phases:

- Pilot phase (2021 - 2023): State participation is voluntary.
- First phase (2024 - 2026): State participation is voluntary.

- Second phase (2027 - 2035): at least 90% of international aviation activity to be covered in the second phase. During this phase, all States will participate except for exempted ones.

CORSIA shall apply only to all international flights on the routes between States, both of which are included in the CORSIA.

As of today, 72 states, representing more than 87.7% of international aviation activity, intend to voluntary participate in the CORSIA from its beginning.

Aircraft LTO (Landing – Take off) emissions regulations and implementations at European airports

Aviation affects the environment via the emission of pollutants from aircraft, impacting human health and ecosystem. Impacts of aircraft operations at lower ground towards local air quality have been recognized. Consequently, various standards and environmental regulations have been introduced to address these LTO emissions, such as the implementations of LTO emissions charges and an incentive-based regulation introduced in Europe [18].

Over the years, NOx emissions have been the primary interest of ICAO standards. The level of stringency of the NOx emission standard has been increased periodically as shown in Table 5.

Standard source	Year introduced	Effective year & affected engine	Reduction of emission limit [a]	NOX emission limit (g/kN) [b]
CAEP/1	1981	1986 (newly manufactured engines)	-	100
CAEP/2	1993	1996 (newly certified engines) 2000 (already certified newly manufactured engines)	20%	80
CAEP/4 [c]	1998	2004 (newly certified engines)	16%	67
CAEP/6	2004	2008 (newly certified engines) 2013 (already certified newly manufactured engines)	12%	59
CAEP/8	2010	2014 (newly certified engines)	15%	50

[a] Percent reduction from the previous standard.
[b] Initial standard has established a limit on NO_x at 100 g/kN of rated engine thrust based on engine pressure ratio of 30.
[c] Does not applied to already certified in-production and newly manufactured engines.

Table 5 - ICAO/CAEP NOx emission standards (Source: ICAO, U.S. EPA) [17].

As an effort to preserve a good local air quality, a revenue-neutral LTO NOx emission charge was settled by several voluntary airports in Europe. For instance, there are currently five European countries charging aircraft for NOx emissions: Switzerland, Sweden, United Kingdom, Denmark and Germany [18].

3.2. Boil-off

During fueling and normal flight operation the LNG is handled at cryogenic conditions and slight gauge pressure of about 0.1 bar related to the cabin pressure. As the total aircraft fuel system is a fully closed process designed for 5 bar gauge pressure using suitable and proven equipment for LNG, no gas can escape. The thermal insulation of all process piping and equipment will minimize environmental heat ingress. The limited heat ingress results in negligible storage pressure increase during flight. The system will safely cope with this due to the suitable design pressure margin. During an emergency case, the system design allows gas venting to the environment in a controlled manner via safety valves.

4. LNG METHANE NUMBER AND EFFICIENCY

What methane number is?

Liquefied natural gas (LNG) is growing as an alternative for diesel fuel in heavy-duty vehicles. The major advantages in terms of pollutant and noise emissions make LNG an attractive for on- and off-road vehicles. LNG is produced at different locations around the world. The composition of the LNG (the 'quality') varies substantially with the geographical origin due to differences in natural gas sources, production technologies and target markets for the LNG.

Variations in LNG composition influence the so-called knock resistance of the fuel. A fuel knock resistance that is too low for the engine for which it is intended causes engine knock, which can severely compromise engine performance, varying from increased pollutant emissions and reduced fuel efficiency to engine failure.

The knock resistance of LNG is characterized by a methane number, which is similar to the octane number used to qualify gasoline. Several methods have been developed to classify gaseous fuels for their knock sensitivity such as the AVL, MWM, CARB, GRI, Cummins, Waukesha Knock Index method, Wärtsilä and PKI MN. These methane number methods give different outcomes for the same fuel composition, which results in confusion for end users and fuel suppliers in the LNG value chain. Currently, ISO/TC 193/WG 8 discusses the best possible yardstick for characterizing the knock resistance that serves the interests of all stakeholders, i.e., the international gas industry, the engine manufacturers and the end users.

Effect on LNG trade worldwide

In the following table is shown the percentage of LNG trade affected in function of the methane number defined, for a global trade production of 231.5 Mt in 2013 (data from Abu-Dhabi and Angola not available) [GIIGNL position paper on the impact of including methane number in natural gas regulation].

Methane number	*LNG trade below MN (Mt)*	*LNG trade affected (%)*
65	0	0%
70	7.01	3%
75	151.74	66%
80	204.55	88%

Table 6 - Percentage of LNG trade affected in function of the methane number

Note: the Table 6 is based on LNG average composition for 2013[2] and The MWM calculation method[3]

As can be seen, if a methane number higher than 80 is requested for using LNG as a transportation fuel, 88 % of world trade production should be treated. On the other hand, the affected trade production below 70 could be higher than the 3 % shown, because, due to a lack of precise export data, the exported amounts from Australia NWS and Indonesia Badak have been included into the other national supplies.

[2] GIIGNL, The LNG Industry 2013, April 2014

[3] EN 16726. Gas infrastructure – Gas quality – Group H

5. BIO-LNG POTENTIAL AND DEVELOPMENT

All organic waste can rot and can produce biogas, the bacteria do the work. LNG, like CNG, can be produced from a variety of renewable, scalable and very low carbon intensity energy sources, such as bio-methane produced from organic waste and biomass through anaerobic digestion and gasification or synthetic methane produced converting carbon dioxide into methane by using hydrogen produced from surplus green electricity. Renewable gas is fully compatible with the current natural gas mix, allowing any blend and unlimited use in the existing infrastructure and vehicles.

Liquefied biomethane as biofuel for HD vehicles is a new business. Its development started at the beginning of the current decade, essentially in Europe. There is still a limited number of plants in operation producing Bio-LNG in Europe (and globally) in 2018, but in the next few years, Bio-LNG as a fuel for LNG trucks is expected to be available in a significant number of European countries, including at least Sweden, Norway, the Netherlands, the UK, Italy, Germany, France, Slovakia and Denmark. This will mark the achievement of another major milestone for the market and the environment, making almost GHG neutral operation really possible for long distance heavy duty trucks, or achieving WTW GHG emissions reduction by at least 80% compared with diesel, depending on the bio-methane source.

By 2030, it seems reasonable to expect that Bio-LNG will be produced in much larger volumes, not only from bio-methane (anaerobic digestion), but also from power to gas and gasification processes, therefore offering great opportunities for GHG emissions reduction in heavy road haulage as well as economically affordable zero or low carbon heavy goods road transport in Europe. (1)

An EBA-NGVA analysis (2) quantified the possible GHG emission reductions of renewable for heavy duty vehicles (HDVs) in 2030, in comparison with diesel. When comparing these fuels from a well-to-wheel perspective for HDVs, the study shows that renewable gas can produce total CO_2 reduction over truck lifetime of 968 to 2315 ton depending on the renewable gas source.

Examples of Bio-LNG plant locations, Europe and global

- Lidköping, Sweden; started operation in 2012, initially run by Lidköping Biogas AB (now Air Liquide), producing transport fuel for cars, trucks and buses in both gaseous and liquefied form.
- Oslo, Norway; opened in 2014 by Cambi AS, with a Bio-LNG production capacity of 11 tons per day
- Attero, Netherlands; pilot plant by Rolande LNG, Gastreatment Services, with production capacity of 177 kg of Bio-LNG per hour / 1,550 tons per year, start of operation in 2014.
- Landschap Vallei in Veluwe, Netherlands; Small scale field test, with Cirmac raw biogas upgrading to practically pure biomethane and Osomo liquefaction using a Stirling Cryogenerator, with a liquefaction capacity of about 7.5 kg per hour.
- Lelystad, Netherlands; Accres DMC biogas upgrading and Osomo's Stirling cryogenerator used for liquefaction.

- Haarlem, Netherlands; Gastreatment Services, with a full-fledged liquefaction system with a capacity of 122 kg Bio-LNG per hour.
- In Northern Ireland, the first Bio-LNG production project was launched in July 2016 by Greenville Energy and Cryo Pur in Tyrone, with planned production capacity of 3 tons of Bio-LNG per day. This Bio-LNG production unit from Cryo Pur was commissioned in October 2017.
- Valenton, France; first Bio-LNG demonstration pilot project BioGNVAL, operated by ENGIE's subsidiary LNGENERATION, coordinated by SUEZ and with Cryo Pur in charge of biogas purification and liquefaction. This Bio-LNG project started in 2013 and the production site was inaugurated in May 2015. Demonstration project period was October 2015 - April 2017.
- In Trondheim, Norway, the Biokraft Norway plant is at present the World's largest Bio-LNG plant. It is a system supplied by Wärtsilä using Purac Puregas process converting cleaned biogas from fishery waste and residual paper mill slurry into LNG. For this plant, Wärtsilä claims a novel natural gas liquefaction technology based on readily available, well proven components, "specially designed to liquefy small methane-based gas streams". 12,5 million normal-cube-metres out the plant is generating. The next step is to double the output. The unique capture process, ideally suited to liquefaction projects, reduces the CO_2 content of bio-methane to below 50ppm, making liquefaction possible. It recovers over 99.9% of the bio-methane from raw biogas by separating the CO_2 through a very efficient process of chemical adsorption with selective organic solvents; the product gas can contain over 99% bio-methane. First deliveries to truck and ships have started.

Examples of new project launched or announced

- In the Netherlands, a number of new Bio-LNG projects are under development. Rolande LNG was awarded EU funding from the CEF programme for its BIO-LNG4EU project. The goal is to install two bio transformation stations (BTS) and four Bio-LNG fuel stations in the Netherlands and Belgium. The two BTS's will transform locally produced biogas to liquefied Bio-LNG. This action is part of a global project of 50 LNG and Bio-LNG refuelling and 15 bio transformation stations that will be established gradually close to large distribution centres and/or to major highways along the TEN-T Core network Corridors in North Western Europe.
- In Germany, Titan LNG and Osomo Projects signed a partnership agreement to build the first German Bio-LNG production facility.
- Bremen, Germany; the LNG Bremen project has been approved for EU funding from CEF programme, enabling HGM to build a Bio-LNG production unit, as well as a supply system to stations. It is a study and full-scale real-life deployment project of a liquefaction and supply facility for LBG at the port of Bremen.
- German energy company Erdgas Südwest GmbH announced a new Bio-LNG production plant using Puregas upgrading technology supplied to Wärtsilä, that reported the technology for this plant representing a new and unique response to market needs to liquefy and store methane-

based energy streams. Both gas cleaning and liquefaction are cost- and energy efficient, thereby making profitable projects possible even for smaller gas streams.

- In Italy, CIB Consorzio Italiano Biogas announced that there are at least ten projects for Bio-LNG production plants, with production capacity from 5 to 50 tons/day.
- Arborea, Sardegna, Italy; Cooperative 3A “Assegnatari Associati Arborea” project is planning to produce ~4.5 tons of Bio-LNG per day using Galileo Cryobox and to build L-CNG stations to use it as fuel for trucks and other vehicles.
- In Italy, Caviro distillery project is planning to produce 8 million Sm^3 equivalent of Bio-LNG per year from grape waste of member wineries.
- In Veneto region, Italy, S.E.S.A. Società Estense Servizi Ambientali S.p.A., a refuse collection and treatment company, was authorized a production plant of 4,500 Sm^3/hour equivalent of Bio-LNG and Bio-CNG, which will fuel 150 waste collection and transportation trucks.
- In France there are several Bio-LNG projects in preparation. At least two more Bio-LNG production plants are planned with Cryo Pur equipment; one in Angers; the other one is part of the CEF funded BioMovLNG, and Proviridis has plans for the installation of a Bio-LNG production unit at a Waste Water Treatment Plant.
- In Slovakia, the project “LBG: Fuelling Renewable Transport” was approved for funding as part of the CEF programme and will include a Bio-LNG production facility in Slovakia, together with a network of stations and roll-out of LNG trucks in the Visegrad countries.
- In Denmark, GreenLNG A/S intends to develop a Bio-LNG production plant in the port of Hirtshals. Planned production capacity is 160 tons per day / 70 million Sm^3 per year equivalent.

6. CONCLUSIONS

LNG is efficient to transport over long distances where pipelines do not exist this due to the fact that LNG takes up about 1/600th the volume of Natural Gas. This makes it cost efficient for transportation as well. LNG has an energy density comparable to diesel fuel, thus it reduces refueling frequency comparing to natural gas forms e.g. CNG.

In terms of emissions LNG produces less greenhouse gas other emissions comparing to other liquid or solid fuels, a clean complete burning fuel. Especially when comparing to Diesel as fuel for HDV it emits 7% to 15% less and comparing to Marine Diesel Oil LNG emits 25% less. It fully complies with the latest requirements set in the applicable regulations for all applications road, rail and aviation transportation as well maritime. Also the treatment of Boil off Gas by the industry makes it more challenging.

LNG as fuel in maritime gives the opportunity to energy independence of the vessel at the ports (not depending on the shore grid connection-many times not compatible) where electricity production is required for the vessel's facilities.

LNG fueled engines have up to 50% less noise emissions than diesel engines (minus 3 to 5 dB on average).

The standardisation and the documentation produced and published by the international gas industry, we mention CEN, ISO and GIIGNL for example, make it a proven safe technology for storage, transportation and usage for the equipment/devices and the operatives.

LNG performs well towards achieving the EU strategies and the industry for a decarbonized, a low-carbon energy reducing the harmful effects to climate.

7. LIST OF ACRONYMS

APU	Auxiliary power unit
AVL	Method, developed in 1970s, to calculate the methane number based on experimental measures of different gas mixtures
BMVI	Bundesministerium für Verkehr und digitale Infrastruktur
BOG	Boil-off gas
CAEP	Committee on Aviation Environmental Protection, is a technical committee of the ICAO
CARB	A method of calculating LNG Methane Number by a specific arithmetic expression defined by the California Air Resources Council (referred to as “CARB standard”
CEF	Connecting Europe Facility
CEN	European committee for standardization
CNG	Compressed natural gas
CORSIA	Carbon offsetting and reduction scheme for international aviation
DLR	German aerospace centre
DMU	Diesel multiple unit
EADS	European aeronautic defence and space company / Airbus
EBA	European biogas association
EMSA	European maritime safety agency
FAIR	Future Aircraft Research
FBOG	Forced boil-off gas
GHE	Green House Emissions
GHG	Greenhouse gas
GIIGNL	The international group of liquified natural gas importers
GRI	Gas Research Institute (GRI) methods used to calculate methane number (ISO/TR 22302)
HD	Heavy duty
HDV	Heavy duty vehicle
HPDI	High pressure direct injection

ICAO	International civil aviation organization (United Nations Agency)
IMO	International maritime organization
ISO	International organization for standardization
LBG	Liquefied Bio-Gas
L-CNG	Liquid to compressed natural gas
LNG	Liquid natural gas
LSFOs	Low-sulphur fuel oils
LTO	Landing – take-off
MDO	Marine diesel oil
MN	Methane number
MTU	Aero Engines manufacturer
MWM	Methane Number calculation method as defined in EN 16726
NBOG	Natural boil-off gas
NGVA	Natural gas vehicle association
NRMM	Non-road mobile machinery
NRSC	Non-Road Steady Cycle (ISO 8178)
NWS	North West Shelf Gas Australia LNG
PKI MN	Methane Number Calculator for LNG (on line by DNV)
RES	Renewable energy source(s)
RLL	Engines for the propulsion of railway locomotives
SI	Spark-ignition engine
TGE	Gas Engineering GmbH
US EIA	United States energy information administration
US EPA	United States environmental protection agency
WTW	Well-to-Wheel study by the European Commission / Joint Research Centre

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