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Bachelor thesis

Liquid Natural Gas

A study of the environmental impact of LNG in comparison to Diesel



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Abstrakt

Flytande Naturgas (LNG) har under flera år funnits som ett alternativt bränsle inom sjöfarten, men på senare tid så har skeppen som drivs av metan ökat markant. En anledning till detta är att LNG innehåller inget svavel samt släpper ut mindre NO_x jämfört med traditionella bränslen. I denna uppsats så kommer LNG att jämföras mot diesel ur ett klimatperspektiv med fokus på koldioxidutsläpp och dess ekvivalenter. International Maritime Organisation (IMO) har infört Energy Efficiency Design Index (EEDI) krav som justerar hur mycket CO₂ man får släppa ut per kilowattimme (kWh), dessa krav kommer dessutom att öka i flertalet intervaller i framtiden, varav nästa intervall redan sker i 2022 för speciella fartygstyper. Metoden som användes för att jämföra bränslena var att beräkna mol-innehållet för både LNG samt diesel, sen från den beräknade data se hur mycket koldioxid (CO₂) inklusive ekvivalenter de släppte ut. Resultatet visade att under optimala förutsättningar så var LNG ett klart bättre alternativ än diesel. Däremot så kan sjöfarten ha ett problem inom framtiden från de krav som berör växthusgaser som kommer att ställas från och med 2050.

Nyckelord

Metan, LNG, Motor, Mol, Skepp, Miljö, Miljövänligt, Tjockolja, Diesel, Marine Diesel, Avgas, CO₂, CH₄, ECA, SECA, NECA, IMO, g/kWh, EEDI, LSFO.



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Abstract

Liquefied Natural Gases (LNG) has been an alternative fuel in the marine industry for several years, but lately, the amount of ships that have been powered by methane has increased a lot. Some of the reasons for this is because LNG does not contain any sulfur and releases less nitrogen oxides than traditional maritime fuels. In this essay, LNG will be compared to diesel from an environmental perspective with focus on CO₂ emissions and its equivalents. International Maritime Organization (IMO) implemented Energy Efficiency Design Index (EEDI) requirements that adjusts how much CO₂ is allowed in the exhaust gas per produced kilowatt-hour (kWh). However, these requirements will increase in intervals in the future, the next one is coming 2022 for specific ship types. The method that is used to compare the fuels is Mole-calculations for LNG as well as diesel, then calculate the amount of carbon dioxide (CO₂) and its equivalents they release. The results show that under optimal conditions, LNG was the superior choice. However, the maritime industry might have a problem with the requirements that will be introduced to greenhouse gas (GHG) emissions in 2050.

Keywords

Methane, LNG, Engine, Marine, Mole, Methane Slip, Ship, CO₂, CH₄, Emission, IMO, Exhaust gas, Environment, Propulsion, Heavy Fuel Oil, Ultra Low Fuel Oil, Diesel, Marine Diesel Oil, ECA, SECA, NECA, IMO, g/kWh, EEDI, LSFO.



Foreword

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List of abbreviations and symbols

CEAS	Computerized Engine Application System
CH ₄	Methane
CO ₂	Carbon Dioxide
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EGR	Exhaust Gas Recirculation
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HSFO	Heavy Sulfur Fuel Oil
IEA	International Energy Agency
IMO	International Maritime Organization
kWh	Kilo Watt Hour
LNG	Liquefied Natural Gas
LSFO	Low Sulfur Fuel Oil
MARPOL	Maritime Pollution
MGO	Marine Gas Oil
NECA	Nitrogen Emission Control Area
NO _x	Nitrogen Oxides
SCR	Selective Catalytic Reduction
SECA	Sulfur Emission Control Area
SFOC	Specific Fuel Oil Consumption
SGC	Specific Gas Consumption
SO _x	Sulfur Oxides
ULSFO	Ultra-Low Sulfur Fuel Oil



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1 Introduction

1.1 Background

During the last century, the climate has been slowly in decline due to pollution from various sources such as air pollution and ocean acidification. Causing a global problem with climate change which can lead to ocean level rising and famine. According to the Paris Agreement all the signatory countries must cut their emissions to limit global warming by limiting the increase of heat on the planet by 1,5 °C but the maritime industry was excluded from this agreement by omission and makes it difficult to associate any emission by ships to be attributed to any single country (United Nations Framework Convention on Climate Change. 2015).

However, since the 1930's, the marine industry has polluted the environment with emissions from Heavy Fuel Oil (HFO) (Wankhede. 2020). The impact of HFO has been seen all over the world, from the arctic to the beaches where spilled oil has washed ashore (Fritt-Rasmussen et al. 2018). The popularity of fossil fueled engines rose during the years in popularity until it became more popular than steam engines in the 1960's (Wankhede. 2020). It wasn't until 1997 an annex regarding air pollution was added into Maritime Pollution (MARPOL), and it was called Annex VI (IMO. 2020). It was not put into force until May 19, 2005.

The prospects for Liquefied Natural Gas (LNG) are due to its availability and its low emissions. The Sulfur Oxides (SO_x) are negligible, and the Nitrogen Oxides (NO_x) levels are reduced by up to 80% due to the properties of methane. Due to the properties, it also reduces the amount of Carbon Dioxide (CO₂) emissions by up to 25% (Latarche. 2018).

However due to methane slips and incomplete combustion, the benefit of using LNG is nullified or even a lesser alternative than Marine Gas Oil (MGO). That is because methane is a hydrocarbon and is a potent greenhouse gas. In comparison to CO₂, the Greenhouse Gas (GHG) effect is 30 times greater for methane, measured under a century (Abbasov. 2019).

- LNG is a fuel used for propulsion of maritime vessels among other things. It consists of Methane (CH₄) and can also be produced biologically. The methane is stored in a liquefied state as it takes up



1/600th of the volume as it does in its gaseous state. Some cars for example use Compressed Natural Gas (CNG), however, due to the massive amounts of gas onboard, it would be extremely dangerous. CNG takes up 2.4 times more volume than LNG (Fritt-Rasmussen et al. 2018).

- HFO is defined by having a density of 900kg per cubic meter at 15 degrees Celsius (Burel, F. Taccani, R & Zuliani, N. 2013).
 - High Sulfur Fuel Oil (HSFO) is an HFO which is defined by having a maximum of 3.5% sulfur content. Not applicable in ECA zones, (Burel, F. Taccani, R & Zuliani, N. 2013) however, with a closed loop scrubber it can manage the SO_x requirements. It requires a closed loop scrubber due to the lower alkaline levels close to shore. However, with dual fuel it is possible to use an open loop scrubber. NO_x emissions equipment is required to clear the Emission Control Area (ECA) demands (Wankhede. 2020).
 - Low Sulfur Fuel Oil (LSFO) is an HFO which is defined by having a maximum of 1% sulfur content. Not applicable in ECA zones after the restriction in ECA areas to 0.1% SO_x content (Burel, F. Taccani, R & Zuliani, N. 2013). However, it can also be used with either dual fuel and open loop scrubber, or a closed loop scrubber. NO_x emissions equipment is required to clear the ECA demands (Wankhede. 2020).
 - Ultra Low Sulfur Fuel Oil (ULSFO) is an HFO or MGO which is defined by having a maximum of 0.1% sulfur content. Can be used in ECA areas with proper NO_x reduction systems (Burel, F. Taccani, R & Zuliani, N. 2013).

It is important to note that an ECA has the requirements of both Sulfur Emission Control Area (SECA) and Nitrogen Emission Control Area (NECA). In accordance with International Maritime Organization (IMO. 2017) regulations, all marine vessels with over 130kW power output need to regulate their NO_x emissions (Abbasov. 2019) (IMO. 2017).



Currently, LNG engines popularity is rising. More and more ships fueled by LNG are in use and being built. Some of the reasons due to the increasing popularity is due to the fact that just by using methane as fuels, the emission from combustion manages the ECA requirements without extensive modifications. The SO_x emissions from LNG are negligible because methane does not contain any sulfur, thus have no sulfur emissions. The environmental downside of using LNG as a fuel is the phenomenon called methane slip. Methane slips are particles from incomplete combustion of the fuel that travel into the atmosphere. Since methane is a hydrocarbon, it has a massive impact as a greenhouse gas. CH₄ has 75 (Olmer. Comer. Roy. Mao. Rutherford. 2017) times higher 20-year global warming potential than CO₂. However, as LNG is still a relatively new fuel in the marine sector, it is not yet as regulated as other fuels, especially with methane slips in mind.

1.2 Purpose and research questions

With the upcoming restrictions to emissions worldwide in the marine sector, LNG is proving to be a competitive alternative to other types of fossil fuels with less emission overall, the purpose of this study is to investigate the pros and cons of LNG as a marine fuel regarding environmental impact in comparison to diesel. Including the use of after treatment of the exhaust gas as well as the exhaust gas itself.

- How does LNG compare to diesel when taking GHG into account regarding CO₂ emissions?
- Are there any international regulations in the marine sector for GHG emissions and what do they say?
- Is there any way to counter the problems with methane slip and, in such case, how?

1.3 Limitations

Most LNG vessels operate with diesel as a back-up fuel for low engine loads therefor the study compares LNG to diesel as a baseline for environmental impact. The environmental impact of NO_x is difficult to examine as it differentiates depending on engine design and is therefore disregarded.



1.4 Discussion regarding sources

Methane slip from gas-fuelled ships: a comprehensive summary based on measurement data is a great source for this study as it is the only study found that contained actual measurements onboard ships of the methane slip when using LNG as a fuel. Their sample size is small because doing these measurements is time consuming and hard since most vessels with LNG have irregular schedules, which makes planning to conduct these measurements difficult. This source also shows the lack of onboard equipment to measure the methane slip since it must be done with external equipment.

MAN energy solutions has been a great help because their engine data and testbed measurements can be found on their site. This was also the only engine manufacturer willing to share this type of data. But the data shown is also strongly deviating from measurements seen in other sources. The methane slip shown is also the same no matter what configuration is done in the Computerized Engine Application System (CEAS) calculator.

1.5 Ethical and environmental discussion

From an environmental standpoint, neither diesel nor LNG is a good option. However, the global economy will never stop, and thus, looking for better options, even if they are still bad for the environment is a crucial step on the road to CO₂ neutrality.

Ethically, information regarding companies has been revealed as it was concluded that nothing negative was said about them. The data used from mentioned companies and their products was and is available to the public.

2 Theory background and model

Awareness regarding the GHG and CO₂ emissions have been acknowledged by some companies and IMO alike. However, due to the slow-paced nature of the marine industry, there is a long adjusting time until actions must be taken from a legal standpoint.

In 2018, IMO developed an initial strategy consisting of three phases designed to approach the problem at hand. The first phase is to increase the requirements for new ships, specifically the Energy Efficiency Design Index (EEDI) (IMO. 2020). With constantly updated requirements, the emissions will successively get better with each generation of ships.

- The first phase of EEDI came into action in 2015, which dictated a reduction of at least 10% carbon intensity.
- The second phase of EEDI came into action 2020, increasing the reduction to 20% carbon intensity.
- The third phase of EEDI will enter in 2025 with a reduction of 30% carbon intensity (IMO. 2019).

The second phase is meant to approach the problem head on, in other words introduce CO₂ emission limitations. The first threshold went into action in 2020, limiting the carbon intensity with 20%. The second threshold that will adjust the global market will be a 40% reduction in 2030 and the third threshold will be 70% in 2050 based of the emissions from 2008.

The third phase will introduce a similar threshold as in phase 2, but for GHG. The limitation will be 50% of the GHG emissions in 2008 by 2050. (IMO. 2020)

However, some of these changes have been fast-tracked by IMO; LNG carriers, gas carriers and general cargo ships will be brought into phase three of EEDI by 2022. Containerships above 200,000 deadweight tonnage will also be fast-tracked; however, they will face harsher reductions than previously mentioned types as they will be adjusted to a 50% reduction of carbon intensity by 2022 (IMO. 2020) (IMO. 2019).



In 2008, the global CO₂ emission was 32,133 million tons from fossil fuels and industries. Of the global total, 1,135 million tons came from international shipping, which accounts for approximately 3.5%. (Olmer et al. 2017)



3 Method

To get usable data about LNG engines the data was generated using the CEAS engine calculations. The data used here were of the G70ME-C10.5 with diesel injection and methane injection and both fitted with either Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) for comparison. This data can also be seen in Figure 1 and 2. All engines were specified to meet IMO tier III regulations (MAN Energy Solutions. 2021).

To see the potential of LNG a breakdown of its components is required, in this study the LNG used was delivered by TitanLNG. This LNG can be seen in Table 1. The molecular weight of each component was calculated and summarized. This was then used to get the carbon, hydrogen, and nitrogen amount in percentage as seen in table 1. This was then used to get the molecular weight average of LNG as seen in table 2. Formula 1 was used to break down the LNG into its core components of carbon, hydrogen, and nitrogen. The carbon percentage of the LNG was then used to calculate CO₂ volume produced by the burning of LNG which was then multiplied by the weight of a cubic meter of CO₂ to get the CO₂ produced per kilogram of fuel burned. This was then used to calculate how much CO₂ was released in the exhaust gas by multiplying it with the specific gas consumption of Engine A. Thereafter the specific pilot fuel oil was added to the CO₂ equivalent emissions.

$$\text{Substance \%} = \frac{\text{Summarized mole(LNG)}}{\text{Summarized mole(substance mole)}} \quad (1.0)$$

$$V_{nCO_2} = 22,7 \times \left(\frac{1}{12} \times \frac{c}{100} \right) \text{ (KMA. 2020, p. 65)} \quad (2.0)$$

$$V_{nCO_2} = CO_2 \text{ Volume in exhaustgas}$$

$$c = \text{Carbon weight by \%}$$

Then the methane slip was converted to a CO₂ equivalent by multiplying it with 25 and added to the carbon emissions of the engines (Olmer et al. 2017). Then a comparison must be made with conventional fuel such as diesel, for



this a diesel of high quality was used with a carbon content of 85.90% and a hydrogen content of 13.60%. The same calculations were made for the volume of CO₂ in the exhaust gas and then converted to CO₂ produced per kilogram of fuel. This however was applied on Engine A but optimized for diesel entirely.

A comparison of the two values was made to get the CO₂ equivalent emissions released depending on engine load and an average between the loads.

Table 1. A breakdown of LNG and its carbon, hydrogen, and nitrogen parts.

Substance	LNG %	Mole	Molecule	Carbon %	Hydrogen %	Nitrogen %
Methane	91,1850	16,043	CH ₄	74,87	25,13	0,00
Ethane	6,9230	30,07	C ₂ H ₆	79,89	20,11	0,00
Propane	1,4070	44,097	C ₃ H ₈	81,71	18,29	0,00
Isobutane	0,1400	58,124	C ₄ H ₁₀	82,66	17,34	0,00
n-Butane	0,2880	58,124	C ₄ H ₁₀	82,66	17,34	0,00
Isopentane	0,0160	72,151	C ₅ H ₁₂	83,24	16,76	0,00
n-pentane	0,0040	72,151	C ₅ H ₁₂	83,24	16,76	0,00
Nitrogen	0,0036	28,014	N ₂	0,00	0,00	100,00

Table 2. A breakdown of the molecular weight of the LNG.

Substance	Mole(LNG)	Mole(Carbon)	Mole(Hydrogen)	Mole(Nitrogen)
Methane	14,62881	10,95223035	3,6765792	0,00
Ethane	2,0817461	1,66304306	0,41870304	0,00
Propane	0,6204448	0,50698431	0,11346048	0,00
Isobutane	0,0813736	0,0672616	0,014112	0,00
n-Butane	0,1673971	0,13836672	0,0290304	0,00
Isopentane	0,0115442	0,0096088	0,00193536	0,00
n-pentane	0,002886	0,0024022	0,00048384	0,00
Nitrogen	0,0010085	0,00	0,00	0,001008504
Summarized	17,59521	13,33989704	4,25430432	0,001008504

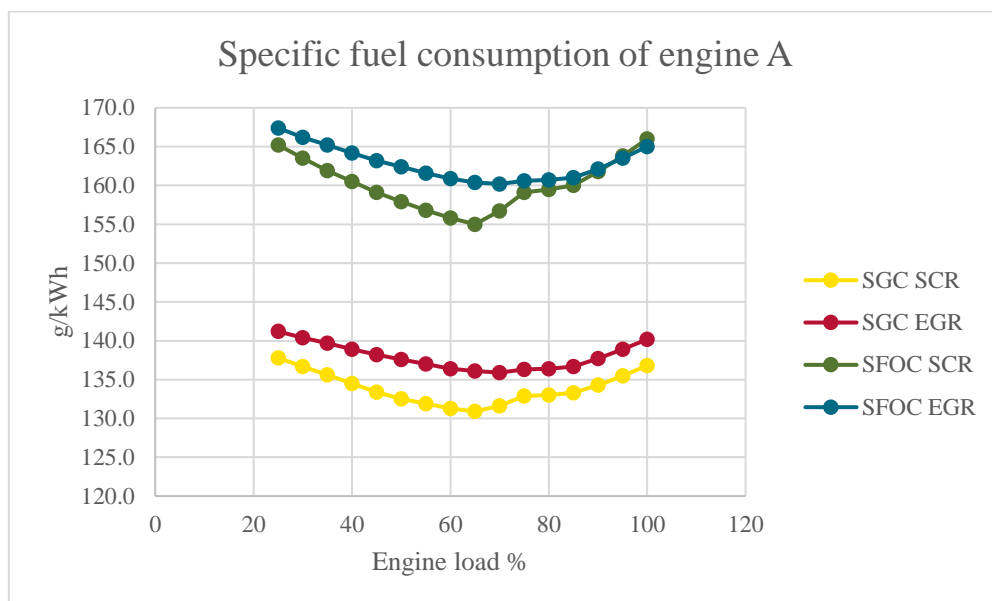


Figure 1. Figure shows the specific fuel consumption of both LNG and diesel for engine A.

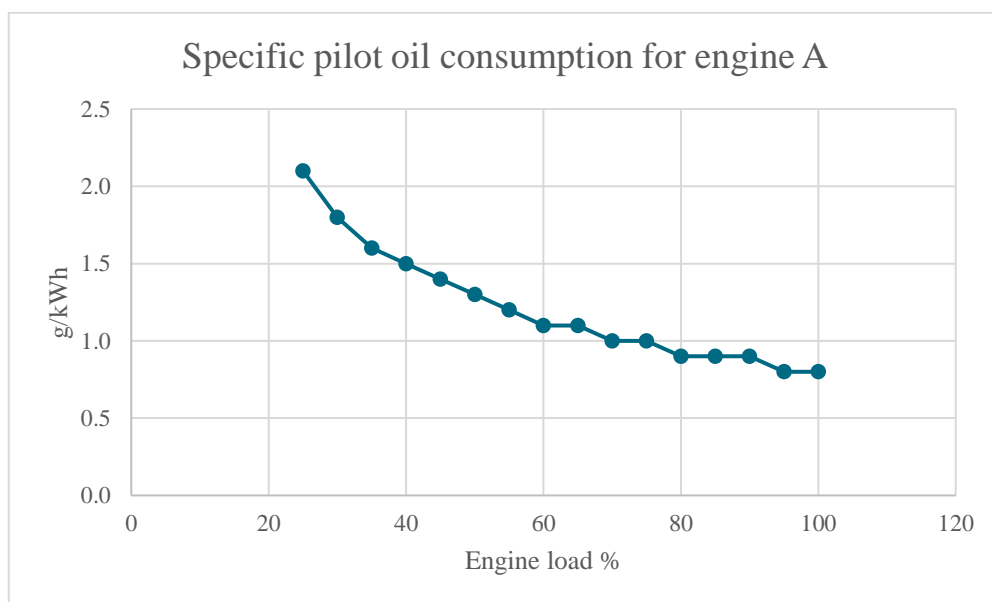


Figure 2. Figure shows the pilot fuel consumption used when engine A runs on LNG the pilot fuel consumption is the same for both EGR and SCR configurations.

4 Results

How does LNG compare to diesel when taking GHG into account regarding CO₂ emissions?

As shown in Figure 3 and 4 LNG is an environmentally friendlier choice when taking the methane slip into account by 24,3% and 23,3% on average depending on the after treatment of the exhaust gas.

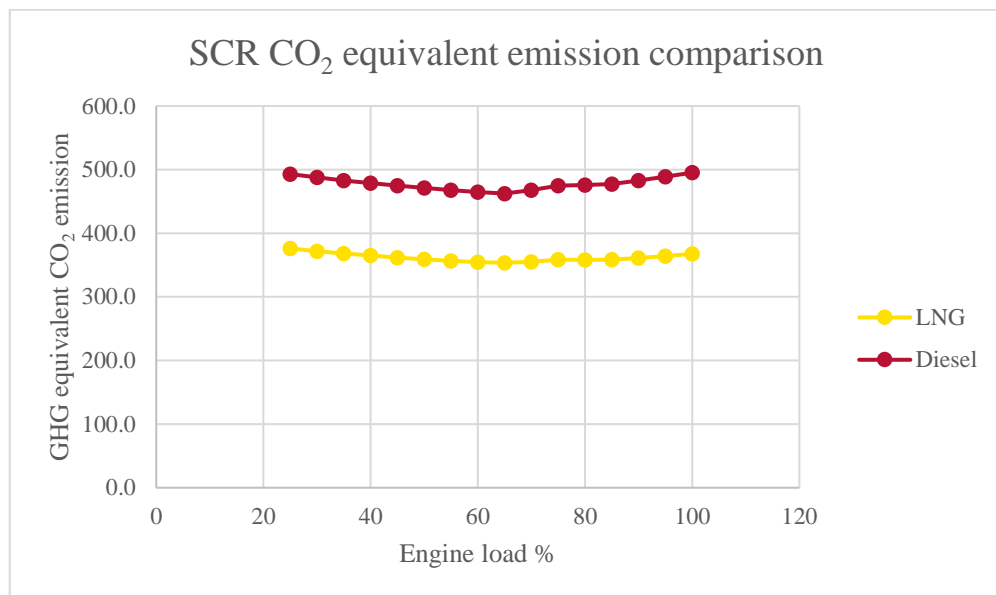


Figure 3. A comparison of fuel emissions between LNG and Diesel with the emissions converted to CO₂ equivalent both engine configurations fitted with an SCR of the same type. LNG is on an average 24,3% better than diesel.

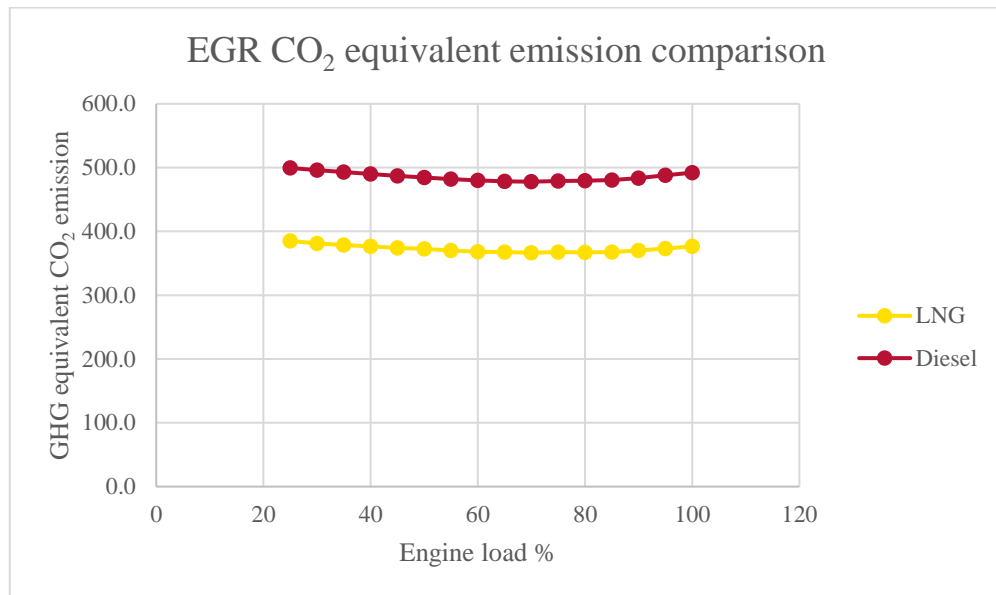


Figure 4. A comparison of fuel emissions between LNG and Diesel with the emissions converted to CO₂ equivalent both engine configurations fitted with an EGR of the same type. LNG is on an average 23,3% better than diesel.

Are there any international regulations in the marine sector for GHG emissions and what do they say?

As shown by IMO on their *Reducing Greenhouse gas emissions from ships* page they show the most clear and easy to understand picture of how international shipping emissions will be handled until 2050. Here it can be seen that carbon emissions must be reduced by 20% by 2020, and this will be revised in 2023, GHG measures will not be a factor until 2050 for most ships which means that the methane slip for LNG engines does not add to the carbon intensity of the goals before 2050 (IMO. 2020).

Is there any way to counter the problems with methane slip and, in such case, how?

MAN Energy Solutions have shown that by increasing the combustion chamber temperature and reducing the void space above the liner; this will increase the amount of fuel combusted which in turn means that it will not be wasted in the exhaust gas as methane slip (MAN Energy Solutions. 2018).



5 Discussion

5.1 Method discussion

A few assumptions have been made in the method calculations such as the fuel being fully combusted while this is nearly impossible, if that was the case there would not be any methane slip. The data for engine A is also uncertain as it was simulated from a testbench and there is no actual data from ships available. The only actual methane slip data that has been found is from (Ushakov, S. Stenersen, D. Einang, P. M. 2018) where the methane slip recorded from a few actual ships were substantially larger, but those engines are also older and from other manufacturers. The diesel used for the combustion comparison is also a very high-quality diesel that contains no sulfur which is unusual outside of pilot fuel usage for ships, however the methane used to comparison is from a standard deliverer for LNG ships and is representative of the quality more commonly available to consumers.

5.2 Results discussion

As LNG is used worldwide for several different sectors, for example industries, ships and so on, many different associations, companies, governments, and authorities discuss how it should be measured. As methane enters the atmosphere it stays there for around 12 years. This started the discussion whether to measure it in a 20-year perspective or in a 100-year perspective. According to the International Energy Agency (IEA), methane has a global warming potential of 84-87 in a 20-year perspective and a Global Warming Potential (GWP) of 28-36 in a 100-year perspective (IEA. 2021). ICCT however has said it has a GWP of 75 in a 20-year perspective and a GWP of 25 in a 100-year perspective (Olmer et al. 2017). This means that there is a conflict of interest when calculating the emissions, companies that wish to produce a product that uses methane will most likely use emission data compared to the 100-year perspective. Since this approach produces better results for the product, while it would be more environmentally friendly to use the 20-year perspective for methane when calculating the emission effects.



The increasing requirements from IMO will hasten the advancement of environmental beneficial advancements. As of 2018, a company introduced an engine (Engine A) designed for container vessels above 200,000 Dead Weight Tonnage (DWT) that complies with the new special regulations for previously mentioned class. The responsible company for “Engine A” has stated that with a complete program for this engine, the methane slip will be 0.2g/kwh with a +/-0.1 tolerance (MAN Energy Solutions. 2020). To achieve low emissions of methane and formaldehydes the combustion temperature exceeds 1300 degrees Celsius (MAN Energy Solutions. 2018). Even though methane contains a negligible amount of nitrogen, air contains about 78%. The amount of NO_x emissions also increases together with increasing combustion temperatures (Ushakov, S. Stenersen, D. Einang, P. M. 2018). On the other hand, there is no after treatment that deals with methane slips, however, there is after treatment for NO_x emissions. Two common aftertreatment for exhaust gas NO_x emissions are SCR and EGR.

The same company also have another engine in development that they have stated will comply with the upcoming 2022 emission requirements for the other fast-tracked vessel types. However, data has yet to be released for the engine, so whether it complies with the regulations or not is yet to see.

However, a study regarding LNG engines at sea showed that among other things, methane slip data was a lot higher when used onboard a ship compared to the manufactures test bench data. (Ushakov, S. Stenersen, D. Einang, P. M. 2018) The reason that the test bench data always seem better than what it is most likely due to optimal surroundings, temperatures, fuel quality and other factors that would impact combustion and efficiency. Necessarily it does not mean that the manufacturers are trying to deceive their clients, but it is noteworthy to keep in mind that their data is in the best of worlds and perhaps not applicable in the standard use of the machinery.

Another noteworthy point is the fact that currently, methane slip is not monitored as a standard in the marine sector, this means that it is currently hard to adjust the operation of the ship to further optimize the ship on sight.

According to (MAN Energy Solutions. 2018) LNG powered engines reduce the CO₂ emissions and its equivalents by around 23 to 24% which is further backed up by the calculations from Figure 3 and 4. It is worth noting that the reduction of emissions only applies at higher loads, and not on low loads.



Presently, most of the methane powered engines are 4-stroke dual fuel types, which use a pilot fuel to ignite the gas to achieve combustion and propulsion of the piston. As data shows in (Ushakov, S. Stenersen, D. Einang, P. M. 2018), as the load drops, the methane slip increases exponentially to massive amounts, to counter this problem, several companies solved it by doing dual fuel engines, which means that at a specific load, the ship switches to MDO instead of gas.

Wärtsilä states that during the last two and a half decades, they have reduced their methane slip with 75% and will continue to reduce it significantly in the coming 3 years (Wärtsilä. 2020).

6 Conclusion

As IMO states, by 2050 the GHG emissions needs to be reduced by 50%, which roughly translates into a reduction of 85% CO₂. Compared to the emissions from 2008, the total CO₂ emission will at the highest be 0,17025 million tons. With our current technology, the limit prescribed by 2050 is impossible to reach with combustion engines, as for every gram of carbon-based fuel pumped in, several times more air is used, which the rest product is CO₂, GHG equivalents and other emissions. LNG is a good step in the way of this, in our calculations LNG contains 11,74% less carbon that has the potential to be converted to CO₂, this combined with less LNG required per kWh makes LNG a good step on the way while technology advances to a level where shipping can function without any carbon emissions.

Upcoming legislation for CO₂ emissions can be met with the use of LNG but this legislation ignores the problem of methane slip and many of the benefits of LNG are reduced because of that methane slip since it is a GHG just like CO₂ is. If the methane slip can be reduced to levels shown from engine A then LNG is a lot better than diesel as shown in the results but if they are close to the methane slip shown in (Ushakov, S. Stenersen, D. Einang, P. M. 2018) then it can even be worse than diesel in terms of GHG emissions as methane gas is considerably worse than CO₂ as a GHG especially if you use the 20-year perspective instead of the 100-year perspective. If the 100-year methane CO₂ coefficient is used instead of the 20-year coefficient than the margin for error in the methane slip is reduced substantially and even a small amount of methane slip is devastating for the environment. It would be wise for the IMO revision of the initial strategy of 2023 to bring up this potential oversight with GHGs until 2050 and the lack of measurements for GHGs in exhaust gas of marine vessels.



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