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Comparative study of LNG/MGO emission levels on a ROPAX ship

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ABSTRACT

Maritime transport emission reduction targets are getting stricter as solutions to reduce the environmental load are actively sought. This study compares emission levels of LNG and MGO fuels on the ROPAX ship. Emission measurements have been carried out on the ship while it was operating in real conditions at sea and include results under different load conditions. The results reveal that methane slip is noticeable under partial load. The results are generalized utilizing the sustainability index approach allowing for the separation of global warming, acidification, eutrophication, and human health particulate air potentials. Although LNG performs better in terms of many environmental effects, due to the methane slip the GWP100 does not differ much from the corresponding MGO values. The values given by the sustainability index are greatly influenced by the fuel price level, and recently the LNG market has been rather turbulent.

1. Introduction.

Ship exhaust emissions mainly consist of carbon dioxide, nitrogen and sulfur dioxides, carbon monoxide, unburnt hydrocarbons, and particles, including significant amounts of water vapor, residual oxygen, and nitrogen (IMO, 2020). Carbon dioxide and methane accelerate climate change (Wang et al., 2022). At the local level, concentrations of particles, sulfur, and nitrogen oxides can rise unnecessarily high and weaken local air quality, e.g., in ports or settlements. (Li et al., 2023; Nguyen et al., 2022; Toscano et al., 2022). However, there are no simple solutions for reducing shipping emissions. Furthermore, as the lifespan of ships is usually 30-40 years, investment decisions of shipping companies have far-reaching effects in terms of emissions (Aakko-Saksa et al., 2023).

Experiences about the effectiveness of ship emission control areas are continuously being accumulated (Li et al., 2023; Yang et al., 2022). This also applies to the Baltic Sea region (Jalkanen & Johansson, 2019; Ytreberg et al., 2021), where a stricter sulfur dioxide restriction zone has been defined (SECA, Sulfur Emission Control Area) permitting a maximum sulfur content of 0.1 % in fuel (IMO, 2019). In non-SECA areas, the sulfur limit is set at 0.5%. Technologies that meet SECA requirements include using low-sulfur fuels such as MGO or LNG, or alternatively the ship must have been equipped with sulfur scrubbers. Finnish Customs statistics (Finnish customs, 2020) highlight that approximately 90 percent of Finland's foreign trade depends either partially or entirely on maritime traffic in the SECA area. Thus, in Finland, the impact of sulfur regulations on the decisions of shipping companies is significant, so the region serves as a good indicator when considering the likely effects of tightening restrictions worldwide (Solakivi et al., 2019).

The Baltic Sea has been defined as a NO_X Emission Control Area (NECA) from the beginning of 2021 when the Tier III restriction came into force for ships built after 2016. No binding CO_2 emission limits have yet been set for maritime transport. However, the greenhouse gas emissions from shipping are gaining increasing attention on global and regional level. In the initial GHG Strategy, IMO adopted a target of reducing greenhouse emissions from maritime transport by 50% by 2050 compared to emission levels in 2008 (IMO, 2018). In 2023, IMO

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revised this strategy, with an updated goal of achieving net-zero greenhouse gas emissions from international shipping by 2050 (IMO, 2023). The chosen technology-free approach may lead to maritime transport, in one way or another, being a part of the international emissions trading system in the future. Regionally, shipping will be included in the EU Emissions Trading System in 2024 (EU/2023/959).

According to the Third IMO GHG study (IMO, 2015), between 2007 and 2012 ship emissions accounted for 3.1% of annual global CO_2 emissions and 2.8% of annual greenhouse gas emissions, with NO_X and SO_X emissions accounting for approximately 15% and 13%, respectively. The latest IMO emissions inventory was published in summer 2020 (IMO, 2020), reporting emission trends between 2012 and 2018. Greenhouse gas emissions had risen to 1.076 million tons (2018), an increase of 9.6% and shipping accounted for 2.9% of global greenhouse gas emissions annually (2018). This report also noticed (IMO, 2020) an increase in methane emissions of ships during this period (approximately 150% increase between 2012-2018). Primarily, this was due to the rise in the use of LNG. The share of multi-fuel engines has grown significantly during this period, especially in the Baltic Sea. Many shipping companies have invested in LNG technology to meet the requirements of the NECA and SECA. During the period, NO_X emissions increased less (+1.2%) than the fuel consumption trend (+5.6%) due to the increase in the share of engines that meet TIER II and III requirements (IMO, 2020).

Although SO_X and NO_X requirements can be achieved by several emission reduction technologies (SCR, scrubbers, MGO, LNG, higher TIER-classified engines), there is no consensus on the best approach to reduce greenhouse gas emissions (Bouman et al., 2017). This is emphasized if the perspective is shifted from a ship-specific examination to a life-cycle approach that includes all greenhouse gases (CO_2, N_2O, and CH_4) from both fuel production and use. The life cycle approach is included in the upcoming FuelEU Maritime initiative (European Commission, 2021b). LNG has often been seen as a comprehensive solution to reduce emissions due to its low particle SO_X and NO_X emissions. Lindstad et al. (2020) recently stated that LNG increases greenhouse gas emissions compared to current diesel alternatives. In addition, according to their study, the reduction in greenhouse gas emissions from HFO/scrubber vessels is reduced by as much as 2-4% compared to MGO if the heavy fuel oil comes from conventional refineries. Thus, their research supports previous observations about the benefits of using scrubbers (Ma et al., 2012) and the challenges of LNG in reducing greenhouse gas emissions (Brynolf et al., 2014; Gilbert et al., 2018). Pavlenko et al. (2020) had similar findings, over a 100-year time horizon, the maximum greenhouse gas benefit of LNG is 15% lower compared to MGO however, this only occurs if ships have a high-pressure dual-fuel (HPDF) engine and methane emissions are well controlled. In a 20-year time horizon, the use of LNG does not benefit the climate, regardless of engine technology (Hult & Winnes, 2020). Recently, other aspects of sustainable development, such as economic and social sustainability, have attracted interest in energy and mobility topics (Wulf et al., 2019). Iannaccone et al. (2020) presented the results of a general sustainability index comparing MGO and LNG, which included environmental, economic, and safety aspects.

New fuel solutions such as liquified biogas, methanol, or ammonia are also being developed. Bouman et al. (2017) compared 150 studies published after 2009 to evaluate options for reducing CO_2 emissions from maritime transport. According to them, biofuels offer the most significant CO_2 reduction potential among alternative energy sources, around 50-80%. Correspondingly, for example, the potential of LNG is around 15-25%, wind power 10-20%, and shore power less than 10 %. In addition, Bouman et al. (2017) state that no single measure is sufficient to achieve significant reductions in greenhouse gas emissions, but emissions can be reduced by more than 75% by 2050 with a combination of measures. However, temporary solutions are also needed to reduce CO_2 emission quickly so that the IMO's previously mentioned ambitious goals are realistically achievable (IMO, 2023).

Intermittently, high expectations have been placed on LNG as a transitional fuel solution (Aronietis et al., 2016; Steuer, 2019; Tvedten & Bauer, 2022; Wood, 2012). Low NO_X emissions and practically zero SO_2 emissions, including the reduction of CO_2 per ton of fuel burned, have made LNG an interesting solution. However, especially ships equipped with low-pressure dual fuel engines cause a considerable amount of methane emissions. Methane is a potent greenhouse gas, and according to Grönholm et al. (2021), methane slip can negate the benefit of reduced CO_2 emissions. The share of LNG-powered RORO and ROPAX ships has increased significantly from 2010 to 2018 (Ushakov et al., 2019). According to Aakko-Saksa et al. (2023), gases are probably one of the applicable options, and an WtW (well-to-wake)-approach is emphasized in the evaluation, but a clear "winning technological solution" has not yet been found. Therefore, investments in multi-fuel engines will probably continue. In order to compare different alternatives, the scientific community needs significantly more measurement data recorded under real operating conditions. The objective of this paper is to present the results of empirical emission measurements carried out on an LNG ship under normal operating conditions, where the engines have been fueled alternately with MGO and LNG.

In this study, the effect of real conditions on the emission levels during normal operations is investigated using on-board flue gas measurements, and the sustainability index is applied to generalize the analysis of the recorded data. The measurements were carried out on a ROPAX ship equipped with dual-fuel engines. During the measurement period, the ship changed the use of LNG and MGO fuels, so the same voyage was undertaken several times with different fuels. The sustainability index approach is based on calculating economic and environmental indices and was used to evaluate the overall sustainable development performance of the alternatives. The comprehensive measurements and analyses carried out in this study, the impact of methane slip, and the proportion of other gaseous components on the overall sustainability performance can be assessed in detail. The results show a large variation in methane slip as a function of engine load, resulting in different environmental and sustainability performance than on MGO fueled voyages.

2. Methods.

In the Baltic Sea, the number of ROPAX vessels equipped with multi-fuel engines (LNG/MGO) has increased rapidly in ferry traffic in recent years. The common profile of these routes is that they are continuous, short intercoastal ferry services. Two vessels operate from Turku (FIN) to Stockholm (SWE), one from Vaasa (FIN) to Umeå (SWE), and two from Helsinki (FIN) to Tallinn (EST). In addition, similar routes are also operated from Sweden to Gotland and Germany. These ships have LPDF (low-pressure dual fuel)-type diesel engines without additional emission reduction technologies such as catalyst systems. On some routes, such as Turku to Stockholm, operation with partially loaded engines is common due to the wide archipelago areas.

In this study, the dual-fuel vessel was chosen as the research object, which operates a 2-hour long fixed route from port-to-port. The characteristics of the ship and its propulsion machinery are described in table 1. The shipping company agreed to sail consecutive voyages with different fuels (LNG and MGO). The route profile includes a short open sea voyage and two port maneuvering periods. The ship was commissioned in 2017, so natural wear and tear are evident in the systems. The operating hours of the measured engines are 21,500 h for ME1 (main engine 1) and 28,900 h for ME5 (main engine 5). Arriving at both ports was smooth due to the fixed schedule and installed auto-mooring system. Based on these measurements and taking into account the similar technical characteristics and solutions of other dual-fuel ferries in the region, conclusions can be drawn about the generalizability and possible needs for additional measurements.

Table 1: Ship characteristics.

Variable	Amount	Unit
Length	212	m
Beam	31	m
Draught	7.1	m
Max. speed	27	knots
GT	49,000	-
ME1 Wärtsilä 12V50DF	11,400	kW
ME2 Wärtsilä 12V50DF	11,400	kW
ME3 Wärtsilä 6L50DF	5,700	kW
ME4 Wärtsilä 6L50DF	5,700	kW
ME5 Wärtsilä 12V50DF	11,400	kW

Source: Authors.

2.1. On-board emission measurements.

The measurements were performed on a ROPAX ferry operating in the Baltic Sea in June 2022, powered by three Wärtsilä 12V50DF and two Wärtsilä 6L50DF low-pressure dual-fuel engines (DF-engine). The installed power was 11,400 kW per 12V engine and 5,700 kW per 6L engine. In normal operation, the vessel uses two 12V50DF engines. The propulsion line is a complete diesel-electric system and there are no separate auxiliary engines are on-board. All engines meet TIER III requirements in gas mode, and TIER II requirements in diesel operation, and no additional emission reduction technologies have been installed (Wärtsilä, 2019). During the measurements, the fuel was changed several times between MGO and LNG to achieve as comparable conditions as possible. The properties of both fuels are presented in tables 2 and 3 (Bunker delivery note LNG, 2022; Bunker delivery note MGO/DMA 0.1, 2022). MGO is a normal, low-sulfur DMA quality, while LNG is mainly methane. Wärtsilä dual-fuel engines require an LNG fuel with a methane number of at least 91, and MGO was used as a pilot fuel for igniting LNG (Wärtsilä, 2019).

Table 2: Characteristics of fuel MGO DMA 0.1.

Variable	Amount	Unit
gross heating value	12.75	kWh/kg
density	846.6	kg/m3
viscosity	3.858	cSt
VCF	1.00017	-
pour point	-9	°C
flash point	66.5	°C
sulphur	0.082	mass %
ash	0.01	mass %

Source: Bunker delivery note MGO/DMA 0.1.

Table 3: Characteristics of fuel LNG.

Variable	Amount	Unit
gross heating value	15.232	kWh/kg
density	429.1	kg/m3
methane	90.3186	mol. %
ethane	8.0489	mol. %
propane	1.2014	mol. %
n-butane	0.1590	mol. %
iso-butane	0.1999	mol. %
n-pentane	0.0155	mol. %
iso-pentane	0.0238	mol. %
nitrogen	0.0019	mol. %
carbon dioxide	0.0019	mol. %
oxygen	0.0000	mol. %

Source: Bunker delivery note LNG.

The exhaust gas samples were obtained from the stack immediately after the exhaust gas boiler through the holes built for this purpose. Each engine has a separate stack line, and the exhaust stream was sampled with a PSP4000-H heated filter probe. Although the flue gases from ships are quite dry, they contain a small amount of water vapor, which affects the measurement results if the sample gas is not dried. The sample was dried with a processing dryer (Permocure Minigas 2812T) that contains a suction pump and works through permeation, where water molecules are removed through ion membrane tubes. This method does not require a condensate tank, so it is suitable for tight spaces in stack structures. During the measurements, clogging was constantly monitored due to the high particle content of the flue gases. All measurements have been performed on dried gas.

Sulfur, carbon dioxides, and carbon monoxide have been measured using the infrared absorption (IR) method. The analysis was performed with a portable Horiba PG350 analyzer. This device was calibrated at the measurement site using a mixture of calibration gas (calibration gas quantity, see table 4). This measurement procedure complies with the standard CEN/TS 17021/2017 (Stationary source emissions, 2017a) for sulfur dioxide, ISO 12039/2019 for carbon dioxide (Stationary source emissions, 2019), and SFS-EN 15058/2017 for carbon monoxide (Stationary source emissions, 2017b).

The measurement of nitrogen oxides have been based on the chemiluminescence (Chemil.) method, and the sample was fed to the analyzer (Horiba PG350) undiluted through a heated sampling line via a dryer. The measurement method is based on the standard SFS-EN 14792/2017 (Stationary source emissions, 2017c). EF-NOX is corrected for ambient temperature and humidity according to the IMO NOx Technical Code (IMO, 2008).

The residual oxygen in flue gases has been determined by the paramagnetic (Param.) method. The flue gas sample was fed to the analyzer (Horiba PG350) through the drier. The analyzer was calibrated with free air (O_2=20.9%) and nitrogen (O_2=0.0%) at the sampling site (table 4). Linearity tests have been performed on the device. The standard followed is SFS-EN 14789/2017 (Stationary source emissions, 2017d).

TVOC (total volatile organic compound) emissions have been measured with a flame ionization (FID) detector (ERSATEC SmartFID analyzer), which is a gas chromatography analyzer. In the detector, the sample burns with the fuel gas, and the carbon contained in the sample generates a measurable electric current when ionized. The undried sample was led along a heated sampling line to the detector. The analyzer was calibrated at the measurement site with propane. Propane-calibrated results are computationally converted to methane-compatible ones. TVOC emission measurements are based on the standard SFS-EN 12619/2013 (Stationary source emissions, 2013).

Table 4: Emission measurement standards, methods, and calibration gas quantities.

Gas	Method	Standard	Calibr.
SO_2	IR	CEN/TS 17021/2017	0/100
NO_X	Chemil.	SFS-EN 14792/2017	0/200
CO	IR	SFS-EN 15058/2017	0/200
CO_2	IR	ISO 12039/2019	0/13
O_2	Param.	SFS-EN 14789/2017	0/20.9
TVOC	FID	SFS-EN 12619/2013	0/100

Source:Authors.

Engine power and fuel consumption data are obtained from the ship's engine control system (Valmet DNA). Atmospheric pressure, relative humidity, and air temperature are measured but these variables are subject to uncertainty due to operating in a real marine environment. In this case however, it is not estimated to cause a significant deviation in the results. The weather conditions were very similar and calm on all measurement voyages. These variables and the measured emission components are listed in Table 5.

Table 5: Research variables and their sources.

Variable	Unit	Source
Shaft power	kW	Ship system
Fuel	kg/h	Ship system
Atm. pressure	kPa	Estimated / Measured
Rel. humidity	%	Estimated / Measured
Air temp.	°C	Estimated / Measured
O_2	%	Measured
CO_2	%	Measured
NO_X	ppm	Measured
SO_2	ppm	Measured
CO	ppm	Measured
TVOC	ppm	Measured

Source:Authors.

These variables are used to determine the realized specific fuel consumption and specific emissions. They are defined in relation to engine power (g/kWh) and fuel consumption in a chosen period (g/kg_{fuel}). This conversion has been implemented according to the ISO 8178-1 standard (Reciprocating internal combustion engines – exhaust emission measurement, 2020). This study focuses on the following components: Carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_X), and total volatile organic compounds (TVOC). The amount of sulfur dioxide is known to be very low with these fuel solutions as is the amount of residual oxygen of the flue gases needed to process the results (ISO 8178). The amount of CO_2 emissions closely follows the actual fuel consumption. NO_X emissions are of particular interest as harmful emissions because the difference between MGO and LNG is known to be considerable. The same applies to TVOC emissions. Based on the composition of LNG (table 3), the amount of TVOC strongly indicates the residual methane in the flue gases. Furthermore, the carbon monoxide level is a good indicator of the completeness combustion process, although there are no limit values set for CO emissions.

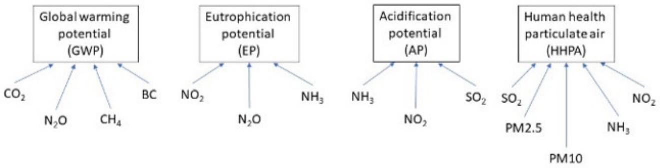
2.2. Sustainability index.

A direct comparison of MGO and LNG is challenging because the emission components produced by these fuels affect the environment in different ways. However, this is a key research problem, especially when considering the generalizability of the results to other LNG ROPAX vessels operating in the Baltic Sea region. This study compares the differences in emission compositions with fuel solutions (MGO and LNG) using the sustainability index.

The sustainability index describes environmental and economic indices and is based on generating, weighting, and aggregating these indices into an overall sustainability index (Iannaccone et al., 2020). For all the indexes, the highest value indicates the worst alternative. In this study, the social aspect of sustainability has been left out of the comparison because the aim is limited by the emission measurements performed. A detailed description of the sustainability index approach can be found in our previous publication (Altarriba et al., 2022), which examined the effect of fuel price, particle reduction, and black carbon.

The environmental index includes four environmental impact categories: Eutrophication potential (EP), acidification potential (AP), global warming potential (GWP), and human health particulate air (HHPA). These categories have been assessed as the most significant environmental impacts of shipping (Bengtsson et al., 2011). Global warming, acidification, and human health particulate air potentials are estimated effects on the air, and eutrophication potential concerns the aquatic environment. Figure 1 shows the emission components affecting the various categories. However, it should be noted that only the components presented in the previous section were measured from the ship, so we do not have measurement data on, for example, black carbon (BC) or particles produced by the ship. The same characterization factors as in the previous study are used to score the environmental indicators (Altarriba et al., 2022).

Figure 1: Emission components that are affecting to different potentials.



Source: Authors.

This specification follows the approach published by Iannaccone et al. (2020) and includes three different annual navigation activities, such as berthing, maneuvering, and navigation in the open sea (Maragkogianni & Papaefthimiou, 2015). This means that the estimation of impact categories is based on annual emissions and thus provides a broader view of the estimated impacts than individual emission measurements. Especially on a route such as this, where the ship operates on a fixed route and schedule, such a generalization can be performed reliably. The total fuel consumption of the ship is estimated using the same principle as Åström et al. (2018) have presented; the aid of engine size [kW], load factors, and annual hours at berth (HB), at sea (HS) and maneuvering (HM). The load factors at sea and main engine power are shown in table 8, and the following values are used for annual hours: HS=4375 h, HM=3646 h, HB=729 h. The annual number of hours figure is based on an estimate of the ship's normal activity during a 24-hour period. In this study, the ship's exhaust gas emission factors and specific fuel consumption are based on the measurements (table 8). The fuel production emission data is based on the work of Bengtsson et al. (2011).

The financial viability of alternative projects is evaluated using the Net Present Value (NPV) method (Iannaccone et al., 2020; Pohl & Nachtmann, 2011). The parameters of the economic index are obtained or evaluated based on literature and are shown in Table 6. Since no external emission reduction technology is used, the only investment cost is the additional cost of the LNG-powered dual-fuel engine compared to a normal diesel engine investment. In this case, this one-time investment naturally applies to both fuels, but the purpose of the distinction is to show the difference to normal diesel engines, which generally has cheaper investment costs than dual-fuel ones. The project lifetime has been set at 25 years, as the technical lifetime of an LNG engine is similar (Åström et al., 2018).

There are four different fuel prices estimation for both LNG and MGO. The average price estimate is based on values from Åström et al. (2018). The current figures have been estimated based on average prices from 2021 and 2022 in different time intervals. Currently, it is difficult to assess the accuracy of fuel price scenarios, especially for LNG. The price of LNG was very predictable for a long time without any significant changes. At the end of 2021 due to international political tensions the price of LNG has been very volatile. Since the outbreak of the war in Ukraine, large price fluctuations have been seen in a very short time. Whether this volatility will continue or the price will settle at a stable level is difficult to predict.

Table 6: Economic parameters.

Variable	Unit	Value	
Proj. lifet.	years	25	
LNG eng.	€/kW	800	(in ad. to norm. inv.)
Env. tax	€/tCO_2	100	(source: IEA 2021)
Disc. rate	[%]	8	
LNG	€/t	610	(mid)
		3538	(current 1)
		1961	(current 2)
		1725	(current 3)
MGO	€/t	885	(mid)
		1084	(current 1)
		1135	(current 2)
		888	(current 3)

Source:Authors.

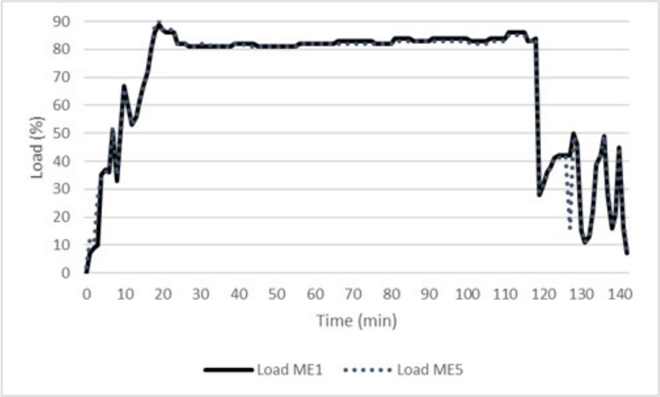
The normalization of the indicators has been performed following the same procedure as Bare et al. (2006) and Iannaccone et al. (2020). In this study, the same reference values have been used for normalization as in the previous study (Altarriba et al., 2022). The selected values are based on literature sources (Crenna et al., 2019; Iannaccone et al., 2020; Laurent et al., 2013; Sleeswijk et al., 2008). The same weighing values are used for the environmental and sustainability indexes.

3. Results.

3.1. Measurement results.

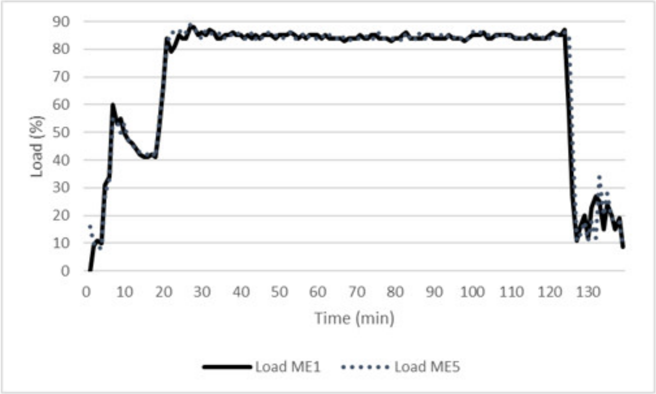
The on-board emission measurements were carried out on 21 June 2022 during two measurement sessions. MGO was used as fuel in the first leg and LNG in the second. The route and schedule are constant, which makes the operating profiles very similar. The voyage takes about 140 minutes, mostly at constant power. Approaching and maneuvering in both ports takes about 20 minutes. Figures 2 and 3 show the load profiles for both main engines (ME1 and ME5) running during both voyages. Both engines are loaded evenly.

Figure 2: Engine loading profiles, leg 1.



Source: Authors.

Figure 3: Engine loading profiles, leg 2.



Source: Authors.

We are particularly interested in two things: How much do the emission profiles of different fuel solutions differ with a constant load in real conditions, and how does operating at partial load affect the generation of emissions? The importance of this latter issue increases when operating on short and/or archipelago fairways. The most significant differences in the amount of emissions are found in the levels of nitrogen oxides and methane emissions, which is why they are the focus of this study. Real conditions present challenges that can be excluded in laboratory conditions. For example, between leg 1 and 2, in the first half, the load of the engines is slightly lower in leg 1 than in leg 2. Therefore, the emissions produced by ME1 are compared in two 60-minute-long periods. The measuring devices are only sufficient for measuring one engine at a time. The operating period of MGO in ME1 is measured at 08:00-09:00 (UTC +2, timestamps in figure 2 are 51-111 min) and LNG at 11:00-12:00 (timestamps in figure 3 are 48-108 min). The average fuel consumption has been 193.2 g/kWh (MGO) and 172.2 g/kWh (LNG). The mean, median, and deviation for each operating mode are found in tables 7 and 8 for both fuels, including measured average values for CO_2, CO, NO_X, and TVOC.

Table 7: Measurement results with MGO.

Var.	Unit	Mean	Med.	Dev.
load	%	83.0	83.0	1.0
fuel cons.	kg/h	1827.2	1838.3	15.4
spec. cons.	g/kWh	193.2	193.4	3.6
pwr	kW	9458.3	9462.0	117.7
CO_2	kg/h	5935.2	5971.2	50.0
CO	ppm	19.5	19.7	1.0
NO_X	ppm	865.4	865.0	3.3
TVOC	ppm	10.4	10.5	0.2

Source:Authors.

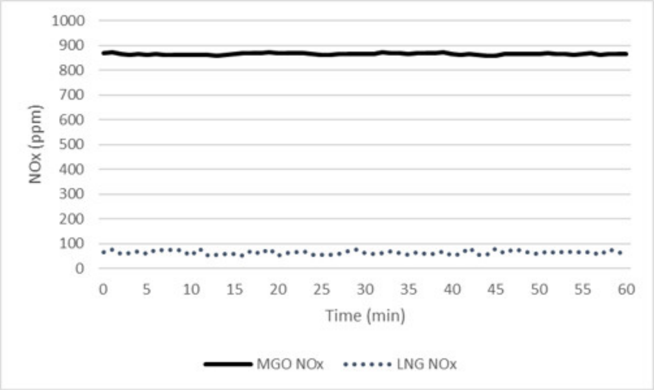
Table 8: Measurement results with LNG.

Var.	Unit	Mean	Med.	Dev.
load	%	84.4	84.4	0.7
fuel cons.	kg/h	1657.2	1652.0	52.4
spec. cons.	g/kWh	172.2	172.2	5.6
pwr	kW	9624.6	9576.0	76.4
CO_2	kg/h	4589.3	4580.5	152.7
CO	ppm	240.7	241.3	15.1
NO_X	ppm	64.4	63.3	8.5
TVOC	ppm	1533.4	1539.4	71.2

Source:Authors.

During the measurement period of LNG and MGO fuels, the load deviates slightly (83.0% and 84.4%), but this difference is not estimated to affect the results significantly. Carbon dioxide emissions closely follow fuel consumption, but high CO emissions in LNG operations indicate a more incomplete combustion process than in MGO operations. As expected, the differences in NO_X emissions are large. The concentration measurement data of the average values shown in tables 7 and 8 are presented in Figure 4. The difference is significant, but interestingly the momentary variation of NO_X emissions is perceptible, although not significantly larger compared to the emissions generated in MGO operations.

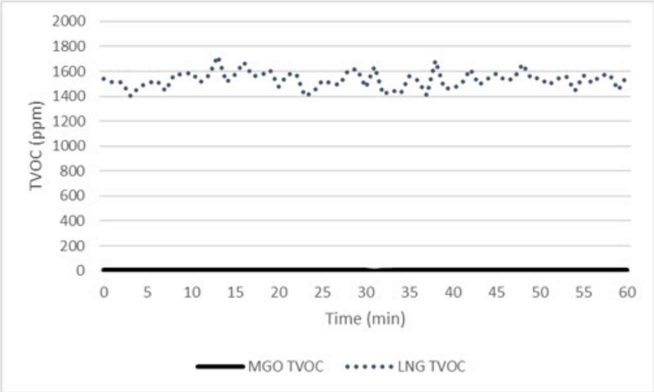
Figure 4: NO_X emissions with LNG and MGO.



Source: Authors.

TVOC-emissions (total concentration of volatile organic compounds) are unburnt fuel, which in practice means HC-emissions for MGO and mainly unburnt methane with LNG. The LNG composition, in this case is 90.32% (mol) methane and 8.05% (mol) ethane (Bunker delivery note of LNG, 2022). In addition, the gas contains small amounts of propane (1.201%) and other gases such as butanes and pentanes. A diesel engine operating with excess air does not leave many unburnt fuel components in the exhaust gases, but when using LNG, the TVOC concentrations are considerable (table 7 & 8). The variation in NO_X emission concentrations should also be considered (Figures 4 and 5).

Figure 5: TVOC emissions when using LNG and MGO.



Source: Authors.

The average emission levels measured in these periods per consumed fuel (g/kg$_{fuel}$) and specific fuel consumption (g/kWh) are shown in table 9. The conversions have been performed based on the ship's voyage data obtained from the engine control system (Valmet DNA, see table 5).

Table 9: Emission levels per fuel type.

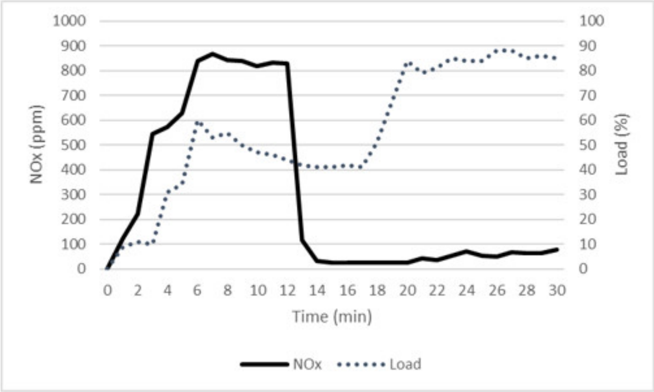
Comp.	MGO (g/kg$_{fuel}$)	LNG (g/kg$_{fuel}$)	MGO (g/kWh)	LNG (g/kWh)
CO_2	3206	2743	619.4	472.4
CO	0.7	8.60	0.14	1.48
TVOC	0.22	32.29	0.04	5.56
NO_X	51.23	3.77	9.90	0.65

Source:Authors.

Carbon dioxide emissions directly depend on the fuel consumed, although in the case of LNG, these emissions per kilogram of fuel burned are lower than MGO. The difference in nitrogen oxide emissions between fuel types is large, which is a well-known characteristic of LNG. MGO has a low sulfur quality (0.08%), so sulfur emissions are low without the use of treatment systems (1.33 g/kg$_{fuel}$ or 0.26 g/kWh). LNG is practically sulfur-free, so there are no sulfur emissions except for the sulfur in the pilot fuel. Measured SO_2 levels for LNG were close to MGO (1.11 g/kg$_{fuel}$ and 0.19 g/kWh), but this is due to equipment measurement error due to the increased amount of CO. There are no legal emission limits for carbon monoxide concentration, but it is listed in table 9 because high CO concentrations indicate an incomplete combustion process. The CO emissions produced by LNG are about ten times higher than the combustion of MGO, even though the engine operates on a fairly optimal load range (tables 7 & 8). This is reflected in high TVOC emissions, too.

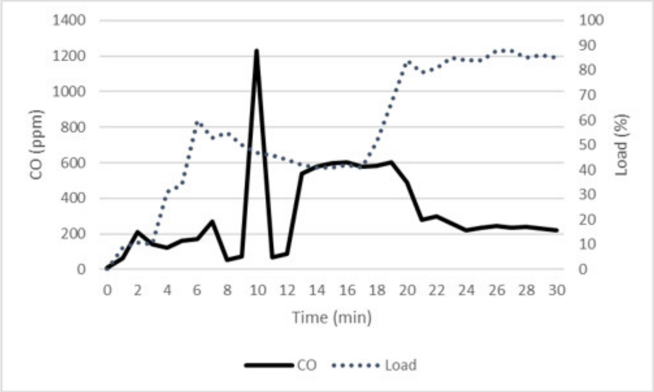
When a gas-powered engine is partially loaded, the share of methane emissions increases considerably. In general, partial loading is avoided for economic reasons, but special situations, such as operating on archipelago fairways, suboptimal scheduling, waiting times in anchorage areas, or using engines during port operations, often require partial loading. During the measurement session performed in leg 2 (figure 3), the engine is partially loaded during the first twenty minutes. In addition, the fuel has been changed during the middle of this period, and for this reason, the measurement period is examined more closely. In the Wärtsilä 12V50 engine, the fuel change from LNG to MGO can be done without significant delay. However, when switching to LNG, the process is slightly longer: The transition takes about 2-3 minutes to minimize disturbances in the gas supply system, and the engine load must be below 80%. Figures 6-8 show the NO_X (figure 6), CO (figure 7), and TVOC (figure 8) emission levels when the transition to gas has been performed in timestamps of 10-13 minutes. Immediately after the transition, NO_X emissions are minimized, and CO emissions increase significantly. However, the biggest change occurs in TVOC emissions. When operating at partial load (time stamps 12-20 min), the TVOC emissions are significantly high, and when cruising speed is reached, the level remains relatively high compared to the period when the engine is operated with MGO (figures 4 and 5, tables 7, 8 and 9).

Figure 6: Change in NO_X emissions during fuel and load changes.



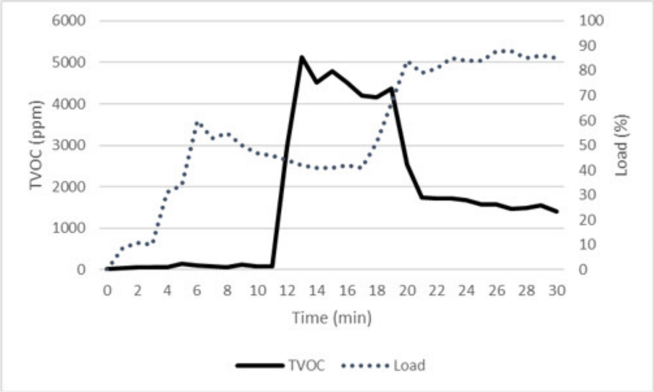
Source: Authors.

Figure 7: Change in CO emissions during fuel and load changes.



Source: Authors.

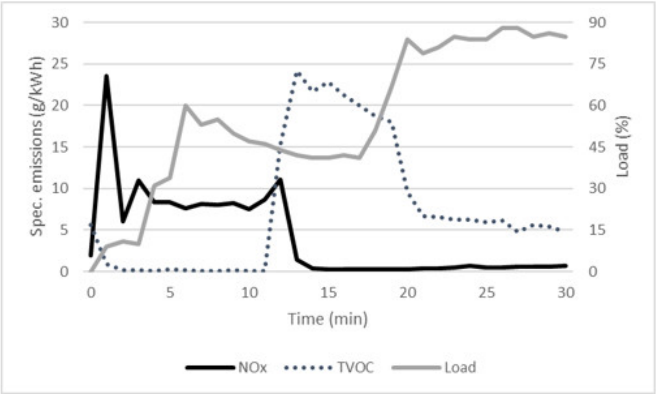
Figure 8: Change in TVOC emissions during fuel and load changes.



Source: Authors.

Figure 9 shows NO_X and TVOC-specific emission levels (g/kWh) for the same period as the data figures 6-8. In addition, the engine load has been added to the diagram. From the start, large calculated changes in specific emission levels can be found, but the more relevant period is the partial load phase at a time step of about 5-20 minutes and the fuel change event at 11-12 minutes. During this period, the average NO_X emissions are 8.00 g/kWh between 5-10 minutes and fall to 0.45 g/kWh (period 15-30 minutes) after the fuel change. Regarding TVOC emissions, there is more variation. In 5-10 minutes, the average was 0.13 g/kWh; in 13-18 minutes, 21.45 g/kWh; and finally, in 25-30 minutes, 5.45 g/kWh. The measurement periods are short due to the normal operation of the ship, but partial loading produces relatively significant TVOC emissions, which, when operating with LNG, are mainly methane.

Figure 9: NO_X/TVOC specific emissions in relation to load.



Source: Authors.

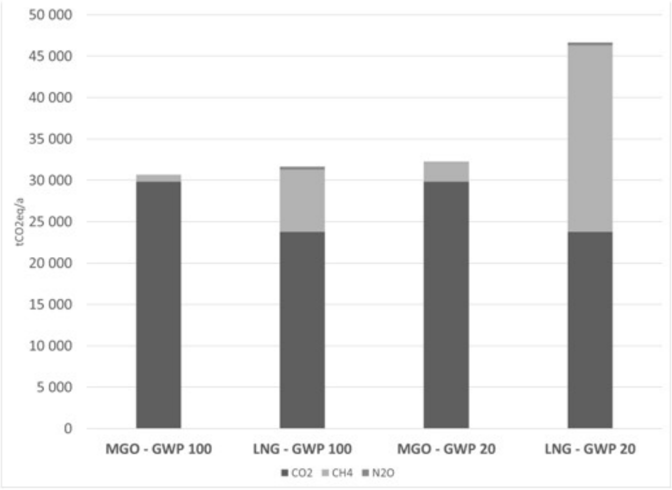
3.2. *Results from sustainability index calculations.*

The comparison of MGO and LNG using the GWP, environmental, and sustainability indices is shown in the following figures 10-12. Figure 10 presents the global warming potential calculated for twenty and one hundred years. The GWP results are presented as an annual amount as previously described. Although LNG produces lower CO_2 emissions per kilogram of fuel burned, this index gives methane much weight when evaluating the global warming impact (figure 10). However, as a short-term gas methane highlights the short-term warming effect. In general, the hundred-year GWP is used as a measure of the relative impact of different GHGs and, for example, the US has adopted this as the primary approach.. However, in this context Lindstad et al. (2020) have emphasized the relevance of twenty-year GWP values because of the urgent need to reduce GHG emissions.

The difference between the alternatives is minimal on the scale of a hundred years. LNG emits approximately 3% more GHGs than MGO. In particular, the difference is minor when the uncertainties related to fuel production and transport chain emission assessments are considered. The difference increases drastically to 45% when the time scale is changed to twenty years. In the literature, the difference between the GWP100 results was 8% in favor of MGO to LNG when considering a similar engine (LPDF medium-speed, 4-stroke engine) as in the current measurements (Pavlenko et al., 2020). On a twenty-year scale, they showed that "an LPDF medium-speed, fourstroke emits 62% more lifecycle GHG emissions than an MSD using MGO" (Pavlenko et al., 2020). Their study had a more comprehensive estimation of upstream emissions.

As mentioned in the previous section, BC emissions affect GWP results, but they were not measured in our project and have been excluded from the analysis. The BC emission factors of MGO are also load-dependent (IMO, 2020), as methane emissions of LNG and BC emission levels of the LNG ships are significantly lower compared to diesel alternatives. The characterization factor for BC changes drastically from GWP100 (900) to GWP20 (3200) (Comer et al., 2017). Therefore, measuring and considering BC emissions would be important in future studies so that the comparison of alternatives would be fair. For example, in our previous study based on values from the literature, black carbon contribution ranged from 0.4 to 13.5% GWP for comparable MGO, LNG, and HFO alternatives (Altarriba et al., 2022).

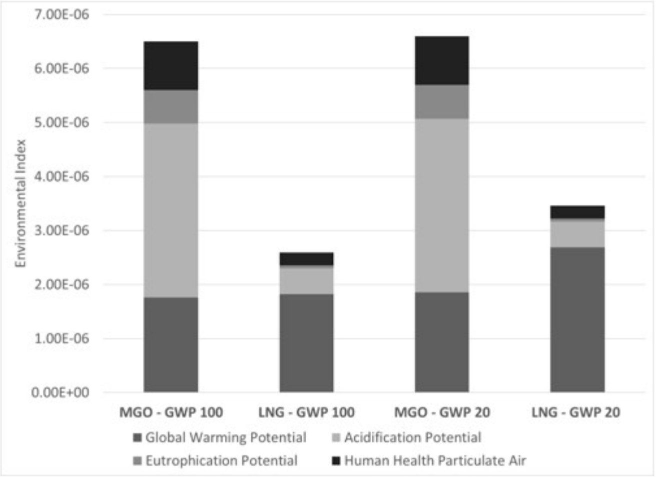
Figure 10: Global warming potential for MGO and LNG with different time scales.



Source: Authors.

In figure 11, the environmental index has been calculated for both fuels on both a hundred- and twenty-year scale. The overall environmental index combines several environmental impact categories described in the previous section. Thus, it is possible to compare alternatives with other environmental effects than, for example, climate impacts alone. Although the global warming potential, especially in the short term, does not favor LNG as an environmentally friendly option, the difference between MGO and LNG increases when other factors are added to the index. In figure 11, environmental indices at the hundred- and twenty-year scales are divided into components, including global warming, acidification and eutrophication potentials, and human health particulate air factor to show the relevance of each impact category. The acidification and eutrophication potentials favor the use of LNG. Low nitrogen oxide emissions of LNG significantly impact these two categories. There is a significant difference between alternatives in the human health index. In this study, the particle matter (PM) emissions were excluded from the measurements and, thus, also from the calculations. However, particle emissions are known to be relatively low, especially with LNG therefore, the difference could be even greater in favor of LNG. The significance of each category could be altered by using different weighting values and an expert panel could be used to evaluate the values.

Figure 11: Environmental index calculated for MGO and LNG for GWP100 and GWP20 potentials.



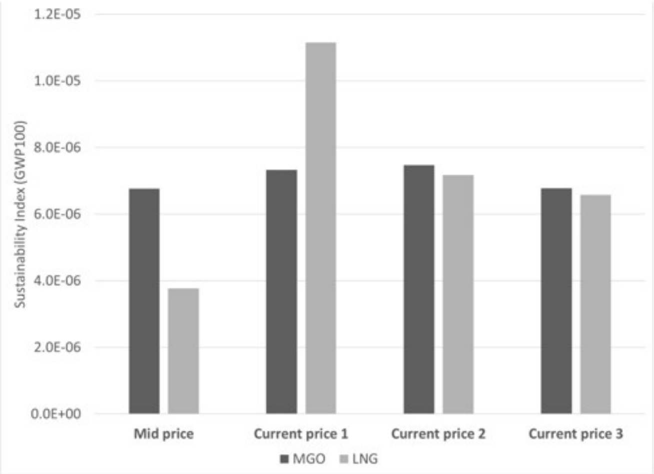
Source: Authors.

The sustainability index of both MGO and LNG, which combines environmental and economic indices, is shown in figure 12. In the mid-fuel price case, MGO receives higher values and therefore LNG is the more tempting option. However, during 2021-2022, LNG prices have fluctuated strongly due to the international political situation. Predicting how the price level of LNG (or fuel oils) will settle in the next few years or decades is challenging. The effect of the fuel prices is clearly visible. The fluctuation of the price of MGO has been lower than that of LNG, so the index values of MGO are at the same level. The greater overall environmental benefit of LNG disappears when current fuel prices are considered. Either the difference is very small (current price 2 and 3), or LNG is the worst option (current price 1). Thus, LNG can become an alternative with a 44% lower sustainability index values or 52% higher values than MGO. These values are on a hundred-year scale, so the results would even be negative for LNG even if the time scale were shorter. This shows how challenging the current environment is for maritime investment planning.

4. Discussion.

High expectations have been placed on LNG as a transitional fuel solution over the past decade. The continuation of strong natural gas price fluctuations caused by the war in Ukraine is difficult to predict, and it greatly impacts the competitiveness of gas as a fuel for maritime transport. On the other hand, the proliferation of multi-fuel engines in new ships enables the flexible use of different fuel solutions, such as the utilization of

Figure 12: Sustainability index.



Source: Authors.

biogas instead of fossil natural gas. This also applies to the possible future spread of synthetic oil and gas fuels (Speight, 2020; Wahl & Kallo, 2022). However, changing the systems always has a two-way effect.

Regarding carbon dioxide emissions during the ship's life cycle, it is clear that a ship's operation at sea dominates the generation of emissions: 96% of emissions consist of operation, 2% from construction, 0.9% from maintenance, and 0.8% from disposal (Chatzinikolaou et al., 2015). The well-to-wake analysis of fossil fuels shows the dominance of emissions during a ship's operation when the proportion of emissions generated in the refining processes or fuel distribution remains low. In practice, low-emission solutions must be sought primarily by reducing emissions during normal operation. However, the situation may be different for new, non-fossil fuels, and most of the emissions may occur during production, for example when producing biofuels. As a result, major changes are needed in assessing the harmfulness of different processes.

Methane slip is a typical characteristic of low-pressure LNG diesel engines (LPDF) (Aakko-Saksa et al., 2023; Grönholm et al., 2021), which is confirmed by our research. The measured levels of methane slip correspond well to previous observations, for example, Sintef has shown 5.3 gCH_4/kWh for LPDF engines (Stenersen & Thonstad, 2017), the same engine type as the Wärtsilä 12V50. So far, methane slip has been accepted, although the FuelEU Maritime proposal does set limits on methane emissions (European Commission, 2021b). However, the dependence of methane slip on engine load is something that has received relatively little attention, even though it is well-known in principle. This remains in a marginal position when looking at large entities, such as the spread of LNG ships worldwide and their operation in the open sea with a constant engine load.

On the other hand, it can have a surprising effect on the overall level of greenhouse gas emissions of the ship, for example, during slow steaming, navigation in archipelago fairways, or on short routes. The degree of methane slip depends strongly on the engine load level, and this depends on the design suitability of the vessel for slow steaming. Diesel-electric propulsion provides flexibility as some of the main engines can rest while others operate in the optimal load range. In shaft-powered solutions, this is more complex, and even diesel-electric ships can operate sub-optimally. In general, route planning focuses on entirely different issues than increased methane emissions during partial load operation. From this perspective, the increased methane emissions during partial load operation are not as marginal as it might seem.

There are numerous short ferry routes operating in the Baltic Sea, especially in the Gulf of Finland, between Finland and Sweden, and the Arkona basin. On short routes, port maneuvering and running of engines in ports play a relatively larger role in the operating profile than in the long-range open sea routes. Route-specific variations are large, as some ships operate daily non-stop traffic, and some others voyage at night, staying in port during the day. In addition, the Archipelago Sea and the front of Stockholm have significant archipelago fairways where voyage speeds remain low. Methane emissions are likely to be high on these routes, but LNG has the advantage of non-existent SO_2 and low NO_X emissions. This advantage is highlighted in terms of people's health when operating in the immediate vicinity of settlements and ports. The presented results of the environmental index also show the superiority of LNG in this respect. The findings of Iannaccone et al. (2020) show similar conclusions, although in their study emissions from fuel production were omitted, and the emission coefficients were based on values from the literature.

The energy crisis caused by the war in Ukraine has increased the price of fossil natural gas. The sustainability index results of this study show drastic changes in the results due to fuel price fluctuations. Even if a solution to the current international situation is found and the energy market normalizes, more attention must be paid to the reliability of energy supply. Crude oil and natural gas production is geographically concentrated in areas that are politically unstable or where political rule is based on oligarchy or dictatorship. In previous oil crises, this political risk was realized. However, there are more and more alternatives to fossil fuels, and synthetic fuels are one such solution (Speight, 2020). However, the production of synthetic fuels is energy-intensive, but in an ideal situation, the production process can be integrated to utilize renewable energy sources such as wind power, which could, in turn, smooth out the natural fluctuations of wind energy production.

Sufficient production requires the establishment of a completely new industry, taking fuel needs into account and this means that there are no quick solutions available. The situation and the EU's climate goals also create longer-term political pressure for investment (European commission, 2021a). Implementing the FuelEU Maritime regulation (European commission, 2021b) requires reducing the carbon intensity of marine fuels and therefore, synthetic fuels could be one solution. However, investments in Finland arouse much interest because there are no regional sources of oil or gas. The manufacturing process enables the recovery of carbon dioxide, reducing the need for the industry's emission allowances. In addition, a comprehensive district heating network has been built in the country, which can be used as a target for this process heat and thus improve the overall economic level of production. The end of natural gas imports from Russia in the spring of 2022 also motivates the development of alternative solutions instead of fossil LNG imports. If synthetic fuels succeed in the market, there will probably be demand for them outside of Finland and Europe as well. It is not unusual for a crisis to act as a catalyst for the development of new solutions.

The regional demand for methane in maritime transport also increases interest. LNG ships operating fixed lines from Finnish ports offer a regional customer base for synthetic methane. Of the synthetic fuels, methane is directly suitable for current dual-fuel engines, in which case additional investments in engine technology are not needed either through retrofits or new ship investments. This is a clear advantage compared to methanol or ammonia. However, in the long term, one uncertainty factor is the transformation in the energy supply of the rest of society. If, for example, methanol breaks through as a fuel in other sectors, its competitiveness as an alternative can increase significantly in maritime transport as well. Although synthetic methane is not a fossil fuel, it produces carbon dioxide emissions. In the production process, the source of carbon can be based on fossil fuels, in which case the solution itself does not necessarily prevent the increase of carbon in the atmosphere. With current internal combustion engines and fuels, reducing emissions can mainly be focused on the end user while examining synthetic fuels the focus should be on the emissions of the entire chain.

Methane emissions do not change whether the fuel is from fossil gas or synthetically produced, but the reduction of methane slip applies to ships operating with synthetic gas. In practice, the combustion process of engines must be developed, or alternatively, methane can be reduced from exhaust gases with catalyst solutions. As far as synthetic fuels are concerned, even more attention must be paid to the entire life cycle of fuel products, so that the necessary actions can be targeted effectively. This applies to new fuel solutions in general. The emissions of fuels such as ammonia or methanol under real operating conditions are an important future research topic. The goal should be to avoid a situation where a technical solution is initially recommended, and a decade later this recommendation is found to be incorrect.

Conclusions.

This paper discusses the differences between MGO and LNG as fuels from an emissions perspective in real-world conditions. To verify the emission levels measurements have been performed on a ROPAX ship operating in the Baltic Sea. MGO and LNG were used alternately as fuel. The ship is equipped with dual-fuel engines without separate emission treatment systems. Engine running data is obtained from the engine control system. The measurement results have been presented, and their environmental effects have been considered using the sustainability index method. Methane emissions have a strong impact on climate, even though their total amount is small.

On the other hand, NO_X emissions are low, and SO_2 is practically non-existent, which favors the use of LNG. However, the indices show that fuel prices also play a decisive role in the overall analysis. In the future, maritime transport will likely see alternative fuel solutions, such as biofuels, methanol, or ammonia. The general environmental effects of these still require further research in many respects. Therefore, to be able to compare them with current solutions, additional information on real operating conditions is still needed.

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