

Article

Methane Slip, Black Carbon and Greenhouse Gas Emissions from an LNG-Fuelled Cruise Ship: Insights from FuelEU and IMO Engine Load Monitoring Methodologies

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Abstract

Liquefied natural gas (LNG) is increasingly used in maritime propulsion systems to reduce atmospheric emissions. However, methane slip from dual-fuel engines remains a critical limitation due to the high global warming potential of methane. This study presents a comprehensive experimental assessment of greenhouse gas (GHG) emissions from a new-generation low-pressure four-stroke dual-fuel (LPDF 4-S) engine installed on a cruise vessel and operating on both LNG and marine gas oil (MGO). Measurements were carried out during full-scale sea trials under real navigation conditions. Results show that methane slip remains strongly dependent on engine load, with low and stable values at medium-to-high loads (1.95 g·kWh⁻¹ average over the 60–90% range) and a value of 5.6 g·kWh⁻¹ at 26% engine load. Compared with the previous engine generation (46DF), the 46TS-DF engine exhibits an approximate 18% reduction in methane slip above 60% load. On a well-to-wake basis, this results in an overall carbon dioxide CO₂-equivalent emission reduction of about 6%, of which 42% is attributable to methane slip reduction and the remainder to improved energy efficiency. In contrast, switching from MGO to LNG operation leads to a 21% decrease in CO₂-equivalent emissions. Black carbon (BC) emissions were measured and as expected despite the limited number of available studies, they were found to be significantly lower in LNG mode, with reductions exceeding 90% compared with MGO operation. Finally, an Engine Load Monitoring (ELM) analysis based on one year of operational data highlights the strong influence of vessel operating profiles on methane slip. The application of both International Maritime Organization (IMO) and FuelEU Maritime methodologies yields consistent methane slip coefficients (1.34% and 1.36%, respectively), significantly lower than current default values, noting that these estimates do not include crankcase emissions. These results demonstrate the importance of integrating real operational conditions into emission assessment frameworks for LNG-fuelled vessels.

Keywords: LNG; methane slip; LPDF 4-S engine; greenhouse gas emissions; black carbon; FuelEU Maritime; Engine Load Monitoring

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1. Introduction

Liquefied natural gas (LNG) propulsion is a relevant option for meeting strict regulatory requirements on atmospheric emissions in maritime transport. It allows reductions in nitrogen oxides (NO_x), particle emissions [1–3], and black carbon (BC) [2] compared with conventional propulsion systems, as well as negligible sulphur oxides (SO_x) emissions due to the very low sulphur content of LNG. Low-pressure four-stroke dual-fuel engines (LPDF 4-S) are currently widely used [4] and can operate on either natural gas or marine gas oil (MGO), providing operational flexibility. They also have fast start-up capability and lower vibration levels than two-stroke engines used on large vessels such as LNG carriers or cargo ships, which makes them suitable for passenger-oriented applications. This type of four-stroke engine is commonly used in ro-pax vessels and diesel-electric configurations, including cruise ships. It also allows lower carbon dioxide (CO₂) emissions compared with diesel-based marine fuels, as natural gas is mainly composed of methane (CH₄) and has a higher hydrogen-to-carbon (H/C) ratio than diesel fuel [5]. However, as with all internal combustion engines, these systems emit a fraction of unburned fuel. In the case of LNG, this is mainly methane, a greenhouse gas (GHG) with high global warming potential. This phenomenon, referred to as “methane slip” [6,7], is a limitation of the technology. It is linked to several combustion mechanisms, including quenching [7], which is more pronounced at low engine load due to lower combustion temperatures, leading to increased methane emissions observed for all LNG engine types [4]. Although the number of available studies remains limited [8], existing results indicate lower methane slip levels in recent engine generations compared with earlier systems [9]. In this context, the present study is based on measurements performed on a new-generation LPDF 4-S engine installed on a recently built vessel and allows comparison with the previous engine generation.

NO_x regulatory frameworks are based on emission factors measured at steady-state operating points (25, 50, 75, and 100% load) in accordance with the International Maritime Organization (IMO) NO_x Technical Code [10]. Recent GHG assessment methodologies, however, introduce an additional 10% load point [11] to better account for low-load operation, where methane slip increases. These GHG emissions are converted into CO₂-equivalent (CO₂-eq.) values for inclusion in GHG accounting frameworks.

At the international level, the IMO has defined a pathway for reducing GHG emissions from maritime transport, together with tools for monitoring ship energy efficiency. It has also advanced methodological frameworks for GHG accounting, including the approval of a life-cycle assessment (LCA) [12] approach for marine fuels, covering Well-to-Wake (WtW) GHG intensity calculations. However, methane slip is not yet explicitly addressed within dedicated regulatory standards currently under development at the IMO.

At the European level, the Fit for 55 package integrates maritime transport into the European Union climate framework. The MRV (Monitoring, Reporting and Verification) [13] regulation requires monitoring, reporting, and verification of GHG emissions from ships operating in the European Economic Area. In parallel, the FuelEU Maritime regulation [14] sets limits on the annual average WtW GHG intensity of the energy used on board ships, while the EU Emissions Trading System (ETS) has included methane emissions in its scope since 2026. These regulatory developments increase the need for consistent quantification of CO₂-eq. emissions. However, experimental data remain scarce for the latest generation of LNG marine engines, particularly when installed in diesel-electric propulsion systems, and, to the authors' knowledge, no published study has yet compared the regulatory methodologies introduced by the European FuelEU Maritime regulation [11] and the IMO guidelines [15] for quantifying methane slip emissions. In this context, the present study addresses this gap by providing onboard measurements from the first new-generation 46TS-DF LPDF 4-S engine installed on a diesel-electric vessel and

by analysing its emissions using Tank-to-Wake (TtW), Well-to-Tank (WtT), and WtW system boundaries to assess overall GHG emission factors of the engine in both MGO and LNG operating modes.

Finally, current regulatory frameworks allow ship operators to report emissions based on actual engine operating conditions [11]. Operational profiles of ships have been shown to have a strong influence on actual emissions in several recent studies [16–18]. This approach, referred to as “Engine Load Monitoring” (ELM), uses recorded engine load profiles to calculate unburned methane emissions. In this context, the present work proposes an emission assessment based on the annual recorded engine load distribution of the vessel, corresponding to the year following the onboard measurement campaign. Two calculation methods are applied, based on the European FuelEU [11] Maritime regulation and the guidelines [15] recently adopted by the IMO at MEPC 84 (Marine Environment Protection Committee). This study provides the first direct comparison of these newly implemented regulatory frameworks for methane slip quantification under real onboard operating conditions, which are expected to form the basis for future emissions reporting by ship operators.

2. Materials and Methods

2.1. Ship, Engine and Operating Conditions

The experimental campaign was carried out aboard a cruise vessel during a five-day sea trial period in May 2024, conducted by the shipbuilder Chantiers de l’Atlantique (Saint-Nazaire, France) as part of the final validation phase prior to delivery. These trials are performed in the presence of the ship owner and classification society, who validate that the vessel complies with its contractual performance requirements. Modern cruise vessels typically rely on diesel-electric power plant architectures, in which electrical generation is decoupled from propulsion and must continuously adapt to variable demands. These demands arise not only from propulsion systems but also from a wide range of onboard consumers, including auxiliary machinery and hotel services. In this context, the vessel is equipped with six Wärtsilä 46TS-DF LPDF 4-S engines (Wartsila, Vaasa, Finland) operating within a diesel-electric architecture, where sailing conditions such as speed or displacement are accommodated through changes in the number of engines in operation and their loading levels. The main characteristics of the investigated engine are summarized in Table 1.

Table 1. Main characteristics of the Wärtsilä 46TS-DF engine.

Engine manufacturer	Wärtsilä
Engine type	LPDF 4-S
Number of cylinders	12
Bore × stroke	460 mm × 580 mm
Rated speed	600 rpm
Rated power	15.6 MW
Air charging system	Two-stage turbocharging
Valve actuation	Variable valve timing
Fuel injection system	Digital common rail fuel injection system

The engine in this study is a standard production Wärtsilä 46TS-DF model, one of the six engines installed on the vessel, and the first commercial installation of this engine type at sea. Compared with the conventional 46DF engine [17–19], the 46TS-DF engine investigated in this study is an evolution of the well-established Wärtsilä 46DF platform, featuring several design improvements including two-stage turbocharging, which results in an increase in power output per cylinder from 1145 kW to 1300 kW, together with im-

proved overall energy efficiency. Both the 46DF and 46TS-DF engines comply with IMO NO_x regulations [10], i.e., Tier II in MGO mode and Tier III in LNG mode, as well as Tier III in MGO operation when equipped with SCR systems (Selective Catalytic Reduction).

The engines are coupled with alternators and collectively supply the electrical power required for all shipboard operations. These engines are designed to operate using two different fuel strategies. In gas mode, LNG is first vaporized and then used as the main fuel, while a limited quantity of pilot MGO is injected to initiate combustion. Alternatively, the engines can function in a conventional diesel configuration, relying solely on MGO.

Sea trials involve a series of validation procedures aimed at assessing system performance under a variety of conditions, including prolonged operation and high-load scenarios in both LNG and MGO modes. In the present study, we had no direct control over engine load. However, we continuously monitored exhaust emissions during both dynamic operating periods, characterized by rapidly changing loads and fuel modes, and intervals of stabilized engine operation. So, despite this variability due to sea trial conditions, intervals of steady operation were identified across a range of loads for both LNG and MGO use. The LNG bunkered for the sea trials was methane-rich, with a high methane content (95.3 mol-%), the remainder consisting of ethane (3.57 mol-%), propane (0.66 mol-%), butane (0.32 mol-%), pentane (0.014 mol-%), hexane (0.0004 mol-%), and nitrogen (0.153 mol-%). The pilot fuel share, consisting of a low-sulfur fuel, ranged from approximately 1% at high load to about 5% at low load conditions.

The determination of emission factors requires not only the measurement of exhaust gas concentrations, but also an estimation of the exhaust flow rate, which is derived from both the fuel consumption and the composition of the exhaust gases, as well as the power output of the engine. These data on LNG gas and pilot MGO fuel consumption, as well as the delivered power, are recorded with a time resolution of one second and were provided by the ship's manufacturer after the measurement campaign.

2.2. Emission Measurements

The sampling system was designed and operated in accordance with ISO 8178 requirements [20], which specify standardized procedures for measuring exhaust emissions from internal combustion engines, including a target sampling line temperature of 191 °C and a maximum residence time of 3 s. In the present configuration, exhaust gas sampling was performed using a probe installed on a flange of nominal diameter (DN) 100 mm located less than 10 m from the engine outlet. This sampling flange was used to access the exhaust gas stream at approximately one-third of the DN 1300 mm. Sampling was performed using a stainless-steel probe with an internal diameter of 6 mm, inserted through the flange into the flow. The sampled flow was distributed across several heated lines maintained at 200 °C to enable simultaneous characterization of both gaseous and particulate emissions while preventing condensation phenomena. The experimental setup is shown in Figure 1.

Gaseous emissions were analyzed downstream of a heated sampling line. The sampled gas was first filtered through a heated particulate filter (PSP 4000, M&C TechGroup, Ratingen, Germany) to remove particulate matter to protect the downstream gas conditioning system. It was then conditioned using a CCS-V unit (Figure 1), which removes water vapor and reduces the gas temperature to near ambient conditions prior to analysis. After conditioning, gaseous concentrations of CH₄, carbon monoxide (CO), and CO₂ were measured using a non-dispersive infrared (NDIR) analyzer (VA-5000, Horiba, Kyoto, Japan). Daily calibration of the gas analyzers was performed using certified calibration gases, with high-purity nitrogen for zero calibration and a certified 4000 ppm CH₄ calibration gas for span.

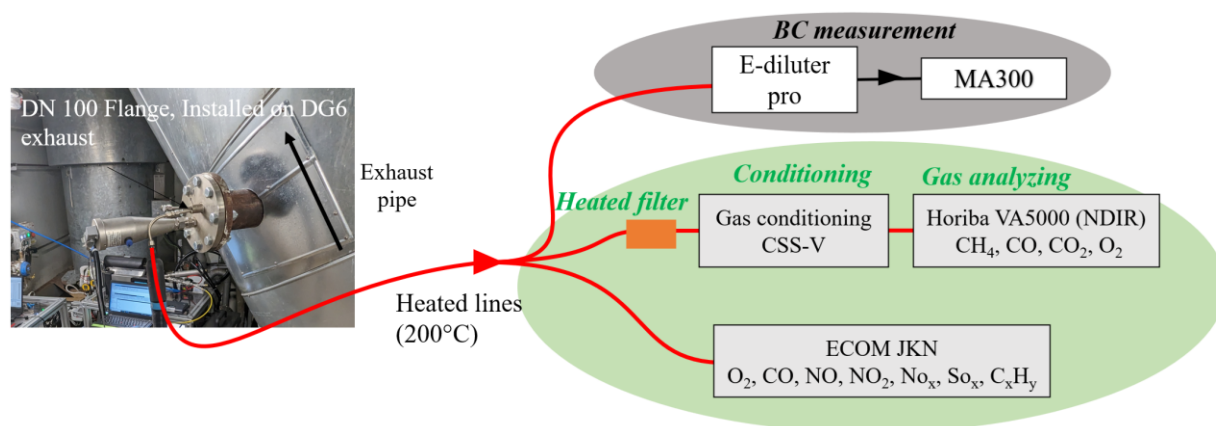


Figure 1. Measurement setup.

NO_x concentrations were determined with an ECOM J2KN flue gas analyzer (ECOM, Iserlohn, Germany), based on electrochemical sensor technology. This portable analyzer integrates a particulate filter and a Peltier-based gas cooler for moisture removal and gas drying. It has previously been used for onboard NO_x measurements in marine applications by Rochussen et al. [21]. Although these measurements are not reported in this study, they confirmed that the measured NO_x emission levels were consistent with the engine's declared IMO Tier II and Tier III compliance.

BC emission measurements were carried out using an MA300 aethalometer (AethLabs, San Francisco, CA, USA). Aethalometers are widely used for black carbon monitoring in ambient air [22]. For exhaust measurements, sample dilution is required. The exhaust gas was conditioned using a two-stage DEKATI eDiluter Pro (Dekati, Kangasala, Finland), applying two successive dilution stages with dilution factors of 5 and 5 under heated (200 °C) and then cooled conditions (20 °C), to reduce gas temperature and particle concentration to levels suitable for the instrument under both MGO and LNG operating conditions. The coupling of an aethalometer with a dilution system has previously been successfully applied to both marine exhaust measurements [23] and laboratory investigations under high soot concentrations [24]. All instruments record data with a one-second time resolution.

Emission factors, expressed in g·kWh^{−1}, were derived from the measured concentrations using a carbon balance approach in accordance with ISO 8178 [20] and the NO_x Technical Code [10]. This method enables the estimation of the exhaust mass flow based on the fuel consumption data combined with the exhaust gas composition, with measured gas concentrations, engine power output, and fuel consumption all recorded at a one-second resolution.

3. Results

3.1. Stabilized Point CH₄ Emission Factors

Based on the onboard measurements, time periods were identified during which engine load conditions were as stable as possible and as close as practicable to the requirements defined for engine bench testing in the NO_x Technical Code [10]. Engine load points are defined under both IMO regulatory requirements [25] and the FuelEU Maritime framework [11], which notably include a 10% load condition. According to these guidelines, a stabilized operating point should correspond to a ten-minute recording period with a one-second sampling frequency, during which the coefficient of variation in the engine load remains below 5%. Under the present test conditions, these criteria were not strictly met. Nevertheless, for both LNG and MGO operating points, the duration of the selected periods ranged from a minimum of five minutes to a maximum of thirty minutes,

with an average duration of approximately eleven minutes. The measured emission factors, calculated from average parameters (engine load, exhaust gas concentrations, fuel consumption, and power output), are presented in Figure 2 as a function of engine load. The results obtained in this study for the 46TS-DF engine are compared with recently published measurements for the conventional 46DF engine architecture [17,19]. Error bars represent the expanded uncertainty ($k = 2$, approximately 95% coverage) associated with each emission factor, obtained by propagating the uncertainties of the main measured quantities, namely engine power, exhaust gas flow rate determined using the carbon balance method, and exhaust CH_4 concentration. CH_4 emission factors and their associated expanded uncertainties are reported for the characteristic engine load points in Table 2.

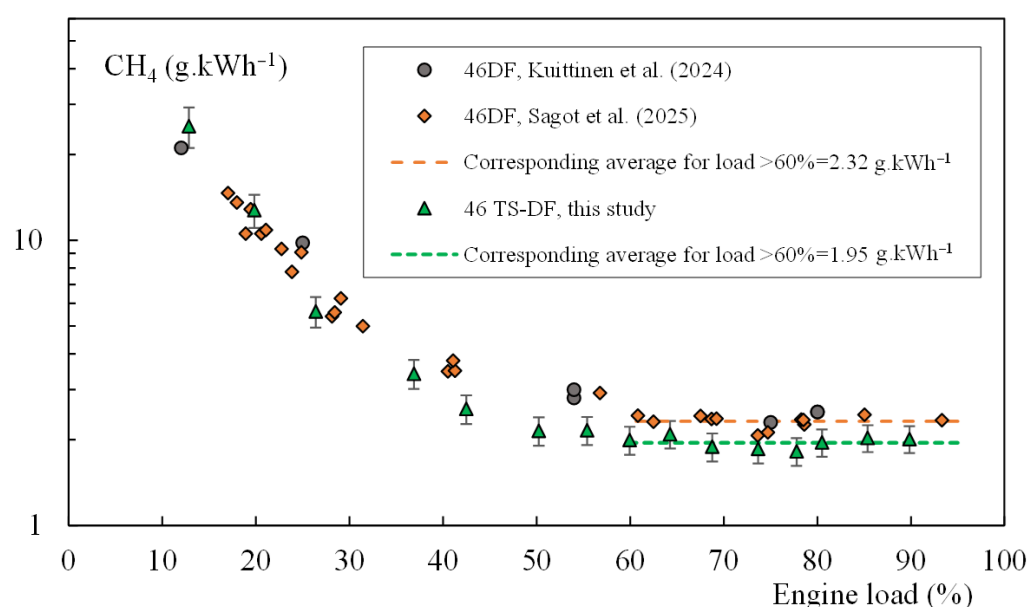


Figure 2. CH_4 emission factor as a function of engine load. Data from Kuittinen et al. (2024) and Sagot et al. (2025), corresponding to references [17] and [19], respectively.

Table 2. CH_4 emission factors ($\text{g}\cdot\text{kWh}^{-1}$) at different engine loads. Uncertainties are expanded uncertainties ($k = 2$, approximately 95% coverage).

Engine Load (%)	12.8	26.4	50.2	73.7	85.4	89.8	100
CH_4 ($\text{g}\cdot\text{kWh}^{-1}$)	25.2	5.6	2.15	1.86	2.03	2.01	1.97 *
Uncertainty ($\text{g}\cdot\text{kWh}^{-1}$)	4.1	0.7	0.25	0.21	0.22	0.22	0.21 *

* Results at 100% load are linearly extrapolated from measurements at 85% and 90%.

It can be observed that, as reported in many previous studies [4,18,26], the methane slip emission factor increases at low engine loads. Relatively little difference is seen between the 46DF and 46TS-DF engines at loads below 40%. In contrast, the results indicate a significant reduction of approximately 18% in methane slip for engine loads above 60% when comparing the 46DF and the 46TS-DF engines. The reduction exceeds the expanded uncertainty ($k = 2$) of the measurements, indicating that it is unlikely to be attributable to measurement uncertainty alone.

Based on the measured values covering a load range from 13% to 90%, the 100% load point was obtained by linear extrapolation of the 85% and 90% load measurements in accordance with the FuelEU Maritime Guidelines [11]. The E2 cycle is defined in the IMO NOx Technical Code 2008 [10] and is commonly used as a reference for engine comparison as it provides a standardized weighting of multiple load points. The cycle consists of four load points (100%, 75%, 50%, and 25% engine load) with weighting factors of 0.20, 0.50,

0.15, and 0.15 respectively, used to compute weighted average emission values for certification and comparison purposes. It is applicable to constant-speed marine engines for ship main propulsion, including diesel-electric propulsion architectures such as the one installed on the vessel studied in this work. From our measurement data, E2-weighted values of $2.20 \text{ g}\cdot\text{kWh}^{-1}$ for the emission factor and 1.36% for the average methane slip coefficient were obtained, placing this engine within the lower range of values reported in the study by Kuittinen et al. [4] for LPDF 4-S engines. These values remain well below the default methane slip factors of 3.1% and 3.5% currently used within the FuelEU Maritime framework [14] and IMO guidelines [12] for the estimation of ship emissions, although it should be noted that the present analysis does not account for emissions associated with crankcase losses.

More recently, Kuittinen et al. [17] reported emission factors and methane slip coefficients averaged over a modified E2 cycle for the 46DF engine. In that study, conducted onboard a vessel in operation, it was not possible to strictly follow the standard E2 cycle, particularly the 100% load point, which was replaced by an 80% load corresponding to the maximum load observed in service. The engine load points and their respective weightings for this adjusted E2 cycle were 25–0.15, 54–0.15, 75–0.5, and 80–0.2. Based on this modified cycle, Kuittinen et al. [17] reported an emission factor of $2.8 \text{ g}\cdot\text{kWh}^{-1}$ and a methane slip coefficient of 1.7%. Applying the same approach to the 46TS-DF engine investigated in the present study yielded values of $2.21 \text{ g}\cdot\text{kWh}^{-1}$ and 1.35%, respectively, corresponding to a significant 20% reduction for both metrics compared to the 46DF engine.

3.2. BC Emission Factors Under Stabilized Conditions

Figure 3 presents the measured BC emission factors for the two types of fuel used in this engine during these sea trials (MGO and LNG), based on stabilized operating points. Error bars denote the standard deviation of results over each measurement period. Emissions measured in MGO mode are significantly higher than those observed in LNG mode, with emission factors increasing as engine load decreases. For loads above 50%, average values of $0.33 \text{ mg}\cdot\text{kWh}^{-1}$ in LNG mode and $5.9 \text{ mg}\cdot\text{kWh}^{-1}$ in MGO mode are observed, corresponding to a 94% reduction when operating in LNG mode compared to MGO.

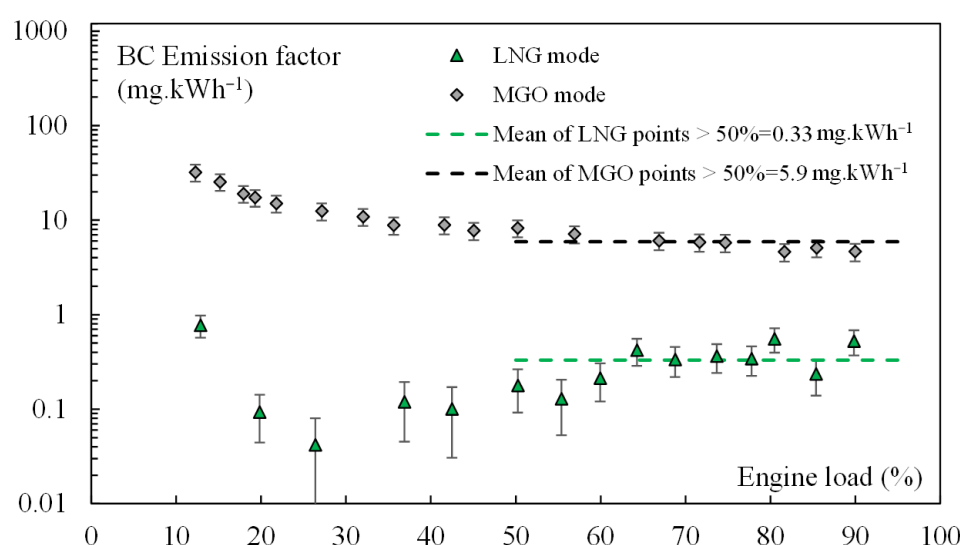


Figure 3. BC emission factor as a function of engine load.

4. Discussion

4.1. BC Emission Factors: Comparison with Related Studies

As observed by Corbin [27], the literature contains very limited data on particulate emissions from marine LNG engines. To enable comparison with the data reported in their study, Table 3 presents BC concentrations, along with average values across the E2 cycle modes. Over this E2 cycle, the emission factors in LNG and MGO modes are 0.40 and 5.9 mg·kWh⁻¹, respectively, compared with 0.7 and 19 mg·kWh⁻¹ reported by Peng et al. [3] for the same cycle.

Table 3. BC emission factors. Standard deviations, shown in grey, are reported in parentheses.

MGO Mode		mg·kWh ⁻¹	LNG Mode		mg·kWh ⁻¹
Engine Load (E2 wt.)		BC	Engine Load (E2 wt.)		BC
12.3%	(-)	32.1 (6.5)	12.8%	(-)	0.77 (0.2)
27.1% *	(0.15)	12.5 (2.5)	26.4% *	(0.15)	0.04 (0.04)
50.2% *	(0.15)	8.3 (1.7)	50.2% *	(0.15)	0.18 (0.09)
74.7% *	(0.5)	5.8 (1.2)	73.7% *	(0.5)	0.36 (0.12)
85.4%	(-)	5.1 (1.1)	85.4%	(-)	0.24 (0.1)
90.0%	(-)	4.7 (1.0)	89.8%	(-)	0.53 (0.16)
100% **	(0.2)	3.9 (-)	100% **	(0.2)	0.63 (-)
E2 cycle		5.9	E2 cycle		0.40

* Load points near 25%, 50%, and 75% are used for E2 averaging. ** Results at 100% load are linearly extrapolated from measurements at 85% and 90%.

The lower emission levels observed in this study may reflect improvements in engine performance as well as the higher power operating conditions considered (480 kW/cylinder at 720 rpm for Peng et al. [3], and 1300 kW/cylinder at 600 rpm in this study). Over the E2 cycle, the reduction between LNG and MGO reaches 90% in this study, although this is lower than reported in the literature, primarily due to a significantly lower weighted emission factor in MGO mode for the 46TS-DF engine. Corbin [27] and Peng [3] both investigated emissions at idle conditions, noting, as highlighted by Peng, that this operating point can be relevant for coastal vessel operations. Our 13% load point does not allow the reduction in BC emissions observed by Corbin et al. at idle conditions in MGO mode to be captured. Emission factors in LNG mode exhibit a minimum around 30% engine load, whereas in MGO mode, they decrease continuously with increasing engine load. It is worth noting that Peng et al. [3] also observed an increase between 50% and 75% load in LNG mode, although with a much smaller amplitude. Corbin et al. similarly reported that engine emissions in LNG mode do not follow a clear trend with load, referring in particular to earlier work by Lehtoranta et al. [28], which reported total PM emission factors of 32, 9, and 20 mg·kWh⁻¹ at 40%, 75%, and 85% load, respectively, indicating a non-monotonic behavior with a minimum at 75% load.

One of the objectives of Corbin et al. [27] was to compare BC measurements obtained with different instruments, and they observed good consistency among the results. They also emphasized the difficulties instruments may encounter when quantifying high (BC) concentrations. This point was also highlighted in the study by Aakko-Saksa et al. [23], which showed that dilution is an important parameter for the use of BC measurement instruments. In our measurements, a dilution factor of 25 was appropriate for MGO operation (maximum concentrations of approximately 0.15 mg·m⁻³ as measured by the aethalometer after dilution), although a lower dilution factor could have reduced measurement uncertainty in LNG mode. The main difficulty during the test campaign was selecting a dilution factor suitable for both modes, given the unexpected transitions between operating conditions.

4.2. Analysis of the Relative Contributions of Methane Slip and BC to GHG Emissions

To analyze the relative contributions of GHG emissions under the two propulsion modes, MGO and LNG, CH₄ and BC emissions were converted into CO₂-eq. values using 100-year global warming potential (GWP100) factors. Values of 29.8 and 273 were applied for CH₄ and nitrous oxide (N₂O), respectively [29], and 900 for BC [30,31].

In addition, to place these emissions within the framework of the FuelEU Maritime regulation [14], emissions were evaluated using the prescribed emission factors. These include values of 0.00011 g N₂O per g of LNG and 0.00018 g N₂O per g of MGO, together with a methane slip factor of 0.00005 g per g of MGO fuel. These factors correspond to TtW emissions and were subsequently converted into CO₂-eq. values. Furthermore, the FuelEU [14] framework accounts for WtT emissions associated with fuel production through default emission factors expressed in gCO₂-eq.MJ⁻¹ for each fuel. Although this regulation does not explicitly promote renewable LNG of biological origin (Bio-LNG) and renewable LNG of non-biological origin (e-LNG), it establishes technology-neutral GHG intensity reduction targets and relies on default WtW emission factors. This regulatory framework therefore provides a strong incentive to use low-carbon methane pathways, such as Bio-LNG and e-LNG, to comply with the progressively stricter GHG intensity limits.

All results, together with the calculation rules used to derive WtW CO₂-eq. emissions, are summarized in Table 4. To enable comparison with literature data, mean emission factors over the E2 cycle are also provided.

Table 4. Summary of CO₂-eq. emissions for the two propulsion modes, MGO and LNG.

MGO Mode		gCO ₂ -eq.kWh ⁻¹							
Engine Load (E2 wt.)	TtW CO ₂	TtW CH ₄ as CO ₂ -eq.	TtW N ₂ O as CO ₂ -eq.	TtW BC as CO ₂ -eq.	TtW Total CO ₂ -eq.	WtT LNG as CO ₂ -eq.	WtT MGO as CO ₂ -eq.	WtT Total CO ₂ -eq.	WtW Total CO ₂ -eq.
	(a)	(b)	(c)	(a)			(f)		
12.3% (-)	815.3	0.4	14.0	28.9	859	0	160	160	1019
27.1% * (0.15)	675.8	0.3	11.6	11.2	699	0	133	133	832
50.2% * (0.15)	616.9	0.3	10.6	7.4	635	0	121	121	757
74.7% * (0.5)	594.6	0.3	10.2	5.2	610	0	117	117	727
85.4% (-)	588.7	0.3	10.1	4.6	604	0	116	116	720
90% (-)	586.6	0.3	10.1	4.2	601	0	115	115	717
100% ** (0.2)	581.3	0.3	10.0	3.5	595	0	114	114	709
E2 cycle	598	0.3	10.3	5.3	614	0.0	117.7	118	732

LNG Mode		gCO ₂ -eq.kWh ⁻¹							
Engine load (E2 wt.)	TtW CO ₂	TtW CH ₄ as CO ₂ -eq.	TtW N ₂ O as CO ₂ -eq.	TtW BC as CO ₂ -eq.	TtW Total CO ₂ -eq.	WtT LNG as CO ₂ -eq.	WtT MGO as CO ₂ -eq.	WtT Total CO ₂ -eq.	WtW Total CO ₂ -eq.
	(a)	(a)	(c) (d)	(a)		(e)	(f)		
12.8% (-)	585.1	749.9	8.0	0.70	1344	205	7.0	212	1556
26.4% * (0.15)	507.3	167.8	6.3	0.04	681	167	3.4	170	851
50.2% * (0.15)	455.4	64.0	5.5	0.16	525	149	1.7	151	676
73.7% * (0.5)	435.2	51.4	5.3	0.33	492	143	1.1	144	636
85.4% (-)	428.6	60.4	5.2	0.21	494	142	1.0	143	637
89.8% (-)	426.8	59.9	5.2	0.47	492	141	0.9	142	634
100% ** (0.2)	421.4	65.3	5.1	0.56	492	140	0.8	141	633
E2 cycle	438	63.6	5.3	0.36	507	144.2	1.2	145	652
Relative difference LNG/MGO					-21%				-12%

* Load points near 25%, 50%, and 75% are used for E2 averaging. ** Results at 100% load are linearly extrapolated from measurements at 75% and 90%.

Measurement: (a) NDIR for CO₂ and CH₄, aethalometer for BC.

FuelEU, TtW [14]: (b) $C_f \text{CH}_4 = 0.00005 \text{ gCH}_4 \cdot \text{gfuel}^{-1}$ for MGO/LFO, (c) $C_f \text{N}_2\text{O} = 0.00018 \text{ gN}_2\text{O} \cdot \text{gfuel}^{-1}$ for MGO/LFO, (d) $C_f \text{N}_2\text{O} = 0.00011 \text{ gN}_2\text{O} \cdot \text{gfuel}^{-1}$ for LNG.

FuelEU, WtT [14]: (e) $\text{CO}_2\text{-eq.} = 18.5 \text{ gCO}_2 \cdot \text{MJ}^{-1}$ for LNG, with $\text{LCV} = 0.0491 \text{ MJ} \cdot \text{gfuel}^{-1}$, (f) $\text{CO}_2\text{-eq.} = 14.4 \text{ gCO}_2 \cdot \text{MJ}^{-1}$ for MGO/MDO, with $\text{LCV} = 0.0427 \text{ MJ} \cdot \text{gfuel}^{-1}$.

As shown in Table 4, the contribution of BC to total $\text{CO}_2\text{-eq.}$ emissions remains very limited. On the E2 cycle, BC accounts for only $5.3 \text{ gCO}_2\text{-eq} \cdot \text{kWh}^{-1}$ in MGO mode and $0.36 \text{ gCO}_2\text{-eq} \cdot \text{kWh}^{-1}$ in LNG mode, corresponding to less than 1% and 0.1% of total TtW $\text{CO}_2\text{-eq.}$ emissions, respectively. Consequently, despite the substantial reduction in BC emissions when operating on LNG, its influence on the overall GHG balance remains negligible compared with methane slip. Nevertheless, the reduction in BC emissions may still provide important environmental benefits through improved air quality and reduced atmospheric particulate emissions.

Figure 4 shows the variation in the contribution of methane slip to CO_2 emissions as a function of engine load, where $\text{CO}_2\text{-eq.}$ values also include estimated nitrous oxide (N_2O) emissions. It remains limited to approximately 12% for engine loads above 60% and is relatively independent of load over 50% load.

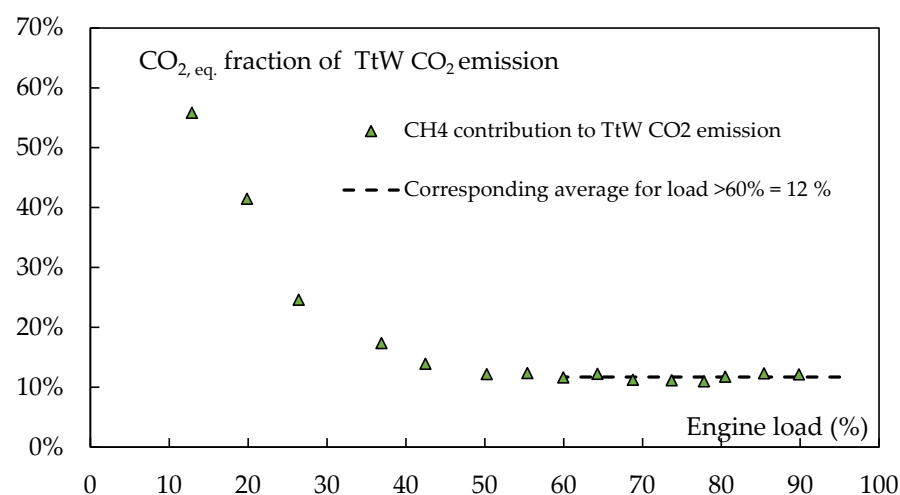


Figure 4. Relative contribution of methane slip to $\text{CO}_2\text{-eq.}$ TtW emissions, as a function of engine load.

The following Figure 5 presents TtW $\text{CO}_2\text{-eq.}$ emission factors for the LNG and MGO modes, showing a crossover at low load. The calculation includes the contribution of BC converted into CO_2 equivalent, as well as calculated N_2O emissions. Due to the contribution of methane slip, $\text{CO}_2\text{-eq.}$ emissions at low load are higher in LNG mode, whereas in the typical operating range of the engine, above 30% load, LNG becomes more advantageous. A relative average gain of approximately 20% is observed for loads above 60%, increasing to 21% when evaluated over the E2 cycle (see Table 4).

The same type of analysis can be conducted on a WtW basis, considering the regulated emissions during the WtT phase. For the calculation of WtT emissions, we rely on the FuelEU regulation [14], which requires accounting for CO_2 emissions associated with the production of fuels such as LNG and MGO, as well as N_2O emissions (see Table 4). As shown in Figure 6, the relative gain of LNG at high load is then limited to 12%, due to the WtT emissions penalty associated with LNG production (see Table 4).

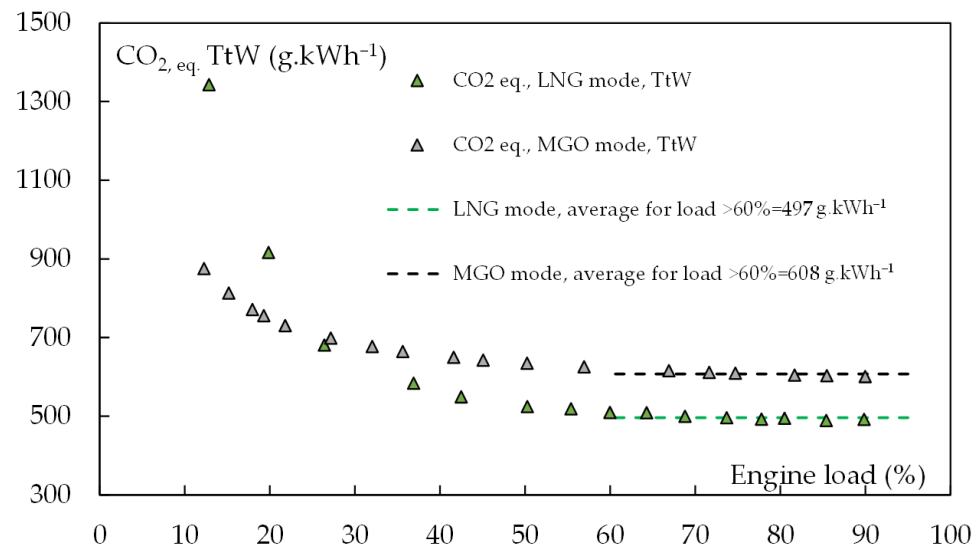


Figure 5. Comparison of CO₂-eq. TtW emissions for both MGO and LNG fuel, as a function of engine load.

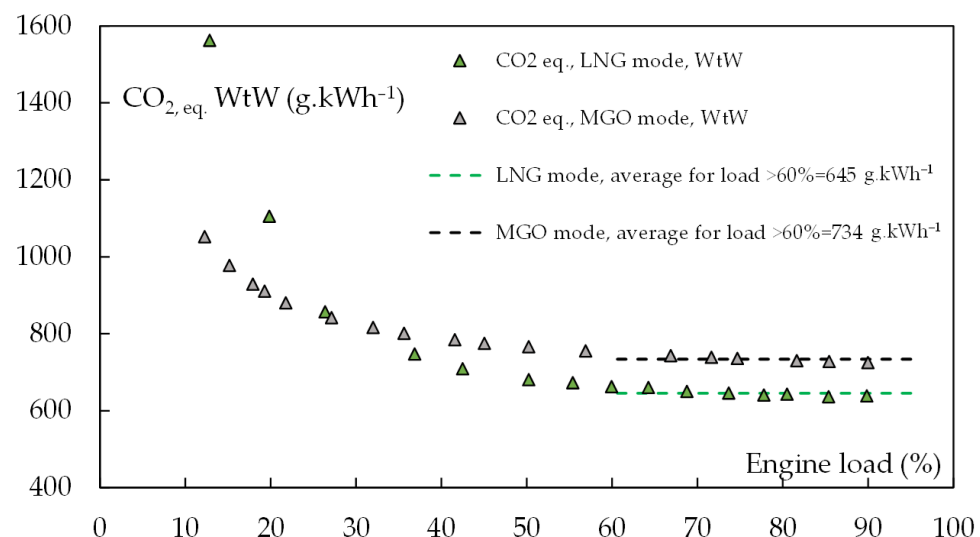


Figure 6. WtW CO₂-eq GHG emissions for both MGO and LNG mode, as a function of engine load.

4.3. Evolution of WtW CO₂ Equivalent Emissions Between 46DF and 46TS-DF

To allow a relative and global assessment of the gains achieved with this new 46TS-DF engine compared to the 46DF [19], Figure 7 presents the total cumulative WtW CO₂-eq. emissions over an E2 cycle for both engine generations operating in LNG (gas mode) and MGO (fuel mode). The stacked bars distinguish the contributions from WtT emissions associated with fuel production and TtW emissions, including CO₂, CH₄ and N₂O. The comparison does not include the contribution of BC, which was not available in the study on the 46DF engine. For the gas mode, the total CO₂-eq. emissions over this E2 cycle decrease from 692 to 650 g.kWh⁻¹, corresponding to an approximate 6% reduction in overall emissions on a WtW basis. Of the 42 g.kWh⁻¹ reduction, approximately 18 g.kWh⁻¹ (43% of the gain) are associated with the reduction in methane slip, while the remainder results from improved energy efficiency. In MGO mode, the observed difference between the two studies is less than 1%.

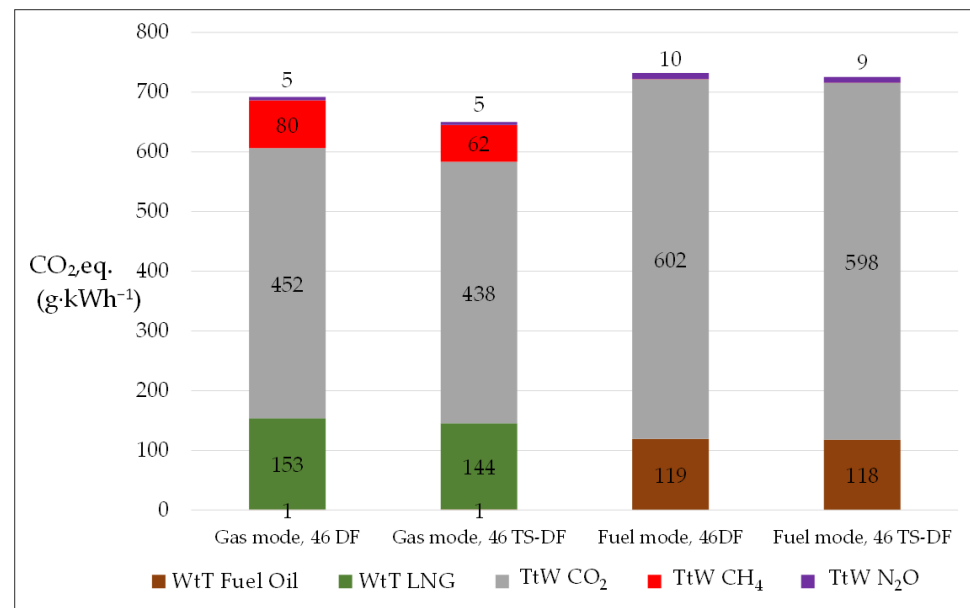


Figure 7. WtW CO₂ equivalent (g-kWh⁻¹) GHG emissions comparison between 46DF and 46TS-DF, for both LNG and MGO modes for the E2 cycle.

4.4. ELM-Based Evaluation of Methane Slip

The previous analysis was based on an E2 cycle to allow an overall comparison between the 46DF and 46TS-DF engines. However, current regulations allow shipowners to report actual emissions based on engine load recordings on an annual basis. This so-called ELM methodology combines engine methane slip coefficients with a year-long analysis of engine operation. To carry out this procedure, we therefore collected these recordings after the experimental campaign for the six engines installed on the vessel for the period from July 2024 to July 2025 with a one-minute resolution. As shown in Figure 8, there is very little variation among the annual load distributions of the six engines, which are used alternately. It can be observed that they operate predominantly above 40% load (the cumulative average operating time of the six engines below 40% load is 10%), with a usage peak centered around 85% load.

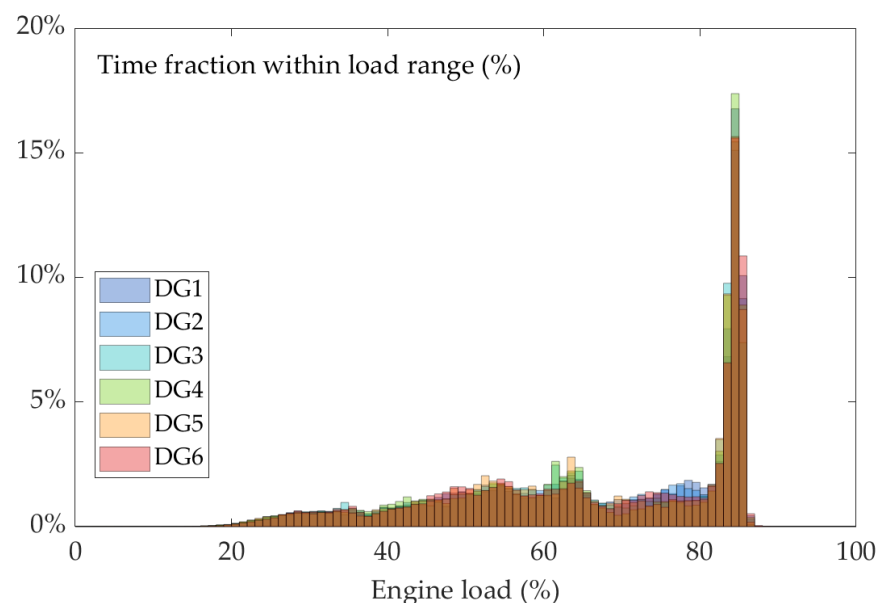


Figure 8. Load distribution for the 6 engines (Diesel Generator) DG1 to DG6.

The ELM calculation procedure, recently adopted at MEPC 84 by the IMO [12], is presented and discussed in detail in [18]. It is based on continuous monitoring of engine load and a segmentation into 30 min intervals, within which average engine load, gas consumption, and methane slip are determined using a load-dependent slip coefficient. The IMO guidelines [15] also specify that the methane slip coefficient is determined by linear interpolation between the closest measured data points above and below the considered load, while for engine loads below the lowest measured load point, the emission value at this point is used, and for loads above the highest measured load point, the value at the highest measured load is retained. By aggregating fuel consumption and methane emissions over a full year of gas-mode operation, an equivalent annual slip coefficient is obtained. At the same time, the new EU directive [11] also defines procedures for verifying actual methane slip emissions from marine diesel engines. Although the two procedures are highly similar, they differ in two specific aspects. First, the FuelEU methodology introduces a more detailed calculation by refining the assessment under dynamically varying engine loads, through the reduction in the 30 min intervals when load variations exceed 10%: “Engine load is averaged in 30 min intervals average if the range does not exceed 10% of the rated power or rated speed of the engine—if above that range the 30 min period should be reduced to the point where that criterion is met, or to the data recording and processing device period, whichever is higher” [11]. Based on one year of data and with a 1 min sampling period of the DG6 engine load, we evaluated the average annual methane slip coefficient using both the IMO and FuelEU procedures. Figure 9 illustrates the 30 min intervals of the IMO methodology (only the last interval is truncated) and the variable-length intervals used in the FuelEU methodology to follow load variations. In both cases, this procedure, illustrated here over a navigation period of approximately three hours, must be applied for the full year, covering the navigation phases in LNG mode. Second, the FuelEU framework requires the methane slip coefficient curve to be extrapolated beyond the measured range at both low and high engine loads. The methane slip coefficient curves derived from the IMO [15] and FuelEU [11] methodologies are both shown in Figure 10 for this study.

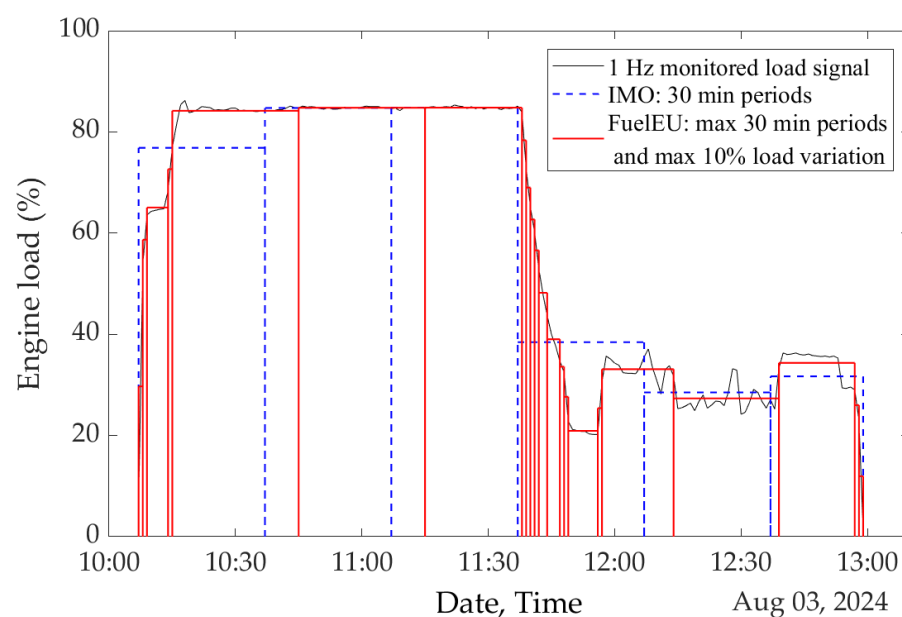


Figure 9. Illustration of the IMO and FuelEU ELM averaging procedure.

Applying these FuelEU and IMO calculation procedures over one year results in methane slip coefficients of $C_{\text{slip,IMO}} = 1.34\%$ and $C_{\text{slip,FuelEU}} = 1.36\%$, respectively, with only a negligible difference between the two methods. This small discrepancy is related to the time segmentation: indeed, there is almost no use of engines at low load. This is confirmed

by the application of the FuelEU methodology, together with the IMO methane slip curve, which yields the same annual value. The additional calculation complexity does not appear to be justified in this case, given an engine operating profile characterized by relatively limited acceleration phases. Finally, it is worth noting that the methane slip values obtained using the IMO and FuelEU methodologies are very close to those derived from the modified E2 cycle (1.35%).

These values are low compared with those reported in the literature for real-world operation, where methane slip coefficients of approximately 1.7% have been reported for diesel-electric architecture [17,19], and 1.57% for a ship equipped with a direct mechanical propulsion system, as reported by Sagot et al. [18]. This is related to the low methane slip level of the engine studied here as well as to the operating profile of this diesel-electric architecture. The impact of the operating profile was assessed by applying the emission factor of this 46TS-DF engine to the annual load profile of a mechanically driven LNG-powered vessel reported in a previous study [18]. Figure 10 presents the two annual engine load distributions, as well as the interpolated methane slip curve derived from the measurements conducted in this study.

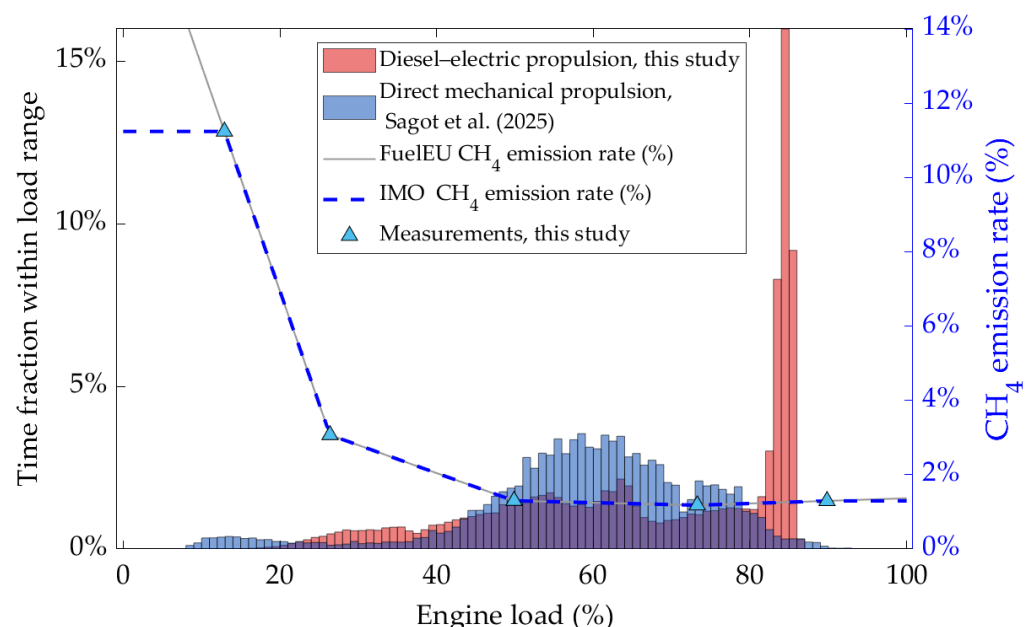


Figure 10. Load distribution for two different ship architectures, Diesel-electric (this study) and Direct mechanical propulsion [18].

Using the 46TS-DF engine investigated in this study together with the annual operating profile previously reported for an LNG-powered ro-pax vessel with direct mechanical propulsion [18], the equivalent yearly methane slip coefficients would be $C_{slip,IMO} = 1.40\%$ and $C_{slip,FuelEU} = 1.42\%$. Using the IMO methodology as reference, this comparison indicates that, for the same engine, the diesel-electric propulsion profile reduces the annual methane slip coefficient from 1.40% to 1.34%, corresponding to an approximate 4–5% decrease, which is, however, dependent on the considered operating profiles.

5. Conclusions

This study investigated methane slip, BC emissions, and associated CO₂-eq. GHG emissions from a new-generation LPDF 4-S engine operating on both LNG and MGO during full-scale sea trials. The analysis combined stabilized operating points and annual ELM methodology to provide a comprehensive assessment of emissions under real operating conditions and across different regulatory perspectives. The results demonstrate

that methane slip remains a key contributor to GHG emissions in LNG operation, particularly at low engine loads. Nevertheless, the investigated 46TS-DF engine exhibits relatively low methane slip levels compared with values reported in the literature for similar engine architectures. When evaluated over stabilized operating points and standardized E2 cycle weighting, methane slip coefficients and emission factors place the engine in the lower range of published values, with an approximate 18% reduction in methane slip observed over the E2 cycle compared with a previous 46DF engine [17].

A comparative analysis of CO₂ emissions on both TtW and WtW bases indicates that switching from MGO mode to LNG mode reduces CO₂ emissions by approximately 21% and 12%, respectively, over the E2 cycle. Crankcase emissions were not included in this assessment. The comparison between both engines indicates an overall WtW improvement of approximately 6% over the E2 cycle, nearly half of which is attributable to methane slip reduction, the remainder being associated with improved energy efficiency. BC was not measured on the 46DF engine. However, results from the 46TS-DF engine indicate a negligible contribution of BC to the overall GHG balance.

Beyond the characterization of a specific engine, this work demonstrates that combining experimentally determined emission factors with long-term engine load distributions provides a robust framework for evaluating real-world methane slip under emerging IMO and FuelEU regulatory methodologies. The close agreement observed between the E2 cycle and ELM approaches further suggests that standardized certification cycles can provide representative methane slip estimates for diesel-electric vessels with limited low-load operation. These results highlight the incentive effect of recent regulations aimed at reducing methane slip emissions, promoting optimized engine load management by shipowners and vessel design solutions developed by shipbuilders such as Chantiers de l'Atlantique to support these operational strategies. From an operational perspective, the results indicate that maintaining higher engine load levels (typically above 50–60%) can contribute to reducing methane slip. In diesel-electric architectures, this can be facilitated by load management strategies such as engine on/off scheduling, which help operate engines closer to optimal efficiency conditions. Future work should extend this methodology to a broader range of vessel types, operational profiles, and engine technologies, including transient operating conditions and after-treatment systems. Emission sources such as crankcase methane emissions and N₂O are included in current regulatory frameworks through default values but remain insufficiently validated by full-scale measurements. Their contribution to total CO₂-eq. emissions remains poorly quantified, highlighting the need for further experimental investigations to improve real-world emission inventories.

Author Contributions: Conceptualization, B.S.; Formal analysis, B.S. and A.M.; Investigation, B.S. and R.D.; Methodology, B.S. and R.D.; Writing—original draft, B.S. and A.M.; Writing—review and editing, B.S. and A.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: Author Aurélia Miquel was employed by Chantiers de l'Atlantique. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ADEME	French Ecological Transition Agency
BC	Black Carbon
Bio-LNG	Renewable Liquefied Natural Gas of Biological Origin
CH ₄	Methane
CO	carbon monoxide
CO ₂	carbon dioxide
DG	Diesel Generator
DN	Nominal Diameter
ELM	Engine Load Monitoring
e-LNG	Renewable Liquefied Natural Gas of Non-Biological Origin
EU	European Union
GHG	Greenhouse gas
GWP100	100-year Global Warming Potential
IMO	International Maritime Organization
LCA	Life-Cycle Assessment
LNG	Liquefied natural gas
LPDF 4-S	Low-Pressure Dual-Fuel Four-Stroke
MGO	Marine gas oil
MEPC	Marine Environment Protection Committee
MRV	Monitoring, Reporting and Verification
NDIR	Non-Dispersive Infrared
NO _x	nitrogen oxides
N ₂ O	Nitrous oxide
SCR	Selective Catalytic Reduction
SO _x	sulphur oxides
TtW	Tank-to-Wake
WtT	Well-to-Tank
WtW	Well-to-Wake

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