# How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis

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## Abstract

International shipping faces strong challenges with new legally binding air quality regulations and a 50% decarbonisation target by 2050. Liquefied natural gas (LNG) is a widely used alternative to liquid fossil fuels, but methane emissions reduce its overall climate benefit. This study utilises new emissions measurements and supply-chain data to conduct a comprehensive environmental life cycle and cost assessment of LNG as a shipping fuel, compared to heavy fuel oil (HFO), marine diesel oil (MDO), methanol and prospective renewable fuels (hydrogen, ammonia, biogas and biomethanol). LNG gives improved air quality impacts, reduced fuel costs and moderate climate benefits compared to liquid fossil fuels, but with large variation across different LNG engine types. Methane slip from some engines is unacceptably high, whereas the best performing LNG engine offers up to 28% reduction in global warming potential when combined with the best-case LNG supply chain. Total methane emissions must be reduced to 0.8–1.6% to ensure climate benefit is realised across all timescales compared to current liquid fuels. However, it is no longer acceptable to merely match incumbent fuels; progress must be made towards decarbonisation targets. With methane emissions reduced to 0.5% of throughput, energy efficiency must increase 35% to meet a 50% decarbonisation target.

# 1. Introduction

While much progress has been made in decarbonising electricity, transportation lags behind [1]. The pathway to decarbonise shipping is particularly contentious. Sea-transport is considered the lowest carbon mode of transport per tonne-km, but its sheer magnitude means international shipping is responsible for 1.1 $GtCO_2$ emissions per year, 3% of the global total [2]. If the maritime industry were a country, it would be the world's sixth largest $CO_2$ emitter – ahead of Brazil and Germany [2]. 'Business as usual' projections see maritime emissions growing by 50-250% to 2050 due to population and economic growth [3], but in 2018 the International Maritime Organization (IMO) announced the first greenhouse gas (GHG) target for international shipping, at least 50% greenhouse gas reduction by 2050 compared to 2008 [4, 5]. Recent IMO regulations on air quality will also significantly reduce $SO_X$ and $NO_X$ emissions, particularly in port emission control areas [6].

Decarbonisation and improving air quality may be driven by a combination of efficiency improvements such as the energy efficiency design index (EEDI), and the use of alternative fuels [2]. Heavy fuel oil (HFO) and marine diesel oil (MDO) represent 98% of fuel used in the industry [7] and while various low carbon fuels are being developed such as hydrogen, methanol or ammonia [8], they are still commercially immature and expensive [9]. Whilst the uptake of battery electric road vehicles has progressed and shows excellent emissions potential, ranges of several thousand kilometres, necessary for deep-sea shipping, are still a distant prospect [10]. Liquefied natural gas (LNG) is the most prominent alternative fuel in terms of current usage, that may offer ~30% reduced $CO_2$ emissions and is cost-competitive versus lower carbon options, and thus is rapidly maturing [2]. By 2017, there were 120 LNG-fuelled vessels in commercial operation, with many also planned or in construction [11]. The share of LNG-capable newbuild was to 5% in 2015, rising to 13% in 2018 [12]. However, methane emissions in both upstream fuel production and engine slip have been shown to significantly affect these benefits. Lowell et al. [13] suggest that high methane emission scenarios result in higher GHG than liquid fossil fuels. These emissions may be highly variable across both engine-types and supply chain routes [14].

Methane is a potent greenhouse gas, so even low levels of emissions may negate the relative carbon benefits of switching from HFO or MDO. Methane is 120 times stronger than $CO_2$ in terms of climate forcing on an instantaneous basis, but is relatively short-lived with an average life span of 12 years, compared to $CO_2$ which persists in the atmosphere for hundreds of years [15]. Consequently, the relative impact of methane compared to $CO_2$ depends on the time frame being considered. Global Warming Potentials (GWP) are widely used to compare GHGs, typically over a 100-year time horizon

– which under-represents the near-term warming impact of methane. It is important to understand both the short- and long-term climate impacts, thus studies should move to considering different time horizons and metrics to better understand the impacts of fuels switching [15].

Methanol could potentially improve air quality and GHG emissions from ships at low cost. It has received some attention to date [e.g. 16, 17] and one marine engine is available which can run on methanol as a dual fuel. As of 2018 there were 7 methanol-fuelled ships in operation, with another 4 planned to be in operation for 2019 [18]. Most methanol production is currently from natural gas (as well as coal, especially in China), incurring a high primary energy requirement, and potentially high supply chain methane emissions.

Previous studies have estimated greenhouse gas emissions from LNG-fuelled ships [13, 19-21] and from methanol [17, 22]. Air quality [20, 21] and cost impacts [23, 24] have also been investigated in others. In particular, Thomson et al. [21] conduct a life cycle assessment of the use of natural gas as a marine fuel for 2 engine-types, using the technology warming potential (TWP) to incorporate the changing climate impacts of a technology shift over time. This study adds to previous work by providing a comprehensive assessment of GHG, air quality and cost impacts of LNG and methanol, in comparison to incumbent liquid fossil fuels and low-carbon alternatives. It is based on the most recent upstream emission data [14] combined with new measurements of LNG ship exhaust emissions [11] to shed light on the influence of technological variability on emissions. This study also determines opportunities to reduce emissions further and estimates the maximum allowable methane emissions to ensure a benefit in climate performance compared to current liquid fuels. These results and insights serve to inform shipping industry investment decisions and provide evidence for policymakers and further academic studies into transforming the shipping industry to meet climate targets.

The next section outlines the methodology and data inventory of the study. Results for GHG emissions, air quality impacts and costs and presented in section 3 and validated against the literature. In section 4, the potential reductions in GHG emissions from LNG-fuelled ships are discussed in relation to methane emissions, engine and ship efficiency and bio-LNG blending. Finally, conclusions, limitations and recommendations are outlined in section 5.

## 2. Methodology

A cradle-to-grave life cycle assessment was performed for the fuel supply chain and combustion of shipping fuel, with a focus on greenhouse gas emissions ($CO_2$ and methane) and air quality emissions ($NO_X$, $SO_X$, CO, particulates). An economic assessment was conducted to compare fuel costs associated with different fuels and engines. The following fuels and engine types were considered, while hydrogen, ammonia, biomethane and biomethanol are also compared in the discussion based on secondary sources:

- LNG: Lean-burn spark ignited (LBSI);
- LNG: Low pressure Dual-Fuel 4-stroke (LPDF 4-stroke);
- LNG: High-pressure dual fuel 2-stroke (HPDF 2-stroke);
- LNG: low pressure dual-fuel 2-stroke (LPDF 2-stroke);
- heavy fuel oil (HFO);
- marine diesel oil (MDO); and
- methanol.

The four LNG engines represent all types currently used as primary engines [11]. LBSI and LPDF 4-stroke engines are typically used in smaller ships, while HPDF and LPDF 2-stroke engines are used on larger vessels such as LNG carriers. Liquid fuel ships (HFO and MDO) were modelled based on the average across several existing LCA studies to gain the broadest consensus view of the technologies. This includes a mix of slow- and medium-speed diesel found in the global fleet of ships, reflected in the variation in efficiencies and emissions estimated here.

The study considers the whole fuel cycle, given average operation efficiencies for each fuel and engine type. Figure 1 outlines the scope of the study with the different stages considered for each fuel and engine type. Note, the study does not specify a ship type, but instead an engine and average efficiency. Ship manufacture itself is not considered, but both direct and indirect emissions across the fuel supply chain are considered from a life cycle perspective. In reality, the onboard fuel delivery and storage are different across the options, but these are expected to represent a minor part of the total lifetime emissions. The study focuses on the main propulsion engine rather than additional auxiliary engines, although results will be transferrable to these (e.g. for estimating total ship operational emissions) if their efficiencies are comparable. Exhaust gas treatment is also excluded from the scope but could be added to liquid fuel engines and to HPDF 2-stroke engines in scrubbing $NO_X$. The inclusion of exhaust treatment would have an impact on emission and cost results and should be further researched to better understand the trade-offs between different LNG engines.

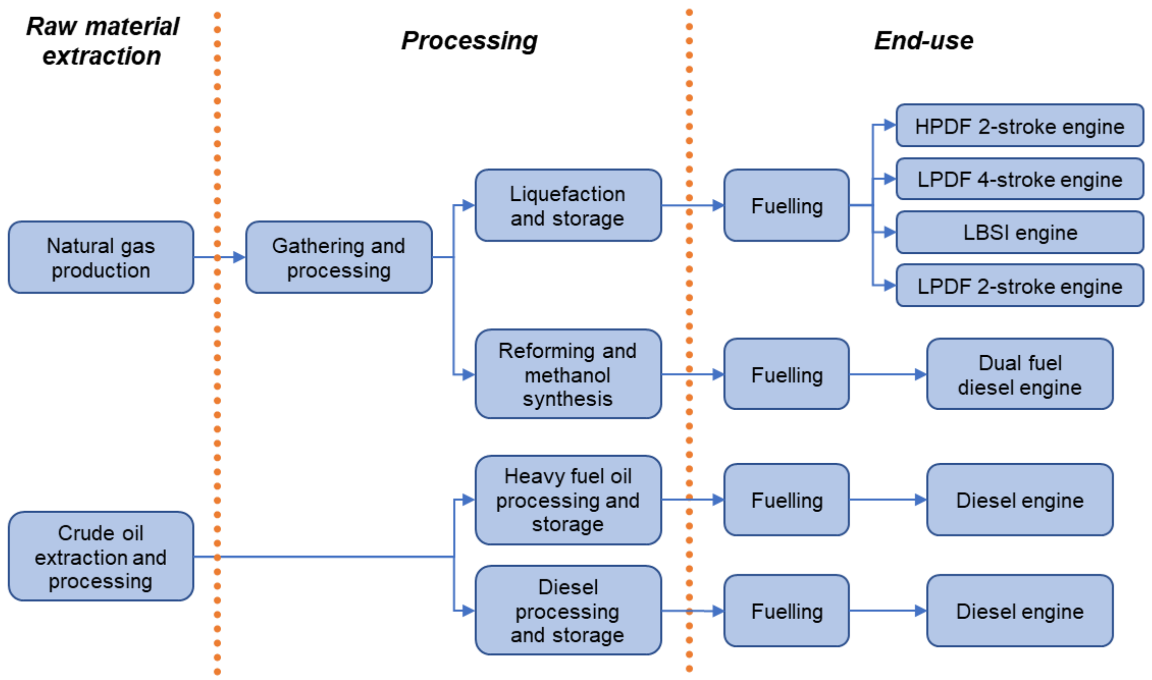


*Figure 1. Fuel supply chains from raw material extraction, processing to end-use for different fuels and engines. Transport steps are not illustrated but exist between each stage.*

Results are given with a functional unit of 1 kWh of output from the engine. The assessment incorporates average efficiencies of different engines as outlined in the inventory assessment below. Operating efficiencies differ among ships, particularly between short-sea and deep-sea operations, as deep-sea engines operate at a steady state for longer periods. Efficiencies used here reflect averages from the literature, but the variation and its impact are discussed in this section as well in section 4.2.

The impacts presented relate to climate change, air quality and costs, a full description of which is detailed in the following section. The use of alternative climate metrics to the global warming potential (GWP) is included, namely the global temperature potential (GTP) across different timescales.

The study uses Gabi thinkstep life cycle assessment software for creation of mass, energy, and emissions balances, and Matlab for data analysis.  It follows the ISO 14040/14044 methodology [25, 26] for environmental assessment, which describes a four-step method: goal and scope; inventory analysis; impact assessment; and results interpretation. The following section details the inventory analysis and impact assessment metrics.

## 2.1 Inventory assessment

### 2.1.1 Supply chains

The study utilises the natural gas supply chain model developed by Balcombe et al. [14] for LNG and methanol, as well as Balcombe et al. [27] for the liquefaction, LNG transport and storage stages. Stages included are pre-production, production and processing, transmission, liquefaction, storage, and delivery. A range of $CO_2$ and methane emissions are derived using the probabilistic distributions for each stage of the supply chain in Balcombe et al. [14]. The median emissions for each stage are used for a central estimate, with $10^{th}$ and $90^{th}$ percentile estimates used for low and high estimates, respectively. Note that these estimates are not region-specific but encompass a wide range which are likely to be broadly reflective of the industry. Liquefaction emissions were separately based on Balcombe et al. [27], giving mean, high and low figures synthesised from several previous studies. Table 1 gives a breakdown of the methane emissions assumed for each stage of the natural gas supply chain.

*Table 1. Estimates of methane emissions from each stage of the natural gas supply chain. Low, central, and high estimates are given for sensitivity assessment. Emissions are expressed as a percentage of delivered gas.*

| | Production and processing [14] | Transport and storage (upstream) [14] | Liquefaction [27] | LNG transport and storage [27] | Total |
|---|---|---|---|---|---|
| **Low** | 0.03% | 0.17% | 0.011% | 0.001% | 0.22% |
| **Central** | 0.22% | 0.43% | 0.35% | 0.012% | 1.03% |
| **High** | 1.82% | 1.42% | 0.63% | 0.032% | 3.91% |

The energy for liquefaction is assumed to come from the combustion of natural gas, requiring 9.4% of throughput based on the mean of 8 studies [13, 28-34]. For LNG transport, the range of $CO_2$ and methane emissions was calculated from NGVA-thinkstep [19] and the IMO study from Korea [35]. Note that LNG shipping figures could be higher in practice, given that the highest value comes from the only primary direct measurement study [35], which acknowledges its own under-estimation. For liquid storage there is very little publicly available data a central estimate of 1-day storage is assumed, with a high and low of 0-2 days of storage as per Lowell et al. [13]. It is conservatively assumed that 10% of boil-off gas is released as methane emissions. For bunkering, it is assumed that 0.22% of LNG is boiled off or displaced as vapour during fuelling, with a 50% capture resulting in 0.11% emission [13, 36]. Additional direct and indirect impacts associated with the natural gas supply chain are taken from the Ecoinvent 3.3 database [37].

For methanol, the conventional production route is via natural gas reforming to syngas and methanol synthesis. It is assumed that this occurs close to the point of extraction thus there is no transport requirement. The production and processing of natural gas is the same for the LNG supply chain. The inventory for gas reforming and methanol synthesis is derived from the NREL database [38], using Ecoinvent 3.3 for ancillary impacts [37]. The upstream impacts allocated to heavy fuel oil and marine diesel oil are taken from Ecoinvent 3.3. For HFO, bunker oil with an average sulphur content of 3.5%w/w is assumed, reflecting the current global sulphur cap (soon to become 0.5% in 2020)[2]. For diesel, the production of low sulphur light fuel oil is used, with a sulphur content of 0.005% w/w. For upstream carbon dioxide emissions, 440 $gCO_2$/kg HFO and 524 $gCO_2$/kg diesel is associated with the production up to point of use [37].

### 2.1.2 Engines

Table 2 presents a review of the efficiencies and emissions associated with each fuel and engine combination. References for each value individually are given in the Supplementary Information.

*Table 2. Summary of engine efficiencies and emissions. '?' denotes no data found. Total fuel efficiency was calculated with the main and pilot fuel consumption rates shown, with a conversion based on an LHV of LNG of 47.1 MJ/kg and assuming MDO is used as a pilot fuel with LHV of 43.1 MJ/kg. Data sources: [3, 11, 13, 16, 17, 19, 20, 22, 39-42].*

| Values | LPDF 4-stroke | LBSI | HPDF 2-stroke | LPDF 2-stroke | HFO | MDO | Methanol |
|---|---|---|---|---|---|---|---|
| Main fuel consumption (g/kWh) | 169.1 | 170.2 | 135.1 | 138.2 | 201.5 | 184.5 | 397.5 |
| Pilot fuel consumption (g/kWh) | 2.5 | 0 | 8.3 | 1.0 | 0 | 0 | 0 |
| Total fuel efficiency (% LHV) | 44.6% | 44.9% | 53.5% | 54.9% | 44.2% | 45.3% | 45.3% |
| $CO_2$ emissions (g/kWh) | 452.1 | 480.5 | 430.8 | 411.6 | 579.4 | 557.5 | 541.4 |
| $CH_4$ emissions (g/kWh) | 5.3 | 4.4 | 0.3 | 3.2 | 0.01 | 0.01 | 0 |
| $NO_X$ emissions (g/kWh) | 2.3 | 1.3 | 10.1 | 2.0 | 13.4 | 14.0 | 1.7 |
| CO emissions (g/kWh) | 1.8 | 1.5 | 0.79 | 1.4 | 0.64 | ? | ? |
| NMVOC (g/kWh) | 0 | 0 | 0.1 | 0.3 | 0.2 | ? | ? |
| PM (g/kWh) | 0.0056 | 0 | 0.11 | 0.0056 | 0.63 | 0.16 | $2.9 \times 10^{-6}$ |
| $SO_X$ (g/kWh) | 0.0048 | 0 | 0.30 | 0.0096 | 5.7 | 0.57 | 0 |

The variation in emissions across engine types is considerable, exemplified by Figure 2 which utilises the most recent data on methane slip. These figures are incorporated into the uncertainties estimated in this study and more information on all emission types is given in the supplementary information. Note that there is little variation in the estimates of methane emissions from the HPDF and LPDF 2-stroke engines. This is not a result of low variability or uncertainty, but due to a lack of data on these relatively new technologies, where all values collected here are from manufacturers data. Particularly for the HPDF engine with low emissions, there is an onus on the industry to demonstrate that these low emissions can be achieved in real-world application and maintained over time.

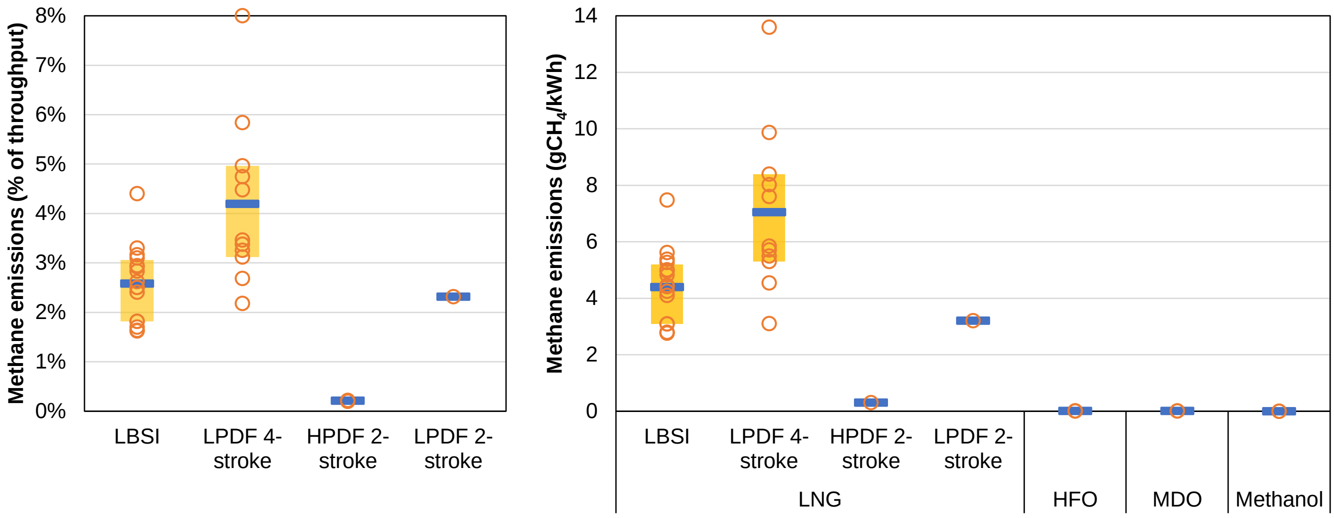


*Figure 2. Estimates of methane emissions from various engines and fuels. The left panel presents emissions from LNG engines relative to throughput, whilst the right panel presents the absolute mass of methane emitted per unit of energy output. Circles represent individual literature estimates, thick lines represent mean values and the bars represent the interquartile range. Data sources: [3, 11, 13, 17, 19, 20]*

## 2.2 Assessment metrics

### 2.2.1 Climate change metrics

Global warming potentials (GWPs) are used to compare the relative impact of different GHGs on climate forcing, by converting emissions into '$CO_2$ equivalents'. GWP is the average time-integrated radiative forcing of a pulse emission over a defined time horizon, compared to $CO_2$. For example, the GWP100 gives the average climate forcing impact over 100 years compared to that of $CO_2$. The 100 year time horizon is most common, giving a $CO_2$ equivalent value of 28–36 for methane (depending on whether various indirect climate effects and eventual oxidation to $CO_2$ are included) [43]. However, there is much criticism about the use of GWP [15], because:

- the selected time horizon has a large impact on the value of the metric;
- despite its name, it does not compare gases against their effect on global temperature, which has a non-linear relationship to radiative forcing;
- it measures an average climate forcing effect over time but gives no indication of the climate impact at an endpoint in time.

These criticisms have led to calls for the use of different time horizons (e.g. 20 years) and different metrics that are better aligned with climate targets, such as the global temperature change potential

(GTP) described in the IPPC AR5 [43]. GTP produces different equivalency values to GWP and is defined as the change in mean surface temperature after a specified time due to a pulse emission, relative to an equivalent pulse emission of $CO_2$. The key differences to GWP are that it is an end-point metric and it estimates the temperature change rather than radiative forcing [44]. This study uses GWP100 as a baseline metric to allow comparisons with other studies. Given the broad range of $CO_2$ equivalences for GTP values over time, GTP is used dynamically to assess the climate benefits: for each year between zero and 100, emissions are multiplied by the $CO_2$ equivalency values. To represent the large range of $CO_2$ equivalencies across different metrics, one large and one small metric value were selected: a GWP20 value of 87 and a GTP100 value of 13 as a proxy to illustrate 'short term climate' and 'long term climate' impacts, respectively.

### 2.2.2 Air quality

The following air quality metrics are used in the study, relating to key impacts associated with shipping:

- $NO_X$ ($gNO_X$/kWh)
- $SO_X$ ($gSO_X$/kWh)
- Total particulates (gPM/kWh)
- Photochemical ozone creation potential (POCP) ($gC_2H_2$eq./kWh)

Whilst emissions of $NO_X$, $SO_X$ and particulates are well-known and widely considered, POCP also represents an important indicator, especially with respect to emission of $NO_X$ and methane. These compounds react in the atmosphere with hydroxyl radicals to produce tropospheric ozone ($O_3$), which at ground level damages human health, ecosystems and agricultural yields [45].

### 2.2.3 Cost

We present fuel costs that incorporate prices and engine efficiencies. Data were collected on the price of each fuel from the last 20 years, as documented in the Supplementary Information. LNG import prices to the US from Canada, Trinidad and Tobago as well as US and Netherlands LNG prices were included [46, 47]. Global average HFO and MDO prices were collected from various sources [36, 47-50], whereas methanol prices were collected from the US, Netherlands, China, Brazil, India and Turkey [51-53]. These costs do not consider additional logistical costs associated with bunkering, where insufficient data was found to incorporate. However, Ship & Bunker [54] estimate Canadian LNG bunker prices at approximately 220–300 USD/t in 2016 and 2017, which falls within the range of prices considered here. Commodity prices have been volatile; two metrics are developed to test price sensitivity. For each fuel, 5 and 10-year historical average prices are used alongside maximum and minimum values, to estimate the relative cost-benefit associated with switching from HFO to alternatives.

# 3. Results: GHGs, air quality and cost impacts

The following sections detail the performance of LNG engines compared to HFO and MDO against GHG, air quality and cost metrics. In summary, LNG performs well for 'long-term' climate change (GTP100), particulates, $SO_X$ and fuel costs, but results are mixed for short-term climate change (GWP20) and $NO_X$, and only under certain conditions are emissions reduced. Methanol performs relatively poorly for most climate metrics, is on par to LNG for air quality indicators but is much more expensive. Results are first presented and then compared against other literature, followed by an assessment of the maximum allowable methane emissions to ensure a climate benefit over HFO.

## 3.1 Greenhouse gas emissions

The LNG-fuelled HPDF 2-stroke and the LPDF 2-stroke engines reduce climate impacts across all metrics, but only when supply chain emissions are constrained. These engines have a higher efficiency (53.5% and 54.9% compared to ~45%), which enhances the lower carbon intensity of natural gas over liquid fuels. Higher efficiency also results in proportional reductions in supply chain emissions, as the engine requires less gas as an input. Additionally, and most importantly from a short-term perspective, methane slip is extremely low for the HPDF 2-stroke: 0.2% versus 2.5-3.1% for LBSI and LPDF 4-stroke). It must be emphasised here that the engines with the lowest estimated impacts are those where there are only manufacturer test-bed data available.

Figure 3 shows GWP100 estimates for each fuel and engine, split by supply chain stage and gas. With methane having a $CO_2$ equivalency of 36, the HPDF engine reduces emissions by 18% with a value of 590 $gCO_{2eq}$/kWh compared to 715 $gCO_{2eq}$/kWh for HFO and 687 $gCO_{2eq}$/kWh for MDO. The LPDF 2-stroke reduces remissions by approximately 8%, whereas the other LNG-fuelled engines increase emissions by 7-9% (746 - 828 $gCO_{2eq}$./kWh for LBSI and LPDF 4-stroke) due to their higher methane emissions. Supply chain emissions contribute 21-24% for the LNG engines and 14-16% for the conventional liquid fuels.

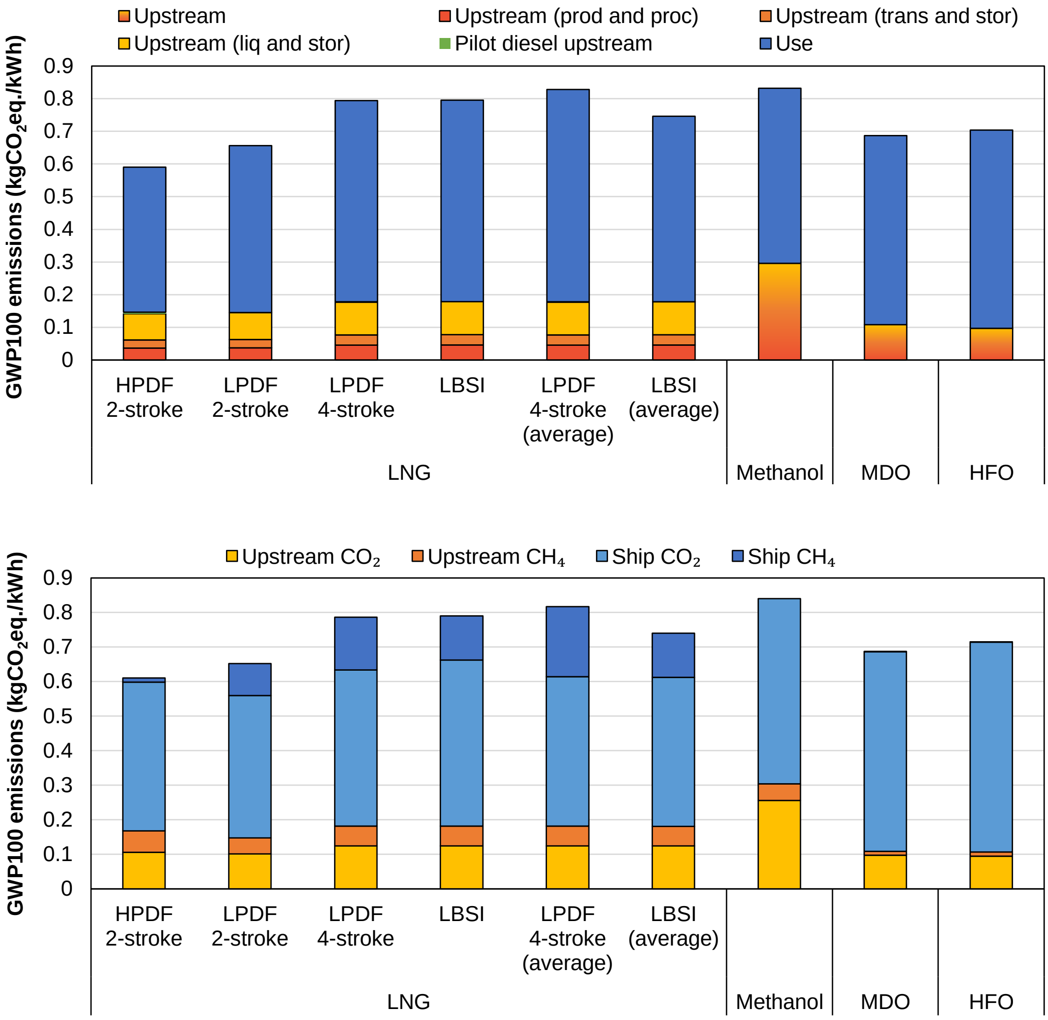


*Figure 3. GWP100 emissions associated with each fuel type/engine case. Emissions are split into (top panel) supply-chain stage and (bottom panel) by gas and into upstream/downstream. Liquid fuel supply chains were not disaggregated into supply-chain stages and so are shown with an aggregated gradient. Equivalent graphs using alternative climate metrics (GTP) are given in the Supplementary Information.*

While end-use emissions from methanol are 8%-12% lower than MDO and HFO, supply chain $CO_2$ emissions contribute significantly due to the energy intensity of methanol production. Upstream emissions contribute 36% of total climate impacts, giving methanol the highest total GWP100 of all options. Different methanol production routes (e.g. from biomass gasification or via catalytic hydrogenation of $CO_2$) would reduce the supply chain emissions whereas biomethanol would produce biogenic combustion emissions which may be discounted.

Using the GTP100 metric (with a lower methane $CO_2$ equivalency of 13), all gas-fuelled engines perform more favourably than the liquid fuels. GHG savings average 12–26% compared to HFO (shown in Supplementary information). Evidently the value and type of climate metric has a significant impact on the inferred benefits of a fuel or technology shift from liquid to natural gas fuels. Figure 4 shows the GTP over time horizons from 0 to 100 years for each engine and fuel, highlighting the possible range of results due to supply-chain.

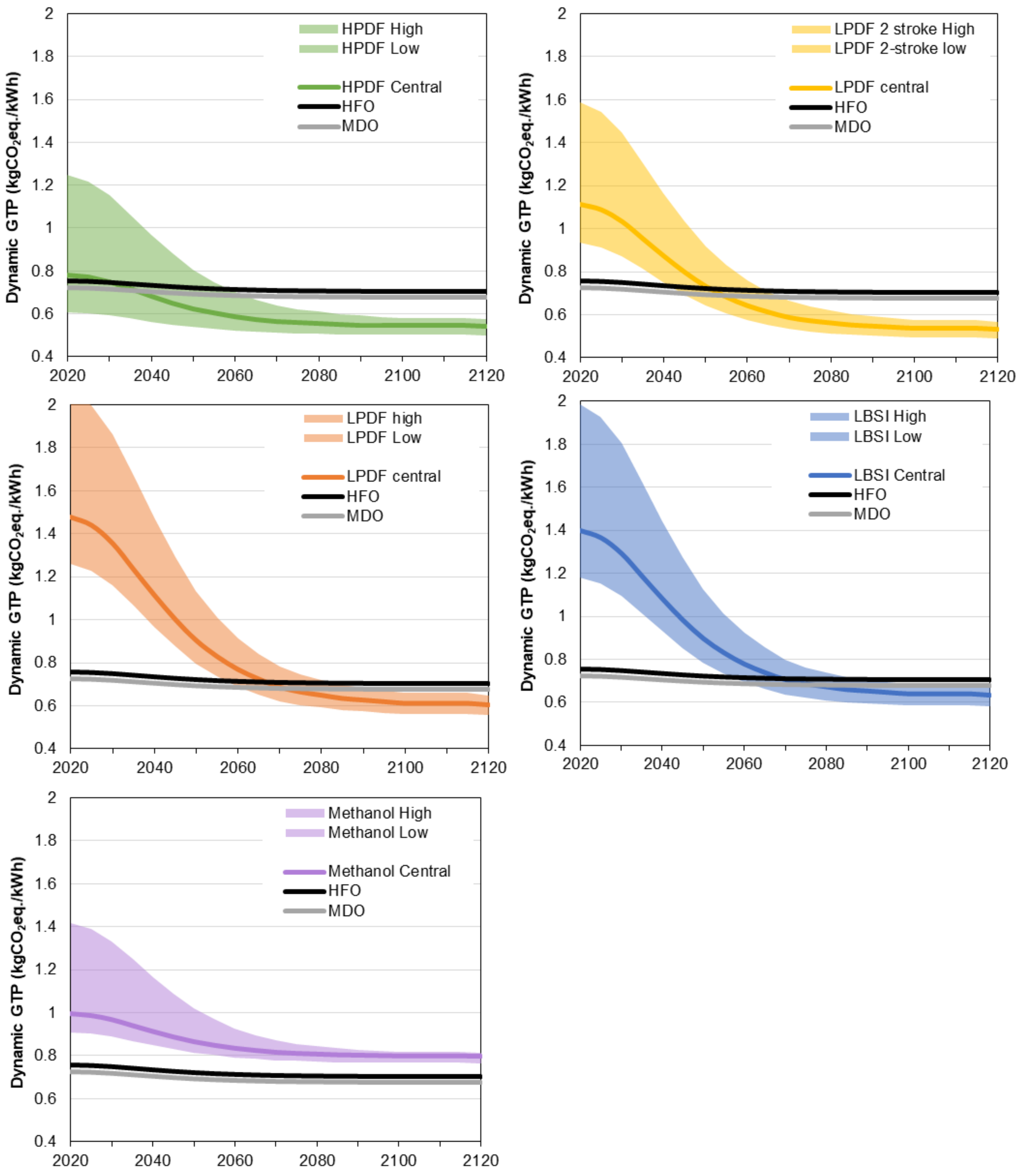


*Figure 4. Dynamic GTP emissions across time horizons of 0 to 100 years for each engine and fuel. The horizontal axis gives the year in which temperature impact is measured for a ship operating in 2020. Panels show LNG-fuelled HPDF 2-stroke engine (green), LPDF 2-stroke (yellow), LPDF 4-stroke (orange), LBSI (blue) and methanol (purple) compared to HFO (black) and MDO (grey) diesel engines over time. Shaded areas represent low, central, and high case supply chain emissions.*

The charts assume a ship operating in 2020 and give the impact on temperature felt across a range of future years. For example, a ship fuelled by HFO and an LPDF 2-stroke engine would have a similar impact on global temperature experienced in 2050, but before that point the LPDF engine would cause more warming (due to short-term methane emissions), and after that point it would cause less warming (due to less $CO_2$ emissions). The HPDF 2-stroke engine yields a reduction in temperature rise under all supply-chain conditions after 40 years. Under central and low supply chain methane emissions, relative benefits are achieved for all time frames for the HPDF, but methane emissions cause higher impacts for the LPDF 2-stroke. For the high supply chain emission case for the HPDF engine, the short-term impact of methane emissions is severe, resulting in increased temperature change relative to HFO and MDO.

For LPDF 4-stroke and LBSI engines, high methane emissions at the point of use quickly reduce the carbon benefit associated with natural gas, where the inflection point for both engines at the central supply chain case is around 50 years (2070). For methanol, total emissions are never lower than HFO and MDO due to high supply chain $CO_2$ emissions. Methane emissions are lower than for LNG but higher than other liquid routes, thus the short-term climate impact is substantially higher.

### 3.1.1 Comparison with prospective low carbon fuels

This study has focused on the currently available fuel options, but there are several prospective fuels that may deliver deeper decarbonisation, namely hydrogen and ammonia, or hydrocarbons produced from biogenic sources. Low carbon fuels such as hydrogen and ammonia exhibit no $CO_2$ emissions upon their combustion (or electrochemical conversion) but must be derived from low carbon supply chains to ensure their environmental effectiveness. Supply chain emissions can vary widely across feedstocks, technologies and regions [55]. To compare the results of this study with these future fuels, the literature was reviewed to assess current understanding of the life cycle environmental impacts. Results for greenhouse gas emissions are shown in Figure 5; results for air quality emissions and cost are not yet possible as these fuels are too nascent.

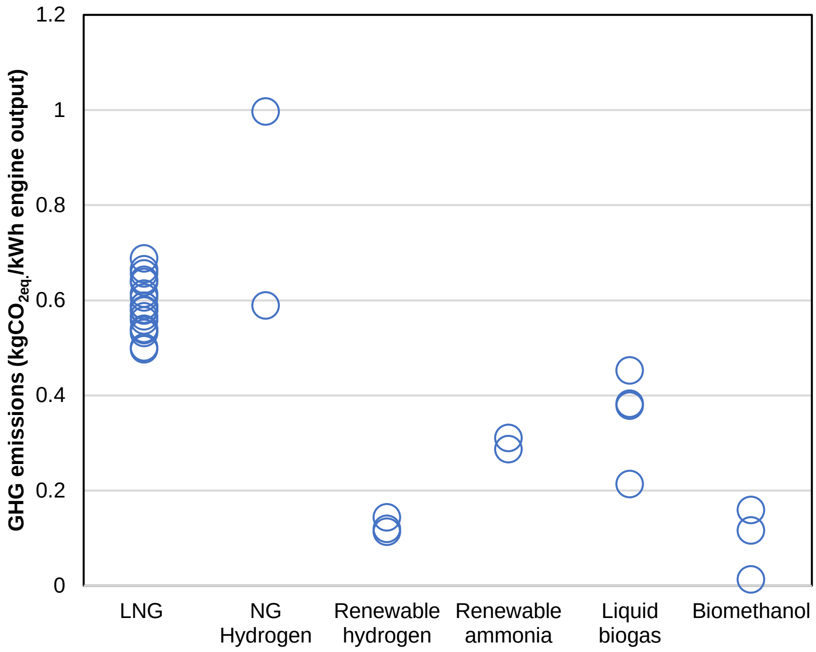


*Figure 5. Central estimates of life cycle GHG emissions from LNG fuelled ships compared to literature estimates hydrogen and ammonia fuel. An engine efficiency of 45% was assumed for renewable hydrogen and ammonia combustion to compare results from Bicer et al. Data sources: [20, 22, 56, 57]*

These fuels may all be either combusted in an engine (or turbine) or used within a fuel cell. The hydrogen feedstock is an important differentiator, where hydrogen produced from natural gas would only give an improvement if carbon capture and storage were to be implemented. Even then, the GHG savings are estimated to be marginal with GHG emissions of 600 $gCO_{2eq.}$/kWh engine output. Hydrogen from renewable electrolysis exhibits GHG emissions of ~120 $gCO_{2eq.}$/kWh, representing a substantial decrease [20, 57]. Estimates of ammonia derived from renewable electrolysis (plus Haber Bosch conversion) are ~300 $gCO_{2eq.}$/kWh which is also an improvement [57].

Liquid biogas (LBG) and biomethanol figures were taken from Brynolf et al. [22] for a study based on willow for the case of LBG, and willow or forest residues for biomethanol. The biogenic sources of carbon result in the discounting of the $CO_2$ released on combustion, meaning substantially reduced total emissions compared to LNG and liquid fossil fuels. Whilst biomethanol has a high energy intensity of production, the overall impact is substantially reduced, particularly when produced from waste residues. LBG is impacted by potential methane slip (where 4% is assumed in this study) which results in higher climate impact than biomethanol.

These preliminary estimates are unlikely to reflect the variation in emissions associated with different fuel supply chains in different regions (e.g. utilising different equipment and with differing weather conditions). Thus, further work is required to develop realistic bounds and optimal supply chains to minimise emissions from low carbon fuels. Additionally, onboard energy conversion systems for low carbon fuels are largely untested in commercial applications, so efficiencies and emissions may vary substantially. Even so, these estimates suggest that renewable ammonia and hydrogen fuels may reduce ship GHG emissions compared to HFO by 60% and 80%, respectively.

## 3.2 Air quality

Air quality impacts from each fuel and engine are illustrated in Figure 6. HFO exhibits the highest emissions in three out of four impact categories, while the LNG fuelled engines exhibit the lowest apart from the HPDF engine. $SO_X$ emissions are largely eliminated with gas fuel and particulate emissions are reduced by 82–89% for all LNG engines compared to HFO. $NO_X$ emissions are reduced by 83–93% for LPDF and LBSI engines compared to HFO, but the HPDF engine results in an increase of 14%. LNG fuelled engines reduce POCP emissions by 21% - 44% compared to HFO, except for the HPDF engine which exhibits similar emissions. The contributors to the POCP are methane and $NO_X$ emissions: whilst methane emissions are reduced with the HPDF engine, the increase in $NO_X$ emissions eliminates the benefit.

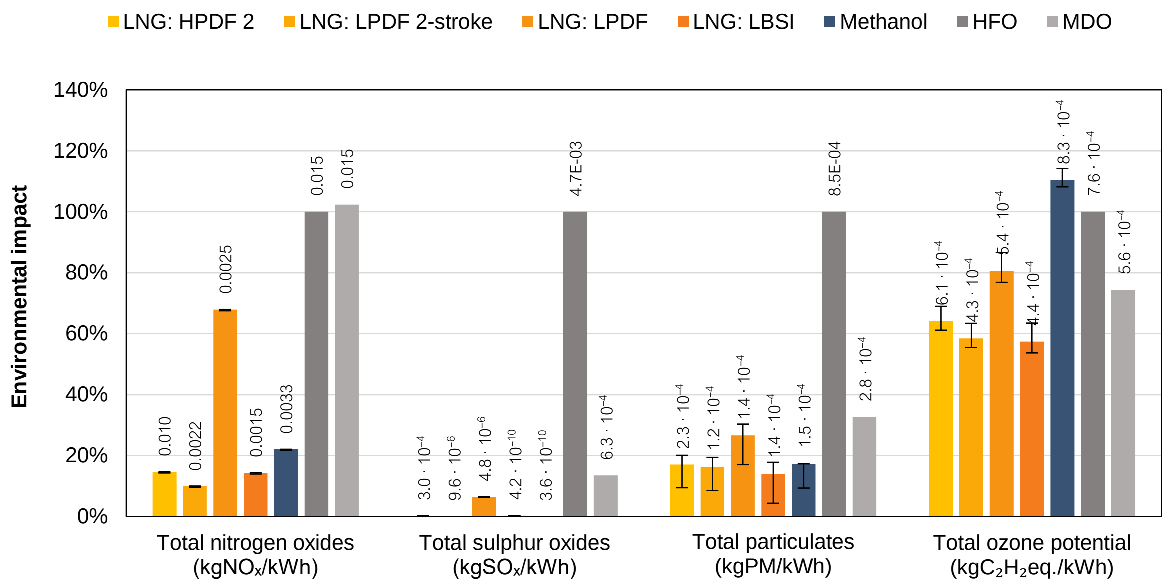


*Figure 6. Air quality impacts associated with each fuel and engine type. Impacts are expressed as a percentage of the average emissions for the HFO option, with the data labels showing the absolute values in units specified in each column.*

## 3.3 Cost

LNG engines exhibit lower fuel costs per kWh of power output, given the fuel prices seen thus far this century. Figure 7 shows the fuel costs over the last 17 years, based on the engine efficiencies assumed in this study. All LNG engines have offered 20–80% lower fuel costs over this time. In comparison, MDO is 10–70% higher cost compared to HFO, whereas methanol is 10–140% higher.

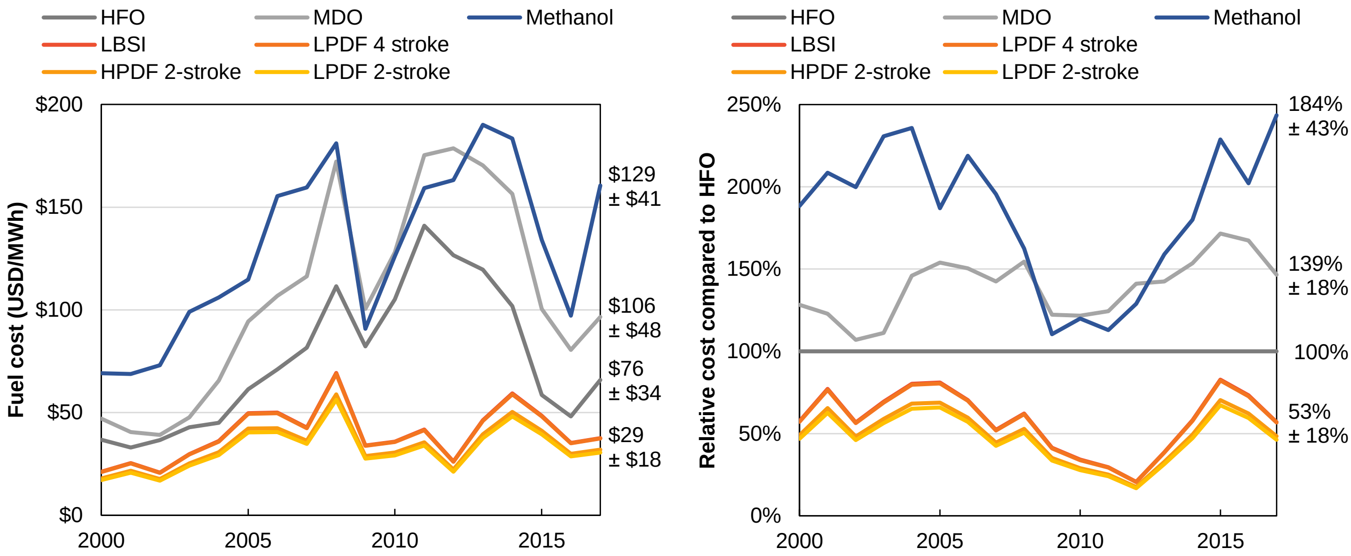


*Figure 7. Historical average fuel costs for each fuel and engine type, given average efficiencies as outlined in the methodology and average fuel costs from various regions including the US, Netherlands, Canada, and India. Estimates are given in absolute terms (left) as well as relative to an HFO baseline (right). Numbers to the right of each plot show the mean and standard deviation over the last five years for each fuel, with the average of all engines used for LNG.*

Whilst the price of all fuels has varied by a factor of 3 across this timeframe, LNG is consistently lowest cost. However, this is offset by substantially higher capital costs for LNG engines and ancillary equipment. Capital costs vary widely depending on ship type and size, as well as market conditions, but may be 5–40% higher than diesel engines [58-60]. Tank costs also impact capital costs, potentially three times the cost of heavy fuel oil tanks given the larger size and greater challenge associated with containing LNG safely [59, 61]. The displaced cargo space associated with LNG tanks may also have cost implications for operators, though these are not well represented in literature. These premium costs are typically paid back via low operating costs within 3-12 years [62-65].

## 3.4 Overall performance assessment

No single fuel/engine option represents the best performance across all impact categories considered. Table 3 gives an overall assessment of each option across the key environmental and cost indicators. Indicators are compared and allocated to 3 qualitative categories (from best to worst) to give a broad overview of performance. The LNG-fuelled HPDF engine performs the best across short-term and long-term climate categories, cost, $SO_X$ and particulates. However, unabated $NO_X$ emissions may be an issue and must be addressed. The other LNG fuelled engines perform favourably for all cost and air quality categories, but poorly for short-term climate impact due to high methane emissions. Methanol from natural gas performs well for air quality but poorly for both short and long-term climate impacts and is worst for cost.

*Table 3. Qualitative assessment of key environmental and cost characteristics for each fuel and engine type. ✓ = best, ✓ = good, - = average, ✗ = worst.*

| | LNG: | | | | Metha-nol | MDO | HFO |
|---|---|---|---|---|---|---|---|
| | LPDF 4-stroke | LBSI | HPDF 2-stroke | LPDF 2-stroke | | | |
| *GWP100* | ✗ | ✗ | ✓ | - | ✗ | ✗ | ✗ |
| *Climate long term (GTP100)* | - | - | ✓ | ✓ | ✗ | ✗ | ✗ |
| *Climate short term (GWP20)* | ✗ | ✗ | ✓ | - | - | - | - |
| *Ozone creation* | ✓ | ✓ | ✗ | ✓ | ✗ | - | ✗ |
| *NOX* | - | ✓ | ✗ | ✓ | - | ✗ | ✗ |
| *SOX* | ✓ | ✓ | ✓ | ✓ | ✓ | - | ✗ |
| *Particulates* | ✓ | ✓ | ✓ | ✓ | ✓ | - | ✗ |
| *Cost* | ✓ | ✓ | ✓ | ✓ | ✗ | ✗ | - |

## 3.5 Comparison of results with the literature

Figure 8 compares the GHG results of this study with other estimates from the literature, split into upstream and end-use emissions. Estimates are between 577 and 738 $gCO_{2eq.}$/kWh power output. In comparison, this study estimates higher emissions, 598–817 $gCO_{2eq.}$/kWh across engine types (524–991 $gCO_{2eq.}$/kWh total range including low and high scenarios), owing to increased supply chain contribution and other factors, as follows.

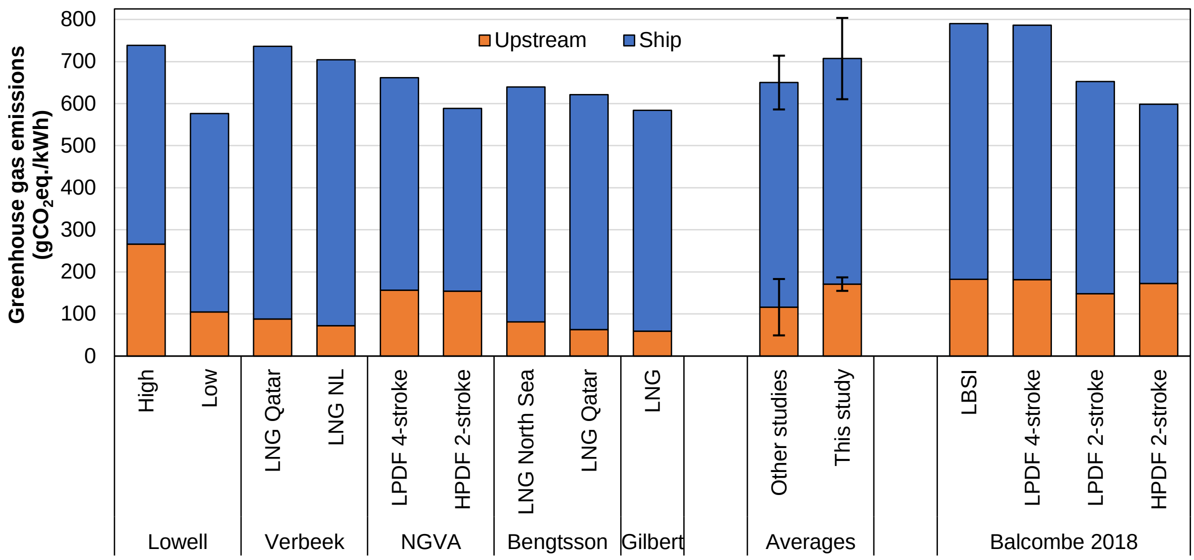


*Figure 8. Comparison of the GWP100 emissions from LNG engines with literature estimates, divided by upstream supply chain and ship emissions. Literature values were transformed using an average 45% efficiency where needed. Data sources: [13, 19, 20, 39, 66]*

Upstream supply-chain emissions differ the most across the studies, particularly the methane component. The variation in methane emissions across literature reflects a genuine variability of emissions across different supply chains and regions [14, 27, 67]. However, the lowest estimates of supply chain emissions are around 60 $gCO_{2eq.}$/kWh, which is extremely low considering the potential contribution from liquefaction alone is estimated to be 80–100 $gCO_{2eq.}$/kWh. Methane slip from the engine also contributes to the differences, particularly compared to the NGVA study [19]. Whilst estimates of emissions from the HPDF engine are similar (589 cf. 598 $gCO_{2eq.}$/kWh), our updated methane figures from the LPDF 4-stroke engines differ significantly (662 vs 787 $gCO_{2eq.}$/kWh).

## 3.6 Maximum allowable methane emissions

Given the critical importance of methane slip and upstream methane emissions, this section assesses the maximum allowable methane emissions to ensure a climate benefit across different timescales compared to HFO. Figure 9 shows the impact of different total supply chain methane emissions with varying $CO_2$ equivalence. The figure indicates that if methane emissions are kept below 0.8–1.6%, a climate benefit is achieved over all $CO_2$ equivalences and timescales compared to HFO (labelled as points a–b in Figure 9). To ensure a climate benefit is achieved over 100 years for all engines and scenarios, methane emissions must be below 1.5–4.9% (labelled c–d) and for 20 years the figure is 0.9–2.2% (labelled e–f). Some supply chains and engine types already exhibit these emission rates below 0.8–1.6%, but emissions could be reduced further, as explored in the next section.

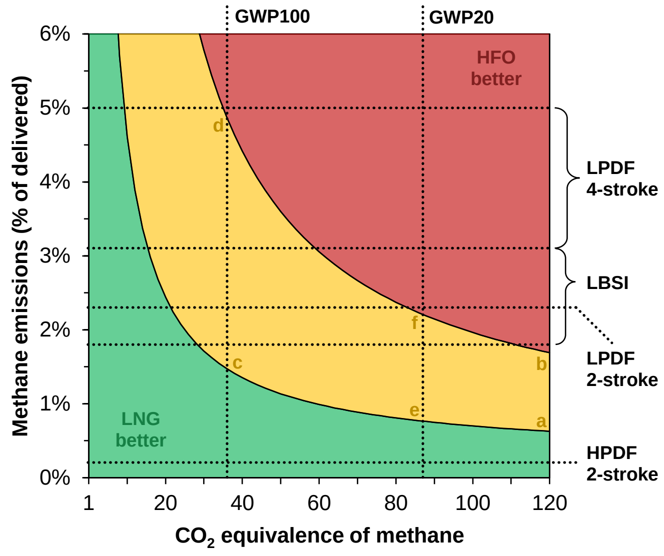


*Figure 9. Maximum allowable methane emissions to ensure climate parity with HFO over time, for different CO2 equivalences (GWP values). The green area represents conditions where LNG is favourable to HFO, the red area is when HFO is favourable and the amber area depends on other aspects such as engine efficiency and supply chain emissions. Methane emissions included are across the whole supply chain including end-use and are expressed as a percentage of total gas consumed.*

# 4. Discussion

Given the recent IMO target for at least 50% GHG reduction by 2050, substantial reductions are required from fuel change, demand reduction and efficiency increase [2]. Note that the IMO target is a total climate emission reduction of 50% which means that the emissions reductions per kWh or per ship must be greater given the projected increase in shipping demand. For LNG, there is potential to reduce GHG emissions, but this is clearly limited by its carbon content. Figure 10 shows the change in total GHG emissions achieved from switching from HFO to other fuels. Two of the four LNG engines give reductions of 8% and 18%, with the HPDF engine offering up to 28% reduction in GHG emissions and the LPDF 2-stroke offering up to 18% (on a GWP100 basis). However, across the range of supply chain and slip emissions for each scenario there is also a risk of LNG engines producing higher emissions than HFO. Consequently, it is vital that LNG supply chains and engines meet the highest standards included within this study.

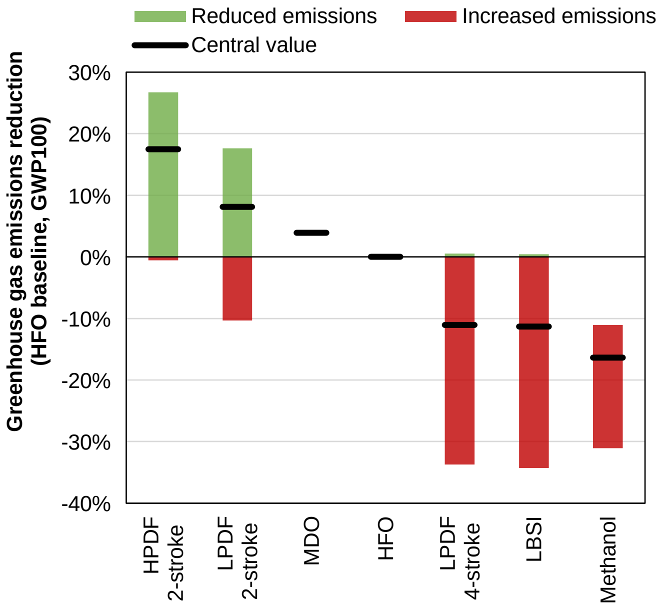


*Figure 10. The emissions reduction potential for each fuel and engine type relative to the HFO baseline. The error bars represent the minimum and maximum values from the scenarios considered in this study.*

There are several options to further reduce emissions beyond those estimated in this study and to meet 50% GHG reduction targets. The requirements for LNG ships to meet a 50% emissions reduction is quantified in Figure 11 via the combined target for methane emissions and ship efficiency improvements. Efficiency increases or fuel savings must be at least 33% to enable LNG ships to meet 50% reduction targets, even with zero methane emissions. With a realistic level of total methane emissions, for example 2% (the International Energy Agency global average [1] plus the low emitting HPDF engine), a ~40% energy efficiency increase would be required to meet a 50% GHG reduction target.

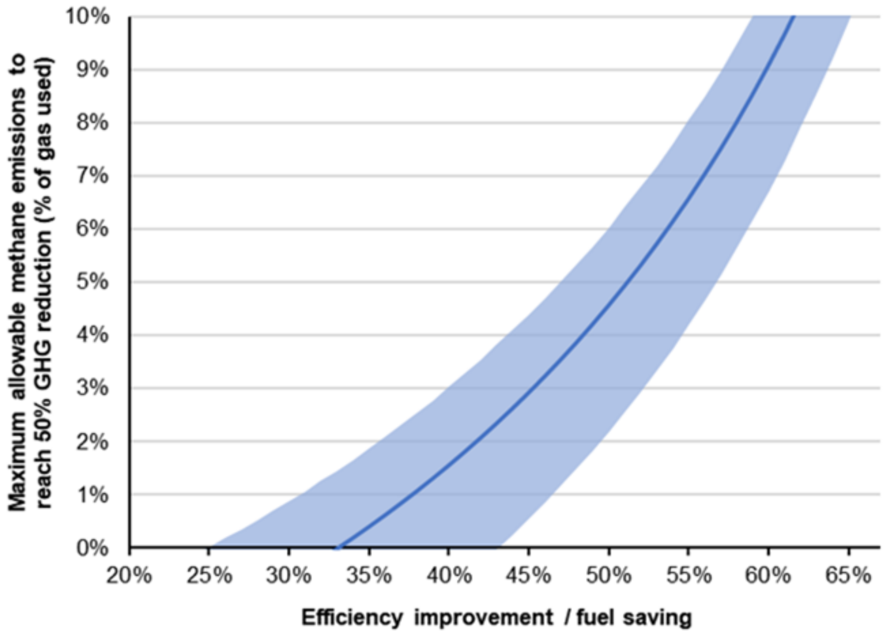


*Figure 11. Maximum allowable methane emissions and operational efficiency increase/ fuel savings required for LNG to meet a 50% GHG emission reduction compared to HFO. The central value represents the HPDF engine with a central $CO_2$ emission scenario, the shaded area represents the lowest and highest across all engines and supply chain scenarios.*

Options for further reducing GHG emissions and increasing efficiencies are explored in the following sections, relating to reducing methane emissions, increasing efficiency, and incorporating biomethane.

## 4.1 Reducing methane and supply chain emissions

Methane emissions can never be eliminated from the upstream supply chain, but significant reductions are possible. Best practice supply chains could achieve emissions of 0.2–0.5% of delivered gas [14]. It is imperative that the effect of super-emitters, a small number of high-emitting equipment or facilities, is minimised. The effective implementation of frequent leak detection and remediation (LDAR) can ensure super-emitters are identified and remediated quickly. The Oil and Gas Climate Initiative (a member organisation of 13 of the largest oil and gas companies) recently committed to reducing their supply chain emissions to 0.2% [68], although this does not include the full supply chain. However, there is still a lack of data to quantify emissions at key supply chain stages, particularly for LNG transport. It is vital that further measurements are taken from a representative sample from the current fleet to quantify methane emissions from LNG carriers.

Regarding ship operation, the low-methane HPDF 2-stroke engine must be validated with operational emission measurements to prove that emissions of <0.2% can be achieved. For the other engines, methane reduction must be a top priority and progress is expected on reducing methane slip if given a suitable regulatory push. Methane emissions could be reduced from higher-emission ships via operational control, engine design or after-treatment. Improved process control, variable valve timing and improved gas metering are operational measures are being implemented by industry, as shown by improved methane slip rates since 2010 [11]. Engine design has also improved to reduce dead space where methane would remain uncombusted. Low engine loads are likely to cause higher emissions and consequently the implementation of cylinder deactivation at low load could reduce total emissions [69]. Lower temperatures cause incomplete combustion and methane slip, which arises from a leaner air-fuel mixture or at low load operation. Consequently, operational control is vital in minimising methane slip. The Sintef report suggests that LPDF 4-stroke engines emissions could be reduced to 1.7%-2.4% [11], but this is not enough to compete with other existing engine types.

Combining low supply chain emissions with the lowest engine emissions, this study shows that total emissions could be constrained to less than 0.5%. As the importance of methane emissions increases with ever-strengthening climate targets, industry may drive even greater reductions. If so, LNG-fuelled ships could deliver emissions reductions beyond 30% compared to HFO. Similarly, $CO_2$ emissions may be reduced further in the supply chain, particularly the liquefaction process. Liquefaction is an energy intensive process where the fuel is typically a proportion of the gas itself. This results in $CO_2$ emissions from combustion, but these emissions are exacerbated per unit of energy delivered as ~10% of delivered gas is consumed as fuel in liquefaction. If fuel were derived from an alternative lower carbon source, this emission could be constrained.

## 4.2 Increasing engine and ship efficiency

A second route to further decarbonisation is to reduce fuel usage from increased energy efficiency. Efficiency gains could be made from the engine and power plant, or from broader ship design or operational improvements. The impact of increased efficiency is two-fold: reducing direct $CO_2$ emissions via burning less fuel, but also reducing the embodied supply chain emissions.

Several engine efficiency improvements have potential in the near future, including exhaust gas recirculation, variable valve timing, improved turbocharging and combustion chamber design [11]. Some of these measures are already operational. Sintef suggest that engine efficiency could increase to greater than 50% from 45–48% with current low-pressure engines [11]. However, newer 2-stroke gas engines already exhibit efficiencies of 53-55% LHV.

There are also several options for improving ship efficiency based on waste heat recovery, slow steaming, hull design and renewables. Typically half of the fuel's chemical energy is lost as waste heat, and can be converted into mechanical or electrical energy with Waste Heat Recovery Systems (WHRS) [70-72]. Several commercial systems are available, but these are generally high cost and complex to retrofit [71, 73], offering fuel savings in the range of 4–16% [70, 71, 74]. Slow steaming is an operational decision that requires no vessel alterations but means more vessels or journeys are required to transport the same volume of cargo. Reducing vessel speed lowers drag and a 10% speed reduction can enable a 15–20% fuel saving [75, 76]. Increased transport times is a result, but there is a cost trade-off between fuel and other operational costs. Slow steaming is estimated to have reduced international shipping emissions by 10–30% over the last decade [3, 77]. Various paints, hull coatings and air lubrication can minimise skin friction and inhibit organism attachment, including biocides (which are generally the cheapest option) and non-stick coatings (which are more ecologically benign) [78, 79]. Modern coatings are expected to reduce fuel consumption by 5–15%[80, 81]. Newbuild ships can be improved further by optimising ship design, with lighter materials, slender hulls and bulbous bows; each believed to save around 10% of fuel consumption[80-82].

Onboard renewables are another option. Several companies are trialling sails and kites to harness wind power [83], which can reduce fuel consumption by up to 25% on smaller ships (up to 10,000 tonnes) [84, 85]. Wind assistance is more beneficial at lower speeds, thus combining with slow steaming would compound efficiency gains. Solar panels are also being demonstrated in several vessels, primarily for auxiliary power requirements, offering up to 10% fuel savings [86, 87]. Hybrid solar sails can provide more of the ship's energy needs whilst preserving limited deck space [80, 83].

Individual efficiency measures can save in the region of 10% of fuel consumption, so several measures must be combined with natural gas engines to comply with the IMO's 50% decarbonisation target. For example, natural gas engines (up to 28% carbon savings) could be combined with slow steaming (10–20%) and wind assistance (15–20%) to meet a 50% reduction in $CO_2$ emissions [2].

### 4.3 Blending or replacing with biomethane

As suggested in the Section 3.1, the replacement of natural gas with biomethane, or liquid biogas, could substantially reduce GHG emissions [88, 89] and could be produced from waste residues or dedicated energy crops. Biomethane is methane produced from biogenic material, for example anaerobic digestion of wet organic matter. As the carbon atoms within biomethane are biogenic, the resultant CO2 emissions from its combustion is often discounted due to the carbon cycle in plant growth. GHG emissions may be ~40% of those from LNG due to discounted biogenic carbon emissions, but are dependent on the feedstock source and production process [2]. It is important to acknowledge that biofuel supply chain emissions are not negligible and methane emissions may be high, both from end-use as well as over the supply chain [90].

Biomethane has the potential to further reduce GHG emissions while complying with air quality regulations too, but there may be resource and cost constraints going forward. Currently, global biogas production is around 1.2 EJ/year [91], whereas fuel consumption from shipping is approximately 13 EJ/yr [3]. Haberl et al. [92] suggest that by 2050, a technical resource potential of 49 EJ/year could be achieved from crop residues, and 39 EJ/year from manure residues [92]. However, these projections do not consider policy or economic constraints, which would reduce these values significantly. Modelling business as usual and decarbonisation pathways with the MUSE integrated assessment model [93] suggests much lower potential for biogas. Production from agricultural, animal, and industrial wastes, as well as energy crops is modelled to reach 1.9-3.2 EJ/year in 2030 and 4.8-15.4 EJ/year in 2050. A description of the model, scenarios and main results can be found in the Supplementary Information.

Even if biofuel production were to achieve larger scales, it may be that other uses of biofuels would be prioritised over shipping: the dependence of decarbonisation pathways on the successful implementation of negative emissions technologies for example. Bioenergy with carbon capture and storage (BECCS) may be essential for achieving net-zero emissions, leaving little scope for use as a shipping fuel. In summary, bio-LNG offers a compatible mix with – or replacement to – LNG and may offer reduced net emissions, but availability is likely to be a barrier to a larger-scale contribution to shipping.

In summary, access to a responsibly managed renewable fuel infrastructure is necessary to meet climate targets, although this will require varying levels of infrastructural (and technology) development and investment. Additionally, the cost of fuel is an uncertainty and may be higher than conventional higher-emitting fuels. The use of biofuels may negate the need for substantial infrastructural development, but there are resource constraints that limit their potential use in the marine sector.

LNG fuel combined with additional efficiency measures on the other hand will require capital investment onboard but is likely to represent a lower cost option. Efficiency measures typically do not require infrastructural reform and so can be carried out on a ship-by-ship basis. This may represent lower cost and logistical/policy challenge, but with the risk of lower improvements in GHG emissions, or even a risk of worsening impacts compared to today should the gas supply chain emissions be unconstrained.

Moving forward, dependence on unabated fossil fuels must be diminished to meet net-zero global emissions rates in the second half of this century. But in the meantime, LNG-fuelled ships with additional efficiency improvements represent an option for emissions reductions at low cost and without substantial infrastructural investment.

# 5. Conclusions

This study has conducted an environmental and cost assessment of four LNG marine engines and compared them to incumbent fossil fuels and methanol. As with most comparative life cycle assessment (LCA) studies, no option presents the lowest environmental and cost impacts across all categories, but HPDF engines perform best in 7 of the 9 categories. The LNG-fuelled HPDF engine exhibits lowest climate impacts, costs, and air quality impacts, apart from higher $NO_X$ emissions. It gives GHG reductions of up to 28% compared to HFO on a GWP100 basis, whilst the LPDF 2-stroke gives reductions of up to 18%. The higher efficiencies of these two engines compared to other engines markedly lowers both engine and supply chain emissions. This compound effect demonstrates that higher-efficiency gas engines could make a large contribution to greenhouse gas reductions. By using the GTP100 metric with a lower methane $CO_2$ equivalency than GWP100, all gas-fuelled engines perform favourably to the liquid fuels, with GHG savings of 12–26% on average compared to HFO. On the other hand, using the GWP20 metric with a high equivalency results in only the HPDF engine being favourable over liquid fuels. However, it must be acknowledged that emissions rates for the HPDF and LPDF 2-stroke engines are yet to be proven and should be the focus of further work. Natural gas supply chain emissions of both $CO_2$ and methane must be proven to be low, to ensure that natural gas can outperform other fossil fuels for marine transport. Methanol from natural gas performs relatively poorly on climate impacts due to the carbon intensity of the supply chain. However, the $CO_2$ emissions from the end-use are slightly lower than HFO and MDO.

LNG-fuelled ships exhibit reduced environmental impacts for the most air quality metrics. However, currently LBSI and LPDF 4-stroke engines emit too much methane (2.5% and 3.1% w/w respectively) to ensure that LNG provides a climate benefit compared to other fuels. This study estimates the maximum allowable emissions from the supply chain and use to ensure a climate benefit over liquid fuels. Total methane emissions must be reduced to 0.8% - 1.6% to ensure climate benefit is realised across all timescales compared to liquid fuels. To achieve such low emissions, methane slip must be reduced to levels assumed for HPDF engines. Additionally, supply chains must ensure that the distribution of emissions is constrained, and the impact of potential super-emitters is minimised by timely and effective detection and remediation techniques.

LNG engines are unable to meet the industry's 50% GHG emissions reduction target without further improvement. Improvements may come from reduced methane emissions, increased engine, and broader ship efficiencies, as well as a potential shift to low-carbon fuels. Total methane emissions could be constrained to less than 0.5%, engine efficiencies could be moderately improved and there is substantial potential for ship efficiency measures relating to waste heat recovery, slow steaming, and hull design. With a methane emission rate of 0.5%, 35% efficiency savings would be needed to meet a 50% emissions reduction. Combined, these measures would serve to meet intermediate climate targets, with bio-LNG, hydrogen and ammonia offering future routes to deeper decarbonisation.

It must be acknowledged that there are very few high-quality and transparent measurements of methane emissions from LNG engines and LNG transport, and this must be urgently addressed. If natural gas is to play a significant role in the shipping sector, methane emissions must be acknowledged, understood, and systematically reduced via technological innovation and effective operation and maintenance practices.

# Conflicts of interest

There are no conflicts of interest to declare.

# Acknowledgements

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# References


[1] IEA. World Energy Outlook 2017. Paris, France2017.
[2] Balcombe P, Brierley J, Lewis C, Skatvedt L, Speirs J, Hawkes A, et al. How to decarbonise international shipping: Options for fuels, technologies and policies. Energy Conversion and Management. 2019;182:72-88.
[3] Smith TWP, Jalkanen JP, Anderson BA, Corbett JJ, Faber J, Hanayama S, et al. Third IMO GHG Study. London: International Maritime Organization; 2015. p. 1-327.
[4] IMO. Adoption of the initial IMO strategy on reduction of GHG emissions from ships and existing IMO activity related to reducing GHG emissions in the shipping sector. In: IMO, editor. Note by the International Maritime Organization to the UNFCCC Talanoa Dialogue. London, UK: International Maritime Organization; 2018. p. 1-27.
[5] Stam C. UN draft calls on international shipping to halve greenhouse gas emissions by 2050. Euractiv2018.
[6] MEPC. Resolution MEPC.176(58): Amendments to the annex of the Protocol of 1997 to amend the international convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto (Revised MARPOL Annex VI) in MEPC 58/23/Add.1 In: International Maritime Organization, editor.2008.
[7] Olmer N, Comer B, Roy B, Mao X, Rutherford D. Greenhouse Gas Emissions From Global Shipping, 2013-2015. In: ICCT, editor.: The International Council on Clean Transportation; 2017. p. 1-38.
[8] Staffell I, Scamman D, Velazquez Abad A, Balcombe P, Dodds PE, Ekins P, et al. The role of hydrogen and fuel cells in the global energy system. Energy & Environmental Science. 2019.
[9] Parkinson B, Balcombe P, Speirs JF, Hawkes AD, Hellgardt K. Levelized cost of CO2 mitigation from hydrogen production routes. Energy & Environmental Science. 2019.
[10] Ramachandran S, Stimming U. Well to wheel analysis of low carbon alternatives for road traffic. Energy & Environmental Science. 2015;8(11):3313-24.
[11] Stenersen D, Thonstad O. GHG and NOx emissions from gas fuelled engines. Mapping, verification, reduction technologies. Trondheim, Norway: SINTEF Ocean AS; 2017. p. 1-52.
[12] Hoffman J. Review of Maritime Transport 2017. New York: UNCTAD; 2017.
[13] Lowell D, Wang H, Lutsey N. Assessment of the fuel cycle impact of liquefied natural gas as used in international shipping. In: International Council on Clean Transportation, editor.: MJ Bradley and Associates & International Council on Clean Transportation; 2013.
[14] Balcombe P, Brandon NP, Hawkes AD. Characterising the distribution of methane and carbon dioxide emissions from the natural gas supply chain. Journal of Cleaner Production. 2018;172:2019-32.
[15] Balcombe P, Speirs JF, Brandon NP, Hawkes AD. Methane emissions: choosing the right climate metric and time horizon. Environmental Science: Processes & Impacts. 2018;20(10):1323-39.
[16] Ellis J. Environmental Performance and Provision of Sustainable Methanol for the Smaller Vessel Fleet. SUMMETH Sustainable Marine Methanol. Sweden: SSPA; 2017.
[17] DNV GL Maritime. Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility. In: Organization IM, editor.2016.
[18] Methanex. Industry welcomes four new ocean-going vessels capable of running on methanol. 2018.
[19] Schuller O, Reuter B, Hengstler J, Whitehouse S, Zeitzen L. Greenhouse Gas Intensity of Natural Gas. Natural & Bio Gas Vehicle Association (NGVA) Europe: Thinkstep AG; 2017. p. 180.
[20] Gilbert P, Walsh C, Traut M, Kesieme U, Pazouki K, Murphy A. Assessment of full life-cycle air emissions of alternative shipping fuels. Journal of Cleaner Production. 2018;172(Supplement C):855-66.
[21] Thomson H, Corbett JJ, Winebrake JJ. Natural gas as a marine fuel. Energy Policy. 2015;87:153-67.

[22] Brynolf S, Fridell E, Andersson K. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. Journal of Cleaner Production. 2014;74:86-95.
[23] Verbeek RP, Kadijk G, van Mensch P, Wulffers C, van den Beemt B, Fraga F, et al. Environmental and Economic aspects of using LNG as a fuel for shipping in The Netherlands: Delft: TNO, 2011.
[24] Deniz C, Zincir B. Environmental and economical assessment of alternative marine fuels. Journal of Cleaner Production. 2016;113:438-49.
[25] ISO. ISO 14040-environmental management - life cycle assessment - principles and framework. Geneva2006.
[26] ISO. ISO 14044-environmental management - life cycle assessment - requirements and guidelines. Geneva2006.
[27] Balcombe P, Anderson K, Speirs J, Brandon N, Hawkes A. Methane and CO2 emissions from the natural gas supply chain: an evidence assessment. In: Sustainable Gas Institute, editor. White Paper Series. www.sustainablegasinstitute.org/publications/white-paper-1: Imperial College London; 2015.
[28] Tamura IT, T.; Kagajo, T.; Kuwabara, S.; Yoshioka, T.; Nagata, T.; Kurahashi, K.; Ishitani, H. M. S., . Life cycle CO2 analysis of LNG and city gas. . Applied Energy 2001;68:301-19.
[29] Okamura T, Furukawa M, Ishitani H. Future forecast for life-cycle greenhouse gas emissions of LNG and city gas 13A. Applied Energy 2007;84:1136–49.
[30] Yoon Sung Yee YT. Life-cycle inventory analysis on fossil energy in Japan. Energy Economics. 1999;25(8):22-48.
[31] Hondo H. Life cycle GHG emission analysis of power generation systems: Japanese case. Energy. 2005;30(11–12):2042-56.
[32] Nie Z, Korre A, Durucan S. Full Chain Analysis and Comparison of Gas-Fired Power Plants with Co2 Capture and Storage with Clean Coal Alternatives. Energy Procedia. 2013;37(0):2840-7.
[33] Pace Global. Life Cycle Assessment of GHG Emissions from LNG and Coal Fired Generation Scenarios: Assumptions and Results In: Center for Liquefied Natural Gas, editor. Fairfax, VA2009.
[34] ARI, ICF. Greenhouse Gas Life-cycle Emissions Study: Fuel Life-Cycle of U.S. Natural Gas Supplies and International LNG. In: International AR, International I, editors.: Sempra LNG; 2008.
[35] IMO. Reduction of GHG emissions from ships: Methane emission from LNG carriers. Submitted by the Republic of Korea: International Maritime Organization; 2017. p. 1-5.
[36] Corbett JJ, Thomson H, Winebrake JJ. Methane Emissions from Natural Gas Bunkering Operations in the Marine Sector: A Total Fuel Cycle Approach. US Department of Transport: University of Delaware; 2015. p. 1-38.
[37] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assessment. 2016;21(9):1218-30.
[38] NREL. US Life Cycle Inventory Database. In: National Renewable Energy Laboratory, editor. www.lcacommons.gov/nrel/search2012.
[39] Bengtsson S, Andersson K, Fridell E. A comparative life cycle assessment of marine fuels: liquefied natural gas and three other fossil fuels. Proceedings of the Institution of Mechanical Engineers Part M-Journal of Engineering for the Maritime Environment. 2011;225(M2):97-110.
[40] Win-GD. 2-Stroke DF Engines – Typical Exhaust Gas Emission Data. Research + Development: Winterthur Gas & Diesel Ltd.; 2018.
[41] MAN Diesel & Turbo. ME-GI Dual Fuel MAN B&W Engines: A Technical, Operational and Cost-effective Solution for Ships Fuelled by Gas. Copenhagen, Denmark2014. p. 1-32.
[42] Wroblewski W. Machinery solution for LNG carrier 174 000 m3. Marketing and Application Win-GD; 2018. p. 1-18.
[43] Myhre G, Shindell D, Bréon F-M, Collins W, Fuglestvedt J, Huang J, et al. Anthropogenic and Natural Radiative Forcing. In: Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.), editor. In: Climate Change 2013: The Physical Science Basis Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2013.

[44] Mallapragada DS, Mignone B. A consistent conceptual framework for applying climate metrics in technology life cycle assessment. Environmental Research Letters. 2017.
[45] Shindell D, Fuglestvedt JS, Collins WJ. The Social Cost of Methane: Theory and Applications. Faraday Discussions. 2017;200.
[46] EIA U. US Natural Gas Imports by Country. US Energy Information Administration,; 2018.
[47] MAN Diesel & Turbo. Costs and Benefits of LNG as Ship Fuel for Container Vessels. Copenhagen, Denmark: MAN Diesel & Turbo; 2012. p. 1-18.
[48] Ship & Bunker. World Bunker Prices. British Columbia, Canada2018.
[49] DNV GL Maritime. Current Price Development of Oil and Gas. Norway2018.
[50] Bunker Index. Bunker Index MDO, BIX MDO. Southport, UK2018.
[51] Alvorado M. Presentation: Methanol. In: IHS, editor.: IHS; 2016. p. 1-34.
[52] Intratec. Methanol Price History & Forecast. Historical Prices in USA, Netherlands, China, India & Forecast. Houston, Texas2018.
[53] Methanex. Methanex Monthly Average Regional Posted Contract Price History. Accessed from: www.methanex.com/our-business/pricing: Methanex Corporation; 2018.
[54] Ship & Bunker. Vancouver Spot LNG Bunker Price at Lowest in Almost 2 Years. America News2018.
[55] Balcombe P, Speirs J, Johnson E, Martin J, Brandon N, Hawkes A. The carbon credentials of hydrogen gas networks and supply chains. Renewable and Sustainable Energy Reviews. 2018;91:1077-88.
[56] Speirs J, Balcombe P, Blomerus P, Stettler M, Achurra-Gonzalez P, Woo M, et al. Natural gas fuel and greenhouse gas emissions in trucks and ships. Progress in Energy. 2019.
[57] Bicer Y, Dincer I. Clean fuel options with hydrogen for sea transportation: A life cycle approach. International Journal of Hydrogen Energy. 2018;43(2):1179-93.
[58] Yoo B-Y. Economic assessment of liquefied natural gas (LNG) as a marine fuel for CO2 carriers compared to marine gas oil (MGO). Energy. 2017;121:772-80.
[59] Taljegard M, Brynolf S, Grahn M, Andersson K, Johnson H. Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model. Environmental Science & Technology. 2014;48(21):12986-93.
[60] Corkhill M. The world's LNG-fuelled ships on order, 2017. In: Shipping LW, editor. LNG World Shipping: Riviera Maritime Media Ltd; 2017.
[61] Speirs J, Balcombe P, Blomerus P, Stettler M, Achurra-Gonzalez P, Woo M, et al. Natural gas fuel and greenhouse gas emissions in trucks and ships. Progress in Energy. 2020;2(1):012002.
[62] Burel F, Taccani R, Zuliani N. Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. Energy. 2013;57:412-20.
[63] Byeong-YongYoo. Economic assessment of liquefied natural gas (LNG) as a marine fuel for CO2 carriers compared to marine gas oil (MGO). 2017.
[64] DNV GL. LNG as ship fuel: the future - today. DNV GL; 2014.
[65] Nader Ammar, Seddiek I. Eco-environmental analysis of ship emission control methods: Case study RO-RO cargo vessel. Ocean Engineering. 2017;137.
[66] Verbeek R, Kadijk G, Mensch Pv, Wulffers C, Beemt Bvd, Fraga F. Environmental and Economic Aspects of Using LNG as a Fuel for Shipping in The Netherlands. Delft, The Netherlands: TNO; 2011. p. 1-48.
[67] Balcombe P, Anderson K, Speirs J, Brandon N, Hawkes A. The Natural Gas Supply Chain: The Importance of Methane and Carbon Dioxide Emissions. ACS Sustainable Chemistry & Engineering. 2017;5(1):3-20.
[68] OGCI. Oil and Gas Climate Initiative sets first collective methane target for member companies. Oil and Gas Climate Initiative; 2018.
[69] Sommer DE, Yeremi M, Son J, Corbin JC, Gagné S, Lobo P, et al. Characterization and Reduction of In-Use CH4 Emissions from a Dual Fuel Marine Engine Using Wavelength Modulation Spectroscopy. Environmental Science & Technology. 2019;53(5):2892-9.

[70] Senary K, Tawfik A, Hegazy E, Ali A. Development of a waste heat recovery system onboard LNG carrier to meet IMO regulations. Alexandria Engineering Journal. 2016;55(3):1951-60.
[71] Singh DV, Pedersen E. A review of waste heat recovery technologies for maritime applications. Energy Conversion and Management. 2016;111:315-28.
[72] Yang M-H, Yeh R-H. Thermodynamic and economic performances optimization of an organic Rankine cycle system utilizing exhaust gas of a large marine diesel engine. Applied Energy. 2015;149:1-12.
[73] Sprouse C, Depcik C. Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery. Applied Thermal Engineering. 2013;51(1):711-22.
[74] Baldi F, Gabrielii C. A feasibility analysis of waste heat recovery systems for marine applications. Energy. 2015;80:654-65.
[75] Faber J, Wang H, Nelissen D, Russell B, Amand DS. Reduction of GHG emissions from ships: Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures. In: (SNAME) TSoNAaME, editor. London, UK: International Maritime Organization (IMO); 2011.
[76] Lee C-Y, Lee HL, Zhang J. The impact of slow ocean steaming on delivery reliability and fuel consumption. Transportation Research Part E: Transport and Environment. 2015;76:176-90.
[77] Cariou P. Is slow steaming a sustainable means of reducing CO 2 emissions from container shipping? Transportation Research Part D: Transport and Environment. 2011;16(3):260-4.
[78] Willsher J. The Effect of Biocide Free Foul Release Systems on Vessel Performance London: International Paint Ltd; 2008.
[79] Swain G. The importance of ship hull coatings and maintenance as drivers for environmental sustainability. Quarterly Journal of Ship Hull Performance. 2011;1(4):50-8.
[80] ITF, OECD. Decarbonising Maritime Transport - Pathways to zero-carbon shipping by 2035. International Transport Forum; 2018.
[81] DNV GL. Low Carbon Shipping Towards 2050. 2017.
[82] Suárez de la Fuente S, Larsen U, Pawling R, García Kerdan I, Greig A, Bucknall R. Using the forward movement of a container ship navigating in the Arctic to air-cool a marine organic Rankine cycle unit. Energy. 2018;159:1046-59.
[83] FathomShipping. Could Wind Power Return To Commercial Shipping? : gCaptain; 2012.
[84] Traut M, Gilbert P, Walsh C, Bows A, Filippone A, Stansby P, et al. Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. Applied Energy. 2014;113:362-72.
[85] IWSA. IWSA Member – eConowind BV. The International Windship Association; 2018.
[86] Royal Academy of Engineering. Future Ship Powering Options - Exploring alternative methods of ship propulsion. 2013.
[87] Bouman EA, Lindstad E, Rialland AI, Strømman AH. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. Transportation Research Part D: Transport and Environment. 2017;52:408-21.
[88] IEA. Biofuels for the marine shipping sector. An overview and analysis of sector infrastructure, fuel technologies and regulations: IEA Bioenergy; 2017.
[89] Florentinus A, Hamelinck C, van den Bos A, Winkel R, Cuijpers M. Potential of Biofuels for Shipping – Final Report. Project number: BIONL11332 ed. Utrecht, Netherlands: Ecofys, European Maritime Safety Agency (EMSA); 2012.
[90] Whiting A, Azapagic A. Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion. Energy. 2014;70:181-93.
[91] Kummamuru B. WBA Global Bioenergy Statistics 2017. World Bioenergy Association; 2017.
[92] Haberl H, Beringer T, Bhattacharya SC, Erb K-H, Hoogwijk M. The global technical potential of bio-energy in 2050 considering sustainability constraints. Current Opinion in Environmental Sustainability. 2010;2(5):394-403.
[93] Kerdan IG, Giarola S, Hawkes A. A novel energy systems model to explore the role of land use and reforestation in achieving carbon mitigation targets: a Brazil case study. Journal of Cleaner Production. 2019;232:796-821.