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CAN NATURAL GAS REDUCE EMISSIONS FROM TRANSPORT?

HEAVY GOODS VEHICLES AND SHIPPING

WHITE PAPER 4

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Preface

The Sustainable Gas Institute at Imperial College London provides thought leadership and authoritative interdisciplinary evidence and analysis on the role of gas in future low carbon energy systems.

We manage, lead and deliver world-class research with our global partners across the spectrum of science, engineering, economics and business to support policymakers and industry in their decision-making.

Aims

- Examine the environmental, economic and technological role of natural gas in the global energy landscape;
- Define the technologies and develop energy systems models that could explore the role of gas and other energy sources;
- Address the global challenge of how to mitigate climate change.

Research Themes

We have three research themes:

1. **Methane emissions** - Comprehensive research into understanding methane emissions in energy supply chains through our Methane Environment Programme. Analysing data, technologies, through policy and regulation to realize the mitigation potential at every stage of the supply chain.

2. **Modelling gas futures** - Whole energy systems modelling to quantitatively assess the role gas will have in the future energy system, and the contribution of specific technologies, through to economics, policy and regulation. This includes the development of a technologically-rich and agent-based Integrated Assessment Model, MUSE.

3. **Gas evidence-base reports** - Rigorous, detailed and peer-reviewed analysis of the evidence on controversial issues around the topic of sustainable gas. This work is conducted through our White Paper Series.

Scope

While the focus of the Institute is natural gas research, the scope is often broader and encompasses work in optimising the sustainability of other energy vectors such as hydrogen, and biogas/biomethane.

Executive summary

Progress on reducing greenhouse gas emissions from transport has been relatively slow, with goods transportation and shipping emissions being particularly difficult to address. Local air pollutants arising from vehicles, such as nitrogen oxides, sulphur oxides and particulates, are also a significant concern for human health. Natural gas is an alternative transport fuel which may help reduce these emissions, particularly in shipping and long distance heavy goods transportation. However, there is some disagreement regarding the potential for natural gas to provide significant improvements relative to current transport systems.

Global traffic of trucks and ships represents a significant proportion of transport emissions, with road freight representing 7% of global energy related CO_2 emissions and shipping representing 2.6% of global emissions in 2015. These emissions are also expected to grow, with some estimates suggesting road freight emission growing by a third, and shipping emissions growing by between 50% and 250% by 2050, largely though increased demand for movement of goods. Decarbonising goods transportation has proved difficult relative to other forms of transport given the relatively long distances that ships and trucks travel.

Trucks and ships also contribute significantly to air pollution, through emission of pollutants such as sulphur oxides (SO_X), nitrogen oxides (NO_X), hydrocarbons and particulate matter. For example, road freight contributes approximately 17% of global NO_X emissions, and shipping contributes approximately 13% of global NO_X emissions and 12% of global SO_X emissions. These pollutants have a known impact on human health, including impacts on lung, heart and brain health. Natural gas has the potential to reduce these air pollution emissions, though as with CO_2 there is debate as to the potential of that reduction.

The aim of this white paper is to examine the evidence surrounding the use of natural gas as a transport fuel to address greenhouse gas and air pollution emissions in trucks and ships. This includes presenting the evidence on gas engine types, their emissions, technical considerations and costs. The report also discusses other options for emissions mitigation in transport including energy efficiency, after-treatment and other fuel-switching options such as hydrogen fuel cells or battery electric systems.

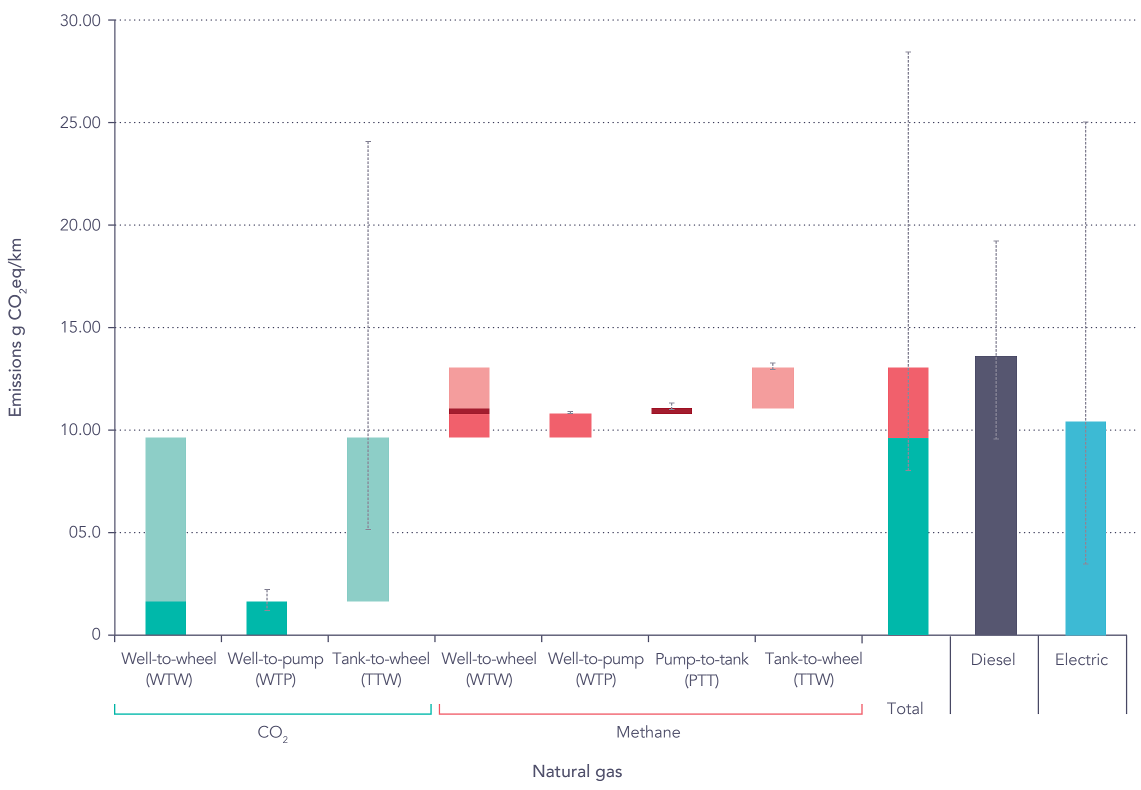
Key findings

1. Natural gas as a transport fuel has the potential to reduce greenhouse gas emissions in trucks and ships by ~16% and ~10%, respectively, comparing lowest estimates.

Greenhouse gas emissions from trucks or ships vary given differences in engine efficiency, methane slip through the exhaust, engine and fuel system methane emissions and supply chain emissions. Estimates of lifecycle emissions show a potential to reduce emissions from natural gas fuelled trucks by ~16% against lowest estimates of diesel truck emissions (Figure ES1). In ships the equivalent potential for lifecycle emissions reduction is ~10% relative to heavy fuel oil ships (Figure ES2).

At worst, natural gas fuelled trucks and ships may have lifecycle emissions exceeding current incumbent diesel trucks and heavy fuel oil ships. Dual fuel trucks in urban driving cycles or ships using low pressure dual fuel or lean burn engines are most likely to exhibit these high emissions.

FIGURE ES1
Breakdown of emissions from the well-to-wheel life cycle of average liquefied natural gas trucks, including the range of emissions estimates.



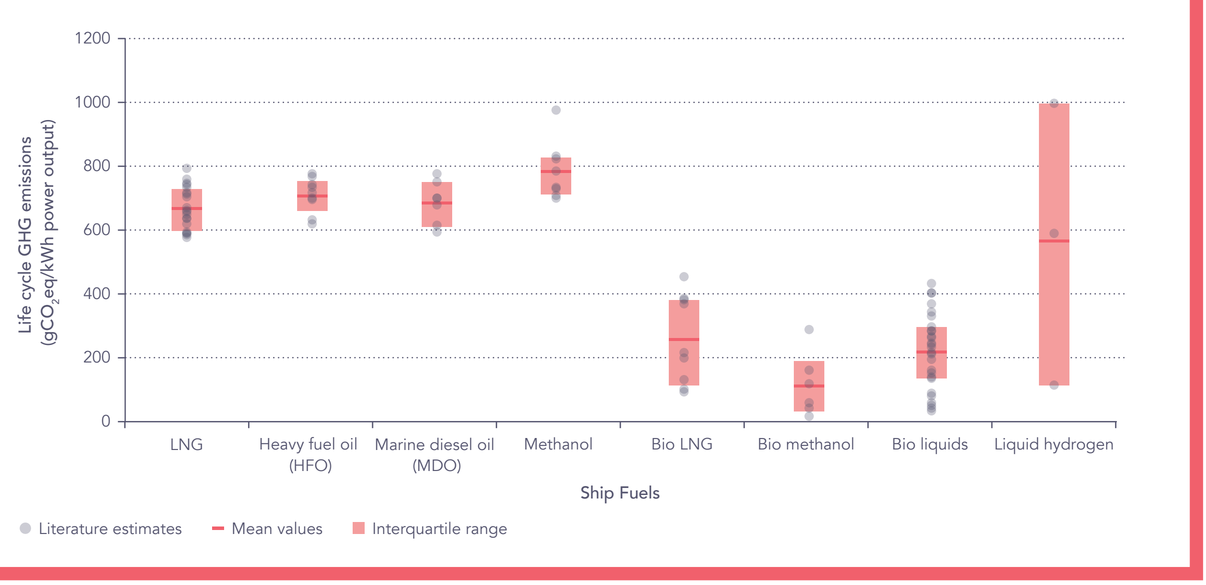


FIGURE ES2
Estimates of total life cycle GHG emissions associated with different marine fuels.

2. Air pollution emissions can be reduced significantly in shipping by switching to natural gas. Air pollution benefits in trucks are reduced given improvements in modern diesel engines.

NO_X emissions from spark ignited natural gas engines may be reduced by up to 80%, though emissions from dual fuel engines may be higher than diesel vehicles. Particulates may be reduced by 18% relative to diesel trucks, though again this is likely to reverse for the case of dual fuel engines. Lowest NO_X emissions are typically achieved on motorway driving cycles, with urban driving cycles leading to higher emissions for natural gas vehicles.

In ships NO_X emissions may be reduced by ~90%, SO_X emissions by ~90% and particulates by up to 98% against the average heavy fuel oil ships. However, there is likely a trade-off between NO_X emissions and methane slip with high pressure direct injection engines providing the lowest methane slip but also the highest NO_X emissions (~15% reduction). After-treatment technologies may be used to address this trade-off.

3. Global greenhouse gas emissions reductions from natural gas trucks and ships may not be sufficient to meet global emissions goals alone.

The technical challenge of long distance goods transportation, and the growing demand for it, create difficulty for decarbonising the sector. Global goals for greenhouse gas emissions reduction will likely require trucks and ships to adopt a combination of options, including efficiency measures, after-treatment technologies and fuel switching away from fossil fuels to low carbon fuels such as biofuels or hydrogen fuel cells.

In shipping, natural gas engines, in combination with ambitious energy efficiency improvements, may go a long way towards achieving the required GHG reduction, potentially reducing these by 35% relative to 2008 fleet emissions. However, even assuming very challenging rates of efficiency improvement it appears difficult to meet a 50% GHG emissions reduction target by 2050 using natural gas engines and ship efficiency improvements alone.

Deeper decarbonisation appears possible if a lower emissions ship technology such as hydrogen fuel cell ships becomes available in the period from 2040 and 2050, potentially leading to a 50% reduction against 2008 fleet emissions. In the meantime, the emissions benefit of natural gas in shipping is attractive, particularly when considered alongside the air pollution benefits.

The future role of natural gas in trucks and ships is in part influenced by the future availability of alternative low carbon technologies. These options are not commercially mature at present, and their future development and cost reduction is an important aspect defining the relative benefits of natural gas use as a transport fuel.

4. Natural gas is currently a cheaper fuel than diesel or heavy fuel oil, helping to 'pay back' the ~20% greater capital cost of trucks and ships that can use natural gas.

The additional capital cost relates to the fuel tank, fuel delivery system and the engine. Natural gas fuel costs are currently less than the fuels they replace. Liquefied natural gas prices have been on average ~50% less than heavy fuel oil prices between 2000 and 2015 and LNG and CNG are ~20% lower than diesel prices, including fuelling costs and duty. This means that the extra investment in natural gas trucks and ships is likely to be recovered by operators through reduced fuel costs, with studies estimating that payback periods between 15 months and eight years for trucks and between five and 16 years for ships. However, there is no guarantee that the current price or tax regimes will always favour natural gas transport fuels. Should prices or duties rise, the potential for payback of additional capital expenditure will diminish.

5. A number of policy options might be considered to minimise greenhouse gas emissions and incentivise the other technologies necessary to meet challenging global targets.

First, policies to help limit supply chain emissions are important. While other initiatives are already scrutinising possible action on the well-to-tank supply chain there is likely a need for policies that specifically monitor and reduce methane emissions throughout the supply chain.

Fuel taxes are also an area where policy and regulation can be applied to incentivise emissions reduction. The current tax differential between natural gas and diesel in trucks is an incentive to switch to natural gas. This is only helpful where its use leads to genuine emission reduction, such that complimentary policy instruments, in conjunction with rigorous and independent in-use testing, should be implemented to ensure that fuel tax benefits applied to natural gas natural are rewarded with genuine reductions in greenhouse gas emissions.

A broad suite of options are likely necessary for sufficient carbon reduction in the truck and ship sectors, including broader fuel switching options, energy efficiency measures and aftertreatment. Incentives or mechanisms to support these technologies will therefore be an important aspect of future policy in this area.

Finally, there are existing policies that can help meet some of the goals discussed above, though they are insufficient in their current form. Strengthening or extending policies such as the energy efficiency design index in shipping may be a valuable route to meeting long term emissions targets.

6. Further understanding is needed on a number of open questions in natural gas as a transport fuel in ship and trucks.

The available evidence suggests that, while estimates vary, there is a potential to reduce both greenhouse gas and air pollution emissions through a switch to natural gas as a transport fuel in ships and trucks. Further, doing so may be economically competitive with the incumbent fuels and engine technologies. However, a number of open questions require further understanding to help maximise the benefits of natural gas within the suite of available emissions reduction options. Areas that need further understanding include:

- **Real-world measurement** of the greenhouse gas and air pollution emissions from the latest natural gas trucks and ships and the supply chains that fuel them;

- **Improvements in technologies** and techniques to reduce these emissions. This includes engine and truck/ship designs to maximise efficiency and minimise methane emissions, and application and refinement of technologies to deal with methane emissions in the bunkering and refuelling of ships and trucks.

- I**mproved modelling of the transport system** to better understand the impact of emissions mitigation measures on total fleet emission and costs. This includes more technology richness, better real-world input data and improved understanding of the interactions between different options.

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List of abbreviations

AMT	Automated Manual Transmission
AR5	Assessment Report 5 (of the IPPC)
ASEAN	The Association of South-East Asian Nations
BC	Black Carbon
BOG	Boil-off Gas
CCC	Committee on Climate Change (UK)
CCS	Carbon Capture and Storage
CH_4	Methane
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
DF	Dual Fuel
DPF	Diesel Particulate Filter
DWT	Dead Weight Tonnage
ECA	Emissions Control Zone
EEDI	Energy Efficiency Design Index
EGR	Exhaust Gas Recirculation
EIA	Energy Information Administration
ETI	Energy Technologies Institute
FC	Fuel Cell
FCH2 JU	Fuel Cell and Hydrogen Joint Undertaking
FGT	Fixed Geometry Turbocharger
GDP	Gross Domestic Product
GHG	Greenhouse Gasses
Gt	Gross Tonnage

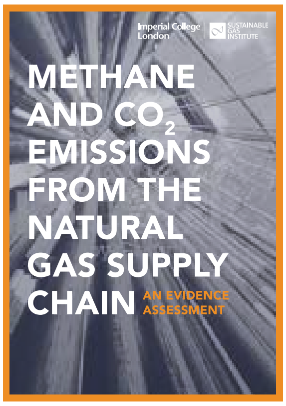
GT	Gas Turbine
GVWR	Gross Vehicle Weight Rating
GWP	Global Warming Potential
H_2	Hydrogen
HDV	Heavy Duty Vehicle
HFC	Hydrogen Fuel Cell
HFO	Heavy Fuel Oil
HGV	Heavy Goods Vehicle
HHV	Higher Heating Value
HPDI	High Pressure Direct Injection
IAM	Integrated Assessment Model
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
IEA	International Energy Agency
IFO	Intermediate Fuel Oil
IIASA	International Institute for Applied Systems Analysis
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
Lbs	Pounds as a unit of weight
LHV	Lower heating value
LNG	Liquefied Natural Gas
LS-LPDF	Low Speed Low Pressure Dual Fuel
MARPOL	Marine Pollution (a convention name)
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil

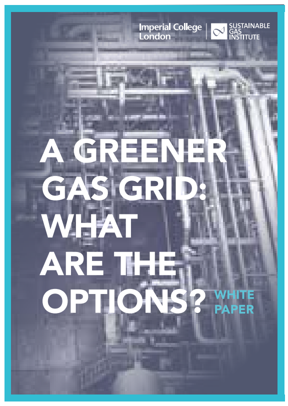
MSD	Medium Speed Diesel
MS-LPDF	Medium Speed Low Pressure Dual Fuel
MUSE	ModUlar energy system Simulation Environment
NGVA	Natural & bio Gas Vehicle Association
NO_X	Nitrogen Oxides
OECD	Organisation for Economic Co-operation and Development
PM	Particulate Matter
POC	Particle Oxidation Catalyst
PTT	Pump-to-Tank
ROI	Return on Investment
RoRo	Roll-on-Roll-off
SCR	Selective Catalytic Reduction
SILB	Spark Ignited Lean Burn
SINTEF	Stiftelsen for industriell og teknisk forskning (Norwegian – Foundation for industrial and technical research)
SIS	Spark Ignited Stoichiometric
SO_X	Sulphur Oxides
SSD	Slow Speed Diesel
TCO	Total cost of ownership
TTW	Tank-to-Wake
TWC	Three Way Catalyst
UKERC	UK Energy Research Centre
VGT	Variable Geometry Turbocharger
WHRS	Waste Heat Recovery System
WTP	Well-to-Pump
WTT	Well-to-Tank
WTW	Well-to-Wheel/Wake

The White Paper Series

The aim of the Sustainable Gas Institute (SGI) White Paper Series is to conduct systematic reviews of literature on topical and controversial issues of relevance to the role of natural gas in future sustainable energy systems. These white papers provide a detailed analysis on the issue in question, along with identifying areas for further research to resolve any shortcomings in our understanding. The reviews also examine key future technologies and provide a critique of assessment processes.

If you want to read more about the White Paper Series, please visit the Sustainable Gas Institute website:
(www.sustainablegasinstitute.org/white_paper_series)





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It should be noted that any opinions stated within this report are the authors' only.

Contents

1. Introduction

Emissions in the transport sector, both greenhouse gases (GHGs) and air pollutants (including oxides of nitrogen (NO_X), oxides of sulphur (SO_X) and particulate matter (PM), are an increasingly important issue in global energy systems. Progress on GHG emissions reduction from transport has been relatively slow, with shipping and road freight GHG emissions particularly difficult to reduce and, until recently, not subject to policy targets commensurate with the 2050 goals of global climate change agreements [1]. In addition, local air pollutants arising from vehicles, such as nitrogen oxides, sulphur oxides and particulates, are a growing concern for human health [2,3]. Natural gas has been suggested as an alternative transport fuel to help combat these emissions, particularly in shipping and goods transportation given the range requirements in these vehicle types [4,5]. However, there is some disagreement as to the potential for natural gas to provide significant improvements over emissions emerging from the current transport system [5].

The Sustainable Gas Institute (SGI) at Imperial College London has conducted a systematic review of the available evidence surrounding the impact of natural gas as a fuel for trucks and ships. This white paper presents the results, examining the evidence surrounding technical issues, emissions and costs associated with increased use of natural gas as a transport fuel. The paper focusses on natural gas as a fuel, the engines needed to use that gas and the supply chain considerations that contribute to total emissions. The findings are presented in the context of the alternative option, including the continued improvement of incumbent diesel technologies, along with battery electric and hydrogen systems. While it is the intention of this report to be geographically broad, much of the evidence arises from countries where gas is used most as a transport fuel.

1.1. The context

In road transport, diesel is the fuel most commonly used in heavy goods vehicles (HGVs) [6]. Continued development of efficiency and emissions regulations in regions such as Europe and the United States, including the reduced sulphur content of diesel fuel, have progressively improved emissions of new vehicles [5]. This has reduced the margin between emissions of diesel and natural gas fired vehicles.

In shipping a number of different fuels are used, representing oil fractions from diesel up to more viscous fuel oils [7]. Regulations in different ports and enclosed water ways often require use of low sulphur fuel oils or diesel in order to reduce local air pollution impacts. There is some debate as to the impact on GHG emissions of moving to compressed natural gas or liquefied natural gas [4, 5]. However, there appears to be a more positive impact on local air pollution through a move to natural gas based fuels in shipping [4, 5].

A key issue for natural gas use for both road transport and shipping emissions is that supply chain emissions of methane, and methane emissions from uncombusted methane in exhaust gasses (methane slip) can increase total GHG emissions significantly, given the high climate forcing characteristics of methane. Understanding the extent of supply chain leakage and methane slip are key to understanding the value of a transition to natural gas fuels in road transport and shipping.

A further issue is to understand to what extent decarbonised hydrogen or battery electric technologies may provide an alternative transport technology that may compete with natural gas in some instances. Outstanding questions include the time scale on which these options might be widely available, what emissions are produced (both GHG and local air pollution) and how does this compare to natural gas?

1.2. Aims and scope

The aim of this white paper is to review the available evidence on the use of natural gas as a transport fuel for heavy goods vehicles and shipping, focusing on the impact that this will have on emissions. This includes discussion of the use of both compressed and liquid natural gas (CNG and LNG). The analysis presented in this report focuses on the following key questions:

- What are the technical considerations in moving towards greater use of natural gas;
- What are the GHG emissions arising from the use of natural gas as a fuel;
- What contribution of these emissions is attributable to methane emissions;
- What role do supply chain emissions play in overall GHG emissions
- What is the impact of this fuel choice on emissions of local air pollutants; and
- What are the cost implications of the use of natural gas in trucks and shipping?

The report includes evidence on costs and emissions from the full supply chain. It lays out aspects of the incumbent fuel options, which includes diesel in trucks and heavy fuel oil (HFO) in ships. The existing emissions of these vehicles and their costs are presented to provide context of the current market, and to provide a benchmark against which improvements in emissions related to fuel switching to natural gas can be measured. This incumbent benchmarking also enables the measurement of the impacts of fuel switching to natural gas on costs, including vehicle costs and fuel costs.

In addition to natural gas as a fuel-switching option for ships and trucks there are also more advanced low carbon options including vehicles based on hydrogen fuel cells and vehicles based on battery electric systems. While these are not central to the evidence analysis, estimates of their costs and emissions are provided to give context to more deeply decarbonising options.

A range of energy efficiency measures are available to both trucks and ships, with significant potential to reduce emissions. Many of these options are independent of the fuel vector used. These are discussed briefly, and the efficiency improvement is quantified, though they are not central to the analysis in this study.

This study is not geographically specific, particularly in terms of international shipping, which is largely regulated based on coordinated international agreement. However, some regions are specifically relevant due to the scale of their truck or ship traffic. This means many studies originate in, or focus on, key regions, including Europe, the United States and China.

Finally, hybridisation of different energy vectors and drive systems is an interesting area of research and has the potential to reduce emissions significantly. While this option is discussed briefly in the context of energy efficiency measures, the wider discussion of this option is out of scope.

1.3. Methodology

This comprehensive review of academic, industrial and governmental literature has drawn on the methodology created by the UK Energy Research Centre (UKERC) Technology and Policy Assessment (TPA) group and refined by the Sustainable Gas Institute for its White Paper Series. The methodology uses systematic and well-defined search procedures to document the evidence review, providing clarity, transparency, replicability and robustness to the analysis. An external expert advisory panel was appointed with a broad range of perspectives to consult on the initial framing and specification of the review procedure, as well as providing additional comments on the emerging analysis. The research outputs have been reviewed by the expert panel prior to publication. The assessment process carried out is presented in Figure 1.

FIGURE 1 Diagram of the systematic review methodology.
Source: Adapted from [8]

Scope the project	Solicit expert input	Review the literature	Synthesis and analysis	Prepare the draft report	Expert panel review and refine	Publish and promote
TASKS • Write a scoping note, outlining aims and search and review protocols	• Appoint expert panel • Solicit expert panel comments on scoping note • Finalise aims and search and review protocols	• Apply protocol to literature search • Detailed and transparent 'trawl' • Identify relevant sources	• Apply protocol for evaluation and synthesis of literature	• Write preliminary draft report	• Solicit expert panel comments on draft report • Revise draft report	• Design and format report • Publish and publicise report • Launch event
OUTPUT • Submit scoping note to expert panel	• Expert panel review of scoping note	• Literature database		• Draft report	• Expert panel review of report	• Publish report

1.4. Important units

Where methane emissions are discussed these are presented as methane emissions as a percentage of total methane passing through the infrastructure or engine (% of throughput).

Where emissions from trucks are discussed these are expressed in grams per kilometre.

Where emissions from ships are discussed the emissions associated with the energy of fuel are expressed as grams per mega joule (g/MJ) and the emissions associated with the power output of a ship's engine (which accounts for engine efficiency) are expressed as grams per kilowatt hour (g/kWh).

These unit choices are chosen to best reflect the units used in the source literature.

TABLE 1
Description of relevant units.

g/km	Grams per kilometre
g/kWh	Grams per kilowatt hour
g/MJ	Grams per mega joulee
gCO_2eq	Grams of CO_2 equivalent

1.5. Supporting work

In support of the research in this white paper, two technical reports have been produced, which review the issues surrounding natural gas use in trucks and ships. These are:

- Technical report 1: Natural gas as a fuel for Heavy Goods Vehicles; and
- Technical report 2: Natural Gas as a Ship Fuel: Assessment of Greenhouse Gas and Pollution Reduction Potential

These are both available on the SGI website at:

www.sustainablegasinstitute.org/white_paper_series/white-paper-4-can-natural-gas-reduce-emissions-from-transport/

1.6. Structure

The rest of the white paper is structured as follows:

- Chapter 2 highlights the relevant details of the incumbent truck and ship sectors;
- Chapter 3 examines the options available to reduce the emissions from these vehicle types

- Chapter 4 lays out the supply chain emissions relevant to natural gas supply networks;
- Chapter 5 examines the evidence surrounding emissions from natural gas use in trucks;
- Chapter 6 examines the evidence surrounding emissions from natural gas use in ships;
- Chapter 7 compares the costs of fuel switching to natural gas as a transport fuel;
- Chapter 8 uses an integrated assessment model developed by the Sustainable Gas Institute, known as MUSE, to examine future scenarios of natural gas in international shipping; and finally,
- Chapter 9 summarises and concludes on the evidence in this report.

2. The current state of trucks and ships

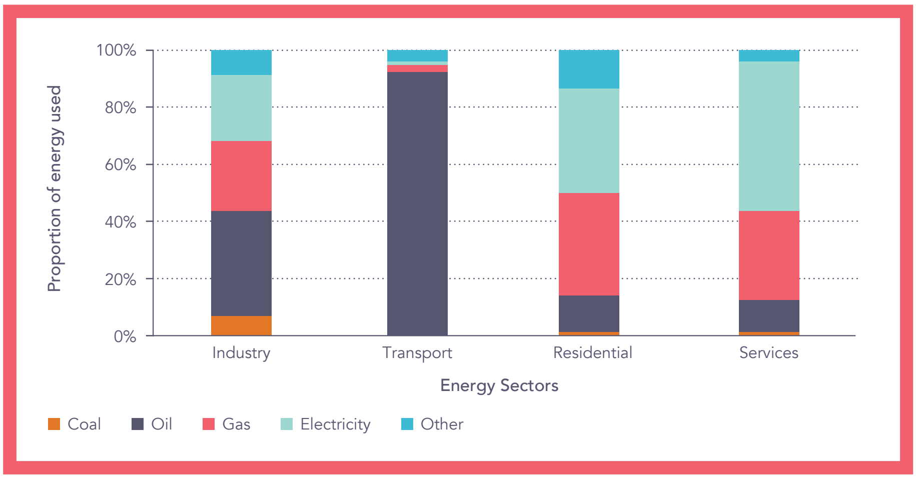
Global traffic of trucks and ships represents a significant proportion of transport emissions, with road freight representing 7% of global CO_2 emissions [6] and shipping representing 2.6% of global CO_2 emissions in 2015 [10]. These emissions are also expected to grow, with the IEA estimating growth in road freight emission by a third [6], and the IMO estimating shipping emissions growing by between 50% and 250% by 2050, largely through increased demand for movement of goods [10]. In addition, road freight contributes approximately 17% of global NO_X emissions, and shipping contributes approximately 13% of global NO_X emissions and 12% of global SO_X emissions [6, 11].

The following section presents some key issues relating to the current state of these transport modes, providing context on which future transport options may be analysed. The section begins by discussing trucks and ships in turn, presenting current vehicle and engine types, and the potential use of natural gas as a fuel for both. The section concludes with an examination of the drivers of change in truck and ship fuels, namely the reduction of GHG and air pollution emissions.

2.1. Trucks

Between 2000 and 2015 the energy consumed by the road freight sector grew by 50% (23 to 36 EJ) and in 2017 32% of transport-related energy demand was due to road freight [6]. By 2030, the World Bank predicts that global freight volumes could grow by 70%, which is greater than the forecast 50% growth in passenger traffic [11]. In OECD countries, transport is the sector that is most dependent on oil as its primary energy source, illustrated in Figure 2 [12]. The primary energy source for road freight is petroleum-derived fuels, accounting for more than 97% of sectoral final energy [12].

FIGURE 2
Sources and proportion of energy used by sector across OECD countries in 2016.
Source: [12]
Note: "Other" includes biofuels and waste, direct use of geothermal/solar thermal and heat produced in combined heat and power (CHP) /heat plants.



2.1.1. What is a truck?

A range of different terms are used internationally to refer to commercial vehicles capable of delivering large quantities of goods over long distances. These are usually classified by the maximum loaded weight limit of the vehicle, usually measured as the gross vehicle weight rating (GVWR). In the United States 'Heavy Duty' trucks are those over 26,001 Lbs, split further into Class 7 (26,001lbs to 33,000lbs or 13 to 16.5 tons) and Class 8 trucks (>33,001lbs or 16.5 tonnes) [13]. In the European Union the equivalent vehicle class is the 'N' class, split into 'N1' (vehicles not exceeding 3.5 tonnes), 'N2' (vehicles not exceeding 12 tonnes) and 'N3' (vehicles exceeding 12 tonnes) [14]. These vehicles are often referred to as heavy goods vehicles (HGVs).

Table 2 compares the truck classifications across four regions, demonstrating the significant variation between classification regimes, and the broad commonality that classification systems begin with the smallest commercial trucks at 3.5 tonnes.

TABLE 2
Heavy vehicle classification schemes in the United States, European Union, China and Japan.
Source: [6]

<table>
<tr><th colspan="2">United States</th><th colspan="4">European Union</th><th colspan="4">China</th><th colspan="4">Japan</th></tr>
<tr><th>Vehicle</th><th>Weight</th><th>Vehicle</th><th>Weight</th><th>Trailers & semitrailers</th><th>Weight</th><th>Trucks</th><th>Weight</th><th>Tractors</th><th>Weight</th><th>Trucks</th><th>Weight</th><th>Tractors</th><th>Weight</th></tr>
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<tr><td rowspan="6">8b</td><td rowspan="6">>27.22</td><td rowspan="6">O4</td><td rowspan="6">>10</td><td colspan="2">25-31</td><td colspan="2">27-35</td><td rowspan="6">11</td><td rowspan="6">>20</td></tr>
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<tr><td colspan="2">40-43</td></tr>
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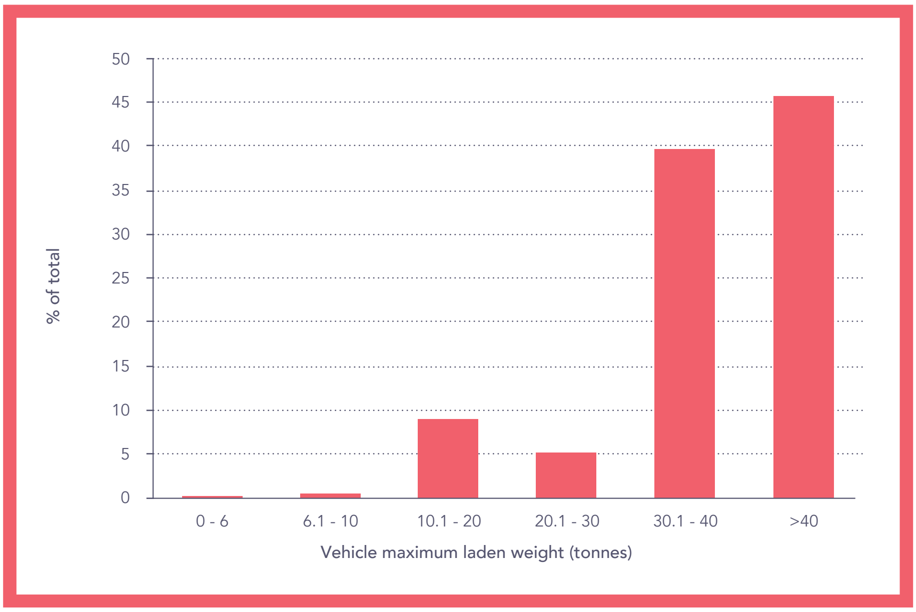
The International Energy Agency (IEA) estimates that HGVs account for approximately 70% of freight activity and about 50% of truck energy use [6]. Figure 3 illustrates the dependence on HGVs for freight transport in the European Union, where more than 90% of freight tonne-kilometres are completed using vehicles with a maximum gross vehicle weight exceeding 20 tonnes [15]. While electrification is becoming a valid alternative for passenger and light duty vehicles, HGVs (and long-distance freight transport) remain dependent on oil as a fuel source.

FIGURE 3
Percentage of freight tonne-kilometres transported by vehicles of different maximum laden weight in the EU-28.
Source: [15]



The literature examining the emissions and future development of trucks is often less specific than the official truck classifications adopted in the relevant country. For the purpose of this report trucks will refer to vehicles greater than 3.5 tonnes and will note any important classification issues where apparent and relevant.

2.1.2. Truck engines and emissions

The majority of trucks in commercial operation use diesel compression ignition engines, where diesel is atomised on injection to the combustion cylinder and ignition is initiated through fuel compression during the piston's compression stroke [16]. This type of engine has been developed for over a century since its first introduction at the end of the 19th century. Table 3 presents the typical efficiency, emissions of common long-haul trucks with diesel engines in Europe and the United States.

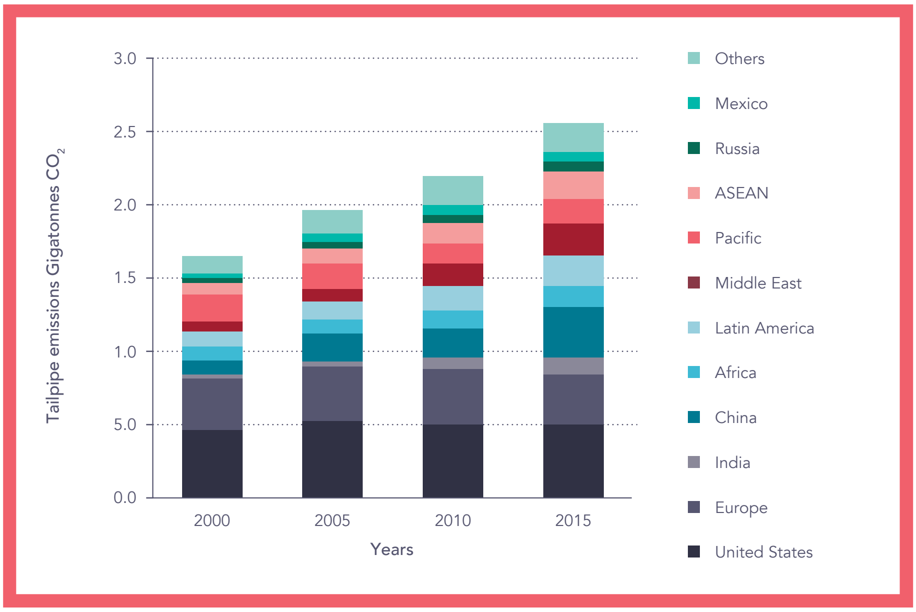
Existing truck engines have historically improved in terms of emissions and fuel consumption, with modern testing programs validating this incremental progression [17]. It is important, therefore, to recognise that in the future diesel trucks may have improved emissions against their current counterparts.

TABLE 3
Example vehicles in the long-haul segment in Europe and the United States
Notes: Engine displacement and configuration from manufacturer's website. Engine emissions control assumed by [18], gross vehicle weight rating (GVWR), annual activity, fuel economy, and fuel consumption information are average values across the EU-27 member states and from US National Research Council (NRC) for the United States.
Source: [18]

	EU	United States
Truck example	MAN TXG	Peterbilt 386
Engine displacement	12.4 litres	12.9 litres
Engine	Diesel: 210 to 220n bar cylinder pressure common rail fuel injection, turbo charged, peak thermal efficiency 43 to 44%	
Transmission	10 to 18 speed automated manual	
Emission Control	Euro VI: Exhaust Gas Recirculation (EGR)+ Diesel Particulate Filter (DPF)+ Selective Catalytic Reduction (SCR)	EPA 2010: Exhaust Gas Recirculation (EGR)+ Diesel Particulate Filter (DPF)+ Selective Catalytic Reduction (SCR)
GVWR	16,000kg to over 40,000kg	14,969kg to over 36,364kg
Annual distance travelled	130,000km	120,700km to 322,000km
Fuel consumption	30.6 litres per 100km	31 to 59 litres per 100km

Global emissions of exhaust CO_2 are presented in Figure 4 by region. This figure only considers CO_2 emissions representing the majority of emissions (see Section 5). CO_2 emissions from freight transport in 2015 represent 40% of transport emissions and 7% of emissions from energy production and use [6].

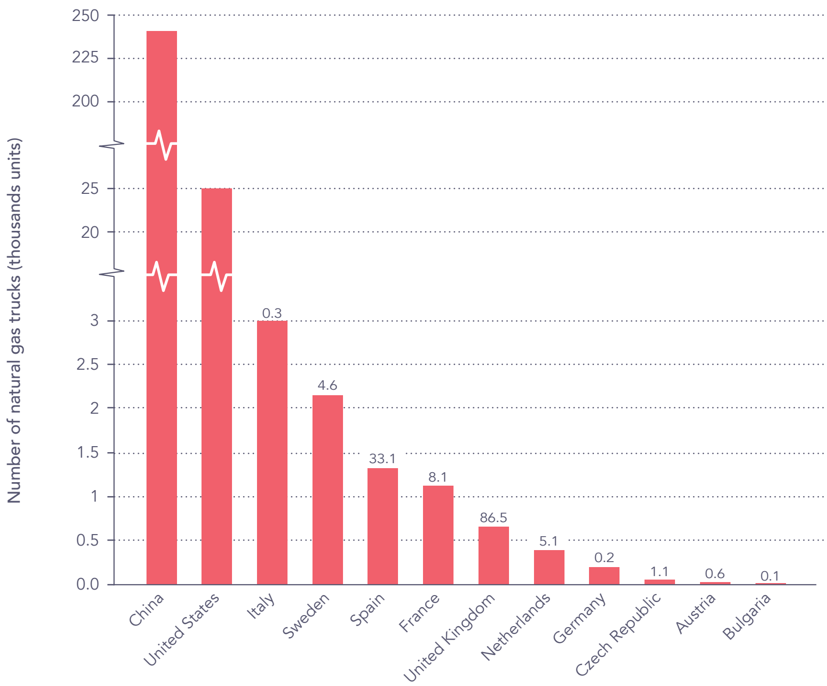
FIGURE 4
Tailpipe CO_2 emissions from road freight transport by region from 2000 to 2015.
Source: [6]
Note: Pacific includes Australia, Japan, Korea and New Zealand. ASEAN is the Association of South East Asian Nations.



2.1.3. Natural gas in trucks

There are currently over 26 million natural gas-fuelled vehicles and over 31,000 refuelling stations across the world, with over 50% of these vehicles in China, Iran, and India [19]. However, the majority of these vehicles are not freight vehicles, with natural gas HGVs accounting for about 1% of total stock in 2015 [6]. These heavy-duty vehicles have been used for various applications including refuse collection, buses, and freight delivery. Figure 5 presents estimates of natural gas truck numbers in China, the United States and a number of European countries.

FIGURE 5
Natural gas trucks in operation across China, the United States and Europe.
Source: [6, 20]
Note: China and United States numbers for LNG trucks only.



Truck manufacturers employ two broad engine types for use with natural gas: spark-ignition engines which use 100% natural gas, and compression ignition dual-fuel engines, which use a small amount of diesel, ignited by compression, to initiate combustion of the natural gas component within the cylinder (Table 4). Broadly, there are two dual-fuel engine types and two spark-ignition engine types. These are summarised in Box 1.

Box 1: Natural gas engine types in trucks

1. Spark ignited lean burn (SILB)

Lean burn engines are designed to allow for greater quantities of air to enter the combustion cylinder than is required for combustion (i.e. greater than in a stoichiometric engine), thereby reducing throttling losses and leading to a smaller fuel consumption penalty compared to diesel than spark ignited stoichiometric (SIS) engines. The lean air/fuel mixture decreases the temperature of combustion and results in lower NO_x emissions [21]. Lean burn engines have poor transient response and performance but may be complemented with advanced fuel control and closed loop technologies that can monitor combustion and provide adjustments if necessary [22]. In many cases, the reduced performance is compensated by the addition of a turbocharger.

2. Spark ignited stoichiometric (SIS)

A spark ignited stoichiometric (SIS) natural gas engine is much like a petrol/gasoline engine. Fuel and air are mixed in the combustion chamber at a ratio that means there is just enough oxygen to burn the fuel. These engines are throttled to control the amount of air entering the combustion chamber, which leads to a fuel efficiency penalty compared to diesel engines. One advantage of SIS engines is that the stoichiometric combustion means that a three-way catalyst can be used to effectively control exhaust emissions of air pollutants and unburned methane (methane slip). Therefore, while these engines typically emit lower levels of air pollutants and methane emissions can be effectively controlled, fuel consumption is typically higher and power output can be limited relative to diesel engines [23].

3.Dual fuel (DF)

Dual fuel engines use two types of fuel to produce combustion as opposed to a single fuel source. Generally, diesel is the primary fuel and natural gas is added to the incoming air in the intake manifold and it is common for diesel engines to be retrofitted [24, 25]. This lean-air/natural gas mixture is ignited by an injection of diesel at the end of the compression stroke. Dual fuel engines can offer advantages over other natural gas engine technologies, including higher thermal efficiency (relative to SI engines), flexible fuel capabilities (dual fuel engines can also run on only diesel), reduced fuel costs, along with the potential to reduce some air pollutant emissions [24, 26, 27].

4. High pressure direct injection (HPDI)

High pressure direction injection engines are a type of a dual fuel engine that use diesel as a pilot ignition source and inject the gas at high-pressure (e.g. >300 bar) into the combustion chamber at the end of the compression stroke in an attempt to improve the combustion of methane and reduce methane slip. In HPDI engines, the diesel injection accounts for approximately 5% of the fuel energy, with the balance provided by natural gas [28]. Some studies have recently claimed that newer generation HPDI engines are able to offer similar levels of performance and drivability to diesel [29, 30].

An overview of the various engine technologies, after-treatment, and natural gas fuel composition are presented in Section 3.1.2. SIS engines can be coupled with three-way catalysts (TWCs) to reduce air pollutant emissions of nitrogen oxides (NO_X), unburned hydrocarbons (HC) and carbon monoxide (CO_2). TWCs are effective at oxidising any unburned methane and therefore lead to low levels of methane slip from the tailpipe. Furthermore, since the combustion of natural gas in an SIS engine produces relatively low levels of particulate matter (PM) and a particulate filter tends not to be required. In contrast, lean-burn engines (SILB, HPDI and DF) must use catalysts that are effective in oxygen-rich environments; oxidation catalysts control HC and CO_2 emissions, selective catalytic reduction (SCR) is used to meet the latest NO_X emissions standards, and diesel particulate filters (DPFs) are required to control particulate emissions. Effective oxidation catalysts that successfully control methane emissions are expensive due to the high quantities of precious metals required (platinum and palladium).

TABLE 4
Natural gas engine technologies, after-treatment, and the percentage of natural gas used.
Source: [30, 31]

Engine Type	After-treatment	Natural gas used [% of total]	Original equipment manufacturer
Spark ignited stoichiometric (SIS)	Three-way catalysts (TWCs)	100%	Cummins, Scania, Waukesha, IVECO[2]
Spark ignited lean burn (SILB)	Oxidation catalyst	100%	Cummins, MAN, Doosan, GE
High pressure direct injection (HPDI)	Oxidation catalyst, Diesel particulate filters (DPFs), Selective catalytic reduction (SCR)	95-98%	Westport, Volvo
Dual fuel	Oxidation catalyst, Diesel particulate filters (DPFs), Selective catalytic reduction (SCR)	0-95%	Volvo (after-market retrofit)

2.2. Ships

International shipping is involved in the transport of an estimated 90% of global trade [32]. In 2017, there were over 50,000 merchant vessels globally [33]. The United Nations Conference on Trade and Development estimated that merchant shipping contributed US $380 billion in freight revenue, nearly 5% of total global trade [34]. The value of goods traded represented approximately 10% of GDP at the beginning of the 20th century, growing to approximately 25% in 2014, more than keeping pace with global GDP growth [35].

2.2.1. Types of ship

International shipping is conducted by a broad range of ship types, ages and sizes. Figure 6, Figure 7 and Figure 8 present some of the key aspects of this diverse fleet.

A number of different types of goods are transported by ship, and the type of ship is often classified by these types of goods. These common ship types include:

- **Bulk carriers** – designed to carry unpackaged cargo such as grains, coal or ore;
- **Chemical carriers** – designed to carry liquid chemicals;
- **Container ships** – designed to carry standardised twenty-foot-long intermodal cargo containers;
- **Crude oil tankers** – designed to carry liquid crude oil;
- **General cargo ships**
- **Liquefied natural gas carriers** – designed to carry LNG; and
- **Roll-on-roll-off or RoRos** – designed to carry wheeled vehicles

Figure 6 shows the composition of the global ship fleet from 2008 to 2017, separated by these common ship types.

FIGURE 6
Number of vessels in the global fleet by ship type.
Source: [36]

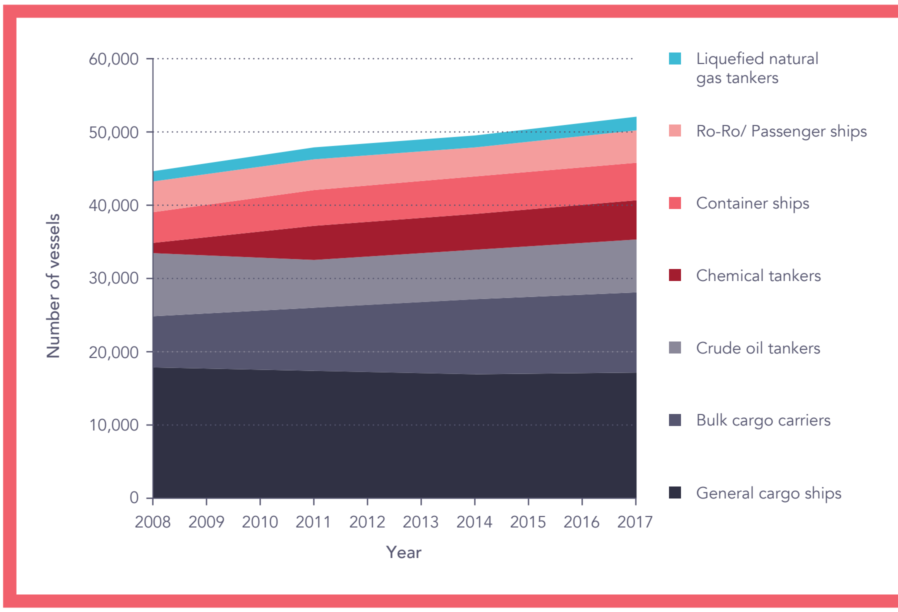
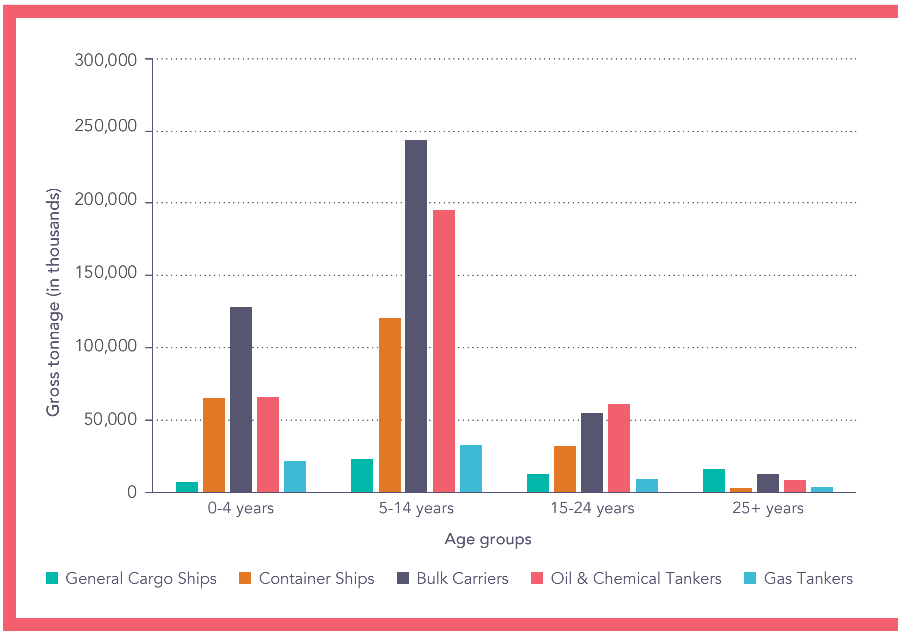


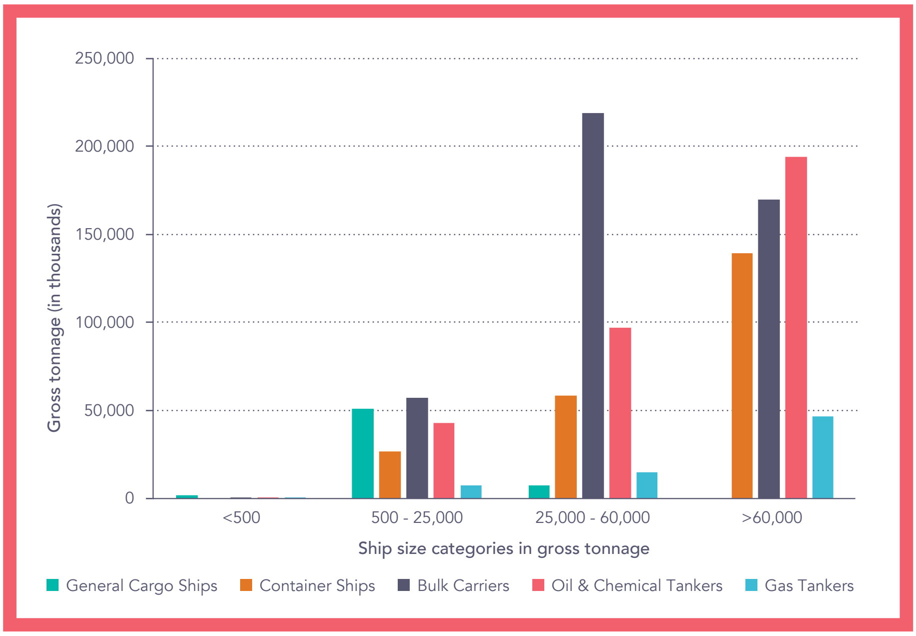
Figure 7 shows the current ship fleet by age and by ship type. This shows that the majority of existing shipping capacity exists in ships built in the last 14 years. Typical ship decommissioning ages broadly range from 25 to 30 years [37]. Combining this with the age profile of ships in Figure 7, it is possible to approximate a decommissioning profile for the existing ship fleet. This is used in Section 8 to inform the modelling of the future ship fleet.

FIGURE 7
Age of vessels in current international ship fleet by ship type.
Source: [37]



Finally, the ship fleet can be described in terms of ship size, which can clearly vary more significantly than the road freight sector. Figure 8 shows the current ship fleet by ship type and by four different size calcifications. This shows the significant majority of ship capacity contained within large and very large vessels. There is an efficiency gain per unit weight and distance of goods transportation associated with larger vessel sizes, which is presented in Section 8 (Figure 52).

FIGURE 8
Size of vessels in current international ship fleet by ship type.
Source: [37]



2.2.2. Typical engines and their emissions

The predominant fuel in international shipping is currently residual fuel, or heavy fuel oil (HFO) which accounted for 72% of all fuel consumed in 2015 [10]. HFO is the residue product of crude oil in refineries and its combustion releases high levels of air pollutants. The main engine types using HFO are either four stroke or two stroke diesel cycle compression ignition engines. Historically larger vessels with greater fuel consumption typically used two stroke engines and these have therefore contributed most to global HFO demand [38].

The CO_2 equivalent emissions from the global shipping industry are summarised in Table 5. Between 2007 and 2015, shipping represents between 2.5% and 3.5% of global CO_2 emissions per year [10,39]. Scenarios developed by the International Maritime Organization (IMO) indicate that this could grow between 50% and 250% by 2050 [39] because of the growing demand for shipping to support international trade and the specific sectoral challenges with switching to lower-carbon fuels.

TABLE 5
Annual GHG emissions from shipping industry as reported by the International Maritime Organisation (IMO) and the International Council on Clean Transportation (ICCT).
Source: [10]

	Third IMO Greenhouse Gas Emissions (GHG) Study (million tonnes)						ICCT (million tonnes)		
	2007	2008	2009	2010	2011	2012	2013	2014	2015
Global CO_2 Emissions	**31,959**	**32,133**	**31,822**	**33,661**	**34,726**	**34,968**	**35,672**	**36,084**	**36,062**
International Shipping	881	916	858	773	853	805	801	813	812
Domestic Shipping	133	139	75	83	110	87	73	78	78
Fishing	86	80	44	58	58	51	36	39	42
Total Shipping	**1,100**	**1,135**	**977**	**914**	**1,021**	**942**	**910**	**930**	**932**
% of global	3.5%	3.5%	3.1%	2.7%	2.9%	2.6%	2.5%	2.6%	2.6%

Global GHG emissions broken down by ship type are shown in Figure 9. Container vessels, bulk carriers and tankers make up more than half of the shipping GHG emissions. Shipping emissions of common air pollutants are summarised in Table 6.

FIGURE 9
GHG emissions from global shipping 2015 as a % of total 932 million tonnes CO_2eq.
Source: [10]

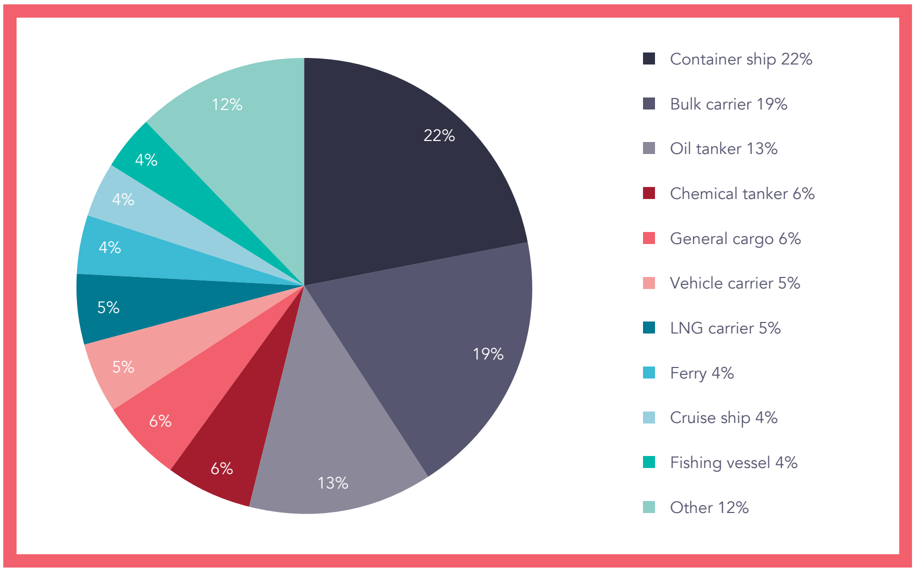


TABLE 6
Annual global air pollution emissions from shipping between 2007 and 2012 in million tonnes.
Source: [10, 39]

Emission type		2007	2008	2009	2010	2011	2012
NO_X	International Shipping	19.93	20.64	19.07	16.71	18.00	17.00
	Domestic Shipping	1.50	1.79	1.00	1.00	1.36	1.21
	Fishing	1.29	1.21	0.64	1.07	0.86	0.79
SO_X	International Shipping	10.75	11.08	11.14	9.87	10.85	9.74
	Domestic Shipping	0.32	0.29	0.23	0.26	0.32	0.26
	Fishing	0.52	0.52	0.26	0.45	0.45	0.26
Particulate matter (PM)	International Shipping	1.50	1.54	1.50	1.33	1.44	1.32
	Domestic Shipping	0.05	0.06	0.04	0.04	0.06	0.04
	Fishing	0.08	0.07	0.04	0.06	0.06	0.04
CO_2	International Shipping	0.83	0.87	0.82	0.76	0.84	0.81
	Domestic Shipping	0.10	0.11	0.05	0.08	0.08	0.08
	Fishing	0.07	0.07	0.05	0.06	0.05	0.05
Black Carbon (BC)	Global Shipping	0.12			0.12-0.283		

2.2.3. Natural gas in ships

Liquefied natural gas (LNG) is currently estimated to make up just 2% of global shipping fuel, predominately from LNG carriers [10]. The number of LNG-fuelled ships is growing and as of May 2018 it reached 253 vessels (121 ships in service and 132 on order) [40]. This is in addition to the fleet of 499 LNG carriers that are also largely fuelled by natural gas [40]. The number of in-service and on-order LNG-fuelled ships in 2018 grew by 17% and 36% respectively between 2017 and 2018 [40]. Further details about the number of LNG-fuelled ships are provided in Table 7.

TABLE 7
Total number of LNG-fuelled ships in May 2017 and May 2018.
Source: [230]

Fleet segment	1 May 2017	1 May 2018
Tankers and bulkers		
In-service	19	24
On-order	28	43
Container and cargo ships		
In-service	11	12
On-order	14	28
Passenger ships		
In-service	40	41
On-order	32	42
Supply and service vessels		
In-service	33	44
On-order	13	19
Fleet totals		
In-service	103	121
On-order	97	132

Norway has pioneered the use of LNG as a ship fuel – outside of LNG carriers – in ferries and offshore service vessels for the oil and gas industry [231]. Other vessel types have been added, including tugs, fish feed carriers, wind farm support vessels, cruise ferries, small chemical tankers and container feeder vessels. More recently, large vessels, including bulk carriers, container vessels, oil tankers, car carriers and cruise ships have been ordered (Table 8) which indicates that almost all vessel types can now be fuelled with LNG.

TABLE 8
List of significant large LNG-fuelled ship orders.
Source: [41]

Ship type	Ship owner/name
Container Ship	TOTE Marlin Class Isla Bella CMA CGM 22,000 TEU
Bulk Carrier	Ilshin Green Iris
Oil Tanker	SCF Group for Shell
Cruise Ship	Carnival AIDANova
Car Carrier	Siem Industries for Volkswagen Group

Box 2: Natural gas engine types in ships

Medium Speed 4-Stroke Lean Burn Spark Ignition (LBSI) engines

These engines run only on natural gas, using a spark plug to ignite the fuel. They convert approximately 42% of fuel energy to engine power output [42] with power output ranging from 316 kW to 9.7 MW. Rolls-Royce Marine/Bergen, Mitsubishi and Hyundai are manufacturer of these engines [231]. Applications have included ferries, small cargo vessels, offshore support vessels and a number of other smaller vessel applications. Adoption has been hampered by the inability to run on traditional liquid fuels as a backup. Rolls-Royce has also recently released a high-speed spark-ignited gas engine for marine propulsion based on its popular MTU 4000 series platform [232]. The stoichiometric EGR spark-ignited engine technology that is popular in heavy duty truck engines is not used in marine applications, however LBSI manufacturers do use richer fuel mixtures (closer to stoichiometric mixtures) in parts of the engine operating range to improve load acceptance as discussed in more detail below.

Medium Speed 4-Stroke Low Pressure Dual-Fuel (MS-LPDF) engines

These engines also operate based on the Otto cycle and require a lower compression ratio than diesel engines of the same size to prevent pre-ignition or knocking. This results in a lower power output per cylinder. The efficiency of these engines is about 44% [42]. When in gas mode, gas is injected into the air intake of each cylinder and is ignited by a pilot injection of liquid fuel. Alternatively, they can operate in liquid fuel mode, providing flexibility to use different fuels depending on fuel availability or price. LPDF engines were initially developed for LNG bulk carries where boil-off gas could be used to power the auxiliary or main ship engines [177]. They have successfully been deployed in ferries, platform support vessels, service vessels, and several other vessel types. These engines are available in power output ranging from 720 kW to 17.55 MW manufactured by Wärtsilä, MAN and MAK.

Low Speed 2-Stroke Low-Pressure Dual-Fuel (LS-LPDF) engines

The larger low-speed 2-stroke dual-fuel engines operate on a similar principal to their 4-stroke counterparts, however when in-gas mode, gas under low pressure is injected into the cylinder before the compression stroke. WinGD licences designs for manufacture of 2-stroke LS-LPDF engines in the power range of 4.5 MW to 65 MW [233].

Low Speed 2-Stroke High Pressure Dual-Fuel (LS-HPDF) engines

Unlike the other three engine types, these engines operate on the diesel cycle. Natural gas at high pressure is injected into the cylinder near the top of the compression stroke. The gas is ignited through an injection of liquid pilot fuel. These dual fuelled engines provide a similar performance to diesel engines with no power or efficiency loss, though NO_X emissions are higher than Otto cycle engines due to higher combustion chamber temperatures. The direct gas injection system assures much lower methane emissions from the engine exhaust. The efficiency of these engines is the same as the low-speed diesel engines they are derived from. Marine LS-HPDF engines are currently manufactured under licence from MAN only for large 2-stroke low-speed engines to provide power up to 42.7 MW [231].

2.3. Motivation to change: reducing emissions

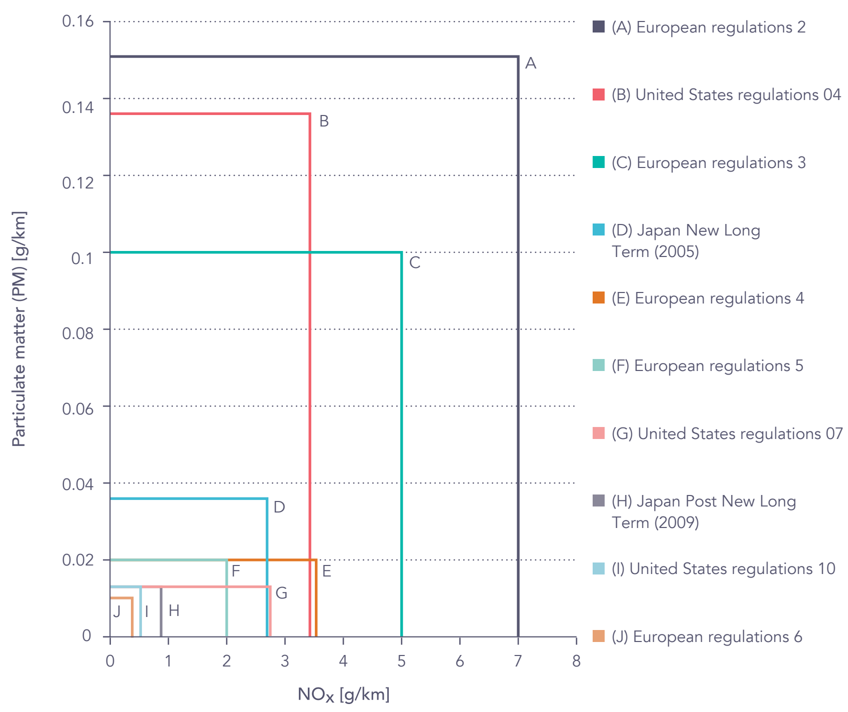
The primary motivation driving a change in truck and ship fuel strategies is the emerging and increasing pressure to reduce greenhouse gas emissions and air pollutants. These emissions arise from a number of sources along the transport fuel supply chain and in end-use in vehicles. In addition to overarching climate targets founded in international agreements, the primary policy mechanisms used to control these emissions are discussed briefly below for trucks and shipping in turn.

2.3.1. Truck emissions and regulation

European emissions regulations for trucks are based on the EURO standards, which sets the maximum emissions permissible for new vehicles. There are currently no formal CO_2 emissions targets, but in May 2018 the European Commission proposed a 15% emission reduction by 2025 and a 30% reduction in 2030 against emissions in 2019 [43]. The United States has entered Phase 2 of the Heavy-Duty National Program, which aims to reduce emissions and increase efficiency of trucks built between 2018 and 2027 against a benchmark 2017 truck [44]. Mandated fuel consumption improvements are specified for a range of different subcategories of Class 7 and Class 8 truck, ranging from 8% to 14% lower than the 2017 benchmark [44].

Japan, China, United States and Canada and Europe are among the early jurisdictions to develop increasing standards for air pollutants [45]. The NO_X and particulate emissions limits established in Japan, Europe and the United States are presented below in Figure 10.

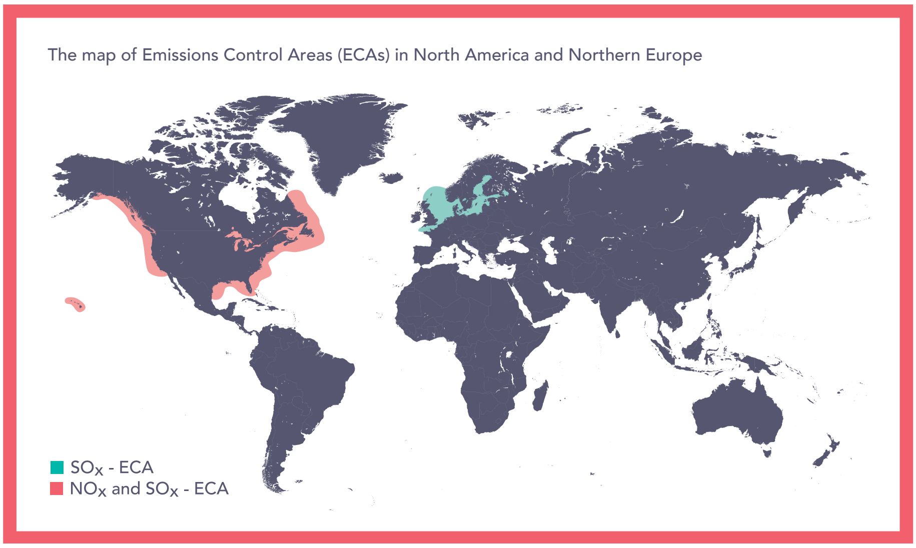
FIGURE 10
Heavy duty diesel emissions legislation in Japan, Europe and the United States.
Source: [46]



2.3.2. Ship emissions regulations

The primary global pollution control mechanism for shipping is the International Convention for the Prevention of Pollution from Ships (MARPOL), Annex VI entered into force in 2005 and has been broadly adopted by countries around the world. The convention establishes limits to sulphur content for fuel and NO_X emissions inside and outside of the emission control areas (ECAs) shown in Figure 11.

FIGURE 11
The map of emission control areas (ECAs) in North America and Northern Europe.
Source: [234]



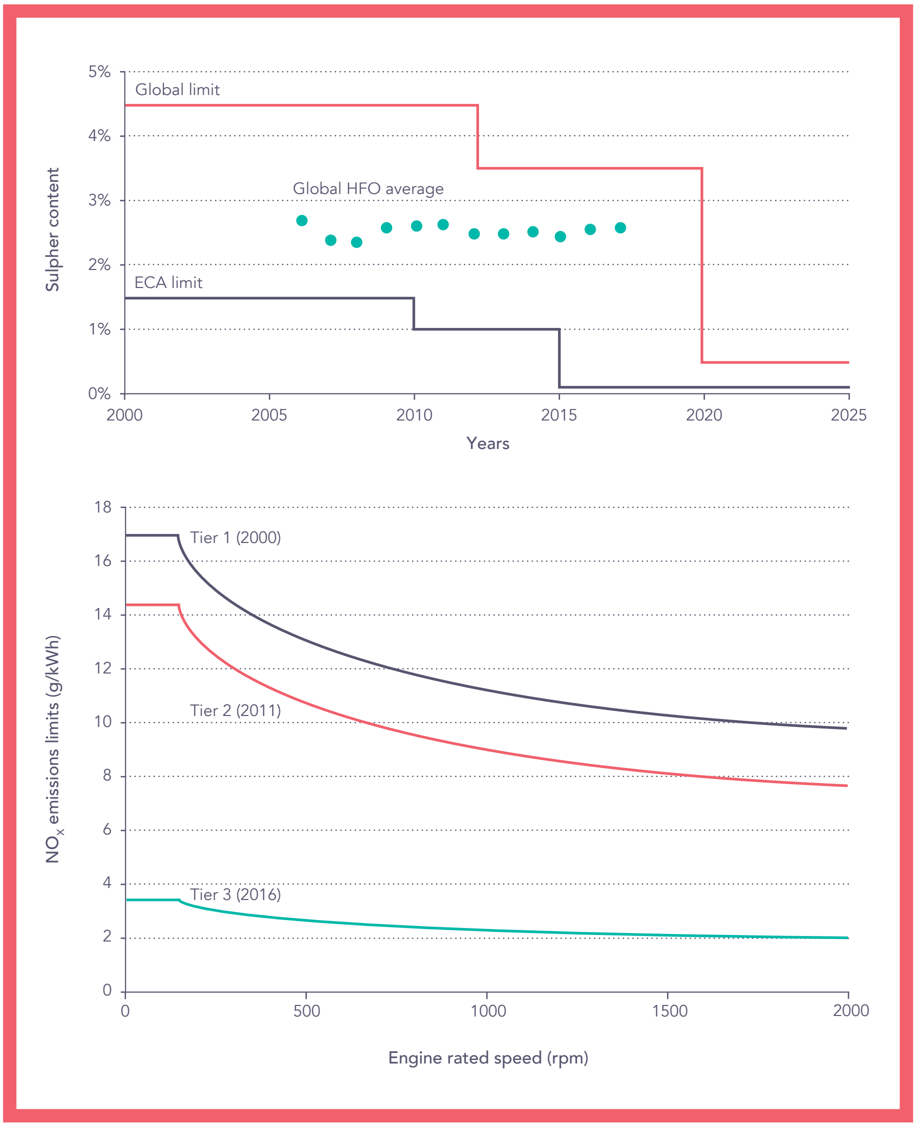
The Energy Efficiency Design Index (EEDI) is also contained within MARPOL Annex VI and mandates a minimum energy efficiency level per capacity mile (e.g., tonne mile) for different ship types and sizes. The EEDI was established in January 2013 to reduce the CO_2 emissions of vessels by 10% and tightens every five years reaching 30% after 2025. Reductions are measured with respect to the average efficiency of the reference ship type built between 2000 and 2010 [235] and alternative fuels, such as LNG, are an acceptable means of compliance with these rules. These measures take effect at an individual ship level, so despite these measures, growth in global shipping may still cause an increase in GHG emissions (Figure 12).

To address SO_X and NO_X emissions MARPOL establishes increasingly stringent limits on the sulphur content of marine fuels and the NO_X emissions in ship exhausts. These limits are presented in Figure 13. The future sulphur limits in particular highlight the need for fuel switching in shipping given that incumbent HFO fuel is significantly higher in sulphur content than the global sulphur content limit planned for 2020, and already above the sulphur content limit imposed within ECAs.

To tackle this challenge of increasing GHG emissions, the IMO's Marine Environment Protection Committee (MEPC) adopted a resolution in April 2018 setting a target of reducing the total GHG emissions from shipping by at least 50% by 2050 below 2008 levels. Given the likely growth in seaborne trade over the next 30 years, this is a challenging target and requires policy support, optimising trade operations, improving engine efficiency, and moving toward low- and zero-carbon fuels [236].

FIGURE 12
Illustration of the Energy Efficiency Design Index (EEDI) phases of staged emissions reductions in shipping from the 10% emissions reduction per ship in phase 1 (2015 to 2020) to the latest 30% reduction in phase 3 (after 2025). Showing the reducing emissions limits with vessel Dead Weight Tonnage (DWT) or Gross Tonnage (Gt).
Source: [47]

FIGURE 13
Sulphur and nitrogen oxides regulations for shipping fuels under MARPOL Annex VI. Sulphur limits for open seas and emissions control areas with points showing the global average in HFO fuel. NO_x emissions limits shown as a function of engine speed for Tier I to Tier III.
Source: [48-50]



3. Reducing emissions from trucks and ships

There are a number of technical and operational options that can be employed to help reduce greenhouse gasses (GHG) and air pollution emissions from trucks and ships. The choice of transport fuel can be a powerful emissions reduction tool within these options. The following section presents the most important emissions reduction options and their contribution to future improvements in truck and ship emissions.

3.1. Emissions reduction in trucks

3.1.1. Efficiency improvements in trucks

The first option to reduce emissions in trucks is to improve overall vehicle efficiency. This has the result of using less fuel per unit of goods transported, and by extension, lower emissions. Table 9 presents the large number of energy efficiency measures available for heavy goods vehicles. The estimated benefit of this list of efficiency options is hard to quantify, particularly given the difficulty in establishing a baseline truck from the highly variable existing truck fleet. However, the establishment of a theoretical baseline truck, and the itemised and cumulative impact of these potential energy efficiency measures are presented by Hill et al and Law et al [18, 46]. These studies concluded that the potential cumulative efficiency of applying a broad range of the efficiency measures listed in Table 9, the efficiency benefit to long haul heavy duty vehicles could result in a reduction in greenhouse gas emissions between 41% and 52% (Figure 14) [18].

This outcome, however, is subject to assumptions about the nature of the drive cycle that the vehicles operation might most closely resemble, the suite of efficiency measures used and the baseline vehicle being compared against. To show the impact of these variables on the energy efficiency benefits of different measures, Badain et al [51] compared different packages of energy efficiency measures and drive cycles against a 2019 baseline vehicle. This study concluded that the potential fuel consumption reduction is between 8% and 10% when considering more conservative drive cycles and technology packages [51].

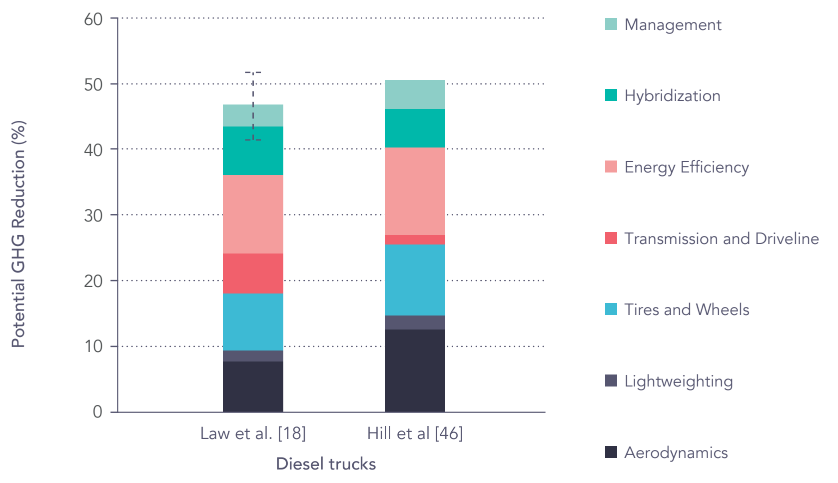
A study of UK truck efficiency measures estimated that efficiency measures may provide between 23% and 43% improvements in fuel consumption by 2050 [52]. However, current trucks already implement many of the available efficiency measures [53]. As the older fleet retires this efficiency benefit will increase against the global truck fleet, though this effect is hard to estimate given current evidence.

TABLE 9
Descriptions of efficiency improvement technologies available in heavy goods vehicles.
Source: [18, 46]

In addition to the emissions reduction potential, measures to improve efficiency have the primary benefit of reducing fuel costs. This makes these efficiency options compelling to truck operators, who may be able to benefit from the 'double dividend' of providing emissions reduction and reducing running costs in tandem [54]. Despite the additional cost of these measures many of the efficiency options have payback periods of less than three years [18].

Technology	Discription
Adaptive Cruise Control	System which controls a vehicle to a set speed, but which also adapts the speed based on the distance to the vehicle in front and maintains a safe distance to the vehicle in front.
Aerodynamic mirrors	Truck mirrors protrude and can affect the airflow around the cab. Rounding the front face of the mirrors can reduce drag.
Air dam	These are downward extensions of the bumper that go towards the front wheels close to the ground. These reduce vehicle drag by diverting air around the side and over the roof of the vehicle rather than under the rough under-body.
Automated manual transmission (AMT)	A manual layshaft transmission which has automatic actuation of gearshifts and clutch operation.
Automatic transmission	Transmission with automated gear shifts which typically uses epicyclic gear sets and a torque convertor.
Cab collar / Cab side extenders	Located at the sides of the rear cab edges, these bridge the gap between cab and body.
Cab deflector / Roof fairing	These are three-dimensional mouldings which fit on the cab roof and, if adjustable, can allow maximum savings with a range of differing body heights. They work by presenting the airflow with a smooth transition from the cab roof to the container.
Cab side edge turning vanes	Usually located on the cab front edges below the windscreen level, these small extension pieces can reduce drag if they cover sharp edges and also help to reduce the build-up of road film and dirt. The feature needs to be specified when ordering a vehicle from new.
Chassis skirts	These side panels cover the gaps next to the under-body on rigid vehicles or articulated vehicle trailers.
Collision warning / mitigation	Using a high performance sensor system collision risk is assessed. If the system detects possibility of a collision it will warn the driver and provide automatic maximum braking to reduce accident severity if deemed unavoidable.
Common rail	A high pressure fuel rail used for fuel injection.
Cruise control	System which control the vehicle to a set speed.
Fixed Geometry Turbocharger (FGT)	An exhaust-driven air pump that forces more air into the engine. Response is controlled simply by diverting exhaust gas around it using a wastegate.
Low rolling resistance tyres	Tyres which are optimised to provide lowest levels of rolling resistance, particularly aimed at long haul vehicle applications.
Tractor and fuel tank fairings	These are panels which enclose the gaps between the front and rear tractor wheels and also cover the fuel tank. These provide a smoother airflow along the side of the vehicle reducing drag.
Turbocompounding	Turbo-compounding utilises an additional exhaust turbine which delivers power to the crankshaft via mechanical gears and a hydraulic coupling. Primarily for Heavy Duty applications.
Twin Turbocharging (series)	Uses a large (low pressure stage) and a small (high pressure stage) wastegated or VGT turbocharger arranged in series.
Tyre pressure indication / monitoring	A system which monitors and can also adjust the tyre pressures to ensure that all tyres are operating at optimal pressures and warns the driver if any tyre is underinflated.
Unit injectors	Unit fuel injectors used in heavy duty diesel engines to inject fuel in the cylinder - is an alternative fuel supply system to common rail.
Variable geometry turbocharger (VGT)	Turbocharger with a variable turbine vane mechanism to control its response to a given exhaust gas flow (no wastegate).

FIGURE 14
Potential new EU vehicle GHG reductions from all technologies.
Source: [18, 46]



3.1.2. Exhaust gas treatment in trucks

In addition to improving the efficiency of trucks, treatment of exhaust gas may be used to reduce emissions of a number of different pollutants. Table 10 presents a number of these exhaust gas treatment options designed to address emissions of particulates, hydrocarbons and NO_X emissions. While these technologies are designed to reduce emissions in exhaust gas, they may also have an efficiency penalty on engine operation. There is also an additional capital and operating cost associated with these technologies that is not covered in this report but will increase the total cost of vehicles.

TABLE 10
Exhaust gas after-treatment options.
Source: [18, 46, 55]

Particle Oxidation Catalyst (POC)	A flow through metallic filter with a reactive wash coat used to reduce particulate matter from the exhaust gas.
Selective Catalytic Reduction (SCR)	Provides continuous NO_X reduction using ammonia generated from injected urea. Urea consumption depends engine-out NO_X level and catalyst temperature.
Exhaust Gas Recirculation (EGR)	Recirculation of exhaust gases into combustion chamber to reduce formation of NO_X emissions.
Diesel Particulate Filter (DPF)	A porous filter which removes particulate matter (PM) from exhaust gas.
Three way catalyst (TWC)	Transmission with automated gear shifts which typically uses epicyclic gear sets and a torque convertor.

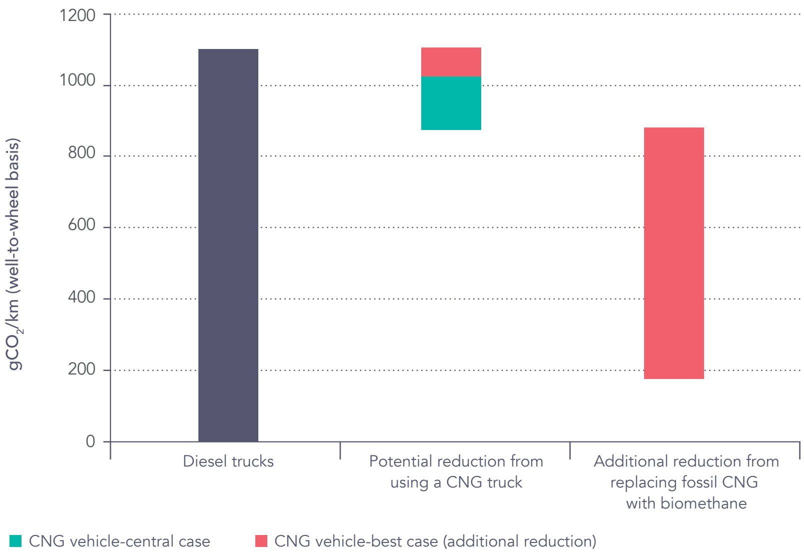
3.1.3. Fuel switching in trucks

A key option to reduce emissions from trucks, and the main focus of this report, is switching fuel, often requiring a corresponding change in main engine. In trucks this primarily means switching to biofuel, natural gas, or options such as batteries and electric motor or hydrogen and fuel cells. This report does not examine the use of biofuels in detail. These fuels have the potential to significantly reduce the CO_2 emissions of individual vehicles and are already implemented through blending in the United States and Europe [56, 57]. However, the global availability of biomass, and the competition for resources across much of the energy economy, limit the overall potential of biofuels to decarbonise the transport sector. Box 3 includes some key details on the potential of biofuels as energy vectors for transport.

Box 3: The carbon reduction potential of biofuels

Biomass can be used as a feedstock to generate a range of different liquid or gaseous fuels suitable for transport applications. This includes the use of wet biomass in particular as a feedstock for biomethane production [58]. Though there are a range of GHG outcomes of producing biomethane, there is the potential to significantly improve the WTW emissions of a natural gas truck [59]. However, there is also an increased cost and competition for resources in the future across a broad range of energy end-uses including power generation, domestic heat and industrial energy demand. Optimistic estimates of the emissions reduction potential of biomethane have suggested that the additional emission reduction of a CNG truck burning biomethane could be over 60% (Figure 15).

FIGURE 15
Lifecycle emissions from CNG trucks. Source: [59]

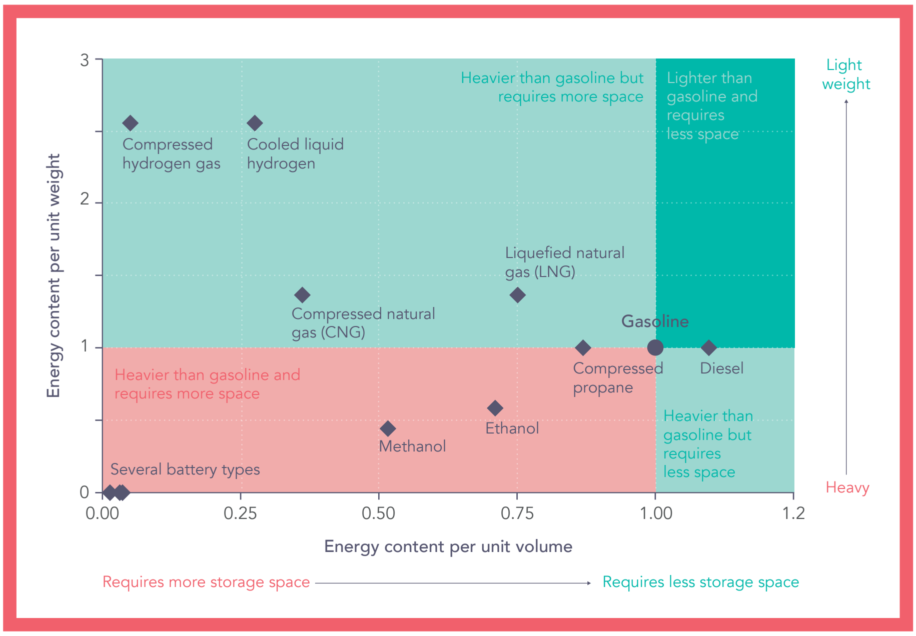


Natural gas has potential to reduce a number of key pollutants from the truck sector. For CO_2 emissions reduction the benefit of natural gas as a fuel lies in the difference in the carbon to hydrogen ratio of the fuel relative to diesel with diesel having a 2:1 hydrogen to carbon ratio while methane has a 4:1 ratio [24]. On this basis approximately 25% less CO_2 is emitted per unit of energy [61, 62]. However, once used to power a vehicle a number of technical issues can diminish this maximum potential GHG benefit of switching to natural gas. These include the efficiency of natural gas engines relative to diesel engines, the amount of diesel used in dual fuel engines [63], methane slip through the exhaust gas, and other methane emissions through engine operation or accidental leaks (see Section 5).

Natural gas has a significantly lower density than diesel; at atmospheric temperature and pressure the density of natural gas is approximately 1,000 times lower than diesel. Natural gas must be either compressed to a pressure of 200-300 bar (CNG) or liquefied by cooling it to -162°C (LNG) to increase the volumetric energy density so that it can be stored on the vehicle in on-board cylinders [64]. LNG is approximately 600 times denser than natural gas at atmospheric temperature and pressure, whereas CNG is 200 to 300 times denser. This means that LNG can offer 2-3 times the energy for the same volume fuel tank. However, the energy content of LNG or CNG per unit volume is still below diesel (Figure 16), meaning that LNG storage tanks would take up more space on the vehicle. Additionally, this does not account for the difference in fuel tank weight between fuels. As high-pressure tanks or cryogenic tanks are likely to be heavier than their diesel counterparts, this reduces the apparent energy density of compressed natural gas and liquefied natural gas.

The energy density (per unit weight and volume) for several transportation fuels, including LNG and CNG are shown in Figure 16. The energy content of natural gas per unit weight is approximately 15% higher than diesel fuel [65], though again this comparison does not account for tank weight, which erodes the energy content per unit weight for LNG in particular.

FIGURE 16
Energy density comparison of several transport fuels.
Note: Indexed to gasoline =1.
Source: [66]



Given the differing energy density between CNG and LNG, this is translated in truck designs to differences in vehicle range. Recent CNG trucks might achieve a 500km range, while LNG equivalent trucks might provide a 1,000km range [67, 68]. This segments the natural gas truck market depending on the operator's range requirements, becoming a key criteria in vehicle purchase. While this is an important aspect of the future of natural gas trucks, this study largely focuses on LNG, which delivers the greatest range accessing the hardest duty cycle to decarbonise by other means.

In addition to GHG emissions, natural gas has the potential to reduce air pollution emissions such as NO_X, SO_X and particulates [69]. The low sulphur content of natural gas results in very low SO_X emissions from gas engines. Particulate emissions are also reduced by switching to natural gas. NO_X emissions can be reduced through fuel switching, though this presents a potential trade off with methane slip relating to operational temperature and injection timing. As a result achieving low methane and NO_X emission simultaneously will likely require a combination of natural gas engines and exhaust gas treatment technologies (see Section 5).

Hydrogen fuel cells or batteries may be used in conjunction with electric motors to provide drive with no direct emissions from the vehicle. However, when including the supply chain emissions associated with electricity or hydrogen production, there are substantial embodied GHG emissions. For example, the grid intensity of UK electricity might produce a WTW electric truck greenhouse gas intensity of over 1,000gCO_2eq/km (Section 5)[1]. However, these technologies also present significant potential to decarbonise though reduction in the CO_2 intensity of the input energy vector (Section 5). While these options have the potential to significantly reduce vehicle emissions they are likely to be more expensive than natural gas trucks or ships (Section 7). There may also be a significant supply chain challenge in terms of the hydrogen or electricity production needed to fuel significant quantities of the heavy goods vehicle sector. These technologies are not the focus of this study but are used to provide context to the emissions reduction proposition provided by natural gas vehicles.

In addition to these options there are a number of additional variations, including:

- Biomass derived fuels including biomethane (Box 3);
- Hydrogen for internal combustion engines;
- Natural gas and hydrogen blending in internal combustion engines [71];
- Catenary charging of battery electric and hybrid trucks [72]; and
- Wider hybridisation of different engines and fuels.

While these are potential contributors to emissions reductions in the truck sector they are not further discussed in this report.

3.2. Emissions reduction on ships

3.2.1. Efficiency improvements in ships

Several operational and technological options may be used to increase vessel efficiency in a similar fashion to those measures discussed in trucks. These include the use of wind propulsion assistance, reducing ship speed (known as slow steaming), low resistance hull coatings and waste heat recovery systems. In addition to those described below, better control and management of power systems may give an additional efficiency increase [73].

1. This includes a grid electricity intensity of 352gCO_2eq/kWh, vehicle efficiency of ~2kWh/km and battery manufacturing emissions represent 33% of per km emissions. Taken from the GaBi Software life cycle assessment model [70].

Wind power

Harnessing wind power using conventional sails or modern alternatives is one efficiency option. These include Flettner rotors, kites or spinnakers, soft sails, wing sails and wind turbines [74]. These do not provide all propulsion needs but provide speed assistance allowing large fuel savings [75, 76] and are more effective at slower speeds [77] and on smaller ships [78]. The compatibility of different designs varies between ship classes due to potential interference with cargo handling [74, 79].

There are a range of fuel saving estimates in the literature: 2-24% for a Flettner rotor, up to 25% for the eConowind sails [80], 1-32% for a towing kite [79], and savings from 10% to 60% at slow speeds [77]. There have been several cargo vessel trials with sail technologies [81], though significant uptake is not predicted until 2025 due to the technologies relative immaturity [74]. Additionally, safety and reliability concerns, as well as a lack of demonstration have been primary barriers to broad adoption across a relatively risk-averse industry [82].

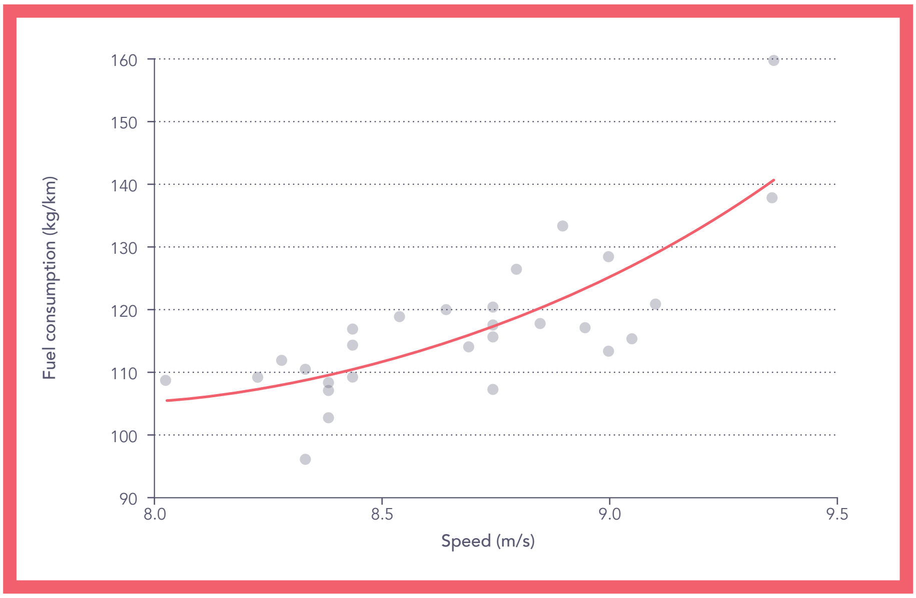
Solar

Solar assistance is also being tested, including systems which use both wind and solar to maximise deck space utilisation. Demonstration projects include automated kite sails from SkySails, a 3,000 tonne 'zero-emission' cargo carrier vessel from B9 Shipping, the UT Wind Challenger hybrid freighter with nine solar sails [81], the EMP Aquarius [83] and the Nichioh Maru [76]. As with wind, the attainable energy is small relative to total ship power demand, though they are useful within the suite of efficiency options [74]. The potential CO_2 reduction for energy generation on-board vessels are estimated to range from 0.2% to 12% [84], while wind-solar hybrid systems may increase fuel savings from 10% to 40% [81].

Slow steaming

Container ships normally have a maximum speed between 23 and 25 knots (44 km/h). However, reducing that speed can have fuel efficiency benefits per tonne-kilometres of goods transported [85]. Slow steaming is defined as 20 to 22 knots (39 km/h), extra slow as 17 to 19 knots (33 km/h) and super slow as 15 knots (28 km/h) [86]. Slow steaming lengthens round-trip time by 10% to 20% depending on the service route and port times [87], but reduces fuel consumption and CO_2 emissions as shown in Figure 17 [86-89]. Longer trip times must be compensated with more ships and larger loads, which reduces the saving. However, Faber et al. [90] estimate that a 10% reduction in speed may deliver a 19% emissions reduction in total. The emissions reduction through slow steaming varies with ship type, size, routes and duties [91]. Additionally, increase fouling and corrosion could result from the altered engine operating conditions of slow steaming, such as low operating temperatures and incomplete combustion [88, 89].

FIGURE 17
Fuel consumption of sea vessels versus average speed.
Source: [87]



A study of approximately 2,000 ships across different regions estimated that container ships utilising slow steaming reduced emissions by 11% between 2008 and 2010 [92]. Vessels on the longest trade routes experienced the greatest benefits, as a function of the amount of slow steaming available on longer routes [92]. Another study made a similar analysis, finding that container ships, oil tankers and bulk carriers reduced fuel consumption by 30% between 2007 and 2012 through slow steaming [49].

Paints and hull coatings

Biological material can attach and grow to the hull of ships. This increases drag, slowing the ship down and increasing fuel consumption [93 to 95]. Slime can increase drag by 1% to 2%, plant material can increase drag by up to 10%, and the worst fouling can increase fuel consumption by 40% to 50% [95 to 97]. On average a typical ship hull loses 1% to 1.2% of fuel consumption to hull fouling [97].

Paints and hull coatings can reduce hull friction and limit fouling, and significant capital is invested in anti-fouling paints [93, 95, 98 to 100]. Tin-based marine coatings were widely used in the 1960-1970s which contained compounds that were detrimental to the environment [74, 93, 99, 101], leading to international legislation banning their use [95, 102].

To date it has not been possible to match tin-based coatings for performance, cost and ease of application, but research is ongoing to find ecologically benign alternatives. Modern coatings can be broadly classed as either biocide based, or biocide free [101]. Biocide based coatings include insoluble matrix (epoxy, polyester, vinyl ester) and soluble matrix (self-polishing, ablative, hybrid) while biocide free coatings include fouling release (silicone elastomers) or mechanical cleaning (epoxy/vinyl esters) type coatings [101].

Waste Heat Recovery

Waste heat recovery systems (WHRS) can convert heat from the exhaust and coolant into useful mechanical or electrical energy [103], with estimates of fuel savings in the range of 4% to 16% [104-106]. A WHRS represents an additional capital cost but fuel savings may result in payback period of less than 3 years [107], and can be cost-effectiveness across HFO and gas engines [108, 109].

3.2.2. CO_2 capture in ships

Exhaust gas treatment can be used to reduce emissions of NO_X, SO_X, CO_2 and methane [110-112]. While NO_X and SO_X treatment options are mature technologies, CO_2 and methane treatment options are at an early stage of development.

Potential routes exist for carbon capture and storage (CCS) to reduce CO_2 emissions from the exhaust. The Calix RECAST design involves scrubbing exhaust gas to capture 85% to 90% of the CO_2, and using the heat generated in the exothermic reaction to provide additional motive power and increase fuel efficiency [113]. A dry lime scrubber would produce inert limestone which could be scattered into the ocean. Any surplus lime remaining in the used sorbent will remove additional carbon from the oceans by converting to calcium bicarbonate, thus reducing ocean acidity [114, 115]. However, this is likely to be an energy-intensive process from a life cycle perspective and the wider impacts of geoengineering approaches such as this are largely unknown [116, 117]. Costs may be significant and more research is required on the localised ecosystem impacts [118].

3.2.3. Fuel switching in ships

Fuel switching in ships includes switching to biofuel, low sulphur fuel oils such as marine diesel oil (MDO) or marine gas oil (MGO), natural gas, or in the longer term, hydrogen, ammonia or methanol which could be used in engines or fuel cells.

As with trucks, **biofuels** could be used to decarbonise shipping. However, the same resource constraints apply, and biofuels will be able to contribute sufficiently to low carbon ambitions (see Box 3).

Alternative **fuel oils** such as MDO or low sulphur fuel oils such as MGO can be used as an alternative to HFO, resulting in lower air pollution emissions. The limits on sulphur in marine fuels in the MARPOL regulations limit the use of certain types of fuels, with a global limit on sulphur content in marine fuels of 0.5% from 2020. This will limit the use of HFO in the future, forcing fuel switching of one form or another. This could include new low sulphur liquid fuels likely to arise in response to IMO 2020 sulphur regulations.

Natural gas has the potential to reduce GHG emissions and other air pollution emissions if used as a ship fuel. The lower carbon to hydrogen ratio of natural gas relative to HFO and MDO, combined with typical engine efficiencies results in direct CO_2 emission reductions up to 30% [119]. However, methane emissions and supply chain GHGs reduce this relative climate benefit.

One of the main issues with lean burn spark ignited (LBSI) and low pressure dual fuel (LPDF) natural gas engines is methane slip, particularly at partial loads. In publications before 2015, methane slip from ship engines was estimated to be between 1.9% and 2.6% [140, 180, 240]. However, recent measurements by SINTEF Ocean [42] in 2017 showed methane slip of 2.3% and 4.1% from LBSI and medium speed (MS) LPDF engines, respectively. This is despite improvements made by engine manufacturers in combustion chamber design and tighter air-fuel ratio control to reduce methane emissions.

As with trucks, there is a competing trend between methane slip and NO_X emissions in marine vessels, especially at low engine loads. LBSI and LPDF engines can control NO_X emissions (for instance to meet more stringent Tier III NO_X emissions) by using lean fuel-air mixture to reduce the combustion temperature [42]. However, this technique increases the chance of incomplete combustion of methane and therefore, higher methane slip. This process also increases CO_2 emissions. Conversely, a rich fuel-air mixture can minimise methane slip, improve load acceptance and reduce CO_2 emissions at a cost of increasing NO_X emissions. In recent years an increase in focus on methane slip has led to reductions which are likely to continue as climate targets become ever more stringent.

Low speed high pressure dual fuel (LS-HPDF) engines have been suggested to have very low methane slip (0.2%) [42]. However, the complex fuel gas supply system required to supply the fuel increases costs by about 40% compared to LBSI and LPDF engines and their NO_X emissions are between diesel and LPDF engines [42]. If an LNG pump as opposed to a compressor is used to produce the high-pressure gas, the energy consumption is similar to the fuel pump used for liquid fuel injection. To comply with the NO_X levels in MARPOL Annex VI-Tier III, these engines should use exhaust gas recirculation (EGR) and/or selective catalytic reduction (SCR) to reduce NO_X emissions [42].

The ability for LBSI and LPDF engines to meet IMO NO_X Tier III emissions standards without the need for additional after-treatment or exhaust gas recirculation makes them an attractive choice for vessels operating consistently in the ECAs where the Tier III standards apply [42], despite the fact that the methane slip from these engine types are higher than that from LS-HPDF engines.

Gas turbines (GTs) have been proposed as an alternative to piston engines due to their more compact and lighter characteristics. However, GTs are less efficient [237]. To increase their efficiency, a combined cycle turbine can be used. GTs are predominantly used in warships, where high power output and rapid response outweigh the operational cost and fuel consumption [231]. GTs have also successfully been deployed in cruise ships. Combined cycle gas turbines with heat recovery have been proposed for LNG-fuelled ships, see Ref. [238] as an example.

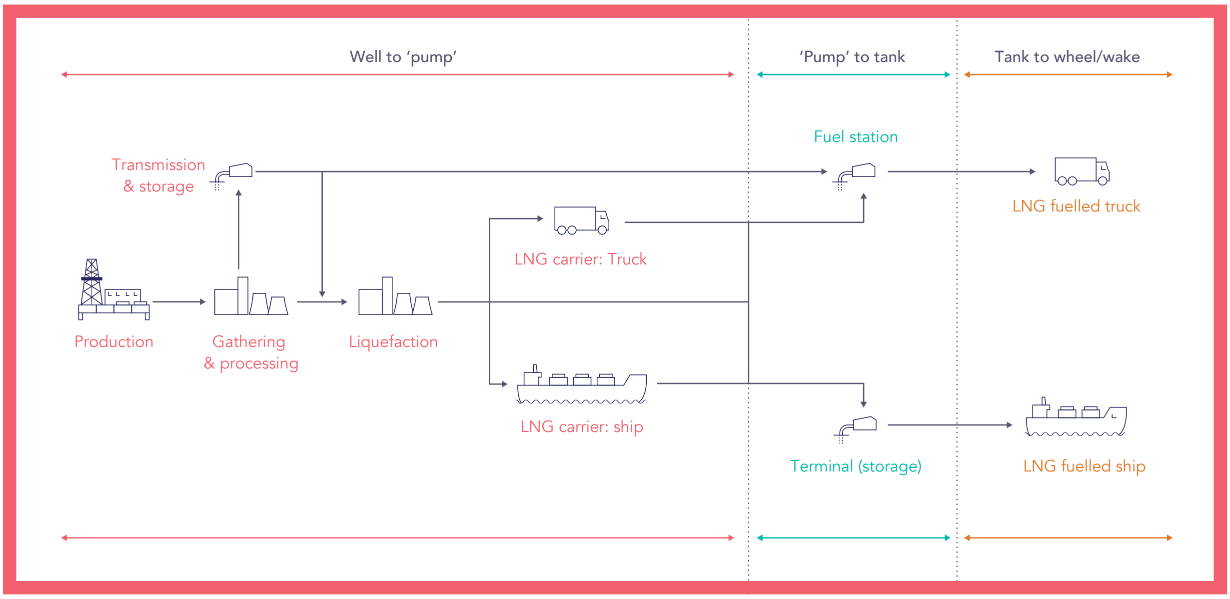
To further reduce the GHG emissions from LNG-fuelled ships, carbon capture and storage systems have been proposed by using the LNG vaporisation system to condense CO_2 from the exhaust stack and store it under the deck. [239]. However, this process is still costly [239], and the storage and future usage of liquid CO_2 make it impractical for widespread usage.

Finally, **hydrogen and fuel cells** have the potential to significantly reduce the emissions from ships, with applications in both propulsion and on-board electricity generation [120-123]. However, these ships are not fully commercially mature, with significantly higher costs than competing technologies and immature fuel supply chains. These propulsion systems have the potential or virtually zero emissions in the tank to wake phase [123], but hydrogen production can create greenhouse gas emissions, largely relating to the hydrogen production method that must be accounted for [124]. The lifecycle emissions of hydrogen combustion can range from greater than natural gas, where natural gas is used to produce hydrogen without carbon capture, to negative emissions, where biomass is used to produce hydrogen in conjunction with carbon capture [125, 126].

4. Supply chain emissions

Emissions arise from various sources along the transport fuel supply chain, as well as end-use. Figure 18 presents an illustrative schematic of the key aspects of the transport fuel life cycle. The life cycle applies to fuel for both trucks and ships, where stages are divided into three categories: well-to-pump (WTP), which captures emissions in fuel production and transportation; pump-to-tank (PTT), which accounts for storage and delivery of fuel to the vehicle/ vessel; and tank-to-wheel/wake (TTW), capturing the emissions arising from the vehicle/ vessel. The first section, WTP, is common for both ships and trucks and is described in the proceeding section, before emissions associated with the truck and ship supply chains are assessed in the following sections.

FIGURE 18
Illustrative schematic of the key stages of the transport fuel life cycle.



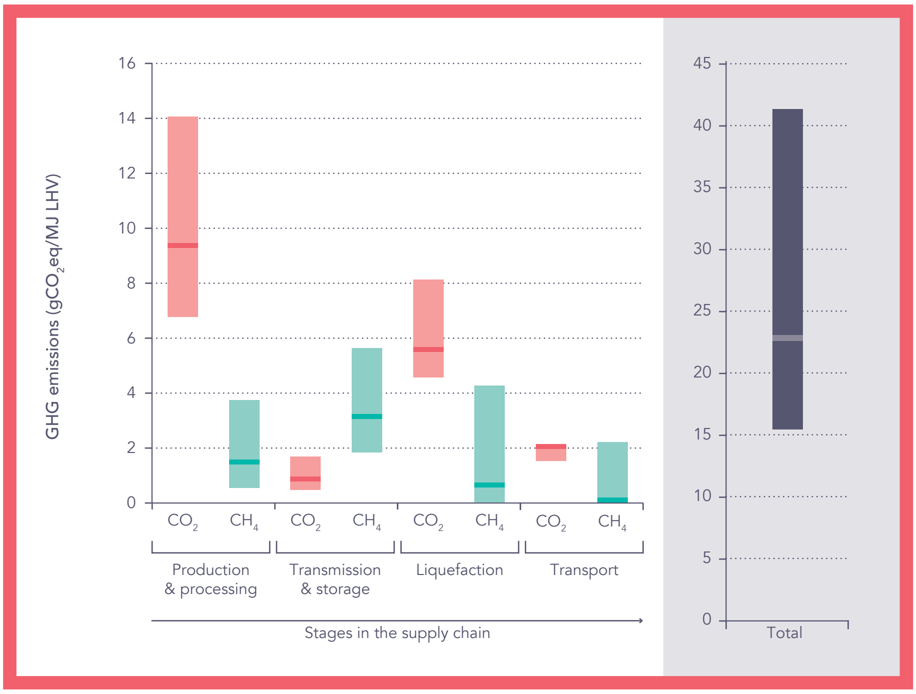
LNG supply chains may be appreciably longer and more complex than conventional gas supply chains as depicted in Figure 18, involving additional processing, transport and storage stages. Consequently, GHG emissions from the natural gas supply chain arise from numerous processes and mechanisms. CO_2 emissions are typically borne from fuel combustion or venting separated CO_2 from raw gas. Methane emissions arise from process venting, incomplete combustion of natural gas (either for fuel or flare), or from fugitive emissions.

There are many estimates of emissions associated with natural gas supply chains. The Sustainable Gas Institute published its first white paper in 2015, detailing a large-scale evidence assessment of methane and CO_2 emissions from natural gas supply chains [127]. This work was continued in 2018 with a characterisation of the distribution of emissions seen across different types of natural gas supply chains [128]. Other relevant studies include the work presented by Cai et al. [129], Burnham [130], Alvarez et al. [131], and Littlefield et al. [132]. The ranges of methane emissions presented in these studies vary significantly and the majority are focused on the supply chains associated with North American natural gas.

A summary of supply chain emissions is presented here, with an aggregation of estimates from these different sources shown in Figure 19 detailing typical ranges of emissions of both CO_2 and methane estimated at different stages of the LNG supply chain. Note that these estimates are not region specific but contains broad ranges to account for differences across regions. There is still much research to be done to better characterise methane emissions across regions outside North America.

In this section emissions are expressed per MJ of natural gas delivered on a lower heating value (LHV) basis. A Global Warming Potential (GWP) 100 value of 34 is used to equate methane and CO_2 emissions, in line with the Intergovenrmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) values that include indirect warming effects and eventual methane oxidation. The assumed GWP value has a large impact when comparing fuels with different emission profiles. It is not within the scope of this study but for more information please see the 2018 review of climate metrics by Balcombe et al. [133].

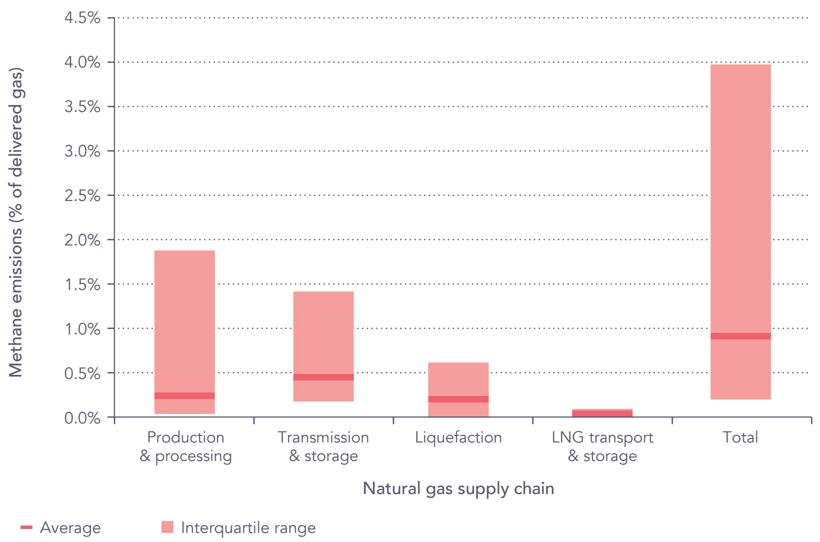
FIGURE 19
Average and ranges of GHG emission estimates for different stages of the supply chain, split by CO_2 and methane.
Source: [134-140]
Note: Blue band represents range of estimates. Red bar represents the mean of estimates.



Clearly estimates of total supply chain methane emissions vary widely and are likely to reflect natural variation across regions, processes, technologies and regulatory environments. Other effects such as methodological variation and representativeness of data adds further uncertainty to emission estimates. Whilst the range of estimates is extremely large, typical total LNG supply chain estimates may be 0.2% to 1% for lower emitting routes or 1% to 4% for higher emitting routes. In comparison, the most recent estimate of total global methane emissions from natural gas is 1.7% of production from the International Energy Agency, or ~3% of gas production if oil and gas are considered collectively [6].

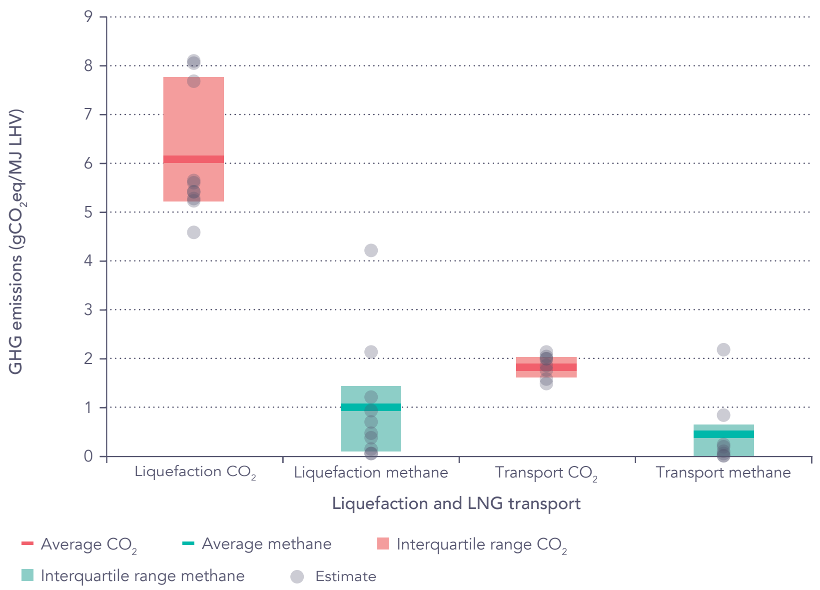
Figure 20 displays the range of methane emissions only, as a percentage of throughput. It indicates a higher variability in the upstream stages and, whilst this may be the case, there has been much less focus on measuring downstream emissions and so there may be additional variability that is unaccounted for here. There are still many gaps in our understanding of methane emissions, their magnitude and variation across different regions and supply chain stages.

FIGURE 20 Averages and ranges of estimates of methane emissions across different stages of the natural gas supply chain.
Source: [134-140]



The LNG supply chain stages are particularly opaque with relatively few high-quality estimates of methane emissions. Figure 21 shows the available literature estimates of CO_2 and methane emissions from liquefaction and from LNG transport. Note that LNG transport refers here to an LNG carrier ship rather than the smaller scale LNG trucks which may exhibit higher emissions.

FIGURE 21 Estimates of GHG emissions from liquefaction and LNG transport, split by CO_2 and methane emissions.
Source: [127, 137, 138]



Key emissions from liquefaction are CO_2 emissions from fuel usage for liquefaction and residual methane emissions from any untreated boil-off gas (BOG). The natural gas is often used as fuel for liquefaction, where 8-14% of gas throughput is used to drive the process. A small amount of electricity is also used for ancillary processes but this is a small addition [137].

Estimates of methane emissions associated with liquefaction are typically low, as central facilities are likely to have effective BOG management and emissions-minimising procedures in place, although there is an absence of publicly available direct measurements to provide assurance (Figure 21). There are typically four options for managing BOG [140]: venting; flaring; using BOG as fuel; and re-liquefying. The NGVA study using industrial reported data to estimate a BOG rate of 1.8% and a re-capture rate of 99%, resulting in an unabated BOG of 0.02% [137].

LNG carrier emissions occur chiefly from fuel use as well as potential methane emissions from storage. There are likely to be different emission profiles associated with intermittent operations such as loading and unloading, port operation and deep-sea, but there is limited data to define such differences. Transport CO_2 emissions are largely estimates from natural gas and fuel oil combustion, whereas methane emissions are typically considered to be very low. BOG associated with unloading to a terminal will typically be captured for injection into a gas grid [140]. However, no data were found on measurements of residual methane emissions. Again, there were very few high-quality measurement data on methane emissions from LNG carriers and it is likely that emissions are under-represented here: there is a high upward uncertainty which should be a priority for both academia and industry to reduce.

Regarding the contribution from CO_2 and methane to total supply chain emissions, CO_2 is the dominant source of emissions for the central supply chain emissions estimate. This is primarily due to the fuel intensity associated with gas processing and liquefaction. However, as shown previously the higher emitting supply chains will have a much higher contribution from methane [134].

5. Trucks: Pump-to-wheel (PTW) emissions

The following section examines the pump to wheel emissions from truck operations, broken into pump-to-tank (PTT) and tank-to-wheel (TTW). This includes an examination of the main truck engine types and how emissions from natural gas vehicles compare to their diesel counterparts. The section first examines emissions from the PTT phase, considering both the fuel station and emissions from the vehicle fuel tank. The TTW emissions are then discussed starting with CO_2 emissions arising from the vehicle tailpipe. Methane emissions, through various mechanisms, are then analysed followed by a discussion of N_2O emissions and air pollution before concluding.

5.1. Pump-to-tank emissions

5.1.1. Sources of emissions

The pump-to-tank (PTT) stage of the life cycle covers the storage of LNG/CNG at the fuel station to its delivery into the vehicle's fuel tank. LNG can be delivered into vehicles in two forms: unsaturated (dispensed at less than −143°C and 0.34 MPa) or saturated (dispensed at −125 to −131 °C and 0.69 to 0.93 MPa). Unsaturated LNG has a lower temperature, higher density and can be stored in vehicles longer than saturated LNG [141]. However, there is a lack of evidence regarding any difference in fuel station emissions arising from these different forms of LNG.

There are some energy/CO_2 emissions in the PTT stage, though most emissions are likely to arise from fugitive methane emissions as equipment is mostly powered by electricity, with associated supply chain emissions. Again, there is limited published evidence on fugitive emissions during the PTT stage. However, leaks may constitute up to 21% of the total PTW methane emissions (1-9% of WTW emissions) [142]. There are several ways leaks can occur and there are some differences between the operation of LNG and CNG stations. Common to both are continuous unintentional leaks from fuel nozzles (and other fuel delivery system components). This is because of imperfect seals that allow pressurised natural gas to escape into the atmosphere. Furthermore, emissions can occur when hoses are connected to vehicles at the start and end of each fuelling event [142]. The two most significant contributors to emissions from LNG in the PTT stage are:

- Boil-off-gas (BOG) management in refuelling stations and bunkering tanks; and
- BOG management in vehicle tanks during or prior to fuelling.

BOG requires careful management to maintain safe pressure limits within tanks while also preventing venting of methane to the atmosphere [141]. While it is possible to re-condense the BOG using an on-site liquefier or directing it into the natural gas grid [141], these options increase the capital and operating costs of refuelling stations. A review of existing LNG station designs found that most have no BOG management [141]. In addition, of patented station designs, 44% have no BOG management [141]. BOG generated in the vehicle's storage tank must be removed at the refuelling station, as otherwise the BOG pressure inhibits refuelling. This is handled by the operating sequence of the refilling system and there are several options for this, with different options having significantly different implications for methane emissions [141]:

- **No vapour to station:** fuel pump pressure is used to overcome the tank's pressure and condense the BOG. This is only possible if the vehicle's tank pressure is sufficiently lower than the relief valve's and the station pump has sufficient pressure available;
- **Vapour back to station:** a vapour return line (routed through the fill receptacle) or a separate vapour return line pumps gas back to the station before fuelling;
- **Vapour back to station during filling:** LNG is transferred to the vehicle while BOG in the tank is returned to the station by a separate vapour return line; and
- **Manual venting:** BOG is vented to the atmosphere to reduce vehicle tank pressure before proceeding with fuelling.

5.1.2. Evidence for methane emissions at fuel stations

A recent methane emissions at truck fuel stations was collected by Clark et al. [142] and these have been incorporated into the latest evaluation of WTW emissions by Cai et al. [129]. The study by Clark et al. [142] followed a bottom-up measurement methodology using a hand-held detector at six LNG stations (fed by cryogenic tanker), measuring emissions from different components of the refuelling station. Sources of emissions included leaks from mechanical fittings, venting, compressors and releases during fuelling hose disconnection. Methane emissions were also characterised at eight CNG stations, seven of which were fed directly from pipelines, and one fed from an LNG station. The summarised ranges of emissions at these fuel stations is given in Table 11.
The upper bound of vehicle fuel tank venting is 3% which has been estimated based on data from Gunnarson et al. [143], Ursan et al. [144] and UNECE Regulation 110 [145]. For full LNG fuel tanks, the minimum holding time without venting is five days [145] and for intensively-used vehicles it is unlikely that there will be venting. However, in the event that a tank remains full after five days, 2% to 4% per day of LNG may boil-off and be vented [143, 144].

TABLE 11
Summary of the range of methane leakage (as a percentage of throughput) during all stages of the pump-to-tank stage.
Source: [142]

	Methane leakage as a % of throughput			
Source	**Low**	**Middle**	**High**	**Note**
Delivery	0.1	0.1	0.4	
Station tank BOG	0.0	0.1	2.0	
Continuous leaks at stations	-	-	-	Negligible
Fuelling nozzle	-	-	-	Negligible
Vehicle fuel tank	0.0	0.1	3.0	
Vehicle manual vent	0.0	0.1	4.2	
Total	0.1	0.4	9.3	

In summary, the main source of methane emissions during the PTT stage is methane venting due to BOG pressure build-up in the station and vehicle fuel tanks. The management of BOG in vehicle tanks, the flexibility of stations to refuel vehicles with different fuel supply systems and the minimisation of BOG generation in station storage tanks are critical to reducing fugitive methane. These goals have driven the agreement by Natural Gas Vehicle Association (NGVA) members to minimise venting at all stages of operation through station design improvements (see http://ngvemissionsstudy.eu/). Other pollutants can be emitted but there is a paucity in the literature on emissions from fuel stations besides methane. As fuel stations meet most of their energy demand from electricity, emissions of non-methane gases are considered negligible. However, if onsite generators fuelled by natural gas were used, emissions of CO_2 and other gases would occur.

5.2. Tank-to-wheel

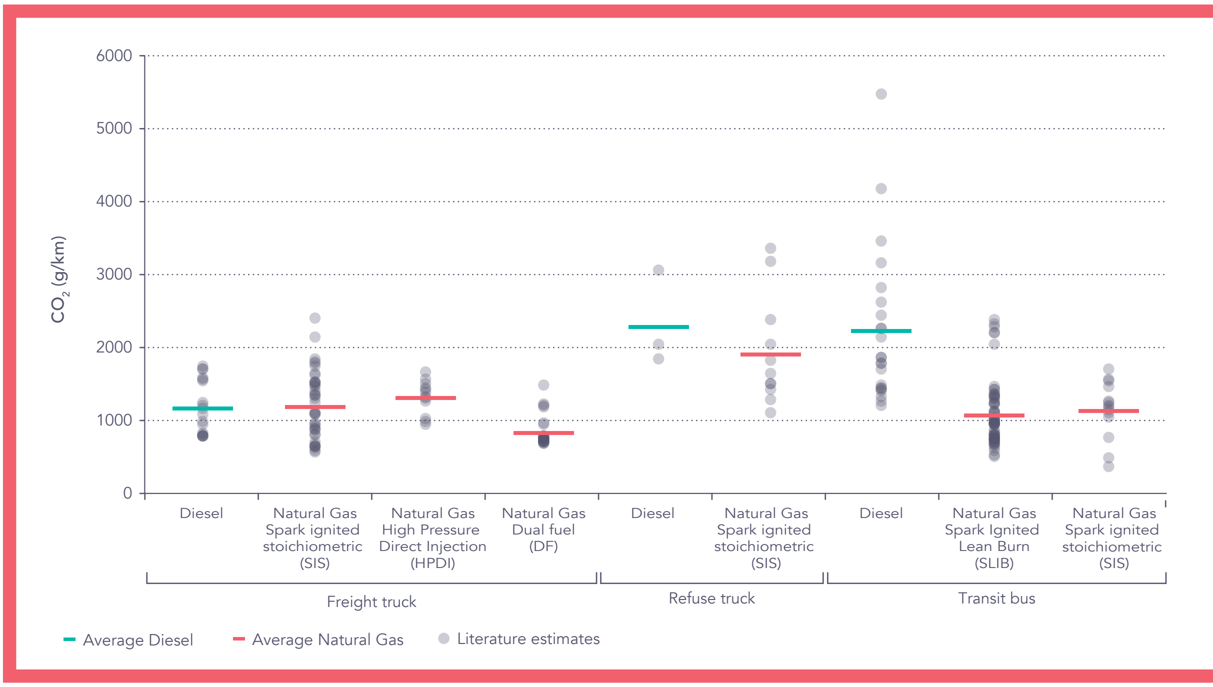
This stage includes the use of fuel in the vehicle, and emissions include those from the tailpipe and any fugitive or deliberate emissions occurring at the vehicle. These emissions include the GHGs CO_2 and methane and also air pollutants. SO_2 emissions from this stage are considered negligible as both CNG and LNG contain low quantities of sulphur. The majority of diesel fuel consumed by the transport sector is also low in sulphur (< 15 ppm) meaning emissions of SO_2 from diesel vehicles are also negligible [146].

5.2.1. Exhaust CO_2 emissions

Several studies have investigated TTW CO_2 emissions of natural gas HGVs (NG HGVs) in the United States and Europe [143, 148-150]. A summary of emissions produced by the various diesel and natural gas HGVs from the literature is presented in Figure 22. This data includes a range of drive cycles for each vehicle type compared, which influences the wide range of estimates. The literature indicates that natural gas HGVs have lower CO_2 tailpipe emissions than diesel but that there is a wide and overlapping range in these estimates.

FIGURE 22
Summary of tailpipe CO_2 emissions from various diesel and natural gas engines
Source: [24, 148, 151-158, 242]
Note: Given drive cycle variation in the included estimates above it is fairer to compare best, worst or central estimates.

A recent on-road study was undertaken by Vermeulen et al. [148], who conducted a series of real-world emissions measurements using two Euro VI compliant Spark ignited stoichiometric (SIS) engine LNG HGVs (Scania G340 with an automatic gearbox and Iveco Stralis Hi Road with a manual gearbox) across urban, rural and motorway drive cycles in the Netherlands. The results were compared against the average of six Euro VI diesel HGVs from previous tests. The average tailpipe emissions produced by the LNG HGVs, across all routes, were generally 5 to 10% lower than diesel and the two emitted less CO_2 across the majority of test cases. However, one test with the Scania G340 (low load condition 10% payload) in urban driving, showed higher emissions than the diesel counterparts. While the sample size of this study is limited, the results are broadly in line with a study undertaken by Cryogas (LNG supplier in Poland) using an Iveco LNG HGV. This study found emissions from LNG vehicles (0.65 kg/km) to be 11% lower than their diesel counterparts (0.73 kg/km) [150]. While the variation in the data remains, the results indicate that natural gas can provide a reduction in tailpipe CO_2 emissions compared to conventional diesel vehicles.



The theoretical maximum reduction in CO_2 emissions compared to diesel is approximately 25% (Section 3.1.3). The reason that CO_2 reductions are lower than this in the data above is because LNG trucks are not as energy efficient as diesel trucks. The fuel efficiency of trucks is dependent on not only the engine technology but other aspects, such as: powertrain efficiency, aerodynamic drag, load conditions and rolling resistance amongst others. Furthermore, the drive cycle can significantly influence fuel consumption, with urban cycles being more intensive than long-haul. A summary of the fuel efficiency of various natural gas trucks relative to their diesel counterparts is presented in Table 12. This shows both significant variation and a considerable fuel efficiency penalty for most natural gas HGVs. For spark ignited stoichiometric (SIS), High pressure direct injection (HDPI) and dual fuel engines, there is a 19% [7% to 44%], 17% [4% to 44%] and 14% [-2% to 40%] fuel consumption penalty respectively, compared to comparable diesel engines. Ongoing testing of new HPDI engines is expected to publish efficiency estimates in 2019, and may corroborate or improve on to lead to published estimates of efficiency estimates for HPDI engines in Table 12, though they were not publically available by time of publishing [159].

Source	Fuel	Engine Type	Fuel consumption relative to diesel counterpart (%)				Source
			Average	Standard deviation	min	max	
Freight truck	Natural gas	Spark ignited stoichiometric (SIS)	119	8	107	144	[148]
	Natural gas	High pressure direct injection (HPDI)	117	12	104	144	[151]
	Natural gas	Dual fuel	114	12	98	140	[24]

TABLE 12
Ranges of the fuel efficiency (based on energy content of fuel) of various natural gas heavy vehicles relative to diesel.

A report by the International Council on Clean Transportation (ICCT) examined numerous available technologies that can deliver diesel fuel consumption reductions (up 30% to 40%) [160], including improved engine technology [161]. Diesel engine efficiency is predicted to increase by 3.5% between 2018-2025 [54] and if natural gas engine efficiency improves at the same rate, the efficiency penalty for natural gas engines will stabilise at 0 to 15% [54,55]. Improvements in engine fuel efficiency will result in reductions in CO_2 emissions from both natural gas and diesel of up to 15% and 40%, respectively, on current technology emissions (Figure 22).

5.2.2. Methane (CH_4) emissions

Methane is an important contributor to greenhouse gas emissions in natural gas trucks given its high climate forcing relative to CO_2. There are three potential mechanisms for methane emissions in trucks:

- Engine slip, where unburned methane passes through to the exhaust due to incomplete combustion;
- Leakage through the engine crankcase, as methane can escape from the combustion chamber into the engine crankcase; and
- Dynamic venting where the fuel rail pressure control system can emit small amounts of gas to the atmosphere to relieve pressure under changing load on the engine (limited to high pressure (HPDI) engine designs) [160].

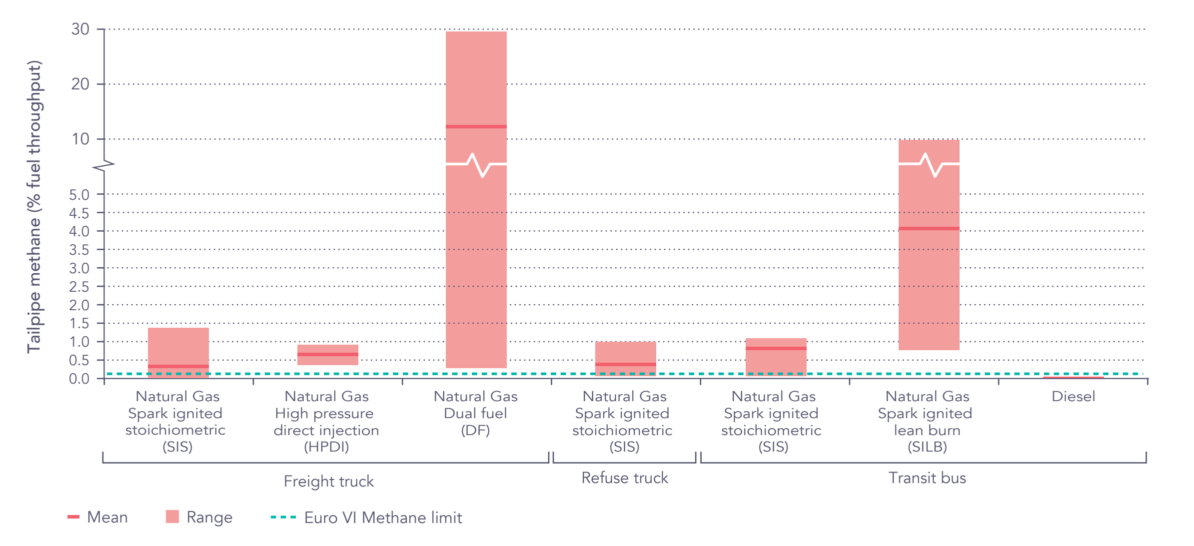
There are a number of techniques to reduce these types of methane emissions. To reduce methane slip in the exhaust gas, catalysts can be used; a three-way catalyst is paired with spark ignited stoichiometric (SIS) engines while a oxidation catalyst is used to control the emissions from spark ignited lean burn (SILB) and compression-ignition (CI) engines [21, 31]. For crankshaft emissions, if the crankcase is open to atmosphere, any methane present will be vented. Therefore, crankcase ventilation systems and improved oxidation catalysts can be used to minimise or eliminate these emissions. However, the ICCT stated that at least up to 2015, there has been little incentive for manufacturers to implement these technologies [160]. Emissions estimates for these three potential mechanisms are presented.

Tailpipe methane

Tailpipe emissions, or engine slip, can be measured as the percentage of fuel which passes through unburnt. The range in emissions of various natural gas trucks (and one diesel for comparison) is given in Figure 23. Of all the natural gas engines the SIS engine produces the lowest emissions. The SILB produces significantly greater emissions, agreeing with the findings presented by Yoon et al. [154]. The emissions from SIS engines are substantially lower because of the high exhaust temperature, while the lower temperatures produced by the SILB engines do not enable the oxidation catalyst to remove comparable amounts of methane [21]. There are numerous factors which can explain the variation in emissions, from differences in vehicle age, catalyst temperature, engine speed, vehicle load, transient behaviour and emissions diffusion between neighbouring micro-trips [161]. However, these results suggest that a SIS engine with a three-way catalyst can provide an effective method for reducing methane emissions. Furthermore, a SILB engine with an oxidation catalyst will not be able to meet Euro VI emissions standards without appropriate thermal management of the gases entering the catalyst.

Methane emissions have the potential to negate climate benefits over diesel. It has been estimated that if engine slip exceeds 2.6 g CH_4/km then total GHG emissions of natural gas freight trucks will be higher than diesel [162][2]. However, this is highly dependent on the fuel efficiency of the truck amongst other factors. In addition, regulations such as the EURO VI limits on heavy duty vehicles in Europe require methane emissions limits significantly below this level (0.5g/km limit) [163]. Assuming a vehicle fuel efficiency of 12MJ/km the EURO VI 0.5g/kWh limit is equivalent to 0.15% of throughput (shown in Figure 23)[3].

FIGURE 23
Summary of tailpipe methane emissions quantified as engine slip (% fuel throughput) for different vehicle and engine types.
Source: [24, 142, 148, 149, 154, 155, 157, 242]

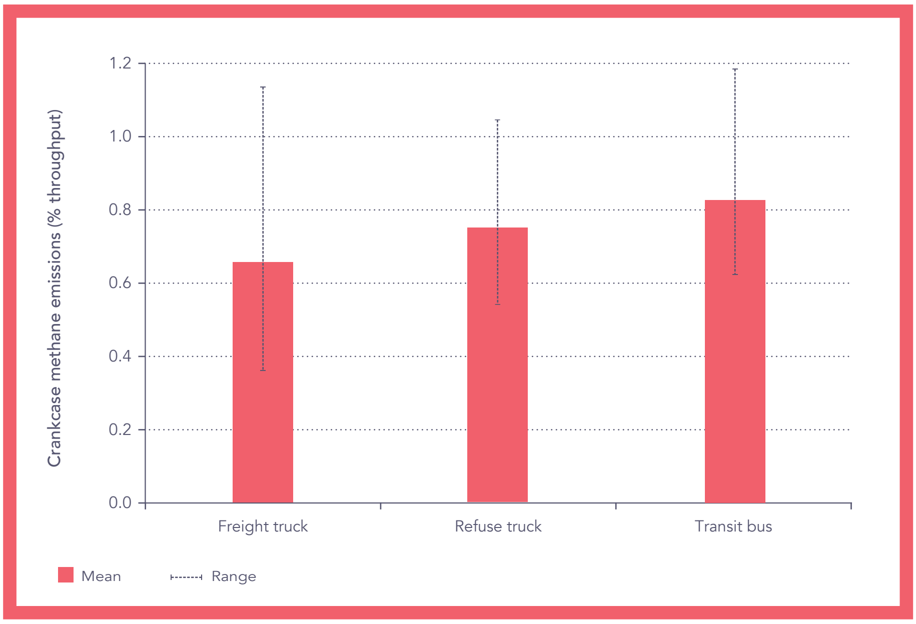


2. This is equivalent to ~1% of methane throughput assuming 12MJ/km fuel efficiency
3. Historically engines are tested in dynamometer laboratory tests. Given that real world driving may introduce other variable there may not be a fair direct comparison between EURO limits and the data captured in Figure 23.

Crankcase methane

Clark et al. [142] summarised all published findings on crankcase emissions from various heavy duty SIS natural gas vehicles (Figure 24). Freight trucks have, on average, the lowest emissions while transit buses have the highest. However, freight trucks also have the biggest range in emissions and can have emissions on par with transit buses, as can be seen in Figure 24. Delgado and Muncrief [160] suggested that if exhaust gas recirculation for a SIS engine is on average 20%, then emissions would be 0.4-0.8% of fuel throughput, which is in the range of the emissions shown in Figure 24. It should be noted that since HPDI engines introduce fuel just prior to ignition, the fuel is unable to penetrate crevices between the piston and cylinder and crankcase emissions are thought to be negligible [160].

FIGURE 24
Summary of the crankcase methane emissions quantified as engine slip (% of fuel throughput) for various natural gas vehicles.
Source: [142]



Dynamic venting (HPDI engines only)

High pressure direct injection (HDPI) engines do not produce significant, if any, emissions of methane through the crankcase. However, they have a dynamic venting system that is used during transient behaviour (sudden changes in engine load), directly venting methane to the atmosphere. The only major study on dynamic venting in HPDI engines was undertaken by Clark et al. [142]. The estimated emissions from four HPDI trucks are shown in Table 13. From the table, it is shown that while it is possible for no venting to occur, emissions can be greater than 2% of the fuel used. Other studies have also suggested that emissions produced by dynamic venting could be within a similar range to crankcase emissions [160]. A return-to-tank system is being employed by Volvo in new HPDI engines. This may have the potential to reduce methane emissions from dynamic venting, though there is currently no available estimate of this technologies performance [165].

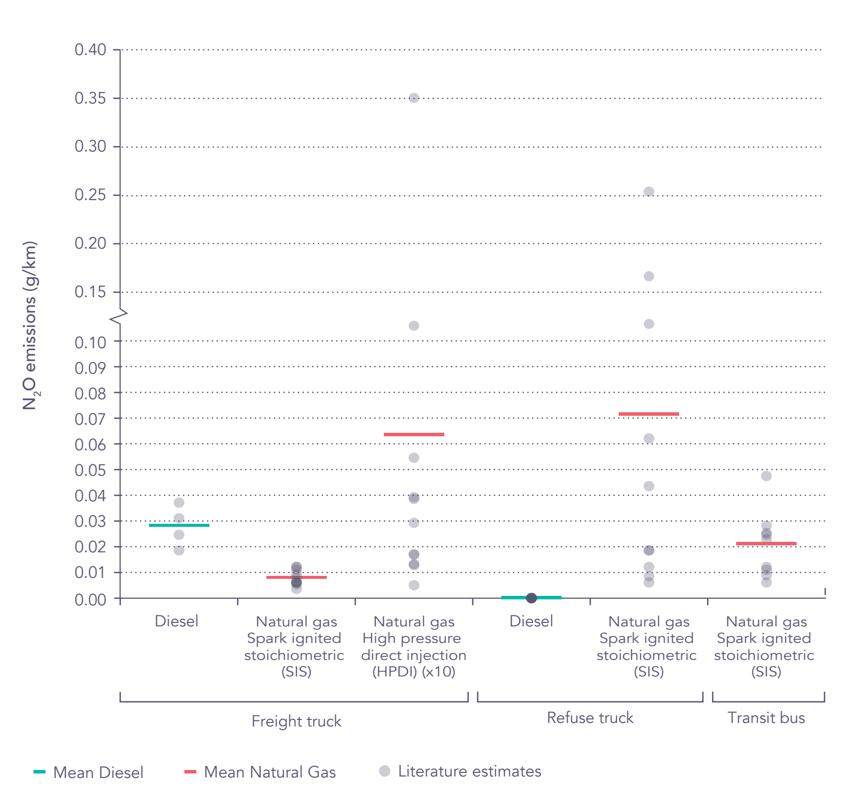
TABLE 13
The fuel-specific methane emissions produced by dynamic venting in high pressure direct injection natural gas vehicles.
Source: [143]

Vehicle type	Engine type	Samples	Methane Emissions [% fuel]		
			Average	min	max
Freight truck	High pressure direct injection (HDPI)	4	0.927	0.000	2.210

5.2.3. Nitrous oxide (N_2O) emissions

Nitrous oxide is a potent greenhouse gas with a global warming potential (GWP) of 298 over a 100 year time-horizon [167] and is produced by the complex combustion process in engines. Emissions are dependent on fuel composition, combustion and emissions control systems and the combustion and catalyst temperatures. Figure 25 summarises the emissions produced by various diesel and natural gas HGVs with different engine types [46, 48, 51, 62]. While the natural gas SIS vehicles were found to have lower emissions, the HPDI was found to emit considerably greater levels of N_2O than diesel. While there is a sparsity in data on N_2O emissions from natural gas vehicles, the data indicates that diesel HGVs may be able to produce lower N_2O emissions. In 2002, Lipman et al. [167] reported that diesel and natural gas vehicles appear to emit similar amounts of N_2O. However, recent design improvements to diesel HGVs have led to a decrease in emissions (relative to older diesel models) making natural gas trucks more N_2O intensive than diesel currently.

FIGURE 25
Summary of the N_2O emissions produced by various diesel and natural gas engines.
Source: [151, 152, 157, 168, 242]

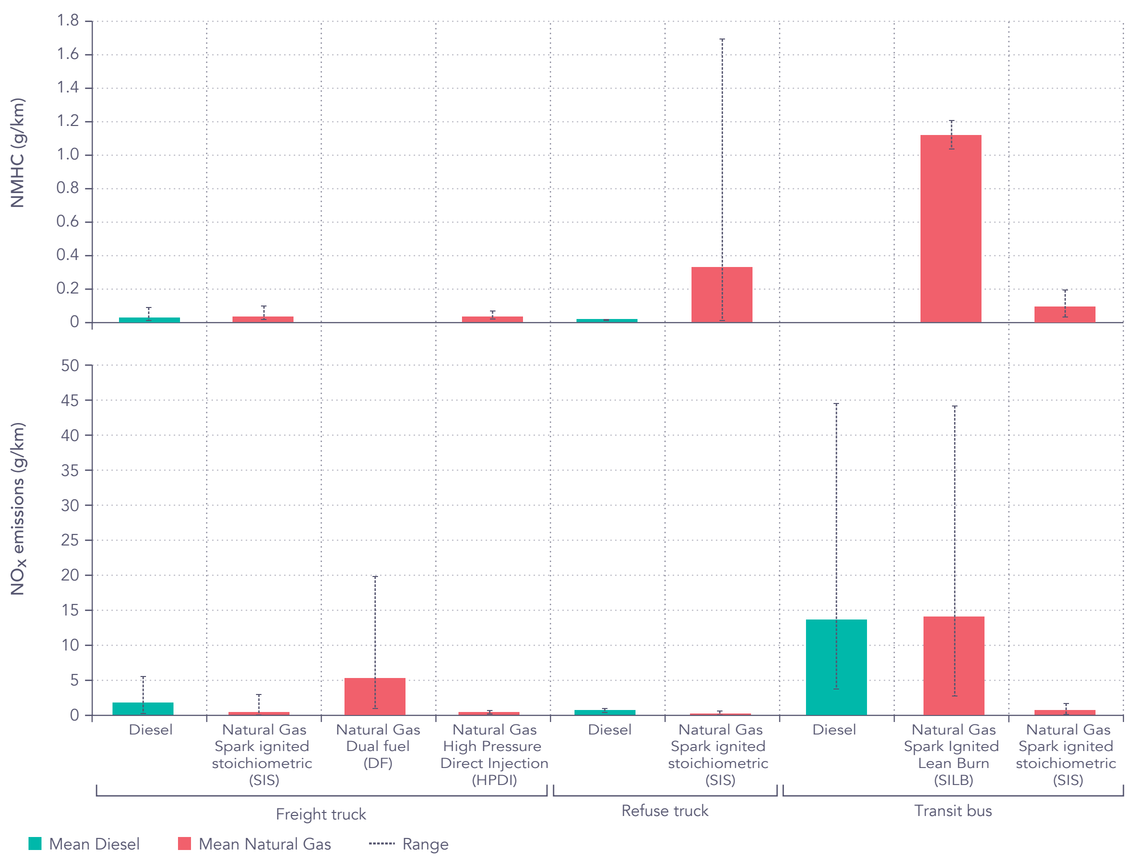


5.3. Air pollution emissions – non-methane hydrocarbons (NMHC), oxides of nitrogen (NO_X), carbon monoxide (CO_2) and particulate matter (PM)

The emission of air pollutants from natural gas and diesel HGVs were collected from a number of studies and are summarised in Figure 26 and Figure 27. The literature indicates that dual fuel HGVs can have the highest NO_X (Figure 26) and particulate matter (PM) emissions (Figure 27), while SIS and HPDI have levels of emissions potentially lower than diesel. However, the SIS produces higher emissions of non-methane hydrocarbons (NMHC) (Figure 26); the HDPI engines emit the least amount of air pollutants of all engines considered. For refuse trucks, the natural gas engine emits more CO_2 and NMHC but produces less NO_X and PM than diesel. The SIS transit bus buses produces substantially lower emissions, except CO_2, than the diesel and SILB which are similar in emissions.

Truck manufacturers have the ability to influence air pollution emissions through vehicle design and aftertreatment technologies. The emissions of vehicles therefor follow, to an extent, the pollution limits of the jurisdiction that they are sold in. This, however, does not capture the difference between vehicle emissions under test conditions and the measured emissions under real-world driving conditions, presented in Figure 26 and Figure 27.

FIGURE 26
Non-methane hydrocarbons (NMHC) and NO_X emissions produced by diesel and natural gas HGVs.
Source: [148, 151-155, 157, 158, 169, 242]
Note: Data for dual fuel engines is taken from a retrofitted Euro V vehicle, i.e. not the latest and strictest Euro VI standard.



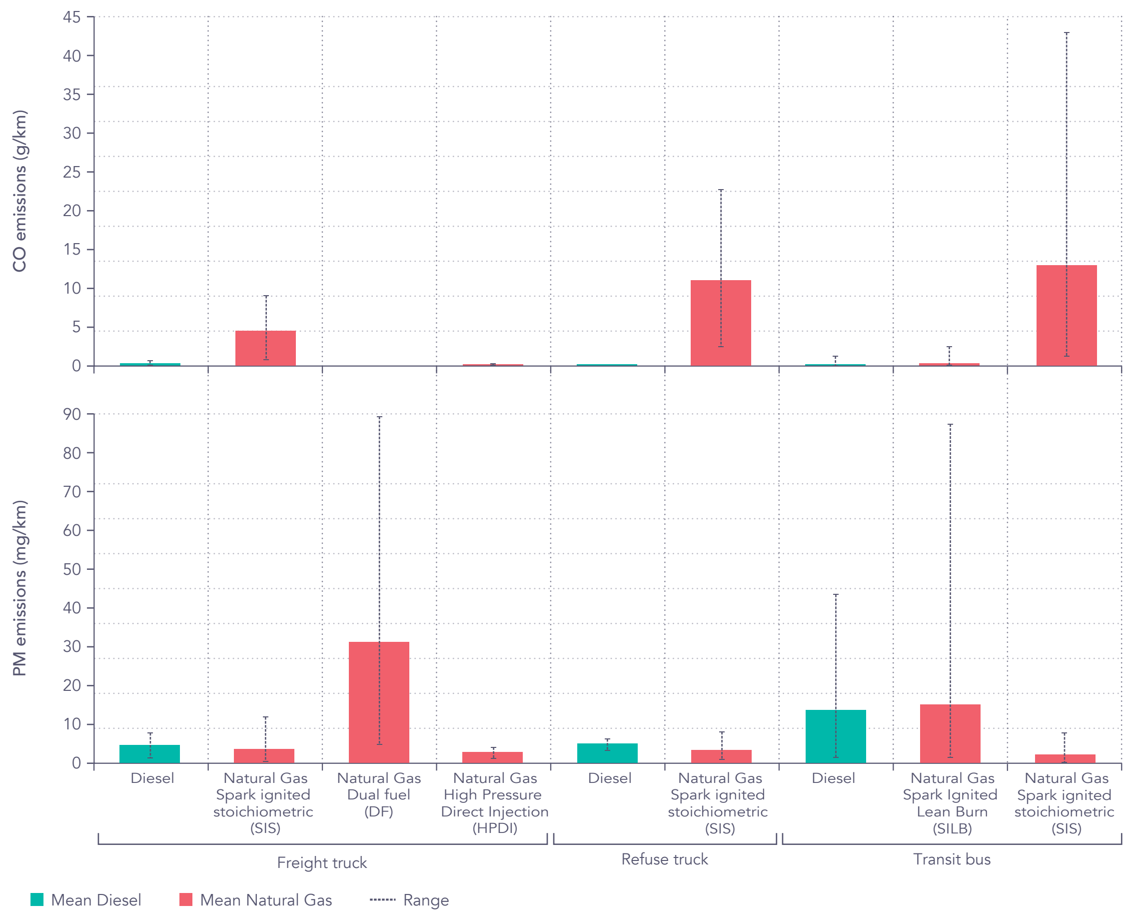


FIGURE 27
CO and particulate matter (PM) emissions produced by diesel and natural gas HGVs.
Source: [148, 151-155, 157, 158, 169, 242]

5.3.1. NO_X emissions

Across a variety of drive cycles and test conditions, both diesel and natural gas HGVs were found to emit substantially more NO_X during urban than rural and motorway driving. There is a notable difference in one study where NO_X emissions from a LNG HGV produced more NO_X than its diesel counterparts [43, 167]. Combining the results of urban/rural/highway driving (15% / 25% / 60%) to represent an average vehicle performance, the vehicle was found to have emissions similar to those of the highest emitting diesel vehicle. A detailed analysis of emissions revealed that the effect of cold engine starts are not as significant for diesel vehicles as they are for LNG [148]. In that study the highest NO_X emissions for a gas truck were 4.5g/km [148][4]. While emissions are higher during a cold start, a three way catalyst (TWC) which heats up rapidly can reduce emissions in SIS LNG trucks. However, higher emissions have also been observed in urban driving during acceleration when the engine and three-way catalyst are warm, resulting in average emissions (during urban driving conditions) being higher than the diesel counterparts. For diesel trucks, high emissions produced in urban driving are primarily due to cold engine starts as the NO_X emissions reduction system (selective catalytic reduction, SCR) requires time to warm up to reach its ideal operating temperature. The emissions produced by a warm engine will be, on average, around 0.5 to 1.0 g/km.

4. This estimate is not included in Figure 26 as it is unclear over which test cycle this is based.

The same LNG vehicle and another LNG truck used in the same study also had higher total hydrocarbon emissions than their diesel counterparts under urban driving conditions, with over 85% of this being methane [148]. As the tested LNG vehicles were relatively new with relatively little ageing of the three-way catalysts, this finding may not be valid for older vehicles. Diesel catalysts also face similar aging issues. Most emissions data for LNG and diesel trucks are for new vehicles and there is a lack of evidence on the effectiveness of ageing emissions control systems.

5.3.2. PM emissions

A study found that emissions from natural gas HGVs varied significantly across different drive cycles; from 80% lower to 40% greater than diesel vehicles equipped with diesel particulate filters (DPFs), depending on the drive-cycle [151, 158]. However, in absolute terms, both natural gas and diesel (with Particulate DPFs) HGVs produced very low PM emissions (0.62 to 6.21 mg/km) [36]. Particle matter (PM) emissions have also been compared for LNG HGVs in comparison to diesel and were found to be lower for motorway driving: 6.0 $x10^{11}$ particles per km compared to $6x10^{13}$ and $2x10^{11}$ particles per km for diesel (non-DPF Euro III truck and Euro V truck with DPF, respectively) [170, 171]. However, on average the LNG HGVs emitted more particles than their diesel counterparts (all fitted with diesel particulate filters).

The latest studies indicate that natural gas HGVs can produce lower levels of air pollutants in motorway driving cycles, but the advantage over diesel is diminished or even reversed in urban driving cycles (Figure 26 and Figure 27) [148, 151 to 155, 157, 158, 169]. Due to the introduction of the Euro VI emissions standards (in Europe) and equivalent standards in the rest of the world the potential benefit is further diminished over most recent diesel truck designs. Advanced emissions control technologies in diesel vehicles, such as selective catalytic reduction and diesel particulate filters to control NO_X and PM, respectively have reduced these emissions measurably. However, there is a lack of data on the deterioration of emissions control systems for both diesel and natural gas vehicles.

5.4. Summary and implications for total GHG emissions

The emissions from trucks can be categorised by refuelling and vehicle operation, and by the main GHGs, CO_2 and methane. At the refuelling station, CO_2 emissions are thought to be relatively low, while the methane emissions from CNG and particularly LNG, may be significant enough to influence overall WTW emissions. Central estimates of methane emissions at this stage are around 0.4% of throughput, though upper estimates place this value at over 9% of throughput.

The most significant parameters influencing GHG emissions from the truck operation are the efficiency of the vehicle and the methane leaked through exhaust, or engine venting. Natural gas trucks emit less CO_2 than diesel equivalents given the lower CO_2 intensity of natural gas compared to diesel (~16% less) though typically not the theoretical ~25% emissions reduction of natural gas relative to diesel trucks. Maximising the potential requires maintaining very close efficiency penalty against diesel engines, and minimising the methane emissions in exhaust and through venting. The long-term view of natural gas engine efficiency, relative to diesel, suggests that energy efficiency penalties will remain in the range of 0-15%. There also exists the potential for methane emissions to increase GHG emission to greater than those of diesel equivalents. Careful choice of natural gas engines and after-treatment technologies is therefore needed to maximise any potential GHG reduction benefits.

The significant variation in tank-to-wake (TTW) methane emissions estimates can be explained by several factors, including: differences in vehicle age, catalyst temperature, engine speed, vehicle load, and duty/drive cycle. Only few measurements exist to quantify non-tailpipe TTW emissions including crankcase emissions and dynamic venting, making this area a key uncertainty.

These are the findings for the pump to wheel system boundary. As discussed in the previous section, the fuel supply chain Well-to-Pump (WTP) also emits CO_2, methane and other air pollutants. Based on the literature presented here and in the previous section, on a full life cycle basis Well-to-Tank (WTW), emissions from TTW are the biggest source of CO_2, methane and NO_X, while the fuel station contributes 0.4% towards methane emissions, as shown in Figure 28. Comparing the best natural gas trucks to the best diesel trucks in Figure 28 indicates a 16% lifecycle GHG emissions reduction potential. Comparing the best natural gas trucks to the best diesel trucks in Figure 28 indicates a 16% lifecycle GHG emissions reduction potential. However, there is a large variation in emissions from all the stages and maximum emissions can be much larger than average emissions. Therefore, it is important that all life cycle stages be considered in order to cut emissions of GHGs and air pollutants from natural gas HGVs.

As mentioned in Section 5.2, methane emissions could increase climate change impacts of natural gas fuelled trucks to higher than diesel. Figure 29 presents the impact of both WTW methane emissions and engine efficiency on total lifecycle GHG emissions relative to diesel trucks. The figure shows that with either supply chain emissions of methane above 3% of throughput or an efficiency deficit of 15% against diesel trucks the WTW GHG emissions from a natural gas fuelled truck will likely be greater than current diesel vehicles. This further emphasises the need to minimise emissions in the WTW system. More research is needed to better understand and quantify emissions from each stage of this WTW life cycle. The fuel consumption relative to diesel is another critical factor in the climate change benefits of fuel switching from diesel to LNG. The figure shows that to maximise the GHG emissions reduction potential natural gas engines need to increase efficiency and minimise the efficiency penalty against diesel engines. With the emergence of new policies to promote these improvements the new truck fleet will likely be constrained to lower emissions levels than today’s fleet.

FIGURE 28
Breakdown of emissions from well-to-wheel (WTW) life cycle of average LNG HGV. Range in emissions for each stage is also shown.
Note: This figure aggregates the evidence in Section 5. In the 'Electric' column the electric mix considered is the UK 2016 mix (42% gas, 9% coal, 19% nuclear , 5% imports, 25% renewables) and the error bars are for the lowest and highest CO_2 intensity electric mixes (100% hydro and 100% coal). The electricity accounts for 67% of the total GWP and the battery manufacture 33%. The truck is modelled on the Tesla Semi which has an estimated fuel consumption of 2 kWh/km.

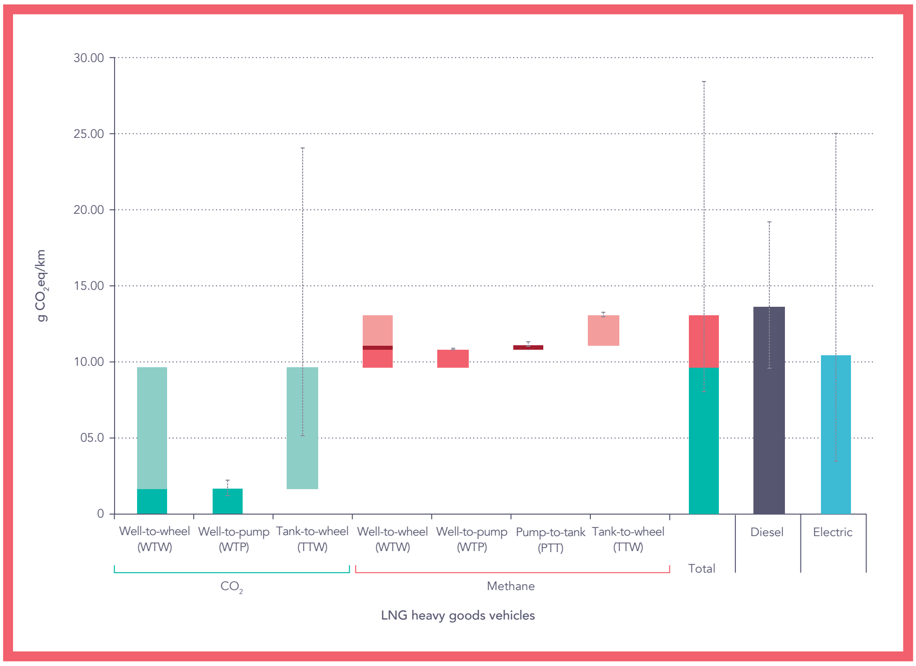
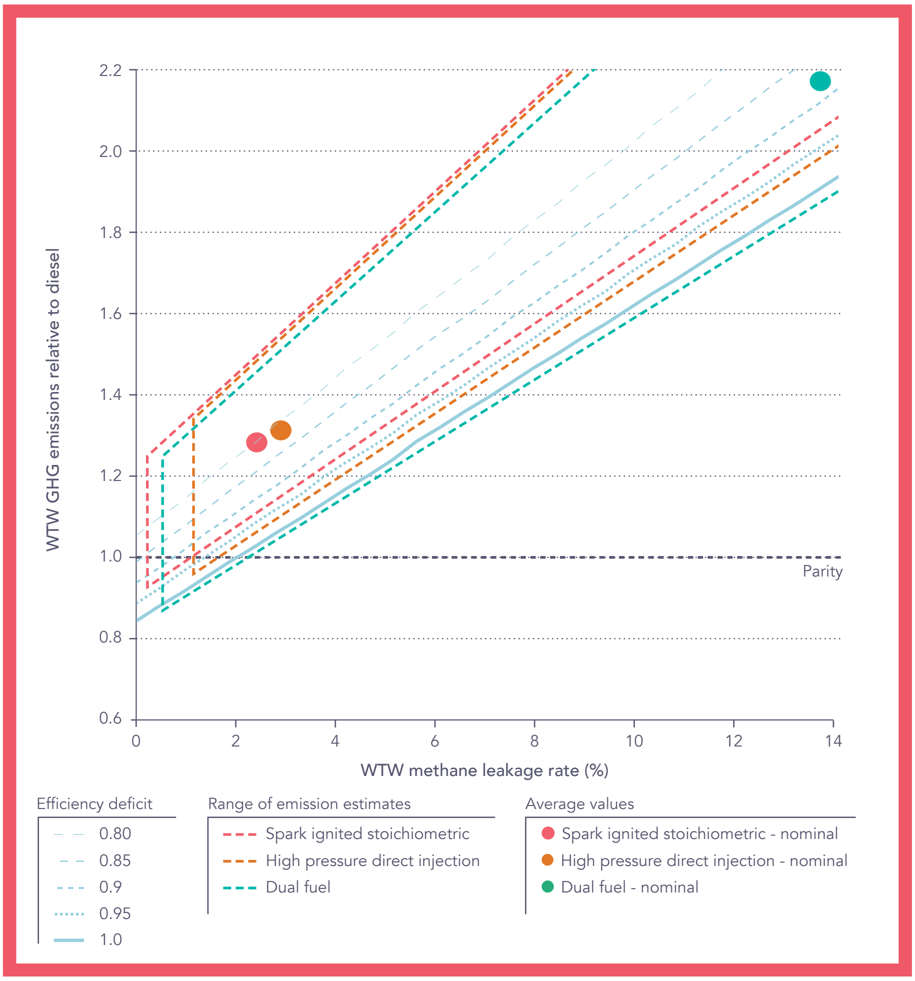


FIGURE 29
Total well-to-wheel (WTW) greenhouse gas emissions as a function of WTW methane emissions for spark-ignited, dual-fuel, and high pressure direct injection natural gas heavy goods vehicle engine technologies relative to diesel
Note: Based on [129] and calculated using range of estimates presented in Section 5. Dotted areas represents the range of estimates of emissions discussed in Section 5. Blue lines represent the differing efficiency deficit between diesel and natural gas vehicles. Dots represent average values for each of the natural gas engine types.



6. Shipping emissions: Bunker-to-wake

The following section examines the downstream emissions arising from fuelling and operating natural gas-fuelled ships. This is categorised as bunker-to-tank and tank-to-wake stages.

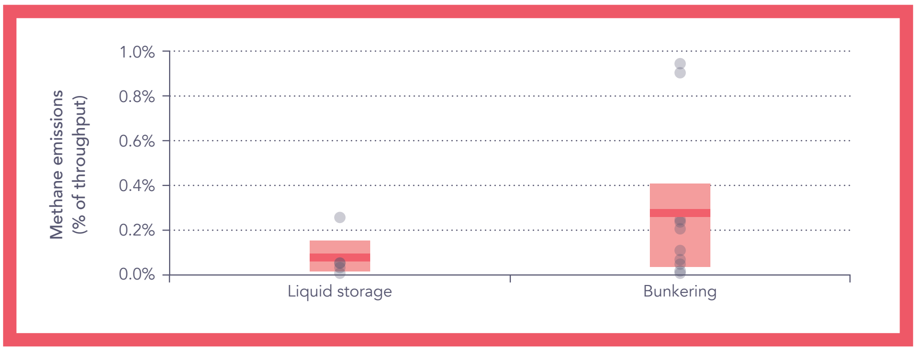
This includes an examination of the main ship engine types (see Section 2) and the proportion of carbon dioxide (CO_2) and methane (CH_4) contributing to these emissions. The section first examines the emissions associated with bunkering, before detailing CO_2, methane and other emissions estimates from vehicle exhaust gas. This section then examines air pollution issues before providing a summary of the environmental credentials of LNG as a shipping fuel.

6.1. Bunker-to-tank

In the bunker-to-tank stage, the operations include the storage of LNG at a terminal or bunkering facility, and the delivery of LNG to the ship. Emissions associated with storage are likely to be from boil-off-gas (BOG) (i.e. methane emissions) or from BOG management, (e.g. CO_2 emissions from fuel use in re-liquefaction). Emissions associated with vessel loading may include methane emissions from vapour displacement associated with changing tank levels, CO_2 from fuel usage or fugitive emissions. Additionally, there may be methane emissions associated with transfer pipe purging as well as flash losses [139]. There are limited high quality data sources for this supply chain stage.

Estimates of methane emissions associated with storage and bunkering are given in Figure 30. Whilst effective BOG management during storage and loading operations are often assumed, Lowell et al. [140] suggest there is more risk of higher methane emissions at more remote bunkering facilities where there is potentially less access to gas infrastructure than at more central, larger, liquefaction sites. Indeed, the higher estimates in Figure 30 are associated with smaller and more remote facilities where re-liquefaction at smaller sites may not be economically feasible. Note that none of these estimates have sufficient transparency to be taken as a representative sample.

FIGURE 30
Estimates of methane emissions from LNG storage and bunkering operations
Source: [137, 139, 140, 172]
Note: Circles represent individual estimates, bars represent mean of estimates and the pink represents the interquartile range.



Bunkering may be carried out via port-to-ship (PTS), ship-to-ship (STS) or truck-to-ship (TTS) methods, depending on the available infrastructure and transfer volume required. These may result in varying methane emissions, as suggested by Corbett et al. [139], but CO_2 emissions resulting from fuel use are likely to be negligible. The Natural & bio Gas Vehicle Association (NGVA) study estimated an electricity requirement associated with ship fuelling of 0.015 kWh/kg LNG [137], which equates to approximately 0.13 gCO_2/MJ LHV LNG assuming an electricity carbon intensity of 400 gCO_2/kWh.

6.2. Tank -to-wake

On-board emissions from tank-to-wake may be numerous in terms of the emission type and the source. This section describes the evidence on GHG emissions associated with end-use as well as the fuel storage and delivery system. First the CO_2 emissions and the impact of engine efficiency are described, before detailing the evidence on methane and other GHG emissions.

6.2.1. CO_2 emissions and efficiency

The key aspects determining CO_2 emissions from ship engines are the fuel used, and the efficiency of combustion. CO_2 emissions arise from main fuel combustion, pilot fuel combustion and ancillary engine fuel combustion. Figure 31 shows literature estimates of CO_2 emissions from engine operation for different fuels and engine types. Note that in this section emissions are expressed per kWh of power output from the engine, in order to incorporate the different average engine efficiencies. LNG engines exhibit emissions of 400 to 470 gCO_2/kWh power output, whereas HFO and MDO options exhibit emissions of 530 to 610 gCO_2/kWh (25th and 75th percentile figures). This means that LNG exhibits a reduction in direct CO_2 emissions of 26% on average, ranging from 12% to 35%. Methanol also exhibits a reduction in CO_2 emissions, albeit only by 7%. Note that for HFO and MDO diesel engines, slow speed and medium speed engines are included within each range. Slow speed diesels (SSD) are typically 2-stroke and used on larger vessels (e.g. container ships), whereas medium speed diesel (MSD) engines are typically 4-stroke and used on smaller vessels (e.g. ferries), although this is not exclusively the case. Emissions from SSD engines are typically lower than MSD engines due to higher efficiencies but the range within the literature is relatively constrained as shown in the Figure 31.

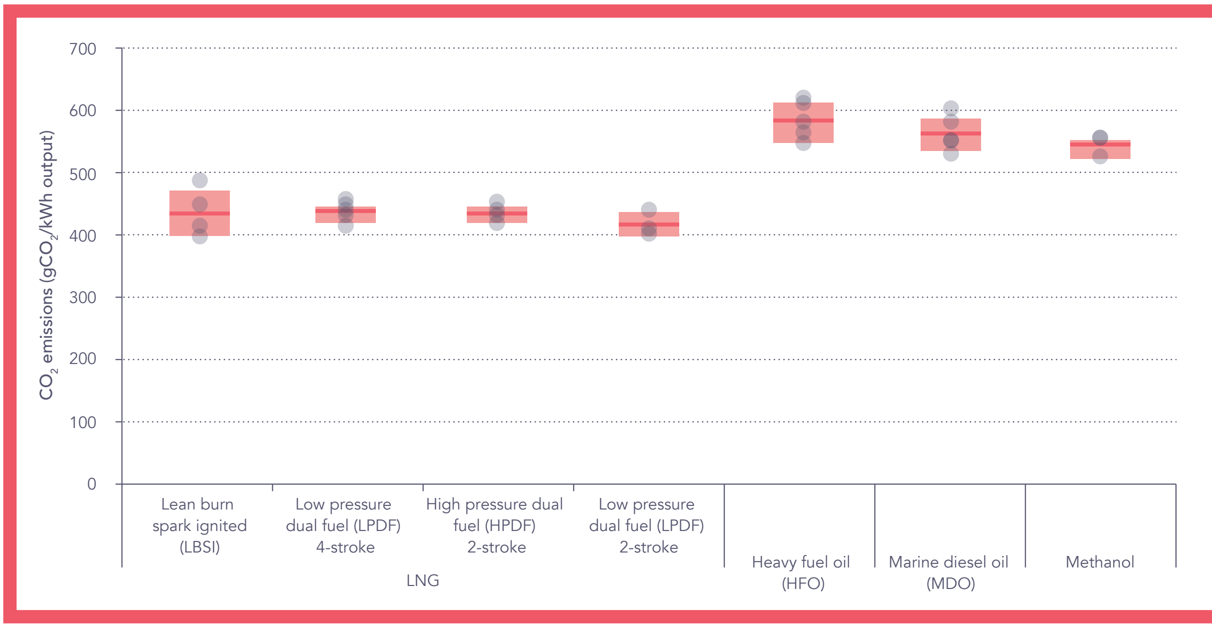
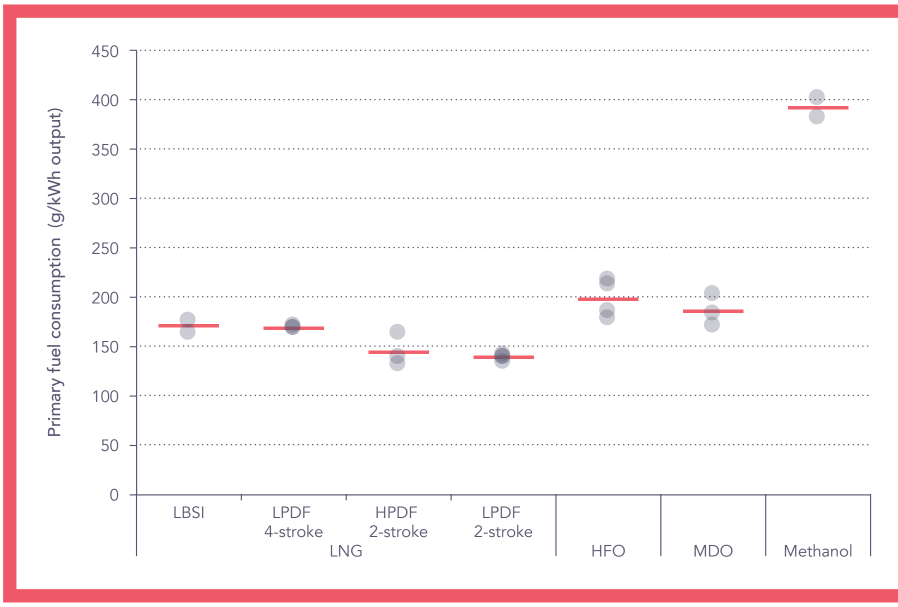


FIGURE 31
Estimates of carbon dioxide emissions from various engines and fuels.
Source: [42, 137, 173-177]
Note: Circles represent individual estimates, bars represent mean of estimates and the pink represents the interquartile range.

CO_2 emissions across the LNG engine types are relatively similar as can be seen, with only the LPDF 2-stroke engine showing lower emissions with an average of 410 gCO_2/kWh. However, there may be more variation than is indicated here. A recent study by SINTEF [42] provided the most robust and transparent set of measurements of LBSI and LPDF 4-stroke engines, both during operation and on test beds. The recommended emission factor for LBSI and LPDF 4-stroke are the highest values shown in the graph, 480 and 452 gCO_2/kWh, respectively.

These higher CO_2 emissions suggest that the efficiencies of these engines are lower than expected and hence fuel consumption is higher. Estimates of primary fuel consumption are shown in Figure 32, where some variation is notable for the LNG engines. HPDF and LPDF 2-stroke engines have noticeably lower fuel consumption, whilst HFO and MDO exhibit higher consumption, and methanol substantially more.

FIGURE 32
Estimates of engine efficiency of various engines and fuels.
Source: [42, 137, 174, 178]
Note: Circles represent individual estimates, bars represent mean of estimates and the pink represents the interquartile range.



It is important to note that, in dual fuel engines using pilot diesel fuel to initiate combustion, system efficiency is governed not only by primary fuel consumption, but by pilot fuel consumption as well as the requirement for ancillary power. Table 14 shows the efficiency of the main LNG ship engine types, and the resulting emissions of CO_2 assuming typically understood CO_2 emissions intensities of LNG, HFO and MDO. In particular the HPDF 2-stroke engine requires a minimum 5% liquid pilot fuel for operation, which impacts upon total efficiency and CO_2 emissions. Even so, both HPDF and LPDF 2-stroke engines have efficiency estimates of 53 to 55% on a lower heating value (LHV) basis, which is substantially higher than the older LNG engines, and diesel engines.

Ancillary power requirements are dependent on the duty of the ship (e.g. a cruise liner would have high power demands), but included in this demand is the fuel delivery system. This is likely to be relatively small, but the high-pressure LNG delivery system requires more power than the low-pressure engine systems. However, this is not included within the scope of this study.

TABLE 14
Typical values for main and pilot fuel consumption, fuel efficiency and CO_2 emissions for different marine fuels and engines
Source: [172]

Values	Low Pressure Dual Fuel (LPDF) 4-stroke	Lean Burn Spark Ignited (LBSI)	High Pressure Dual Fuel (HPDF) 2-stroke	Low Pressure Dual Fuel (LPDF) 2-stroke	Heavy Fuel Oil (HFO)	Marinee Diesel Oil (MDO)
Main fuel consumption (g/kWh)	169.1	170.2	135.1	138.2	201.5	184.5
Pilot fuel consumption (g/kWh)	2.5	0	8.3	1	0	0
Total fuel efficiency (% LHV)	44.60%	44.90%	53.50%	54.90%	44.20%	45.30%
CO_2 emissions (g/kWh)	452.1	480.5	430.8	411.6	579.4	557.5

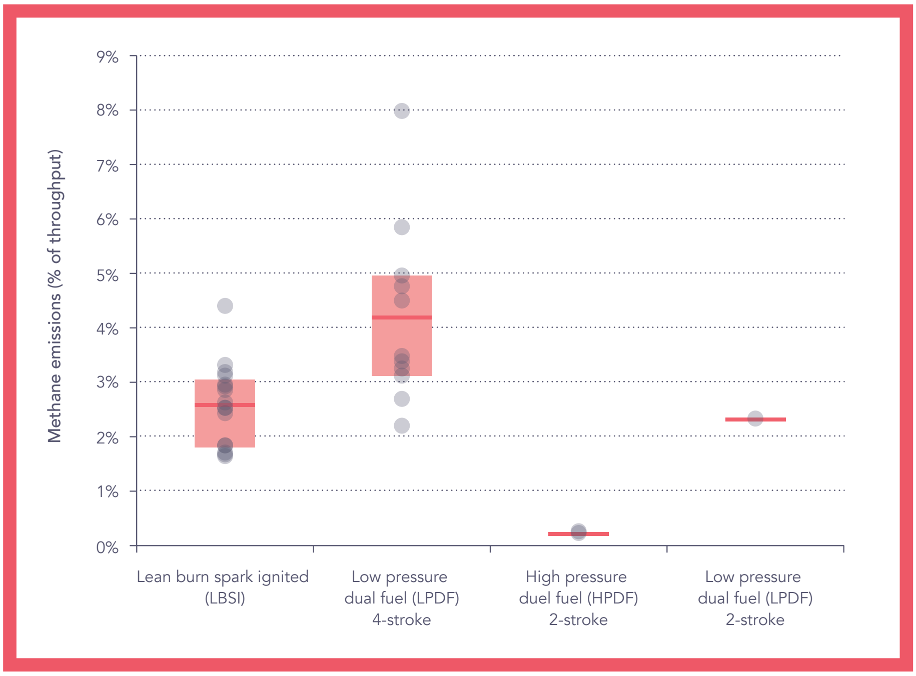
Given the link between efficiency and CO_2 emissions, increasing engine efficiency could be an important tool in reducing emissions. The SINTEF report [42] suggests that efficiency improvements could result in engine efficiencies of greater than 50% (presumably on a lower heating value basis), where current low-pressure engines currently exhibit efficiencies of 45-48% LHV. However, newer gas engines such as the HPDF 2-stroke and LPDF 2-stroke already exhibit efficiencies of 53-55% LHV. In the longer term, the efficiency of natural gas engines might improve incrementally, as has been the case in diesel and HFO engines in the past [180] . However, there is little evidence in the literature to help define the rate of improvement.

6.2.2. Methane emissions

On-board methane emissions have been shown to be highly variable for those engines that have been tested, but only two out of the four main engine types have been assessed (LBSI and LPDF 4-stroke). Furthermore, only exhaust emissions have been tested. Whilst these are highly likely to represent the majority of on-board methane emissions, other sources of on-board methane emissions may occur that have not been assessed, for example intermittent venting of storage or fuel delivery systems, fuel purging or more broadly fugitive emissions. Given the high GWP of methane, measuring such emissions is an important area for future research, and a holistic measurement assessment of LNG-fuelled ships would be required to effectively characterise emissions and rule out additional emission sources.

In publications before 2015, methane slip from ship engines was estimated to be between 1.9% and 2.6% [140, 181]. However, recent measurements by SINTEF [42] in 2017 showed much broader variation, with average methane slip of 2.3% (1.6% to 3.3%) and 4.1% (2.7% to 5.8%) from LBSI and LPDF 4-stroke engines, respectively. Note these only include engines built since 2010 and includes improvements made by engine manufacturers in combustion chamber design and tighter air-fuel ratio control to reduce methane emissions. Estimates and measurements of methane emissions from four different LNG engines are summarised in Figure 33.

FIGURE 33
Estimates of methane emissions from various natural gas engines.
Source: [42, 137, 140, 173-175]
Note: Circles represent individual literature estimates, bars represent mean estimates and the pink bar represents the interquartile range



Whilst the figure shows high variability in emissions for LBSI and LPDF 4-stroke engines, the other two (HPDF and LPDF 2-stroke) have no associated measurements of their methane emissions other than from the manufacturers. It is expected that the LPDF 2-stroke engine exhibits slightly lower methane slip than the LBSI and LPDF 4-stroke, whilst the HPDF 2-stroke exhibits extremely low emissions at approximately 0.2% of throughput. However, there is a requirement to validate these data with real-time in-situ emissions monitoring to ensure that low emissions can be achieved or to determine where the greatest potential reductions exist.

Analysing the methane slip and NO_X emissions in marine vessels shows a competing trend between these species, especially at low engine loads. LBSI and LPDF engines can control NO_X emissions (for instance to meet more stringent Tier III NO_X emissions) by using lean fuel-air mixture to reduce the combustion temperature [42]. However, this technique increases the chance of incomplete combustion of methane and therefore, higher methane slip. This process also increases the carbon monoxide (CO) emissions. On the contrary, a rich fuel-air mixture can minimise methane slip, improve load acceptance and reduce CO_2 emissions at a cost of increasing NO_X emissions. Despite the best efforts of engine manufacturers to eliminate them from LBSI and LPDF engines, these undesired emissions will continue to reduce the GHG benefits of natural gas fuelled ships using these engine types.

6.2.3. Other GHG emissions: black carbon and N_2O

Black carbon (BC) and nitrous oxide (N_2O) emissions also contribute towards the GHG intensity of shipping fleets. Whilst N_2O only represents 1% of estimated annual shipping emissions, black carbon is estimated by one study to contribute 7% on a 100-year time horizon, and 21% on a 20-year basis [181].

BC is a solid material, a product of incomplete combustion of HFO and (less so) MDO. According to the ICCT 2017 report, ships emitted approximately 67 kilotonnes of black carbon in 2015 [181]. It has an extremely high initial radiative forcing but has an atmospheric lifetime of only two days up to a few weeks [182]. The global warming potential (GWP) of BC under 20-year and 100-year horizons were estimated to be approximately 3,200 (270 to 6,200) and 900 (100 to 1,700), respectively [184]. However, there is a high uncertainty in these values.

The ICCT study [182] estimated BC emission factors to be 8.4% of total particulate emissions from each of the fuels (HFO, MDO and LNG), but based on an estimate of BC emissions from an HFO-fuelled diesel engine. In reality different fuels are likely to exhibit different particulate components, but it is anticipated that LNG fuelled ships exhibit very low black carbon emissions given that particulate emissions are so low, as shown in section 6.4.3.

Given the high GWP values, life cycle estimates are extremely sensitive to the assumed emission factor. However, most studies investigating the life cycle emission of marine fuels do not include BC emissions at all. With a GWP100 of 900 and BC emissions of 0.053 and 0.013 g/kWh power output for HFO and MDO respectively, total GWP100 figures are increased by 6.3% (47.6 gCO_2eq/ kWh) and 1.7% (12.1 gCO_2eq/kWh) respectively. This demonstrates the large contribution of BC to short-term warming from liquid fuels and should not be neglected.

6.3. Total ship life cycle GHG emissions

Estimates of total life cycle GHG emissions for LNG and other fuels are somewhat more constrained than the ranges seen for methane emissions, as shown in Figure 34. Broadly, LNG estimates are slightly lower than those of HFO (6% lower on average and 10% lower comparing lowest estimates), whereas conventional methanol is 11% higher. There is a broader range for LNG than the liquid fossil fuels due to differing estimates of both methane slip and upstream supply chain emissions.

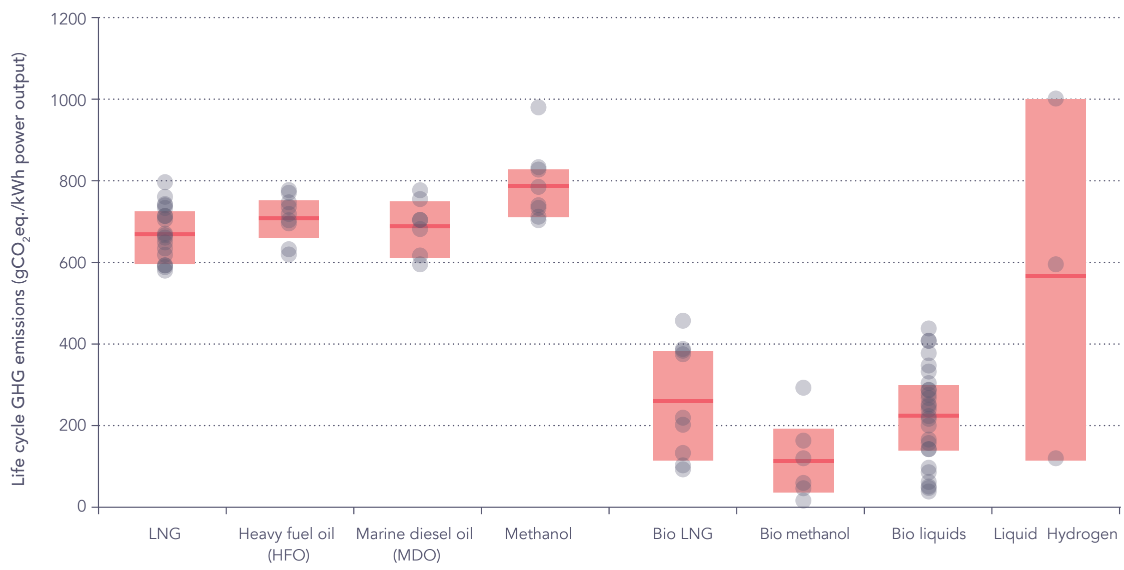


FIGURE 34
Estimates of total life cycle GHG emissions associated with different marine fuels.
Source: [119, 133, 137, 140, 174, 175, 178, 180, 184-186]
Note: Circles show individual literature estimates, the bar represents the mean and 10% lower comparing lowest estimates and the pink are denotes the interquartile range.

The figure also includes various literature estimates of potentially lower carbon fuel alternatives, including methanol, bio LNG, bio liquids and liquid hydrogen. Bio-based fuels show much larger reductions than LNG: 64% for bio-LNG; 84% for bio-methanol; and 69% for other bio-liquids. It should be noted that there are large variations in estimated emissions from bio-sources, due to large differences in feedstock and processing requirements. Liquid hydrogen estimates are even more varied, reflecting the potential to be sourced from a wide variety of both fossil fuels and renewable resources [187].

Examining estimates of LNG options in more detail, Figure 35 shows a range of estimates of total life cycle GHG emissions, split into upstream and ship-based emissions. In addition to the literature review of estimates GHG emissions, a new study was commissioned for this white paper to provide greater insight into estimates of life cycle GHG emissions associated with LNG fuelled ships. The study, is Technical Paper 2, referred to in Section 1.5, and available at **www.sustainablegasinstitute.org/white_paper_series/white-paper-4-can-natural-gas-reduce-emissions-from-transport/**. The results of the life cycle assessment are compared here with other evidence, where a large range of estimates are seen. Particularly high variation comes from the upstream emissions. The lowest estimates of supply chain emissions are around 60 gCO_2eq/kWh, which is extremely low considering the potential contribution from liquefaction alone which may be 80 to 100 gCO_2eq/kWh (if fuelled by the natural gas itself). Methane emissions account for most of the variation in the upstream emissions estimates, which may reflect a genuine variability of emissions across different supply chains and regions.

FIGURE 35
Life cycle GHG estimates of emissions associated with LNG fuelled ships, split by upstream and on-board contributions
Source: [137, 140, 172, 174, 180, 188, 241]

Methane slip from the engine also plays a large part in the variation in estimates. For example, the NGVA study estimated emissions associated with the use of two engine types, LPDF 4-stroke and HPDF 2-stroke. For the LPDF 4-stroke, an emission of 1.8% was assumed, which is approximately half of the recommended emission factor estimated by SINTEF (4.1%) [42].

By using the central estimates of emissions of CO_2 and methane from each stage of the supply chain, life cycle GHG emissions were estimated for the different LNG engines and compared to the liquid fuels, shown in Figure 36 [173]. As can be seen, the sensitivity of CO_2 and methane emissions to the rank-order preference of each technology is high. The following are key findings from this analysis:

- On-board CO_2 emissions are the dominant emissions of all fuel options technologies, highlighting the need to remove the carbon or to derive from a biogenic source.
- Methane emissions have a strong influence on total emissions for LNG.
- Supply chain emissions are high for natural gas, in particular for those associated with liquefaction and from methane.

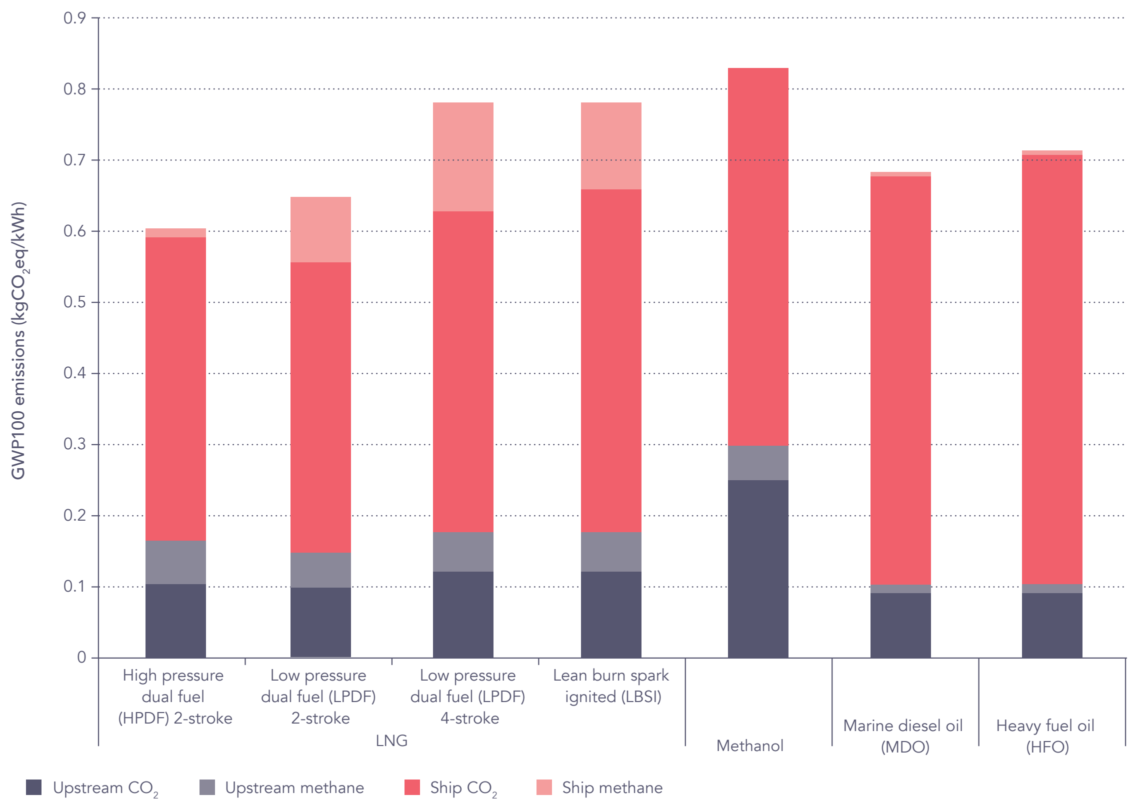


FIGURE 36
Life cycle GHG estimate of emissions associated with LNG fuelled ships compared to liquid fuels split by upstream and on-board contributions from CO_2 and methane.
Source: [172]

It is clear that end-use combustion CO_2 emissions are the dominant source of GHG emissions for all fuels and engines. Notably, the higher efficiencies associated with the LPDF 2-stroke and HPDF 2-stroke engines serve to both reduce these CO_2 emissions, as well as reducing the upstream supply chain contribution due to lower fuel requirements.

The importance of methane emissions on the GHG result should not be understated: lower methane emission LNG options perform the best whilst the higher emitting options perform worse than the liquid fuels, with the exception of methanol owing to its energy-intensive supply chain. If LNG is to contribute materially to the shipping sector, methane slip must be minimised to the levels suggested of the HPDF engine, whilst great care must be taken to utilise the better-performing natural gas supply chains with lower embodied emissions [135].

A large proportion of the LNG supply chain emissions arise from the liquefaction process, where much of the natural gas (~10%) is used as fuel to drive the liquefaction process. If an alternative low-carbon fuel were used for the process, the benefits would be two-fold: lower emissions associated with the process; and increased product volume, which lowers the levelised emission profile.

6.4. Air pollution emissions

6.4.1. Sulphur oxide (SO_X) emissions

The negligible sulphur content of natural gas leads to very low SO_X emissions from LNG ships, particularly in comparison to HFO ships, consequently LNG could contribute to meeting SO_X emissions limits. As described in Section 2 the maximum allowable sulphur content in Emission Control Areas (ECAs) is currently 0.1% and in 2020 there will be a global limit of 0.5% [119]. Figure 37 shows a comparison of SO_X emissions estimates for different fuels and engines, comparing to the current and future SO_X regulations.

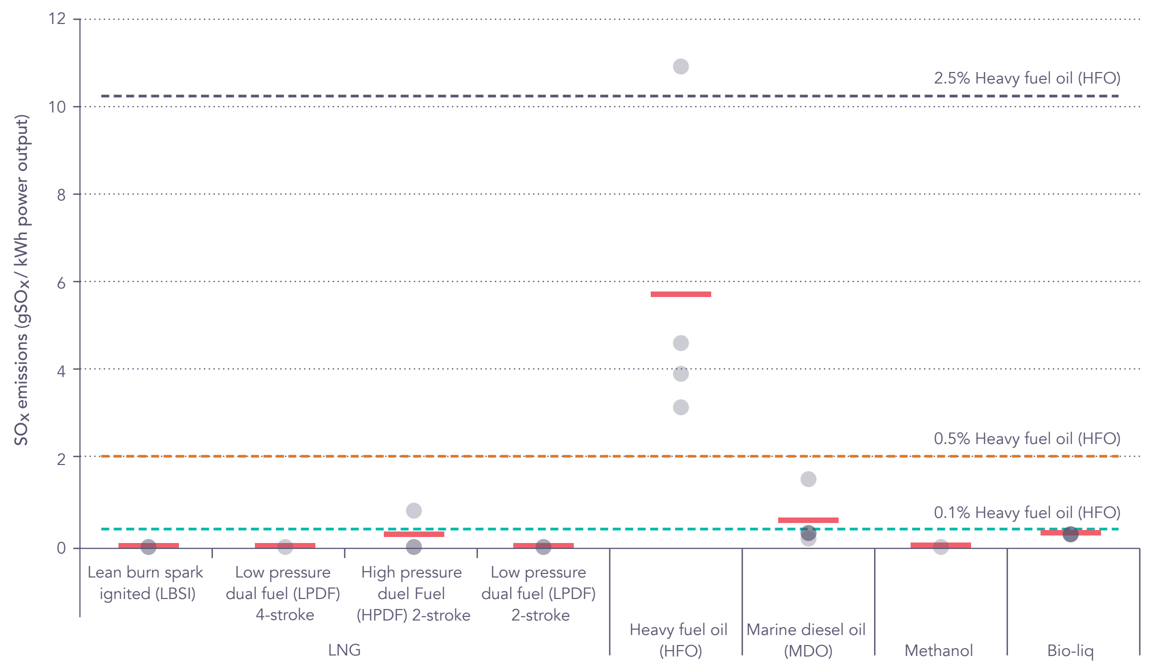


FIGURE 37
Literature estimates of SO_X from different fuels and engine types.
Source: [42, 119, 173-177]
Note: Horizontal dashed lines represent regulatory limits, as detailed in Section 2. Circles represent individual estimates, bars represent mean of estimates

HFO and MDO would not meet the most stringent targets without fuel pre-treatment or exhaust treatment. LNG options reduce SO_X emissions by 80-90% and meet SO_X targets for all estimates except one, which is taken from the HPDF 2-stroke manufacturer brochure [177].

6.4.2. Nitrogen oxides (NO_X) emissions

Estimates of on-board NO_X emissions are shown in Figure 38 and compared to the IMO NO_X emissions tier standards for a range of engine speeds. The results indicate that:

- HFO and MDO, while meeting IMO Tier II emissions standards, cannot meet the more stringent Tier III standards without any after-treatment and/or EGR.
- LBSI and LPDF 4-stroke engines are observed to be an effective means to meet IMO Tier III NO_X emissions with 77% and 70% lower WTW NO_X emissions than MSD engines, respectively.
- Similarly, LPDF 2-stroke engines have 74% lower WTW NO_X emissions than (SSD) engines and also meet the Tier III standards for low-speed engines liquid fuelled
- LS-HPDF engines, while reducing NO_X by 22% compared to liquid fuelled engines, do not meet Tier III standards and would require EGR or SCR in in order to meet Tier III NO_X standards [42].

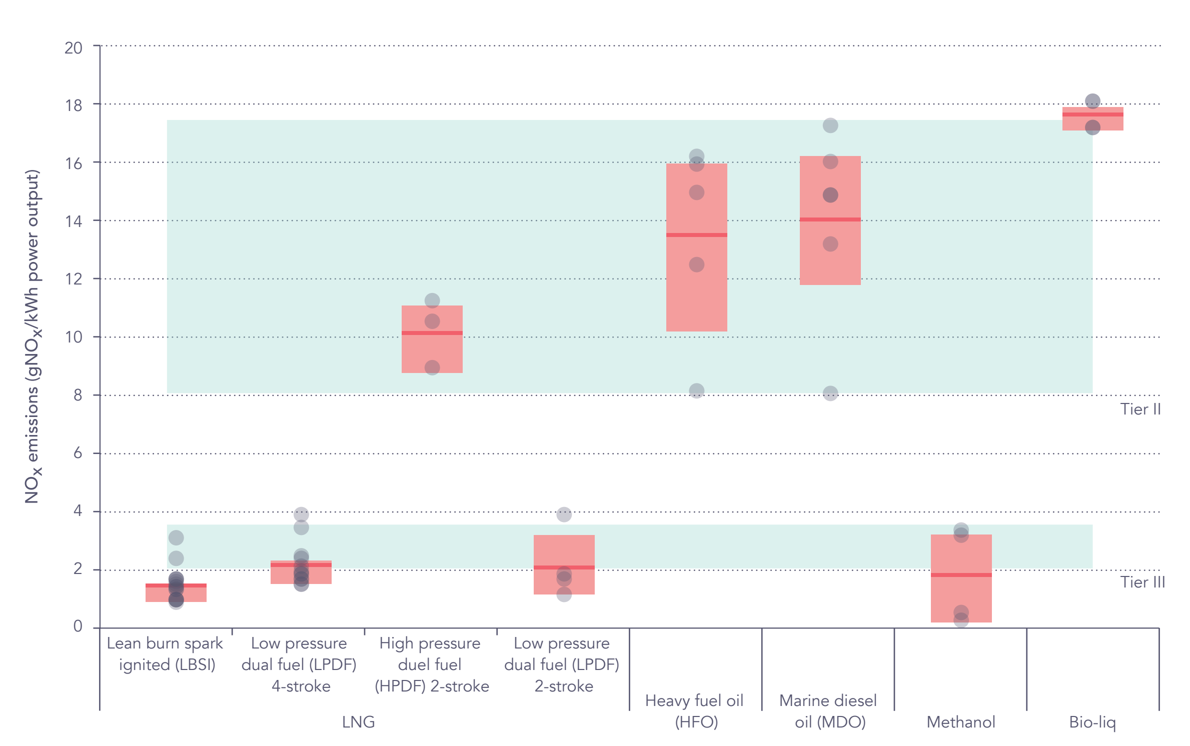


FIGURE 38

Estimates of total NO_X emissions for different fuel and engine types.

Source: [42, 173-176, 189]

Note: Circles denote individual literature estimates, the bar denotes the interquartile range and the green areas denote Tier II and III NO_X emissions limits.

6.4.3. Particulate matter (PM) emissions

The direct PM emissions from the LNG- and HFO-fuelled ships are shown in Figure 39. It should be noted that PM emissions are directly affected by the sulphur content of fuels. The PM emissions from diesel engines under varying sulphur content were obtained from Comer et al. [182]. The results of the analysis of PM emissions from LNG and HFO supply chains indicate that:

- LBSI, LPDF 4-stroke, and LPDF 2-stroke engines have 97 to 98% lower PM emissions than HFO and MDO engines.
- HPDF 2-stroke engines have 35% lower PM emissions than MDO.
- Using fuels with 0.1% sulphur contents will reduce the baseline PM emissions from liquid fuelled engines up to 85%.

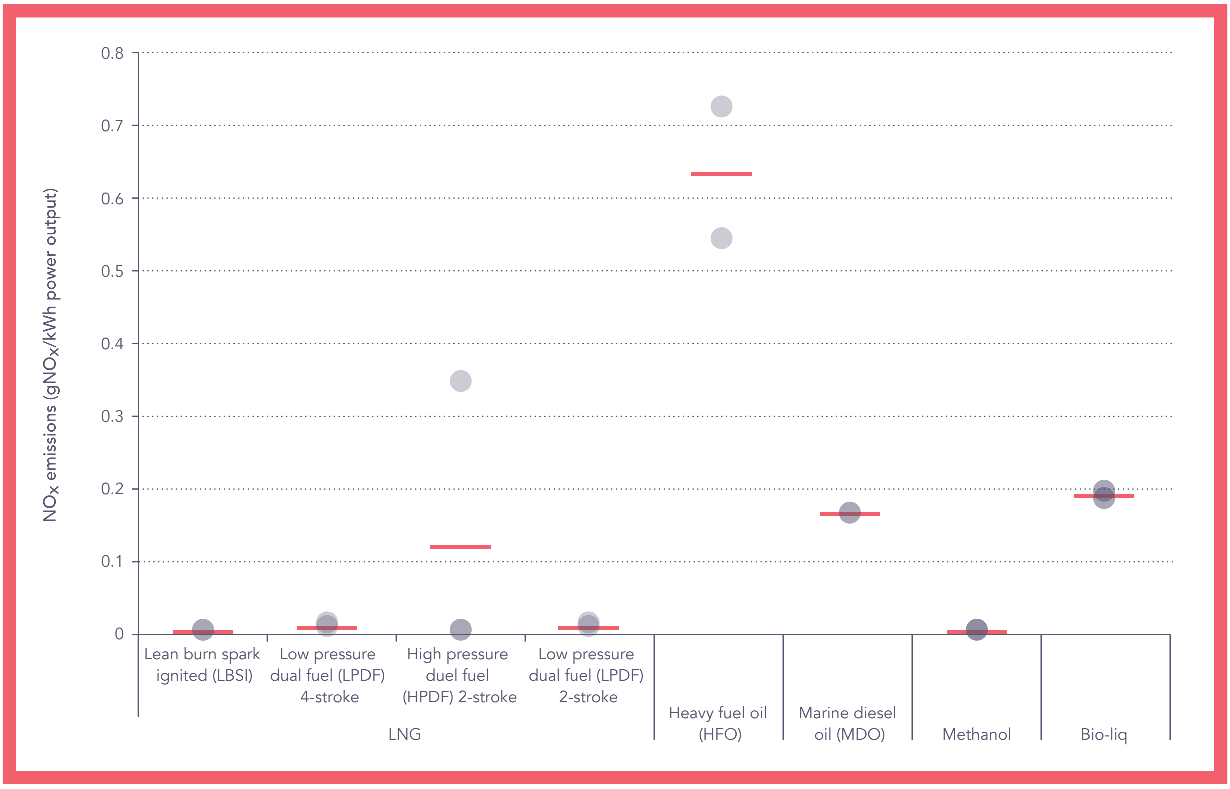


FIGURE 39
Life cycle PM emissions for different fuel and engine types.
Source: [42, 174, 177, 189]
Note: Circles represent individual estimates, bars represent mean of estimates.

6.5. Summary of environmental impact of LNG as shipping fuel

In summary, it is clear that LNG offers significantly improved air quality impacts and moderate reductions in CO_2 emissions, but methane emissions eliminate this carbon benefit in some cases. Air quality impacts are reduced by 80% to 90%, with the exception of NO_X emissions from the HPDF engine.

Methane emissions from two of the four LNG engines considered are unacceptably high with respect to reducing climate impacts. This creates a challenge in demonstrating the role for LNG in decarbonising the maritime sector. Reducing these emissions and providing more robust, transparent and representative measurements of methane emissions will be key to demonstrating any significant role. With the lowest estimates of supply chain emissions combined with the lowest methane slip and high efficiency engines, an emission reduction compared to HFO of up to 28% is possible [172]. However, comparing best estimates of both HFO and natural gas ships suggests a 10% lifecycle GHG reduction. Great care must be taken to ensure that emissions from the supply chain are minimised and low slip engines are utilised. One of the studied engines may exhibit very low methane emissions, but there is a need for real-world, independently measured and validated data sources to confirm these credentials [172].

While the existing ship fleet and available engines are analysed above, the nature of emerging emissions regulations and agreements in shipping suggest increasing pressure on emissions. The impact of these regulations is yet to be seen in the development of the future ship fleet.

7. Costs of natural gas as a transport fuel

The costs associated with natural gas as a transport fuel are key drivers in vehicle or ship purchasing decisions. Fuel costs may be the dominant operating cost and the engine type plays a key role in defining the difference in ship or truck (capital) cost. This section explores both these issues in turn, before making some comparisons on a total cost of ownership (TCO) basis.

7.1. Fuel cost

The cost of natural gas to vehicle or ship operators is influenced by a number of factors, including;

- The wholesale gas price, which varies over time and location;
- The form natural gas is stored in; and
- The taxes or duties applied to the fuel.

The first two of these factors vary, but have historical trends that can be examined. In contrast, the taxes and duties typically applied to transport fuels are not mirrored in natural gas, though this may change in the future. This is particularly the case for road fuels, where duties are attached to the sale of transport fuels in many countries.

Should demand for natural gas as a transport fuel increase significantly this would also have an influence on the natural gas price, though this is an aspect of future fuel price that is not typically covered in the transport literature.

A number of studies compare the price of incumbent fuels with the price of natural gas as either liquefied natural gas (LNG) or compressed natural gas (CNG), drawing the conclusion that natural gas is relatively cheap, providing an economic basis for a transition to natural gas as a transport fuel [20, 190-197].

7.1.1. Ship fuels

Figure 40 presents the historical prices for three shipping fuels: heavy fuel oil (HFO), marine diesel oil (MDO) and LNG. The data in Figure 40 are normalised to 2017 US Dollars and presented in dollars per GJ of fuel. This data can also be presented in dollars per kWh of engine output, accounting for variations in engine efficiency. However, the differences in engine efficiency have a small impact on the cost to ship operators relative to the significant differences in fuel prices.

The LNG prices compared here are wholesale prices in the United States and Europe and may not fully capture the costs of bunkering and refuelling. However, these costs are not expected to play a significant role, with several studies comparing similar estimates of LNG price to conclude that there is a potential cost benefit over incumbent fuels such as HFO and MDO [121, 194-196]. One study assumes that costs of small-scale distribution of LNG to deliver to a wider shipping market might increase fuel costs by approximately 30%, though this study still finds LNG a cheaper fuel than HFO on an energy basis [197]. Another estimate of bunkered LNG suggests that, based on a recent low price, bunkered LNG is 35% cheaper than intermediate fuel oil (IFO380)[5], and 65% cheaper than marine gas oil (MGO) [198]. International shipping also largely avoids the types of fuel tax applied in many countries to road fuels, therefore these types of additional cost to LNG as a shipping fuel have not played a role in the analysis of costs in Figure 40.

FIGURE 40
Comparison of the price of different shipping fuels in 2017 United States dollars per GJ of fuel.
Source: [197, 201-202]
Note: Fuel prices from Europe and the United States.

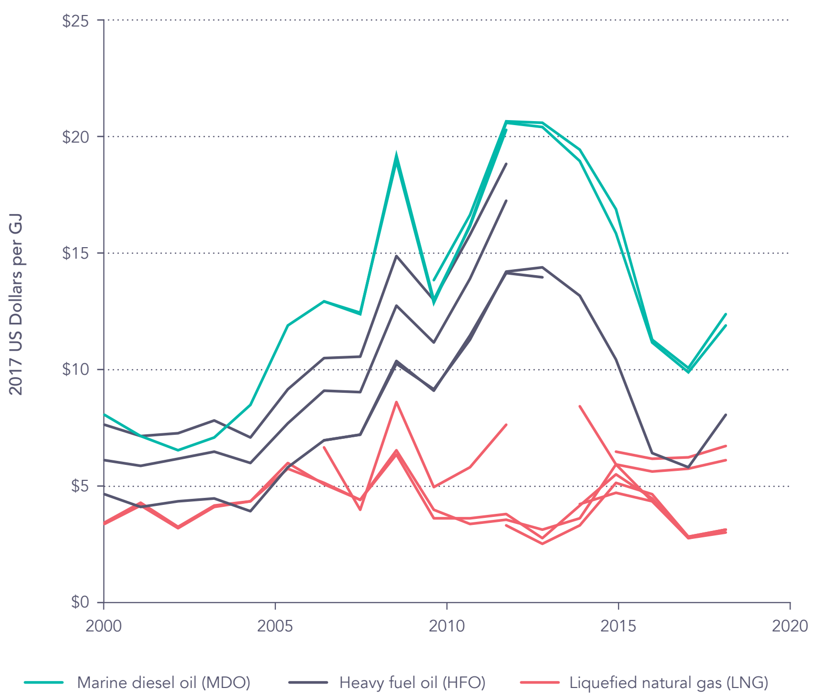


Figure 40 shows that the prices of incumbent HFO and MDO are significantly higher than LNG. LNG is on average ~50% less than HFO and ~65% less than MDO within this time period. However, this data also suggests volatility in fuel price, including periods where the difference in price between HFO and LNG is significantly narrowed, or in some cases entirely eliminated. Given this volatility, there is uncertainty regarding the future trend in these prices, though one study models a static price difference between LNG, HFO and low sulphur marine fuels out to 2030 [197].

5.Intermediate fuel oil 380 is a blend of gasoil and heavy fuel oil, with less gasoil than marine diesel oil, a maximum viscosity of 380 centistokes and less than 3.5% sulphur

The literature on ship fuel costs do not typically discuss the potential impact a substantial increase in LNG demand on LNG fuel price. As an indication of scale the global market for LNG is currently 15,736 PJ, while the global ship fuel market is 11,920 PJ, therefore an increase in ship market demand for LNG could have a significant impact on total LNG demand [10, 203]. A knock-on reduction in HFO and MDO demand could also reduce their prices, which would reduce this price differential further. Assessing different scenarios of change in future fuel demand and the impact on price is an area for future research, where integrated whole systems economic models might provide useful insights.

7.1.2. Truck fuels

The comparison of truck fuels on a similar basis to that for ship fuels illustrates the significant impact that fuel duties and taxes can have on the fuel price. Figure 41 compares retail prices for diesel, CNG and LNG in the United States. With fuel duty CNG and LNG gives fuel cost reductions of 20% to 23%. Again, this comparison indicates that fuel cost may provide an economic incentive to transition towards natural gas as a truck fuel, given its price discount relative to diesel on an engine output basis.

FIGURE 41
Comparison of the price of different truck fuels in 2018 in United States dollars per GJ of fuel in the United States.
Source: [204]

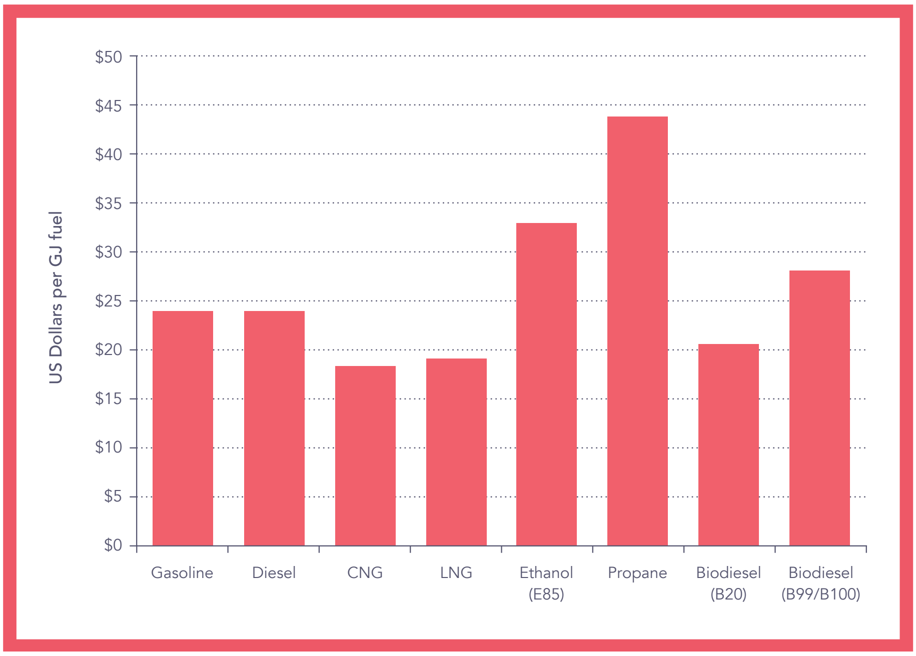


Figure 42 presents LNG, CNG and diesel prices in several European countries. This demonstrates three things:

- CNG and LNG are significantly cheaper than diesel on an energy basis in the majority of countries. Sweden is the only country where diesel LNG and CNG are closely prices, driven by the high fuel duty applied to natural gas in that country [205].
- There is significant variation in all fuel prices between countries. Again this is driven to a large extent by differences in VAT and fuel duty [205].
- In many countries there is little difference between CNG and LNG. This is counterintuitive given the greater cost associated with liquefaction of

LNG relative to the cost of CNG compression. However, this is thought to be related to pricing behaviour by the fuel station operators, who may do this for marketing and promotional reasons [205].

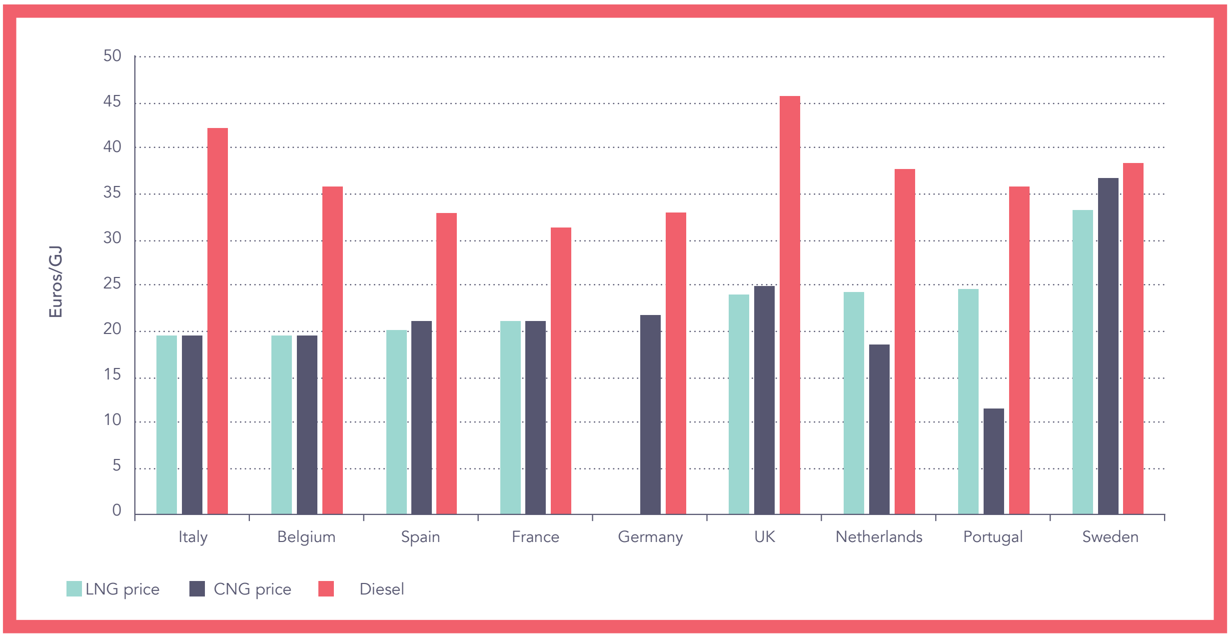
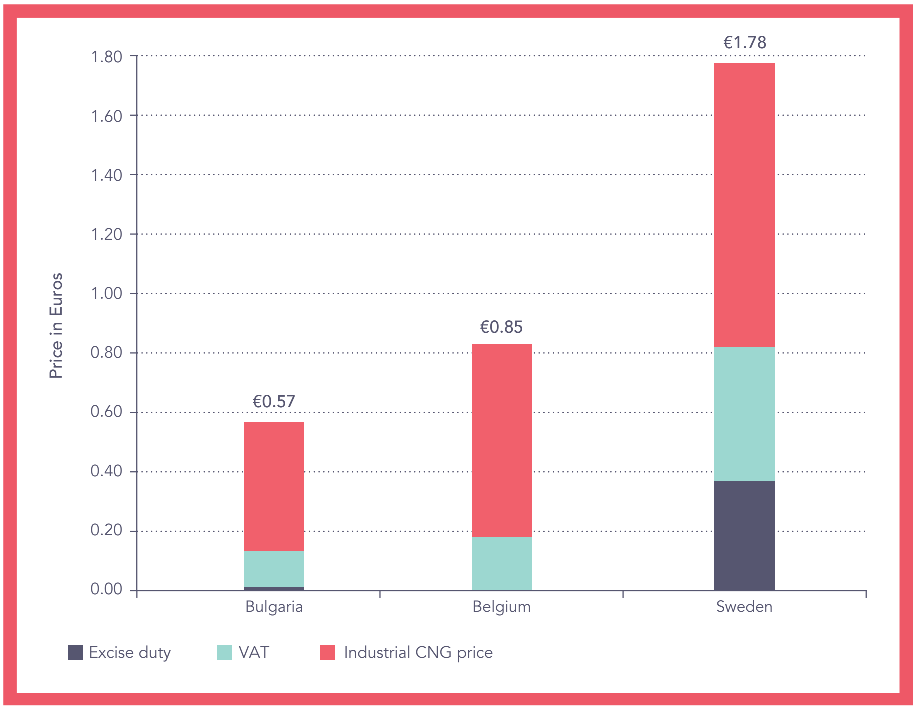


FIGURE 42
LNG, CNG and diesel prices in a number of countries in Europe in 2016.
Source: [205]

A significant proportion of the apparent price difference is a function of the fuel duty applied, with duty on natural gas fuels typically significantly less that on liquid road fuels [204].

Figure 43 illustrates the differing fuel duties applied to CNG in three European countries. This illustrates the relatively low tax in comparison to tax on diesel, which is presented for European countries in Figure 44. This also highlights the significant variation in fuel taxes across different countries.

FIGURE 43
CNG price comparison in Bulgaria, Belgium and Sweden in 2018.
Source: [206]



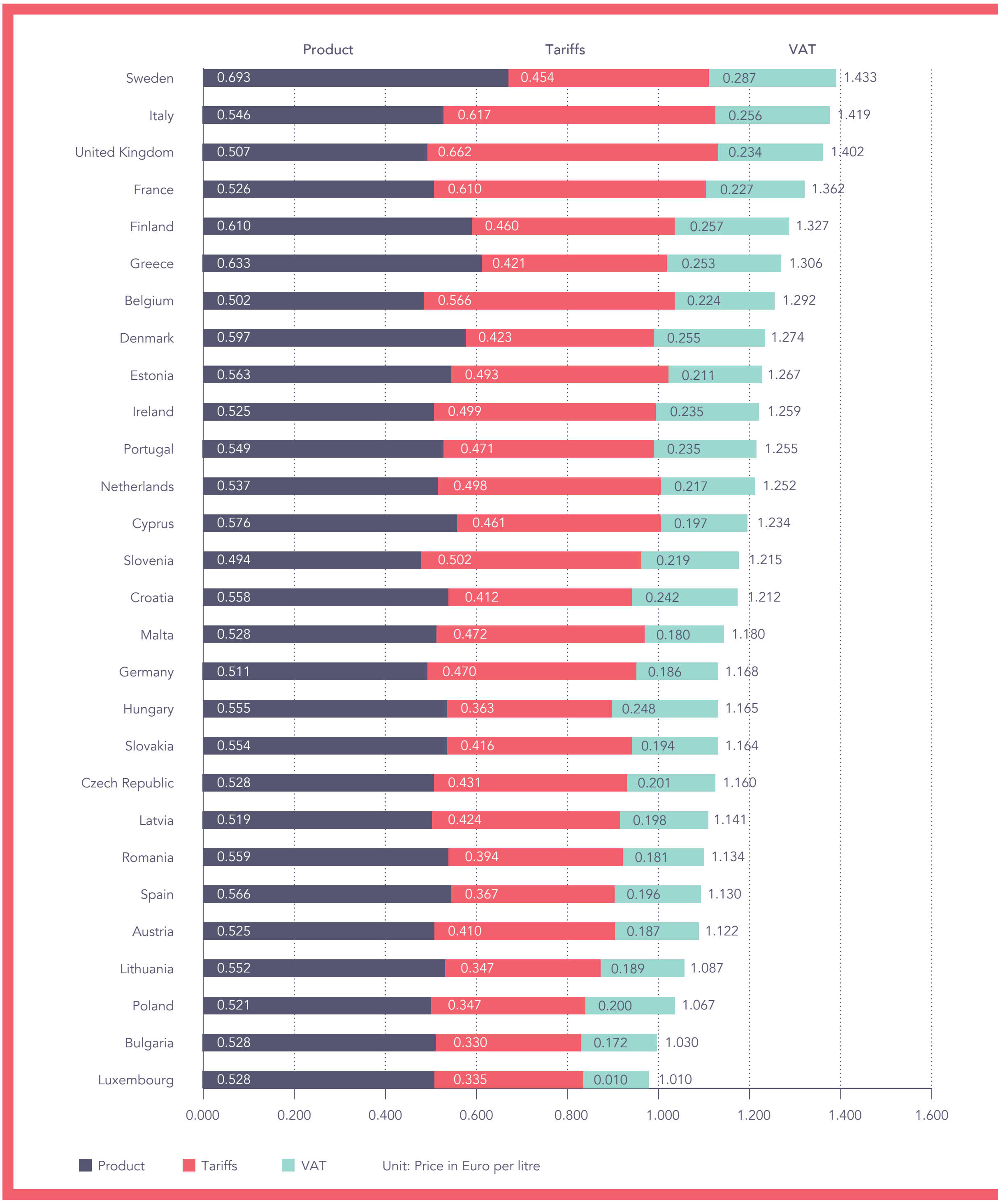


FIGURE 44
Diesel prices including tariffs and VAT in different European countries in 2018.
Source: [207]

Since fuel price and tax varies with jurisdiction and fuel, and may also be changed in the future, it is challenging to draw conclusions regarding the future price trends for these fuels. Pressure may emerge for governments to increase the duty on natural gas road fuels as demand increases [208]. This is an issue highlighted by Joss [191], who examined the UK fuel duty on CNG, LNG and diesel. To illustrate the potential impact of future increases to natural gas road fuel duty they compared the potential equalisation of duty on these three fuels on a CO_2 and energy basis (Figure 45). The price differential tightens significantly in both cases, though CNG and LNG both remain cheaper than diesel, reflecting the difference in the underlying fuel prices without duty.

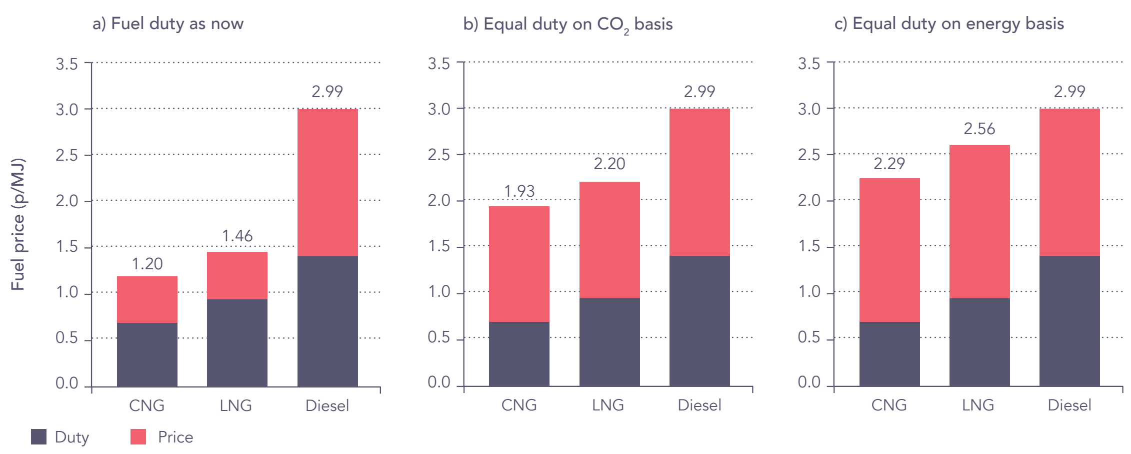


FIGURE 45
Fuel prices for three different approaches to fuel duty in the UK.
Source: [191]

7.1.3. Fuel cost summary

In summary:

- The cost of incumbent liquid fuels such as diesel and HFO is typically higher than that of equivalent forms of natural gas, including both CNG and LNG;
- In ship fuels this is particularly apparent when comparing low-sulphur fuels such as MDO and LNG.
- In truck fuels, the significant influence of fuel duty creates most of the price difference seen between diesel and CNG or LNG. This therefore creates a sensitivity in fuel price to regulatory influence, either in the reduction of incumbent fuel tax or in the introduction of increased taxes on natural gas fuels.
- The influence of increasing demand for natural gas as a transport fuel is not typically discussed as an influencing factor on future fuel prices. Should natural gas substitute significantly for HFO, MDO or diesel then there would be a positive influence on the price of LNG or CNG and a corresponding negative influence on HFO, MDO or diesel. This would impact the future price differential between these fuels.

7.2. Vehicle cost

The cost of vehicles represents a significant proportion of capital costs for truck or ship operators. The cost of new ship or truck designs incorporating engines that can utilise modern lower carbon fuels will, in the short term at least, be greater than the cost of the incumbent vehicle designs. Much of that increased cost lies in the engine and fuel system costs. While these are not particularly more sophisticated than incumbent engine designs, the additional cost is thought to be largely a function of the relatively low volumes of production currently [191]. The cost differential may therefore narrow over time if natural gas vehicle adoption increases. The additional cost for natural gas ships and trucks, and indicative estimates of other vehicle designs are presented in this section.

7.2.1. Ship costs

There are relatively few publicly available estimates of ship costs in the literature, that cover incumbent HFO fuelled vessels, natural gas fuelled vessels and hydrogen fuelled vessels [121, 196, 209, 210]. This makes comparing across different studies a challenge given the large variations in prices between ships of different duties, sizes, and countries of origin, as well as studies with different published dates and various units used. The transparency of studies is also a challenge, with many studies omitting details of vessel size, engine size or disaggregation of engine and tank costs. Table 15 represents estimates of full ship costs normalised in 2017 US dollars. This comparison highlights a number of key issues:

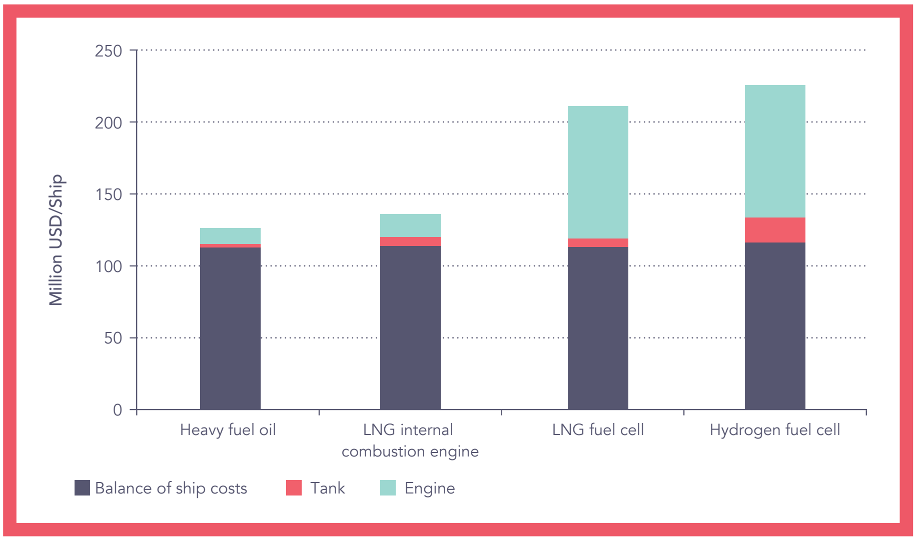
- First, gas options are a higher cost due to the additional cost of engines, fuel supply systems and LNG fuels tanks. Where there are directly comparable estimates this cost premium is 6%-10% [120, 209]. The additional cost of these components is highlighted in Figure 46 which shows data from [120]. However, total costs are still dominated by the balance of ship costs in HFO and natural gas ships based on these estimates.
- Second, there is a large variation in the cost estimates of the various ship types in Table 15. This range is a function of the vessel and engine size, fuel tank size and vessel range, the country source of data and age of data.
- Finally, while the gas engines represent a small increase relative to the incumbent liquid fuel engines, hydrogen power trains have a much more significant impact on ship costs. Figure 46 suggests that a significant proportion of that cost is dictated by the cost of the fuel cell stack, while the cost of hydrogen tanks also plays a significant role relative to the cost of tanks in vessels using liquid or natural gas as fuel.

In addition to this evidence there have been statements as to the cost of newer HPDI natural gas engines for ships. One statement suggests that these engines will cost 15% to 40% more than LPDF engines [210]. However, this cost premium, when integrated in total ship costs, will be smaller relative to total ship costs.

TABLE 15
Estimates of total ship cost and ship cost per kW of engine output in 2017 US dollars.

Fuels	Engine size (kW)	Ship type	Ship cost ($)	Cost ($) per kW engine	Source
Heavy fuel oil (HFO)/ Marine diesel oil (MDO)	9,801	Bulk carrier	30,639,033	3,126	[197]
	2,400	Short sea	18,119,719	7,550	[121]
	11,000	Deep sea	80,140,927	7,286	[121]
	23,000	Container	131,600,927	5,722	[121]
	9,801	Bulk carrier	30,699,092	3,132	[197]
	14,500	Gas carrier	40,400,000	2,786	[210]
Low Pressure Dual Fuel (LPDF)	2,400	Short sea	19,258,672	8,024	[121]
	11,000	Deep sea	87,802,979	7,982	[121]
	23,000	Container	141,696,199	6,161	[121]
	14,500	Gas carrier	44,400,000	3,062	[210]
Hydrogen Fuel Cell (HFC)	2,400	Short sea	27,541,972	11,476	[121]
	11,000	Deep sea	137,088,613	12,463	[121]
	23,000	Container	234,003,222	10,174	[121]

FIGURE 46
Breakdown of cost components of four different ship types in 2014.
Source: [121]



7.2.2. Truck costs

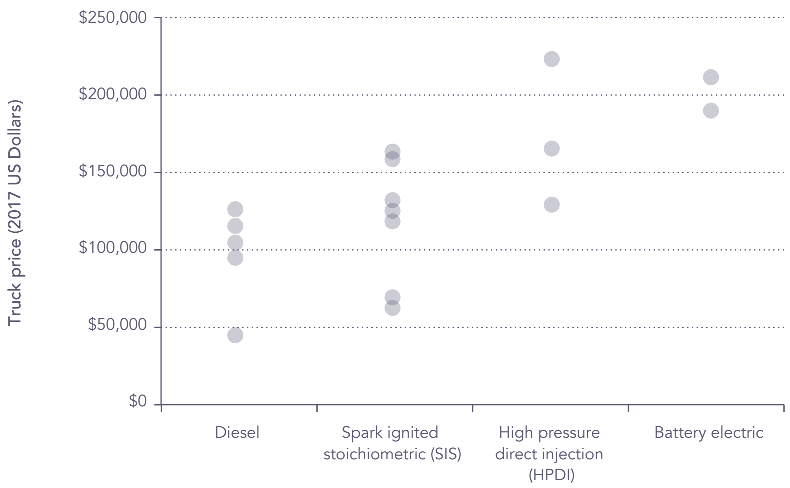
A number of studies provide estimates of the cost of trucks, engines, or the cost differential to incumbent diesel vehicles [20, 129, 191, 211 to 214]. These estimates are presented in Figure 47, normalised in 2017 US dollars per vehicle based on costs stated in published year. This does not consider cost reduction potential. Several key issues are highlighted by this comparison, which show some similarities to the issues identified for ship costs in the previous section.

First, gas vehicles appear more expensive than incumbent diesel vehicles, with directly comparable estimates suggesting a price premium of ~25% to ~50% for SIS engines and ~30% to ~90% for HPDI engines against diesel fuelled trucks. Second, there is significant variation in costs for each engine type, which is a function of vehicle and engine size, the country source of data, as well as the age of the data. To compare these costs to zero emissions vehicle options, Tesla have stated that the first versions of its proposed 'Tesla Semi' has an expected price of between $180,000 and $200,000 for a version with an 800 km range [213]. This estimate is towards the top of the range of estimated high-pressure-direct-injection (HPDI) trucks. However, for final details of pricing, the fact that the electric truck may have only 80% of the range of an LNG truck and the potential of loss-leading pricing behaviour limit the value of direct price comparison.

It is also possible to retrofit existing trucks with natural gas engines at a reduced costs relative to new vehicle cost [190]. This may cost in the region of $30,000 dollars excluding the residual value of the truck [190].

There are few estimates of the cost of hydrogen fuel cell powered trucks, though these might be able to provide reduced emissions through low carbon hydrogen in the future [215]. The Fuel Cells and Hydrogen 2 Joint Undertaking (FCH2 JU) provide an estimates for the cost of a hydrogen fuel cell powered long distance truck (>12 tonnes) at $340,000 to $375,000 [215]. This study also estimates significant cost reduction in the future arriving at $130,000 to $143,000 by 2030 [215]. It is uncertain over what timescale these trucks might become a more competitive economic prospect.

FIGURE 47
Estimates of truck cost for different engine types.
Source: [20, 129, 191, 211-214]



7.3. Total cost of ownership (TCO) and the payback proposition

The additional capital costs associated with natural gas engines for both trucks and ships is tempered by the potential fuel cost savings identified in Section 7.1. To understand the cost-effectiveness of the various options it is necessary to collectively assess fuel, capital and depreciation costs as well as other factors.

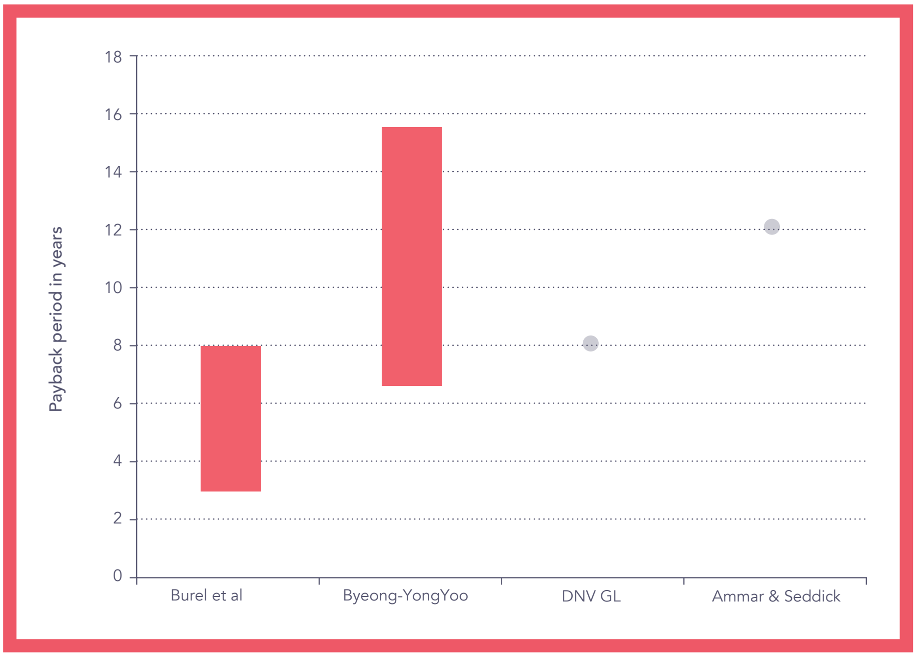
A number of studies have investigated the implications of capital and operational costs on the total costs of ownership (TCO). Given the higher capital cost but lower operating costs of natural gas engines, a common assessment of LNG vessel cost in relation to incumbent designs is as a payback period, or time taken to recover the higher capital cost of LNG investment through the operating cost savings associated with the cheaper LNG fuel. These studies are discussed below for both ships and trucks.

7.3.1. Total costs of LNG ship ownership

Several studies give estimates of several elements contributing to the total cost of LNG fuelled ships [121, 194 to 196]. Various options are compared over time with other fuel options including incumbent HFO fuelled vessels, MDO/MGO fuelled vessels, or investment in other emissions mitigation technologies such as exhaust gas scrubbers to mitigate SO_X emissions [192 to 195].

The literature typically concludes that the extra investment in LNG ships is paid back within the lifetime of the vessel. The studies in Figure 48 measure payback periods of investing in LNG ships against the costs of MGO/MDO ships, or HFO ships including aftertreatment technologies necessary to meet future air pollution limits. This demonstrates a range from 3 to nearly 16 years needed to pay back the initial LNG investment through reduced fuel costs.

FIGURE 48
Payback periods for LNG ships estimates in four literature estimates.
Source: [192-195]
Note: Payback period in [193] LNG against MDO, with range a function of varying LNG price from ~25% below to ~20% over the HFO price. Payback period in [193] measured between LNG and MGO, with range a function of varying the additional cost of the LNG system between 10% and 15% of the MGO engine. [194] and [195] measure the payback period between LNG and HFO including necessary aftertreatment technology.



Total costs of natural gas trucks ownership

Similar to ships, numerous studies estimate different elements contributing to the total cost of natural gas trucks [20, 190, 191, 216]. Many of these studies compare natural gas trucks to diesel fuelled trucks, giving payback periods, which estimate the length of time it takes to recover the higher initial capital cost of natural gas trucks through the comparatively lower fuel costs [20, 190, 191].

A recent study in the UK by the Energy Technologies Institute (ETI) [191] examined the potential future of natural gas fuelled trucks, comparing different gas engine options with a conventional diesel truck. With a 32% higher capital cost for an LNG natural gas truck, the payback time is five years on a TCO basis assuming current UK fuel duty and with government projections of fuel price over time [191]. The study also states that a 32% incremental cost is sufficient to install an HPDI engine, thought to be Euro VI compliant [191].

Ivanco et al. [190] examined the return-on-investment (ROI) associated with retrofitting diesel trucks with a dual fuel engine. The study demonstrates the impact of a range of fuel price differentials and annual distance travelled on the time to pay back the initial capital investment, estimated at $31,000 (Figure 49). The study found that at a fuel price discount of ~50% below diesel and 100,000 miles annual distance travelled that the retrofit investment would be paid back in 15 months. However, if the fuel price differential is reduced to 10% the payback period increases to 8 years[6].

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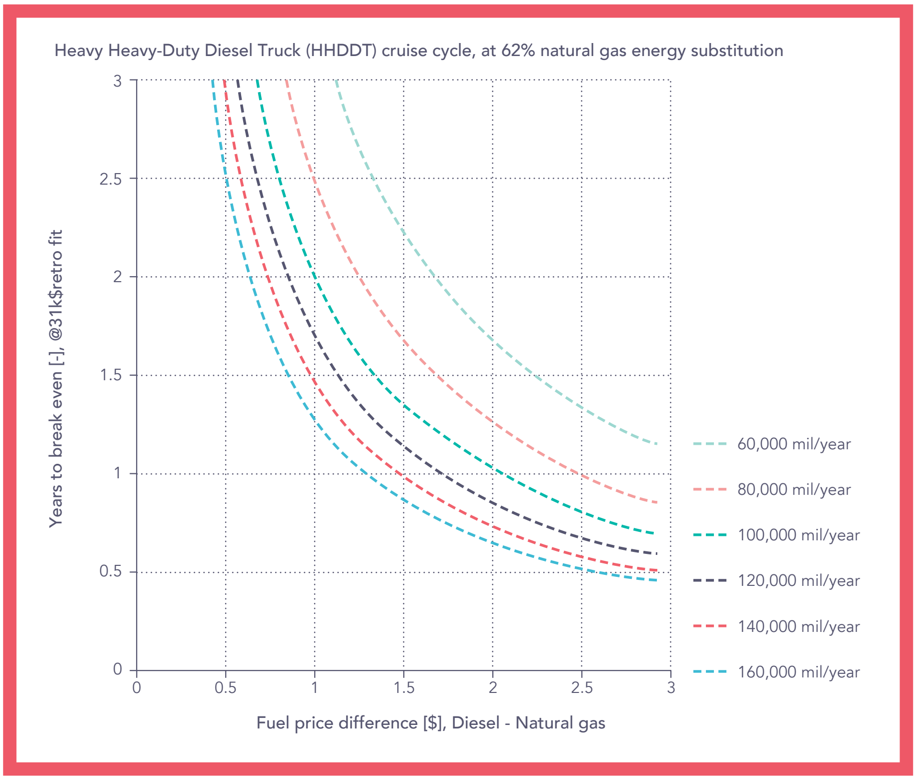
6. This study appears to compare the price of diesel to the price of natural gas on a Gasoline Gallons Equivalent (GGE) basis. The conversion value is not disclosed but if the difference between energy density of diesel and gasoline has not been properly accounted for the price differential may have been overestimated in this study.

FIGURE 49
The impact of annual distance and fuel price differential on payback period of investment in dual fuel engine retrofit in a long-haul truck.
Source: [190]



Finally Gabl [20] compares the cost of diesel to dedicated natural gas trucks on a TCO basis. The study assumed that the incremental cost of the natural gas truck was €20,000, a diesel cost based on diesel prices in 2016 in Europe. On this basis the initial extra investment in the natural gas engine is payed back in five years. This study also examines the sensitivity of this finding to changes in the capital or fuel cost differential. This examination found that reducing the fuel consumption of the natural gas truck by 15% would reduce the payback period to three years, while reducing the incremental truck purchasing cost by 15% reduced the payback period to four years.

In summary, natural gas trucks exhibit higher capital costs by approximately 20% to 75% compared to diesel, but reduced fuel costs give an expected payback period of 15 months to eight years, based on assumptions on duty cycles and distance travelled. Given an expected truck life span of 10 to 15 years, there is an expectation that natural gas trucks will be cheaper on a TCO basis, unless fuel tax increases significantly. As well as capital and fuel costs, key factors affecting cost effectiveness are the expected utilisation, duty cycle and mileage of the truck.

7.4. Additional cost issues

Various additional cost aspects are discussed or quantified in the literature but are less central to the main body of research literature. Such aspects include external social costs, remanufacturing costs at end-of-life, residual vehicle value and non-fuel operating costs, which are all discussed here briefly.

7.4.1. External social costs

One aspect not typically accounted for in TCO studies is the external costs associated with emissions. While this study has addressed a range of GHG and air quality emissions issues associated with vehicle fuels, the costs of these have not been covered. The literature examining costs of natural gas fuelled vehicles typically does not cover this type of externality as an economic factor. However, this impact is discussed in some reports [216].

The European Environment Agency estimated the social cost of particulate and NO_X emissions across the countries of the EU. This equates an economic cost to the social impacts of the unwanted emissions, such as the health impacts of NO_X or particulate emissions. They find that, on average, the cost of PM25 is ~€38 per kilogram, and the cost of NO_X emissions was ~€12 per kilogram. If social costs of emissions are integrated more commonly in economic assessments of transport fuel options in the future this may present an additional cost metric to inform vehicle purchase decisions.

7.4.2. Remanufacturing of end-of-life diesel engines

The possibility of 'remanufacturing' end-of life diesel truck engines into either diesel or LNG fuelled engines is investigated by Shi et al [217]. This study examined the full life cycle of this remanufacturing process, including the remanufactured engine use and the future or avoided landfill or incineration costs. Of these two types of reused engines the study found that, much as with building new engines, there is a cost premium associated with the LNG engine. Similar to the discussion in the previous section, the lower cost of LNG fuel relative to diesel makes the LNG more cost effective over the full lifecycle of the engine [217].

7.4.3. Vehicle residual value

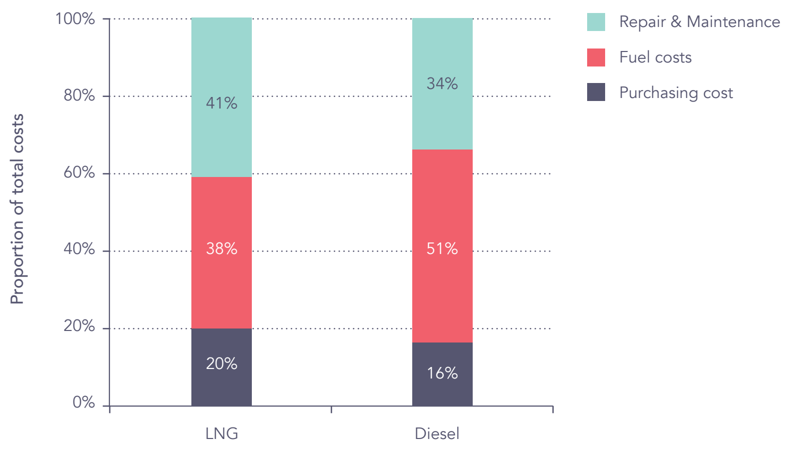
The residual value of trucks or ships as an economic benefit to operators has not been examined in any detail in the study so far. Often this cost is included in TCO calculations such as the ones summarised above. However, some studies choose to assign no residual value to natural gas vehicles after their first economic use [192]. This may be a precautionary assumption given the uncertain secondary market for LNG fuelled vehicles in particular, given the uncertainty in the future distribution of LNG as a fuel, and the important safety issues associated with handling LNG as a fuel.

7.4.4. Non-fuel operating costs

The literature is relatively comprehensive when addressing the fuel costs associated with ship and truck designs. However, there are also other, non-fuel operating costs that influence the total costs of trucks and ships. Some studies assume that these costs are a small proportion of operating costs, being dwarfed by fuel cost [193]. Though this may be the case for ships the maintenance costs for trucks are likely to make up a higher proportion of the

TCO [20]. In addition, there is likely to be a cost differential in these other operating costs between LNG and incumbent liquid fuel vehicles [20]. This is demonstrated in Figure 50.

FIGURE 50
The relative proportion of capital, fuel and maintenance costs for LNG and diesel fuelled trucks.
Source: [20]



7.5. Summary

The examination of costs of LNG as a truck or ship fuel has highlighted several key issues which are summarised below:

- Typically, ships or trucks that use natural gas as a fuel are more expensive to purchase than the incumbent HFO or diesel vehicle. This incremental cost is in the order of 6% to 10% for ships and 30% to 90% for trucks.
- In contrast, the key forms of natural gas that may be utilised as transport fuels, CNG or LNG, have historically been less expensive than the incumbent HFO or diesel vehicle on an energy basis.
- In general, total cost of ownership (TCO) estimates suggest that the initial extra capital investment in natural gas ships or trucks is payed back through the reduced fuel cost significantly within the lifetime of the vehicle, between 15 months and eight years for trucks and between five and twelve years for ships.
- A significant proportion of the cost benefit of natural gas as a road transport fuel is accounted for by the tax rate applied to these fuels, though natural gas also appears cheaper before tax considerations. This leaves the cost proposition of natural gas vehicles exposed to regulatory change, and supply-demand economics, both of which could erode the economic proposition presented most commonly in the literature. International shipping, in comparison, does not have the same type of fuel tax regime currently.
- Should natural gas prices increase this could significantly extend the necessary payback period of natural gas vehicle investment.
- More research is needed to understand the likely development of natural gas price in the future as the natural gas vehicle fleet increases placing pressure on the supply demand balance, and on the regulators, who set taxes on natural gas transport fuels.

8. The impact of natural gas ship engines on global emissions using the MUSE model

The previous chapters have highlighted that natural gas fuelled ships have the potential to modestly improve greenhouse gas emissions compared to liquid fuels and that this is potentially economically feasible. However, the impact of these characteristics on global decarbonisation targets is complex and difficult to infer from studies that consider a technology in isolation. This chapter examines the potential contribution of natural gas to reduce emissions in shipping up to 2050 using a global energy systems model, known as MUSE.

As with many aspects of the global energy system, transport energy systems are complex and multifaceted. These systems are also linked to wider world economic systems. In order to handle the many interrelated variables of such systems, integrated assessment models (IAM) are often employed to examine their potential development over time. The Sustainable Gas Institute has developed such a model, called MUSE, designed to examine the techno-economic aspects of the whole energy system, including the global transport system [218]. This section details the development of a shipping module within the MUSE model framework, designed to better characterise the shipping sector, in order to examine the role of natural gas as a shipping fuel.

The shipping sector was chosen as the focus for this modelling investigation due to the global nature of the regulatory framework within which the international shipping sector operates. It was not possible to conduct a similar analysis of truck fleet development within the timeframe of this report. However, this is still a key transport mode where natural gas may play a future role, and will therefore be an aspect of further research carried out at the Sustainable Gas Institute.

This section first describes the general structure of the MUSE model and then provides more detail on the structure of the shipping module. Finally, the chapter will present the results of an analysis of the future development of natural gas as a ship fuel. This study examines only one future demand scenario and future research could investigate a broader range of future demand for goods transportation through international shipping.

Box 4: The structure of the MUSE model

MUSE is a recently-developed integrated assessment model (IAM) which uses a bottom-up approach to technology characterisation [218]. MUSE enables the generation of multiple scenarios of long-term energy technology transitions (from 2010 to 2100) on a global scale with a disaggregation into 28 regions where the effects of technological breakthroughs and policies can be explicitly modelled. It is designed to inform stakeholders about the value and role of technologies in a low carbon world as well as to enable robust development strategies, business models and R&D investment prioritisation. It can also be used to produce consistent climate change mitigation pathways by calculating a carbon price in each time period that would lead to emissions reductions to a specified budget level.

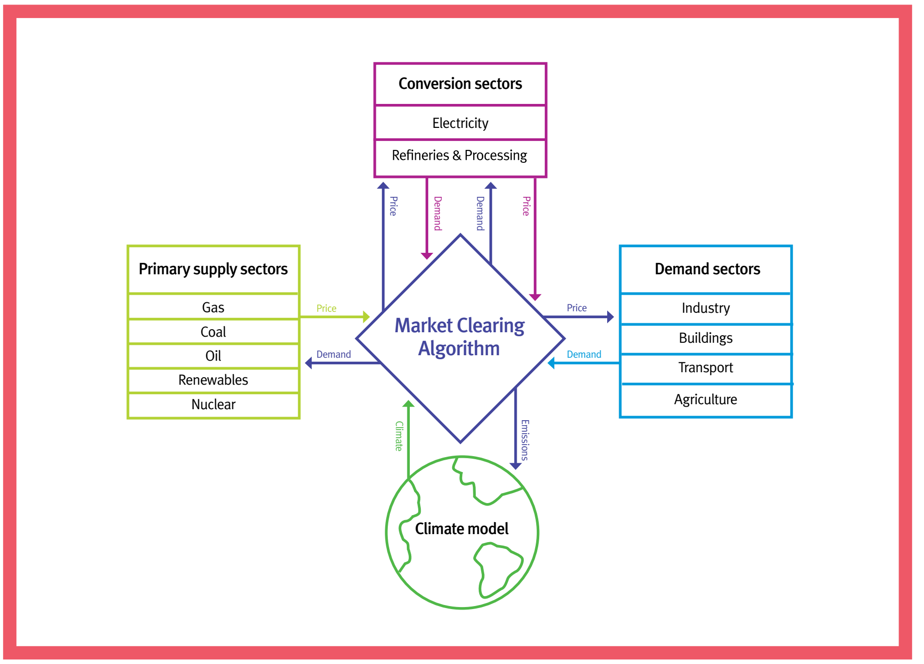
Figure 51 presents an illustrative representation of the MUSE model structure. This diagram shows the modules representing primary energy and conversion sectors, from which shipping fuel production is characterised, and end-use demand, within which the shipping module is located.

MUSE is a modular simulation model, in which the energy system is described by different sector modules, each of which uses specific metrics to drive the operational and investment decisions appropriate to the sector in question. The model simulates the whole energy system (including demand, conversion, and supply) with a high degree of technical detail, using a bottom-up approach to technology characterisation where capital and operating costs, as well as environmental performance, are modelled.

The demand sectors characterise end use services for industry, transport (where the shipping module is located), buildings, and agriculture, and from these, model the corresponding energy consumption, environmental emissions, and stock ownership. In the conversion sectors, the primary energy resources necessary to produce the fuels used are estimated from the operation of the available technologies. The extraction of primary energy commodities is modelled by the supply sectors.

These both interact through a market clearing algorithm, which represents a micro-economic price-quantity mechanism through which demand and supply are balanced. More information on the MUSE model can be found on the Sustainable Gas Institute website [218].

FIGURE 51
Model architecture of MUSE showing main data flows between supply, conversion and demand sectors.



8.1. The international shipping module

To characterise international shipping, the global fleet is broken down by vessel class as follows:

- General cargo vessels
- Bulk carriers
- LNG carriers
- Crude & chemical tankers
- Container ships

These classes account for 70% of international shipping by vessel number, with other vessel types not included in the study such as offshore support vessels and passenger ferries [36]. As a result the total emissions calculated in the MUSE international shipping model are lower than historical emissions estimated by the IMO and ICCT [10]. In order to factor this into the calculation of the emissions reduction of 50% against 2008 emission the target we compare here is calculated on the IMO 2008 emission estimate minus the proportion of 'other vessels', giving a 2050 50% emission reduction target of 362 Mt CO_2 equivalent.

The modelling process performed by the shipping module consists of three steps, which can be summarised as follows:

- For each class of vessel, the global fleet is sorted into four tonnage bins. This structure is based on a detailed analysis of the efficiency and emissions characteristics of each vessel class according to tonnage [218] and the age profile indicates the expected decommissioning schedule of the fleet. It was found that emissions per tonne nautical mile are highly dependent on tonnage, and vary by class [219], but this dependence does not appear sensitive to the age of the vessel (Figure 52).

- Global demand projections for each of the shipping classes are calculated using regional GDP-per-capita projections, based on the International Institute for Applied Systems Analysis (IIASA) shared socio-economic pathways database [219].

- New shipping capacity (i.e. the new shipping fleet) needed to meet the difference between the declining existing fleet and growing future demand is built based on simulating investment preferences, taking into account endogenous fuel prices and endogenous emissions price projections based on a 2-degree scenario in the MUSE model. It is important to characterise not only new technologies, but also improvements to existing technologies (due to engine management systems, burning cleaner diesel, etc.) against which these new technologies compete.

FIGURE 52
The relationship between operational efficiency and tonnage.
Source: [218, 220]

Model cases are generated with a range of expectations about the future rate of efficiency improvements and capital costs of both LNG-fuelled and conventional vessels. Efficiency and cost estimates are taken from a variety of sources [221-223], and change with time to reflect likely improvements. The emissions price is generated endogenously by MUSE in order to restrict global GHG emissions below a prescribed budget in each time period, with results presented out to 2050. Emissions pricing is also not restricted only to CO_2, but also to methane, using its 100 year GWP of 34 [226]. The characterisation of upstream, processing and transportation emissions from LNG is particularly important when comparing the merits of LNG vs HFO as a fuel in shipping, and MUSE models these in detail [227, 228].

A table presenting the technological and cost characteristics of the technologies available to the shipping module in presented in Annex Table A1. The module selects new-build shipping capacity from this list based on the levelised cost of a tonne-km of supply. This levelised cost includes capital, operating, fixed, fuel and emissions costs. The technologies considered includes:

- Heavy fuel oil (HFO) and marine diesel oil (MDO) fuelled ships, representing the incumbent technologies (with HFO unavailable after 2020);
- A number of natural gas engine options including low-pressure and high-pressure duel fuel engines, spark ignited engines and gas turbines; and,
- Technologies, hydrogen fuel cell ships to represent the potential of less mature but lower carbon advanced technologies.

This suite of technology options was chosen to help illustrate the challenges of decarbonising global shipping emissions, though in the real world a broader range of options exists, including increased hybridisation, ammonia, methanol and others.

8.2. Results of the international shipping modelling

8.2.1. Four model cases

In order to examine the future development of shipping fuel choices four cases were modelled: Case 1 – current policies, Case 2 – extended EEDI, Case 3 – HFC option, and Case 0 – reference. These are described below.

Case 1: Current policies
This first case represents current policies and technologies. The model follows the CO_2 reduction steps imposed by the current energy efficiency design index (EEDI), with 20% CO_2 emissions improvement in new ships by 2020 and 30% CO_2 emissions improvement in new ships by 2025 (Section 2). The model only requires CO_2 emissions reduction, and has no direct influence on emissions of methane [229]. Emissions reductions are delivered through engine choice or wider efficiency improvements, designed to represent the potential for ship design efficiency measures such as those discussed in Section 3. The model then proceeds with annual efficiency improvements in line with historical norms, at 1% efficiency improvement per year, which would be achievable through engine or non-engine efficiency measures [179]. This case does not include hydrogen fuel cell ships. The efficiency measures are assumed to come from a combination of the various engine and ship technical and operational efficiencies discussed in Section 3.

Case 2: Extended EEDI
In this case the EEDI is extended in order to improve the ability of the existing technologies to meet deeper decarbonisation by 2050. The model follows the existing EEDI and then establishes a new goal of 40% CO_2 emissions

improvement by 2030. This is equivalent to a 2.25% annual CO_2 emission improvement, over twice the historical efficiency improvement [180]. The current observed 1% annual efficiency improvement is followed after 2030.

Case 3: Hydrogen fuel cell (HFC) option
In this case the extended EEDI from Case 2 is followed. However, the technological options are increased to include hydrogen fuel cell ships, as shown in the Annex.

Case 0: Reference
In this final reference case no efficiency improvements are mandated after 2010. All emissions reductions are therefore due to the CO_2 emissions advantage of the new engine technologies, rather than the suite of efficiency options improving aggregate efficiency of the new fleet. This does, however, include efficiency benefits associated with an increase in average ship size, as the model installs natural gas engines in larger, more cost effective ships. This scenario allows for the impact of EEDI over engine choice to be examined in more detail.

8.2.2. Results

Case 1: Current policies

Figure 53 shows the results of Case 1 in terms of ship engine type contributing to global demand for shipping in the future. The first trend demonstrated in this figure is the significant growth in global shipping demand: a ~70% increase by 2050 relative to 2015. The role that HFO has in delivering this future demand diminishes, with no new HFO ships built after 2020 and the existing HFO vessels being decommissioned by 2050. This is in line with expected trends because of the challenging 2020 SO_X emissions limits (see Section 2). In the short term most of the shipping demand not met by HFO is delivered by ships using MDO. This reflects the relatively low capital cost of these ships relative to the other options. The growing role for MDO is slowed in 2030 due to the need to meet increasing demand and compensate for the diminishing HFO share without increasing emissions under the EEDI regulations. The remainder of future shipping demand is therefore met through the increasing role for gas fuelled ships. This is split across all the natural gas engine technologies available in the model. The split is relatively even, suggesting that, on the basis of the decision making in the model, the lower emissions associated with high pressure gas engines are offset by the higher capital costs.

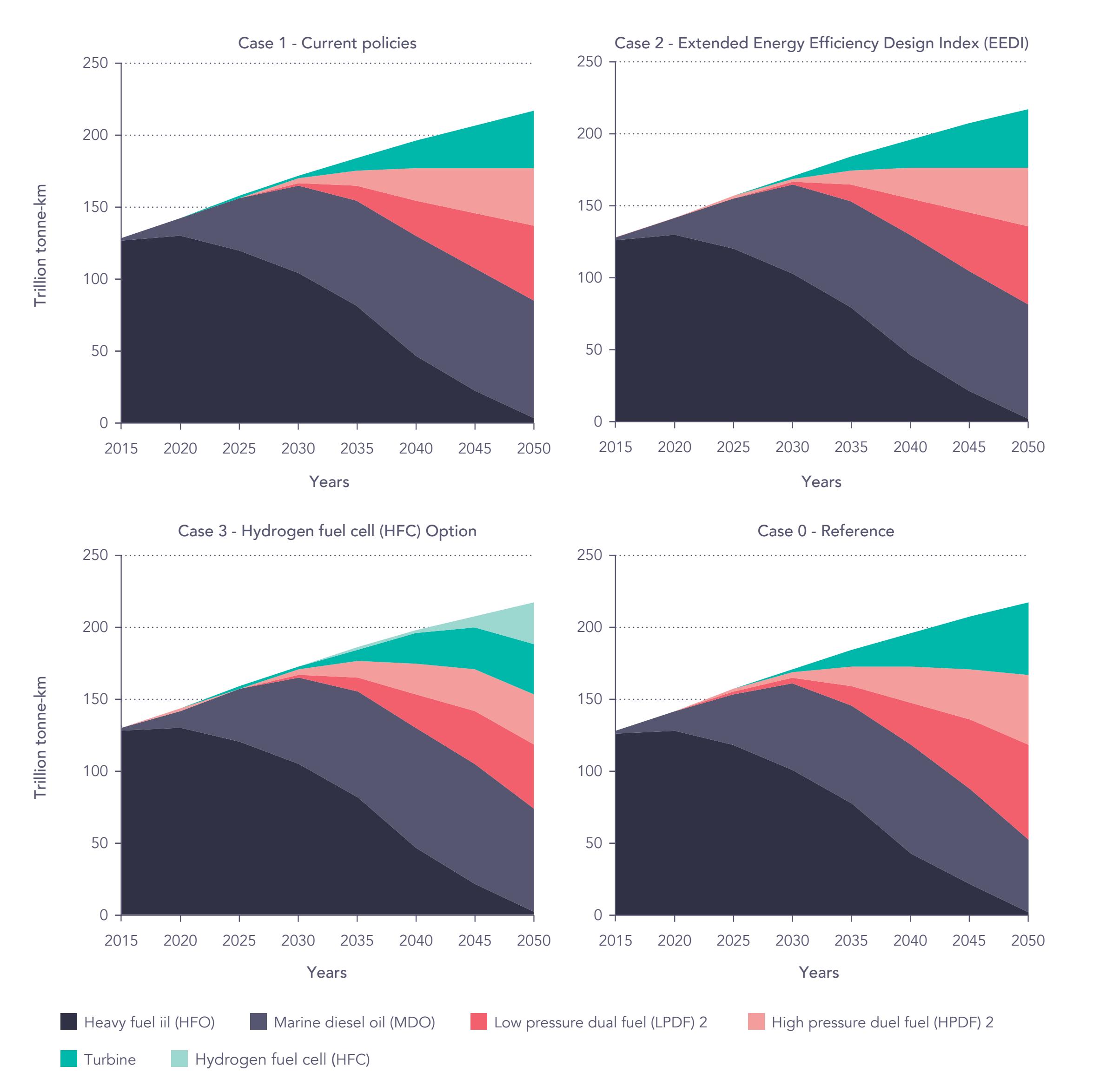


FIGURE 53
Global seaborne trade in Case 1 - Current policies, Case 2 - Extended EEDI,Case 3 - HFC Option and Case 0 - Reference. (from left to right, top to bottom), showing rising demand for shipping and the mix of engine types in the global fleet.

The results in terms of emissions are shown in Figure 54, which disaggregates the relative contribution of CO_2 and methane, and provides an estimate of the 50% emissions reduction against emissions in 2008. This demonstrates a 35 % emissions reduction from emissions in 2015. The level of methane emissions is relatively small, though it does grow towards 2050, due to the increasing role of natural gas fuelled ships. Methane emissions rise from 0.5% of total emissions in 2015 to 6.7% in 2050.

The implication of this case is that with current policy and technology, GHG emissions reductions are achieved but are insufficient to meet a 50% GHG reduction target against 2008 levels, and exceeds the target by 15%.

FIGURE 54
Figure 54: Total CO_2 and methane emissions in Case 1 - Current policies, Case 2 - Extended EEDI, Case 3 - HFC Option and Case 0 - Reference. (from left to right, top to bottom).

Case 2: Extended EEDI

The results of Case 2 are very similar to Case 1. This case considers the extended EEDI requirement for new ships to meet a 40% emissions reduction after 2030. This results in a small decrease in MDO vessels being built from 2030 (~1.8% in 2050), and a correspondingly small increase in natural gas fuelled ships against that seen in Case 1(~1% to 1.2% in 2050). This shift helps meet the 40% CO_2 reduction in the new fleet from 2030, but only results in a 36% GHG emissions reduction between 2015 and 2050, marginally better than Case 1. Given that a 40% EEDI by 2030 is equivalent to over twice the historical fleet average trend in efficiency improvement this demonstrates the challenging nature of the current 2050 GHG emission reduction target. The proportion of methane in 2050 in the emissions total increases from 6.7% in Case 1 to 7.8% in Case 2 on a CO_2 equivalent basis. A contributory factor to the relatively small GHG impact of the extended EEDI in Case 2 relates to the role of methane emissions, which are not influenced by the CO_2 specific EEDI.

Case 3: HFC option

In Case 3 the introduction of hydrogen ships is apparent in Figure 53, which shows a growing role for these ships from 2040 to 2050. This is driven by the increasing CO_2 model price, which begins to favour lowest carbon ship technologies towards the end of the 2030s. The impact of this change is that the international shipping sector reduces emissions by 40% between 2015 and 2050. This reduction is close to the 2050 emissions reduction target of 50% reduction against emissions in 2008. Further, methane emissions are slightly reduced as a proportion of total emissions, down to 7.5% of total emissions, and removing these emission from the total results in a CO_2 emissions total in 2050 below the 50% reduction target.

Case 0: Reference

In the figures above the drivers of decarbonisation include engine/fuel choice and wider ship efficiency measures, making it difficult to identify the contribution of each. In this final reference case the EEDI policy measure is removed, and no wider efficiency measure are considered. This limits the model to examine only the impact of natural gas engines on emissions. In this case a significant number of natural gas fuelled ships are built in the period after 2030, and by 2050 these ships represent 76% of ship tonne-kilometres travelled. However, carbon equivalent emissions are increased by 15% by 2050, demonstrating that LNG ships are likely to be insufficient to counteract the increasing demand without the EEDI measures. Whilst CO_2 emissions are approximately the same in 2050 as they are in 2015, increased methane emissions contribute to the 15% increase. It is notable that by 2035 emissions are on a declining trend, but clearly this is insufficient in meeting climate targets. This case highlights the huge challenge of increasing demand for international shipping, the need to combine multiple decarbonisation options in future ship design and the increasing role that methane emissions plays in the future if the uptake of natural gas engines becomes widespread.

8.3. Conclusions of the international shipping modelling

The broad conclusions from the modelling exercise are as follows:

- Under current policies, meeting a 50% CO_2 reduction target in international shipping is highly challenging. Increasing demand for shipping in the coming decades contributes significantly to emissions, while the majority of technologies available to meet that growing demand still emit significant quantities of CO_2.

- The introduction of natural gas fuelled ships helps to reduce total GHG emissions in international shipping, though this is insufficient to reduce emissions on its own given the estimates of future demand. This is exacerbated by methane emissions, which are not influenced by the

EEDI requirements. There is therefore a need to provide appropriate regulations for the changing ship fleet of the future, for which methane may become an increasingly important factor.

- Current EEDI measures end in 2025 and extending these to a 40% CO_2 reduction target in new ships by 2030 further reduces the 2050 GHG emissions total by 1.2%. However, this is again not sufficient to reduce GHG emissions below the current 2050 target, while at the same time being a challenging measured against historical efficiency improvements.

- Including a low GHG emissions technology option in the form of a hydrogen fuel cell vessel improves the chance of meeting the 2050 target significantly though it should be noted that this technology is as-yet uncommercial at scale, and total emissions impacts will depend heavily on the source of the hydrogen. Most of these vessels are deployed after 2040 as the models carbon price begins to favour these more expensive but lower carbon ship engine options.

- Finally, beyond 2030 the price differential between the main three competing technologies is relatively small. As such a range of unmodelled or non-cost factors may determine which technologies are commissioned by ship operators under these conditions.

9. What does it all mean? Findings and Conclusions

9.1. Summary of main findings

9.1.1. Natural gas options to reduce emissions from trucks and ships

Using natural gas as a transport fuel is one way to reduce emissions from trucks and ships. This option sits within a raft of other fuel switching, energy efficiency and exhaust gas treatment options. Many of these options can be used in combination, providing significant potential for decarbonisation. However, the contribution that natural gas can make to emission reduction is constrained by a number of factors that must be well understood before judging the benefit of natural gas as a transport fuel.

First, there are several different engine types that can use natural gas, including engines that use only natural gas, and variants that use both natural gas and liquid fuel. The emissions from these engine types vary and there are a number of trade-offs between engine types in terms of engine efficiency, methane slip, and NO_X emissions in particular. Exhaust gas after-treatment options are available to mitigate emission of the important GHGs and air pollutants and maximising the benefits of natural gas as a transport fuel will in part rely on the optimisation of engine design in combination with these after-treatment options. In particular the use of high-pressure duel fuel engines in shipping, and spark ignited stoichiometric engines in trucks, may have the potential to minimise methane slip, though at the expense of NO_X emissions, which may require after-treatment to meet NO_X emissions limits in some regions.

There are also a raft of energy efficiency measures available now or in the near future that can contribute to significant emissions reductions in ships and trucks. Many of these measures can be used in combination with engine and fuel options, delivering significant combined emissions reductions. However, these are independent of natural gas and are likely to be pursued regardless of the future development of natural gas as a transport fuel.

Other fuel switching options exist including the use of vehicles using hydrogen or electricity and electric motors. These technologies have the potential to reduce emissions significantly, eliminating direct engine related emissions entirely. However, these are less developed technologies and need more time to reach practical deployment. This highlights the need to understand the role of natural gas in the near future when emissions reductions are needed but more technically advanced options are not fully commercially deployable. The defining point at which hydrogen or electric trucks become available is therefore also a key aspect of future research.

9.1.2. Emissions estimates from natural gas trucks and ships

The greenhouse gas emissions reduction potential of natural gas engines is defined by the lower carbon intensity of the fuel relevant to incumbent liquid fuels. However, total greenhouse gas emissions are influenced by other emissions sources including:

- **the difference in engine efficiency** between natural gas and incumbent liquid fuel engines, experienced as difference in CO_2 emissions in the exhaust per unit of engine energy output;
- unburned natural gas emitted within the exhaust gas stream, known as **methane slip;** and
- **methane emissions** from the engine and fuelling system, such as crank case venting, dynamic venting or accidental fuel system leaks.

Given the wide variation in estimates of these emissions there is a wide range of potential GHG emissions from natural gas fuelled trucks and ships. At worst, natural gas fuelled trucks and ships may have supply chain and in-use emissions exceeding current incumbent diesel fuelled trucks and heavy fuel oil fuelled ships. However, best estimates of lifecycle emissions show a potential to reduce emissions from natural gas fuelled trucks by 16% against best estimates of diesel truck emissions, with average estimated emissions across all engines of 1,300 gCO_2eq/km and best emissions from spark ignited engines of 810 gCO_2eq/km. In ships the equivalent potential for emissions reduction is 10% relative to heavy fuel oil ships including emissions from the supply chain, with best emissions from high pressure dual fuel engines reaching ~600gCO_2eq/kWh.

Expanding this to total well-to-wheel/wake greenhouse gas emissions includes:

- Supply chain emissions, at 140 gCO_2eq/kWh
- Bunkering or fuel station emissions – at 9.3 gCO_2eq/kWh for trucks or 8.2 gCO_2eq/kWh for ships.

This gives a total well-to-wheel/wake in total well-to-wheel emissions of 810 to 2,840 gCO_2eq/km for trucks and 580 to 800 gCO_2eq/kWh for ships.

The efficiency of incumbent technologies will also improve incrementally over time. This will erode the relative benefit of natural gas engine emissions reductions, with some estimates suggesting that engine efficiency improvements in diesel may keep pace with efficiency improvements in natural gas engines. There is also a challenge in interpreting estimated emissions in the absence of real-world emissions measurement. Independently verified in-use data is currently limited but is needed to corroborate the current expectations regarding engine emissions performance.

Air pollution emissions are likely to benefit from more significant reductions through fuel switching to natural gas. In trucks, NO_X emissions may be reduced by 80% and particulates by 18% comparing the average diesel and SIS engine trucks, while in ships NO_X emissions may be reduced by over 90%, SO_X emissions by up to 90% and particulates by up to 98% against HFO fuelled ships. However, there is likely a trade-off between NO_X emissions and methane slip with engines that provide the lowest methane slip also providing the highest NO_X emissions. Optimising best overall emissions requires the implementation of engine type and after-treatment options in careful combination.

9.1.3. The costs of natural gas as a fuel for trucks and ships

Choosing natural gas trucks or ships typically involves additional capital costs relative to incumbent liquid fuelled trucks or ships. This additional cost relates to the fuel tank, fuel delivery system and the engine. There is some indication that the additional cost of natural gas engines will reduce if manufacturing increases, though this is unlikely to be reflected in the fuel tank and fuel system costs, which inherently require more components and materials.

The additional costs of LNG trucks is 20% to 75% more than diesel fuelled trucks and the additional cost of LNG ships is 20% to 50% more than HFO fuelled ships.

In contrast the cost of natural gas as a fuel is expected, by many estimates, to be less than current fuel costs, both in terms of the energy content of the fuel and the energy output of the engine, which accounts for differences in engine efficiency. This creates the possibility of a payback period, where the additional cost of the truck or ship is recovered by the operator through reduced fuel costs. LNG prices have been on average ~50% less than HFO prices between 2000 and 2015 and LNG and CNG are ~20% lower than diesel prices, including fuelling costs and duty.

Payback of the initial capital investment in natural gas trucks or ships depends on a number of factors, including fuel cost differential, and the annual fuel usage of the vehicle. However, studies often estimate payback within the first life of the truck or ship, creating an economic benefit of fuel switching to natural gas for vehicle owners. Estimates of payback period are between 15 months and 8 years for trucks and between 5 and 16 years for ships.

Tax and duty implications on fuel costs are a significant proportion of the fuel price differential in truck fuels. This aspect is therefore a key element of the payback proposition. Should natural gas displace incumbent fuels then the current tax regime for natural gas as a transport fuel may be under pressure, and duty or tax raises may follow. There are several ways that taxes might be increased to align with incumbent taxes on liquid fuels, though final prices are likely to remain cheaper than liquid fuels given the relatively low wholesale price of gas. However, reducing the price difference between natural gas and liquid fuels will extend the payback period, and studies that examine higher natural gas prices in the future highlight the potential that natural gas vehicles might not be able to pay back within the lifetime of the vehicle under these conditions.

9.1.4. Implications for global emissions

Natural gas has the potential to reduce global emissions from trucks and ships in the medium term. However, this potential relies on the real-world performance of vehicles and the minimisation of emissions in the fuel supply chain and refuelling processes. In addition, global goals for GHG emissions reduction in shipping, and increasingly likely GHG reduction necessary in trucks to meet national decarbonisation commitments, require greater GHG reduction than is achievable with natural gas engines alone.

In shipping, natural gas engines in combination with other efficiency improvements can go a long way to meet significant global GHG reduction, as discussed in Section 8. However, even assuming very challenging rates of efficiency improvement it appears challenging to meet a 50% GHG emissions reduction target by 2050 using natural gas engines and ship efficiency improvements alone. The MUSE modelled shipping case with most significant greenhouse gas reductions builds an increasing number of hydrogen fuel cell ships in the period between 2040 and 2050 (Case 3 – Hydrogen Fuel Cell (HFC) option). In addition, real-world GHG emissions have the potential to be greater than existing estimates, particularly when including supply chain and refuelling emissions and given the relatively poor level of research on these emissions sources. Higher real-world emissions rates from natural gas trucks and ships would further increase the challenge of meeting global climate change goals with these technologies.

9.2. Implications for policy

There are a number of implications for policy arising from the analysis of natural gas as a transport fuel in trucks and ships. First, the supply chain is likely to play a more significant role in the total GHG emissions of natural gas fuel than in incumbent liquid fuels. Minimising supply chain emissions will therefore for have an important role to play in emissions reduction strategies. Emissions in the natural gas supply chain are already under scrutiny, with current recommendations including better measurement and reporting of emissions and investment in emissions reduction technologies. Policy to support these measure would benefit natural gas in all its uses, including transport. Emissions at the refuelling station, including tank venting (the pump-to-tank phase) may not be included in these supply chain policies and regulations. These stages in the supply chain are therefore likely to need policies and regulations of their own to incentivise or require action to minimise these.

The current duty on vehicle fuels varies significantly by jurisdiction, fuel, and intended end-use. Shipping fuels tend not to pick up duty while in trucks, diesel receives significant duty in many countries while natural gas as a transport fuel it taxed significantly less. However, fuel tax is often used as a mechanism to price carbon intensive activities, which may encourage modification of fuel tax regimes in the future. Additionally, if the use of natural gas as a transport fuel was to increase significantly, displacing more heavily taxed liquid fuels, then increases to the tax on natural gas may occur in order to recover lost tax revenue. In the event that fuel tax is modified, it would be prudent to incentivise carbon emissions reduction. However, this is difficult to achieve given the uncertainty in GHG emissions that may arise from natural gas vehicles and the multiple cost factors that come together in the total cost of ownership proposition that ultimately informs fuel switching choices.

While natural gas may have a decarbonisation role in transport, vehicle or fuel options that provide more significant decarbonisation will likely be needed to meet global decarbonisation goals. This is likely to mean battery electric or hydrogen fuel cell based vehicle options, which are currently relatively expensive in terms of both the production of the energy vector and the vehicle manufacture. This means that policies will be needed to drive down the costs of these options. This may include measures to directly assist in the development of the technologies (technology-push policies) and measures to support and encourage demand for these technologies (market-pull policies). Broad carbon focussed interventions, such as carbon taxation would also work to support these technologies into commercial maturity.

The modification of existing policies is likely to be a key aspect of measures to decarbonise trucks and shipping. Section 8 begins to examine the existing energy efficiency design index (EEDI) policy in shipping, and the impact of extending the current policy on emissions in 2050. Given the recently established 2050 greenhouse gas emissions target in shipping, examination of policy is necessary and there is suggestion in the literature that the extension of the EEDI policy should be part of that process.

9.3. Open questions

New research is needed to understand a number of issues around natural gas as a transport fuel in ship and trucks. First, there is some uncertainty in the real-world performance of newer natural gas vehicle designs. While estimated emissions data is often based on simulated operation under test conditions, data on emissions performance of these vehicles in real-world operation is often less available. In addition, other vehicle emissions sources such as tank venting and accidental emissions in the fuel system are likely additional to the emissions included in simulated operation data. Measurements of these types of emissions in real world operation is a key area for future research.

Methane slip in the exhaust gas of natural gas engines is a significant factor limiting their decarbonisation potential. There is ongoing research into the reduction of methane slip through various approaches and this is likely to be a continuing challenge that will benefit from further attention. Where trade-offs between methane slip and NO_X emissions are encountered there will be a need for complimentary research into after-treatment technologies and the optimisation of these two aspects of natural gas engine emissions.

In addition to technical research, more research is needed into the modelling of truck and ship operation. For instance, there are a large number of energy efficiency measures and engine options in addition to fuel switching to natural gas. Many studies examine the impact of these measures on total achievable emissions reduction. However, the interaction of different technology measures may not be additive, with measures such as slow-steaming in ships likely to have an impact on the value of other measures such as the effectiveness of hull coatings to reduce friction or wind technologies to provide supplementary drive or power. More sophisticated modelling of the interaction between all technical options in truck and ship design may be needed to better understand the likely benefit of these options on total emissions from ship or truck fleets, and the cost per unit of emissions reduction, which will also be affected by these types of technology interactions.

Whole system modelling of truck and ship fleets is also required. To best understand these transport systems requires integrating a wide range of variables. This includes aspects of future demand for goods transportation, market prices for input costs (such as fuel), decommissioning profiles for existing fleets, impacts of carbon pricing and policies and future implementation of advanced technology options and vehicle design. Given the highly complex nature of these variables and their interactions, these models are an essential aspect of research into the future impact of technology choices and policy initiatives to meet long term decarbonisation goals.

9.4. Conclusions

Natural gas as a transport fuel has the potential to reduce GHG and air pollution emissions from trucks and ships. However, supply chain emissions, relatively lower efficiency in gas engines, and methane emissions from the vehicle all reduce the emissions reduction potential of natural gas. The value of natural gas as a transport fuel in the future is therefore dependent on maximising the GHG and air pollution benefits it provides. The constrained level of emissions reduction available in natural gas engines also indicates the need for a wider range emissions reduction measures in order to meet longer-term emissions reduction goals. The challenge is therefore to understand the extent to which natural gas can usefully contribute to emissions reduction, and also establish at what point in the future lower emissions fuels and energy vectors should be used to drive further emissions reductions.

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Annex

Table A1: Input data on ship engine costs and emissions for modelling in Section 8

Process (engine name)	Engine Capital Cost (USD2010/ kW)****	Capex (MUSD2010/ tkm)	Fixed Opex (MUSD2010/ tkm)	CO2 Emissions (g/ kWh	Methane Emissions*** (g/kWh	NO_x Emissions (g/ kWh	SO_x Emissions (g/ kWh)	Efficiency** (g/kWh)	Pilot fuel consumption (g/kWh)
HFO* (conventional heavy oil - benchmark)	465	2.35E-12	5.96E-14	579.4	0.01	13.4	5.7	2.02E+02	0
MDO (conventional marine diesel oil)	465	2.35E-12	5.96E-14	557.5	0.01	14	0.57	184.5	0
LPDF4**** (LPDF 4 stroke)	674			433	7	2	0.0048	169.1	2.5
LPDF2 (LPDF 2 stroke	674	2.56E-12	7.15E-14	411.6	3.2	2	0.0096	138.2	1
HPDF2 (HPDF**** 2 stroke	943.6	2.84E-12	7.15E-14	430.8	0.3	10.1	0.3	135.1	8.3
LBSI**** (lean-burn spark ignition)	674			431.4	4.4	1.3	0	170.2	0
Turbine (Gas Turbine)	1023	2.91E-12	7.15E-14	437.9	0	0.25	0	159.2	0
HFC (Hydrogen Fuel Cell)	3720	5.64E-12	8.58E-14	0	0	0	0		0

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