MARITIME
FORECAST TO 2050

Energy transition outlook 2018

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MARITIME FORECAST TO 2050

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FOREWORD

It gives me great pleasure to be introducing a second Maritime Forecast to 2050, part of our Energy Transition Outlook series.

This new publication builds on last year's very well-received Maritime Forecast and allows us to both refine the predictions and add more useful information, based on new modelling results, technology, and regulations.

One of the additions in the new Maritime Forecast is an outlook on emerging international regulations and the growing drive to cut shipping's emissions to air and water and reduce our industry's carbon footprint. We think that decarbonization will be one of the megatrends that will shape the maritime industry over the next decades, especially in light of the new IMO greenhouse gas (GHG) strategy.

Responding to the trend towards decarbonization, we have included more material on the many alternative fuel and technology options that the maritime community may be considering utilizing over the coming years.

We offer some insights into potential new fuel solutions, the maturity of emerging technologies, and how they might develop in the market towards 2050. By modelling energy use, fuel mix and emissions we have developed a CO_2 pathway for the world fleet hat fulfills the IMO GHG ambition.

KNUT ØRBECK-NILSSEN

CEO
DNV GL - Maritime

However, because the needs and perspectives of the many stakeholders in our industry are very different, it is very challenging to pick “winners”. For this reason we also provide a systematic and practical framework for assessing the fuels to aid in decision making.

As we head toward 2050, our industry still faces considerable uncertainty in changing markets, regulatory changes, new technologies, and the effects of digitalization. In the past, we have mainly had to deal with changing ship sizes and cargoes, but not radically different designs, digital technologies, engines, and fuels.

> “Decarbonization will be one of the megatrends that will shape the maritime industry over the next decades, especially in light of the new IMO greenhouse gas strategy.

The pace of technological change has increased rapidly, and the impact of each new cycle is harder to assess. Therefore, we have proposed a “carbon-robust” approach, which looks at future CO_2 regulations and requirements and emphasizes flexibility, safety, and long-term competitiveness. In this edition of the Maritime Forecast, we take the carbon-robust approach and offer a new frame-work that is designed to help empower decision making on future assets. Furthermore, we show-case the application of the model in a case study for a carbon-robust bulk carrier.

To 2050, shipping will maintain its centrality to global trade and the world’s economy. But the energy transition and regulatory changes will have a significant impact on the industry. This makes it more important than ever before to examine the regulatory and technological challenges and opportunities of future scenarios, to ensure, thereby, the long-term competitiveness of the existing fleet and newbuildings.

Knut Ørbeck-Nilssen,
CEO of DNV GL - Maritime

CONTENTS

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

A global transition towards greater use of renewable energy and less use of fossil fuels is underway and will progress towards mid-century. There is also rising interest in sustainable development, and action to establish circular economies to reduce consumption of virgin materials.

The ongoing digital transformation will – through automation, robotization, and adaptive manufacturing – have a large impact on global value chains. It will also advance the design and operation of ships, and create new business models. For shipping, there is increasing pressure to decarbonize and to reduce emissions to air. This will impact asset value and earning capacity more significantly than in the past. It will shape the future fleet in important ways, particularly in the choice of fuels and technologies.

This publication is one of DNV GL's new suite of Energy Transition Outlook (ETO) reports. It provides an independent forecast of the maritime energy future and examines how the energy transition will affect the industry. Trends and drivers factored into our long-term projections are outlined in the integrated approach to forecasting. Our focus this year is the challenge of decarbonization facing the maritime industry. Our intention is to provide guidance for stakeholders coping with increasing uncertainty, risk, and opportunities.

SEABORNE TRADE OUTLOOK TOWARDS 2050

Based on the updated model for the DNV GL Energy Transition Outlook 2018, we forecast a rise of nearly a third (32%) in seaborne trade measured in trillion tonne-nautical miles per year for 2016–2030 (see Figure 1). We see increases in tonne-mileage over the forecast period for all trade segments except crude oil and oil products. The largest relative growth in trade is for gas and container cargo, for which we see a tripling and doubling, respectively, by 2050. We predict only 5% growth in trade over the period 2030–2050.

For bulk, there is sustained growth in tonne-miles for grain and minor bulk throughout the forecast period. For iron ore, we expect strong growth until 2030, more than offsetting an expected decline in coal transport. The total bulk trade increases by 39% over the period, maintaining bulk as the largest ship segment; however, most of this growth is expected in the first 20 years of the forecast period.

REGULATORY AND STAKEHOLDER OUTLOOK

To ensure compliance and to make the right business decisions, it is crucial to understand the existing and future regulatory framework, and the expectations placed on shipping from external stakeholders.

Over the past decade, shipping has seen a surge of environmental regulations. Impact on shipping in the next five years will include:

- The global sulphur limit for ship fuels, as set by the International Maritime Organization (IMO)
- IMO Tier III requirements for limiting nitrogen oxides (NO_X) in Emission Control Areas (ECAs)

– The regulation of ballast-water management in accordance with The International Convention for the Control and Management of Ships' Ballast Water and Sediments.

Greenhouse gas (GHG) emissions will be the main challenge for the next decades. In addition to global carbon dioxide (CO_2) requirements, we will see local, regional and national requirements to reduce harmful emissions of NOx and sulphur oxides particles.

We expect safety regulations to be improved incrementally. This relates mainly to ensuring that new environmental technologies and fuels can be applied safely, and to address challenges linked to digitalization, such as cyber risk, autonomy, and control systems.

The key challenge for shipping will be to decarbonize its activities. The IMO has recently adopted a strategy aiming to at least halve total GHG emissions from shipping by 2050 when compared with levels in 2008.

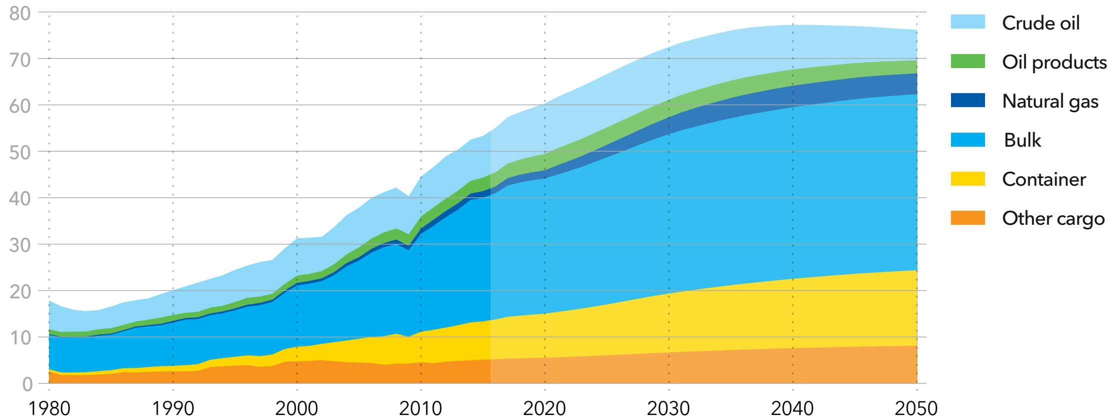
The IMO targets are ambitious and will require application of currently immature technologies and solutions, acceptance of lower speed, and deployment of large volumes of carbon-neutral fuels. Such fuels will also be essential to achieve the IMO vision to fully decarbonize shipping somewhere between 2050 and 2100.

Although the IMO's ambition is clear, its conversion into practical regulations is still unclear. To meet its targets, the strategy must be followed by mandatory requirements for individual ships, and by other policy measures to support development and implementation of new technologies and fuels.

FIGURE 1

World seaborne trade in tonne-miles

Units: Tt-nm/yr



FUEL AND TECHNOLOGY OUTLOOK

Fuels that could contribute to meeting the IMO targets include ammonia, biofuels, electrification, electrofuels[1], hydrogen, and nuclear power. In each case, it is important to take a lifecycle perspective to ensure that energy used to produce the fuel is from renewable sources or from fossil sources using carbon capture and storage.

The selection of fuel will be based on a compromise between the benefits and drawbacks of the various fuel options being compared. The cost associated with machinery, as well as the expected fuel prices and availability of bunkering infrastructure, will be key barriers. Safety will be a primary concern. It can be translated into monetary terms once a design has been established and the necessary safety measures identified.

The many alternative fuels, and their diverse characteristics, make it difficult to identify 'winners and losers' clearly. This is why we introduce a concept for the 'ranking of alternative marine fuels', as an important new feature in this latest Energy Transition Outlook report. It describes a multi-objective approach focused on the environment, economics, and scalability, to evaluate promising fuels.

Operational and technical energy-efficiency measures complement the fuel options. Reducing vessel speed is an especially effective operational measure, with a large fuel-saving potential. Substantially reducing speed will impact the transport system and require the industry and related stakeholders to collaborate to realize this potential. However, our Automatic Identification System (AIS) -based study of the world cargo fleet reveals how it spends much of its time at anchor or in port. Resolving this inefficiency, perhaps through emerging digital technologies, could contribute to reduced sailing speed and thereby lower fuel consumption.

Technological developments in batteries, drag reduction, energy efficiency, materials science, and propulsion will provide the basis for key specifications of new ship concepts to reduce energy losses and improve overall performance. Only a fraction of the fuel energy going into a ship's main engines ends up generating propulsion thrust; the rest is lost as heat. Exergy (or useful work) analysis reveals insights about the energy losses in a ship's energy cycle and assists the prototyping of novel mature and immature technologies to improve the energy efficiency.

The concept of hybridization is a promising ongoing development, where the benefits of two or more configurations for saving fuel are combined. A hybrid electrical ship could contain alternative diesel engine configurations, marine fuel cells, battery packages, and even retractable wind turbines, solar panels, and sails.

FLEET OUTLOOK

Integrating our knowledge of future trade demand, regulatory developments, and technology and fuel advances, we have modelled the uptake of a wide range of alternative fuels, energy-efficiency measures, and other emission-reduction technologies.

Measuring in deadweight tonnes (DWT), we predict:

- The fleet size will increase by more than a third (35%) by 2050

1 Electrofuels is an umbrella term for carbon-based fuels, such as diesel, methane, and methanol, which are produced from CO_2 and water using electricity as the source of energy.

– The crude oil fleet will decline by 30% by mid-century, peaking in 2030 at about 20% larger than today, then shrinking
– Today's product tanker fleet will decrease by 8% by 2050.

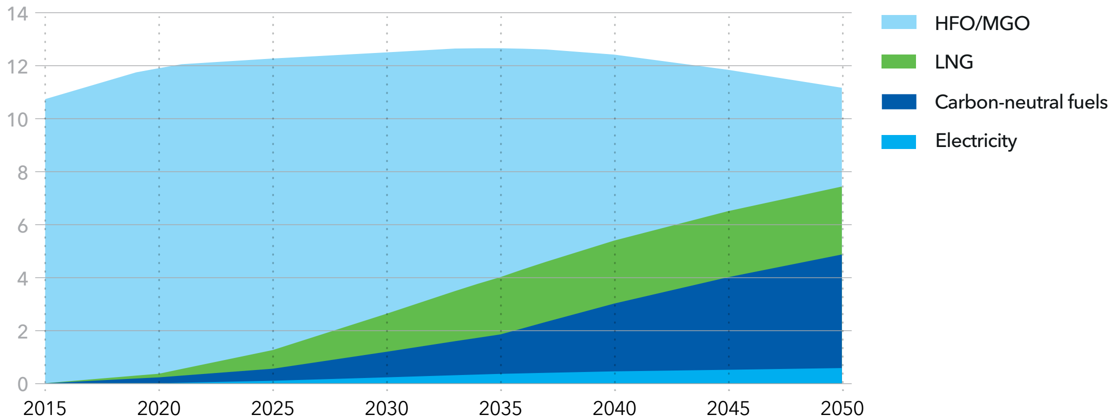
One of our key assumptions is that IMO GHG reduction targets will be met. Beyond 2035, we will see the full impact of gradually improving the energy efficiency of new ships and the shift to alternative fuels. Fuel consumption per tonne-mile will decline by, on average, 30% by 2050. We find that total energy use in international shipping will increase from about 11 exajoules (EJ) to 13 EJ during 2016–2035. It will then decrease to 11 EJ in 2050, which equates to nearly 270 million tonnes of oil equivalent (Figure 2).

Our model finds that by 2050, 39% of shipping energy will be from carbon-neutral fuels, which will have overtaken the 34% share of liquid fossil fuels, such as heavy fuel oil (HFO) and marine gas oil (MGO). Liquefied natural gas (LNG) and liquid petroleum gas (LPG) will, together, have a 23% share. Electric batteries will be an energy source on one third of all ships from mid-century, providing about 5% of the total energy for shipping. We have not evaluated which carbon-neutral fuels will be preferred, as this will depend on future production costs, availability, and infrastructure. Short-sea and non-cargo shipping will use 40% of the total energy; and, in these segments, electricity will constitute more than a tenth (11%) of energy use.

FIGURE 2

Shipping energy mix

Units: EJ/yr



THE CARBON-ROBUST SHIP

Fleet forecasts, as presented in this report, contain inherent uncertainties and depend heavily on assumptions. Regulations on CO_2 are poised to shape the future fleet. Developments in fuels and technologies are rapid, with potential game-changing consequences. Add in 'traditional' concerns over market cycles, trade demand, and supply, there are many aspects to consider when, investing in new tonnage. How can a shipowner wanting to invest today, handle this uncertainty and associated business risks to make the right decisions?

In this study, we present a further and significant development of the carbon-robust ship concept that we introduced in 2017. A new model now evaluates fuel and technology options by comparing the break-even cost[2] of a design to that of the competing fleet of ships (see Figure 3). The cost structures of competing fleets are compiled on the basis of scenarios, including, for example, regulations, fuel prices, and technology developments.

We showcase the model here to gain insights into what a carbon-robust bulk carrier would be like under possible future CO_2 regulations. We use the model for exploring key questions for three design alternatives for a ship designed today and built in 2020. The design alternatives are a standard ship, an LNG-powered ship, and a fuel-effcient option.

The study shows significant differences in competitiveness over the life of a vessel, depending on different scenarios. One striking finding is that investing in energy efficiency and reduced carbon footprint beyond current standards seems to increase competitiveness over the lifetime of the vessel. The study also suggests that owners of high-emitting vessels could be exposed to significant market risks in 2030 and 2040 in scenarios where low-emission vessels attract premium rates or avoid CO_2 taxes or levies.

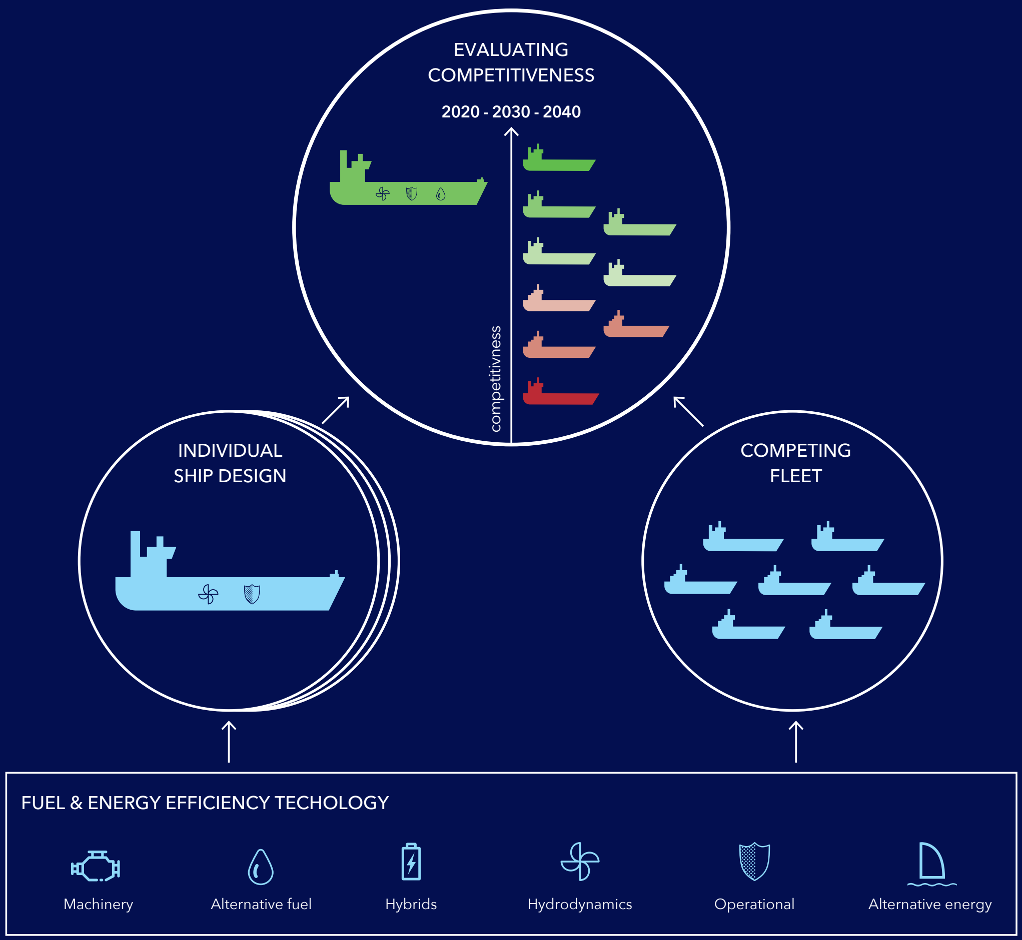
In this report, we have explored the maritime implications of a global transition towards an increased use of renewable energy and a diminishing use of fossil fuels, which is underway and will progress towards mid-century. As discussed, uncertainty is high. However, we believe that this uncertainty is manageable. By applying a structured, knowledge-based approach, supported by modelling tools, stakeholders can stay ahead of industry developments and remain competitive moving forward.

> "One striking finding is that investing in energy efficiency and reduced carbon footprint beyond current standards seems to increase competitiveness over the lifetime of the vessel.

2 The break-even cost is the minimum rate that a ship must secure to cover all costs

FIGURE 3: OUTLINE OF THE CARBON ROBUST MODEL

Competitiveness of selected individual ship designs is evaluated against the competing fleet of ships at a given point in time (e.g. 2030 or 2040) using the break-even cost or CO_2 emissions as a measure. The user can draw on a pool of fuel and technology options in creating the individual ship designs. For the competing fleet, fuel and technology uptake are governed by pre-set scenarios.



CHAPTER

1

INTRODUCTION

INTRODUCTION

A global transition towards greater use of renewable energy and less use of fossil fuels is underway and will progress towards 2050. One consequence is that shipping is experiencing increasing pressure to decarbonize its practices and operations, and to reduce emissions to air. This will impact on asset values and earning capacity more significantly than in the past. It will shape the future fleet in important ways, particularly in the choice of fuels and technologies.

There is rising interest in, and action to establish, circular economies to reduce consumption of virgin materials. This will impact on global and regional trade volumes and patterns and hence on shipping that transports such materials. The ongoing digital transformation, through automation, robotics, and adaptive manufacturing, will also greatly affect global value chains. It will advance the design and operation of ships, and enable new business models.

This publication is part of DNV GL's new suite of Energy Transition Outlook (ETO) reports. Alongside a main outlook ('the main ETO report'), the suite includes three separate reports discussing implications for maritime, oil and gas, and the power and renewables industries.

This latest publication provides an independent forecast of the maritime energy future and examines how the energy transition will affect the industry. It significantly updates our 2017 forecast (DNV GL, 2017b). Our focus this year is the challenge of decarbonization facing the maritime industry. We highlight main developments and changes regarding shipping activity and fuel consumption in recent years (chapter 2), and project the development in goods to be transported towards 2050 (chapter 3).

DNV GL'S SAFETY AND SUSTAINABILITY MISSION

Driven by our purpose of safeguarding life, property, and the environment, DNV GL enables organizations to advance the safety and sustainability of their businesses.

Around 70% of our business is energy related.

We provide classification, technical assurance, software, and independent expert advisory services to the maritime, oil and gas, and the power and renewable energy industries. We also provide certification, and supply chain and data management services to customers across a wide range of industries.

Regulatory development and technology drivers factored into our long-term fleet projections are outlined in chapters 4 and 5. Our modelling of the global shipping fleet is based on the transport demand and, as described in chapter 6, the most likely trends that we foresee in regulation and technology. The model focuses on the size of the fleet, its energy efficiency, fuel mix, and carbon dioxide (CO_2) emissions.

Chapter 7 describes by shipping segment, key issues to monitor over the next five years, and discusses factors that could shift our projections in future updates. We present a further and significant development of the carbon-robust ship concept that we introduced in 2017. As stated in the Executive Summary, a new model now evaluates fuel and technology options by comparing the break-even costs of a design to that of the competing fleet of ships. This aims to support maritime stakeholders evaluating the long-term competitiveness of their vessels and fleet in order to future-proof their assets (chapter 8).

Looking further forward, uncertainty confronting the industry seems only to increase. We stress that our modelling presents our best estimate of the future that we foresee, not a collection of scenarios. The coming decades to 2050 hold significant uncertainties regarding, for example: economic development; future energy policies; human behaviour and reaction to policies; the pace of technological progress; pricing trends for existing and new technologies. Our intention with this study is to help maritime stakeholders navigate the future.


OIL TANKER

CHAPTER 2

SHIPPING NOW

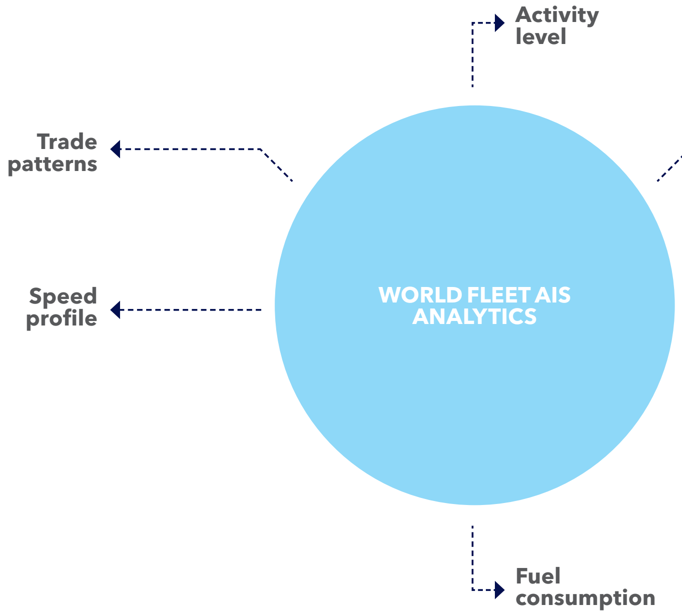
2 SHIPPING NOW: WHAT TRACKING DATA SHOW

Aiming to forecast the future is meaningless unless we understand the present. This chapter highlights the main characteristics and developments in world fleet activity, along with fuel consumption and emissions in recent years.

The modelling for this has been conducted with DNV GL's software, MASTER (Mapping of Ship Tracks, Emissions and Reduction potentials), the use of which has been described previously (e.g., Mjelde et al, 2014; DNV GL, 2014a; DNV GL 2018c; d). The model uses global ship-tracking data from the Automatic Identification System (AIS), enriched with ship-specific data from other sources (Figure 2.0.1). The key question of how global trade and the world fleet will develop towards 2050 is addressed in chapters 3 and 6 of this report.

FIGURE 2.0.1

Insights gained using DNV GL's software, MASTER, with AIS-data enriched with data from other sources to analyse key performance characteristics and technology potential for the world fleet.



2.1 CHANGE IN WORLD CARGO FLEET FUEL CONSUMPTION 2013–2017

In DNV GL's previous ETO report for the sector, we reported that the world fleet consumed about 250 million tonnes of oil equivalent (Mtoe) of marine fuel in 2016 (DNV GL, 2017b). These numbers originate from AIS-modelling of fuel consumption, where all commercial ships with AIS-transponders are included. Our detailed analysis of global ship traffic employs ship movement data from the AIS, mandatory for ships of 300 gross tonnes (GT) or more, sailing internationally, and for all cargo ships of 500 GT or more. Small vessels without AIS are not included: although there are many, their contribution to total emissions is limited.

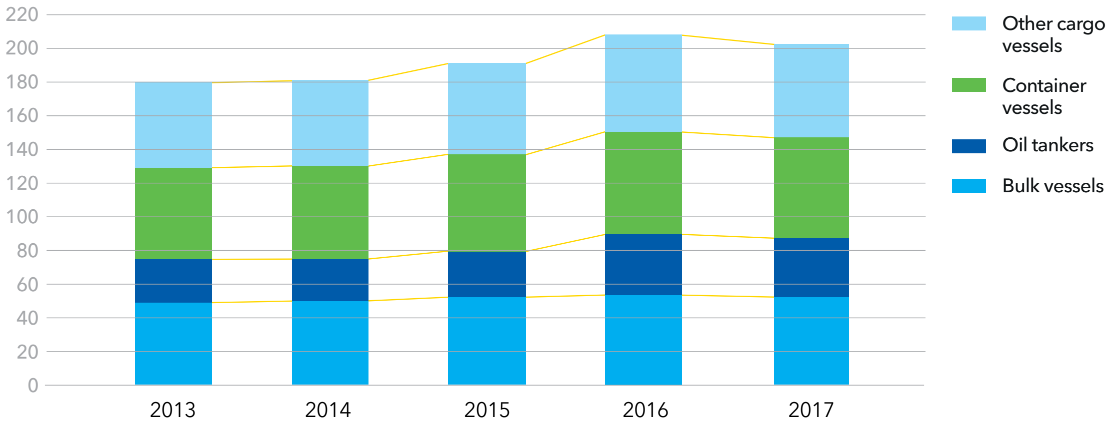
The cargo-carrying fleet of bulk vessels, container vessels, oil tankers, and other cargo vessels[3] accounts for 89% of the total fuel consumption (DNV GL, 2017b). The remaining 11% is consumed by passenger vessels, fishing vessels, offshore vessels, and other service vessels. Here, we focus on the cargo-carrying fleet, which accounts for most emissions globally. However, it is important to recognize that when domestic shipping emissions or impacts from short-sea shipping are the issue, the contributions from non-cargo vessels may be far more important, and should not be disregarded.

3 Other cargo vessels include chemical tankers, gas tankers, general cargo vessels, RoRo and refrigerated cargo vessels.

FIGURE 2.1.1

World cargo fleet fuel consumption

Units: Mt/yr



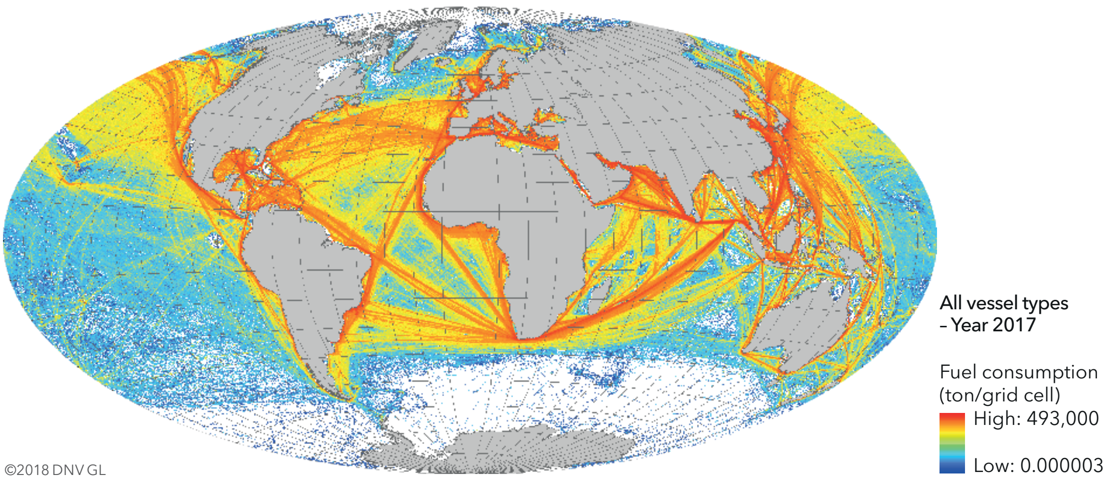
This study has prepared historical AIS-based modelling of fuel consumption for the world cargo fleet for 2013–2017, during which period annual fuel consumption grew (Figure 2.1.1). The peak in 2016 was 15% more than in 2013. Between 2016 and 2017, fuel consumption decreased by about 3%. The reductions in 2017 occurred in all ship segments except gas carriers, where fuel consumption increased. In 2017, container vessels accounted for the highest consumption, followed by other cargo vessels, bulk vessels, and oil tankers.

Carbon dioxide (CO_2) emissions from the cargo-carrying fleet in 2016 and 2017 were found to have been 664 million tonnes (Mt) and 647 Mt, respectively.

Figure 2.1.2 shows the ship traffic density for 2017 in terms of fuel consumption. Compared with 2016, traffic increased in Asia with new bulk routes, and in the Indian Ocean and Pacific Ocean with more traffic in specific trade routes.

FIGURE 2.1.2

Ship traffic density 2017 by fuel consumption



2.2 MAPPING FLEET PERFORMANCE IN 2017

We have also applied AIS-based modelling to calculate fuel consumption in various main operating modes: stationary (0 knot, kn); manoeuvring (1–5kn); and, cruising (more than 5kn). The split is based on the AIS-calculated speed over ground for each vessel and summarized for all cargo vessels.

Figure 2.2.1 shows the variation in the share of time spent in each operating mode by major ship types. Time spent in port/at anchor (stationary) ranges between 37–54% depending on ship type. This reflects variations in trading patterns, services, turnaround time, and operational efficiency. Bulk and container ships have the lowest share of time being stationary and in manoeuvring mode, and oil tankers have the highest share of time in these modes.

A further breakdown of the cargo-carrying fleet in seven size segments (Figure 2.2.2) shows that the largest ships spend 70–75% of the time in cruising mode at more than 5kn. The share of time spent in this mode is as low as 20–30% for the smallest size categories, except for container vessels. The small ships spend larger portions of their operation in short voyages with frequent port calls, which naturally reduces the time spent in cruising mode. However, there is most likely potential for the existing fleet to improve its effectiveness to reduce stationary time, potentially allowing the fleet to lower overall fuel consumption by reducing sailing speed. Another area for fuel savings is to reduce ships' consumption of energy while they are being unproductive waiting for transport work.

FIGURE 2.2.1

Share of time per operation mode in 2017 by cargo vessel segment

Units: Percentages

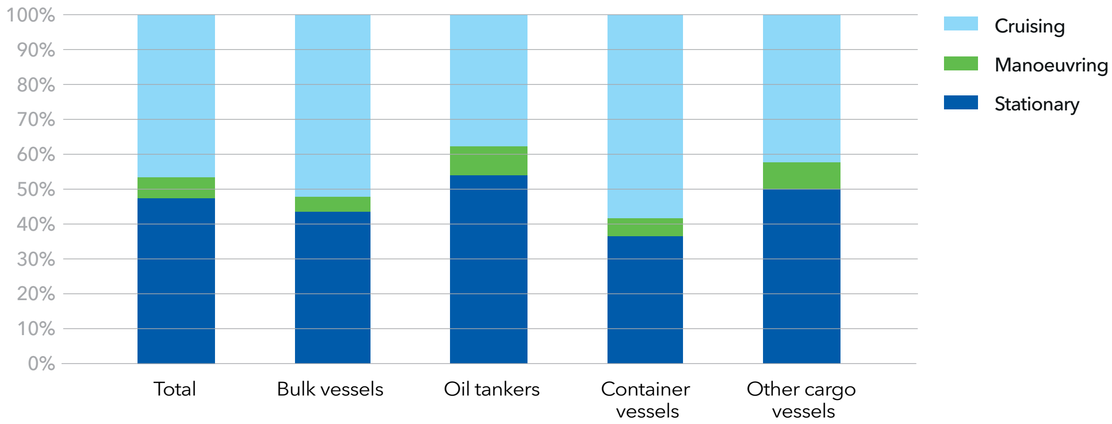
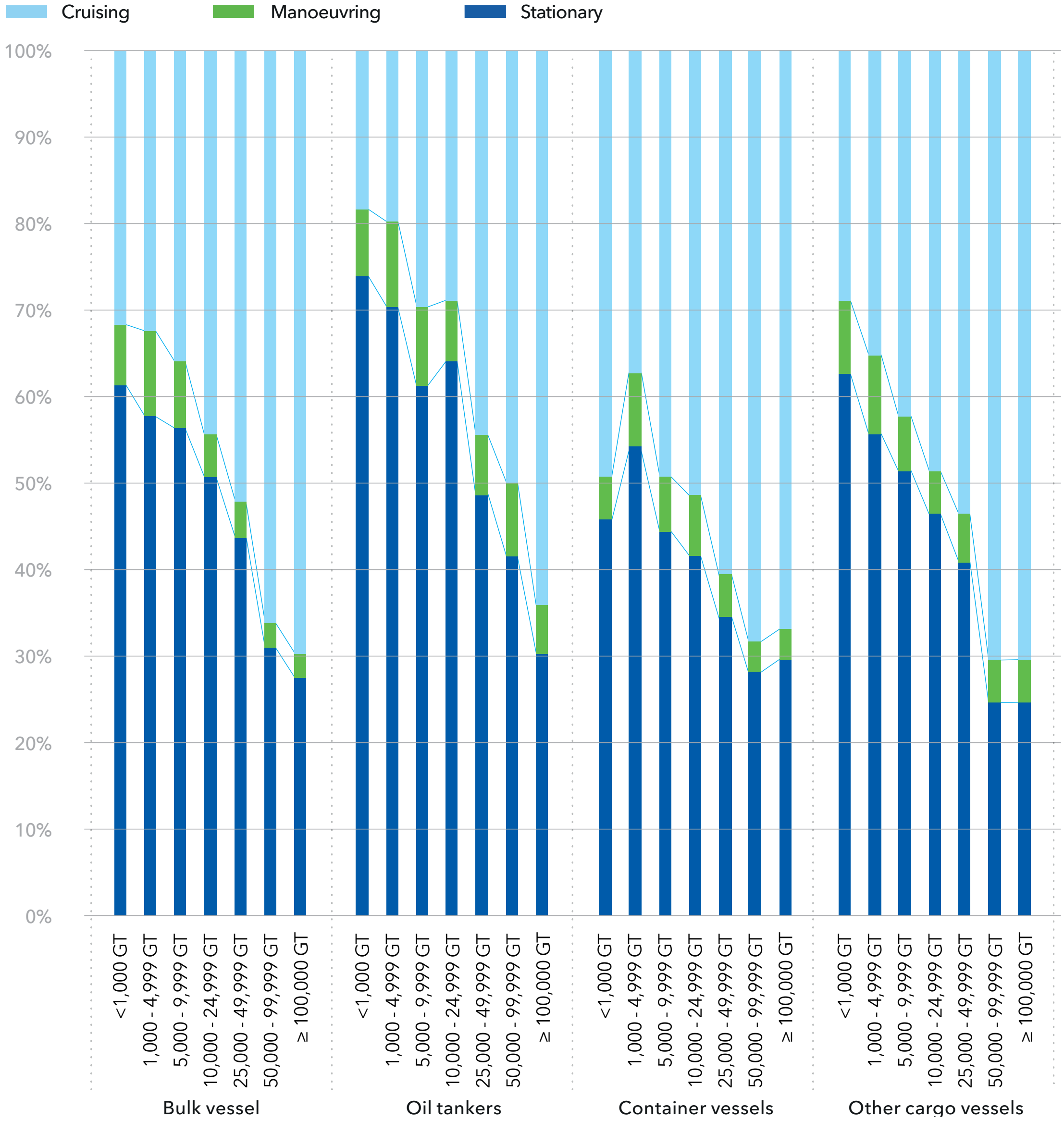


FIGURE 2.2.2

Share of time per operation mode for cargo vessels by ship type and size

Units: Percentages



2.3 SPEED PROFILE ANALYSES FOR THE WORLD FLEET

Figure 2.3.1 shows the average operational speed profile for all cargo vessels in cruising mode (more than 5kn) for the years 2016 and 2017. This is calculated as the average time spent in each speed segment for all ships for each year. The speed profiles do not vary much between these years. Compared with 2016, we find that in 2017 slightly more time was spent in the interval 11–13kn, and slightly less in 14–17kn.

Figure 2.3.2 shows the average operational speed profile for main cargo vessel types in cruising mode (more than 5kn) in 2017. Bulk vessels, oil tankers, and other cargo vessels typically operate at 12–13kn. The larger ships, mainly above 25,000 GT, are typically deployed on long-haul routes and tend to operate at higher service speeds than the smaller vessels, which typically operate in intra-regional shipping (short-sea shipping). Figure 2.3.3 shows the operational speed profile for container vessels split across short-sea and deep-sea shipping.

FIGURE 2.3.1

Operational speed profile for cargo vessels

Units: Share of time

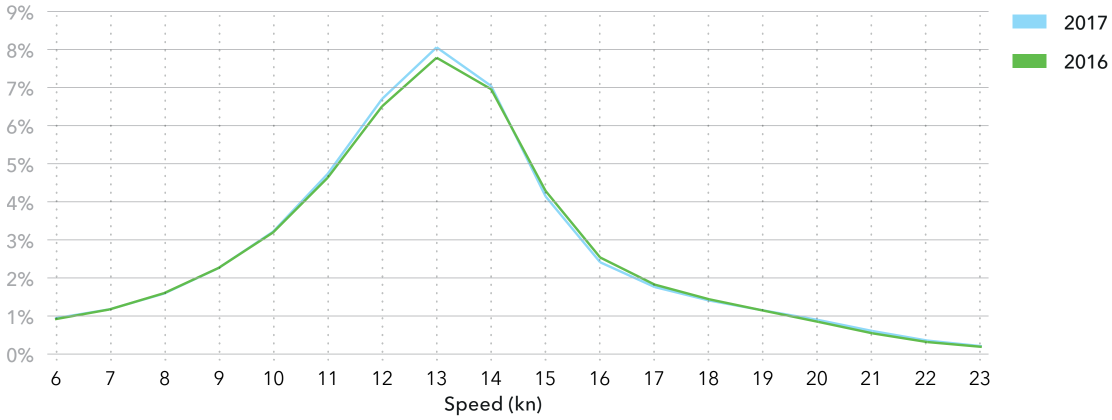


FIGURE 2.3.2

Operational speed profile for cargo vessels in 2017

Units: Share of time

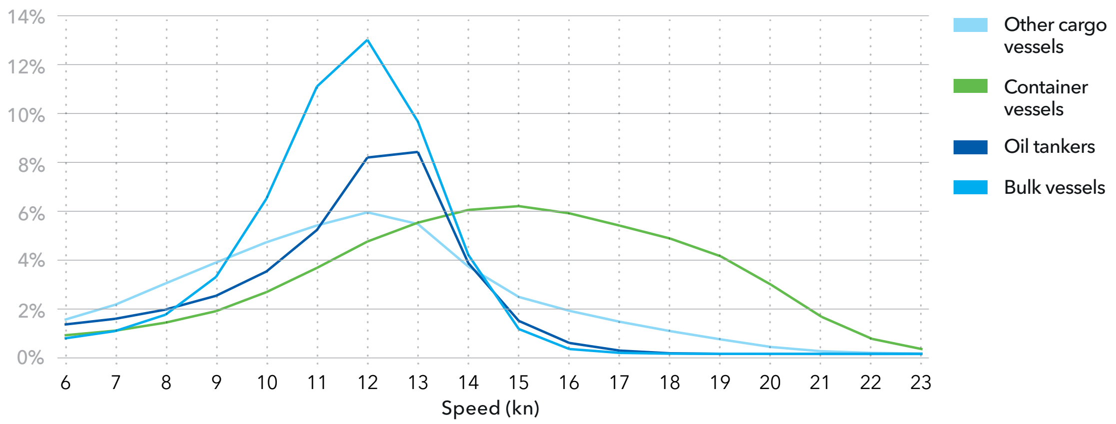
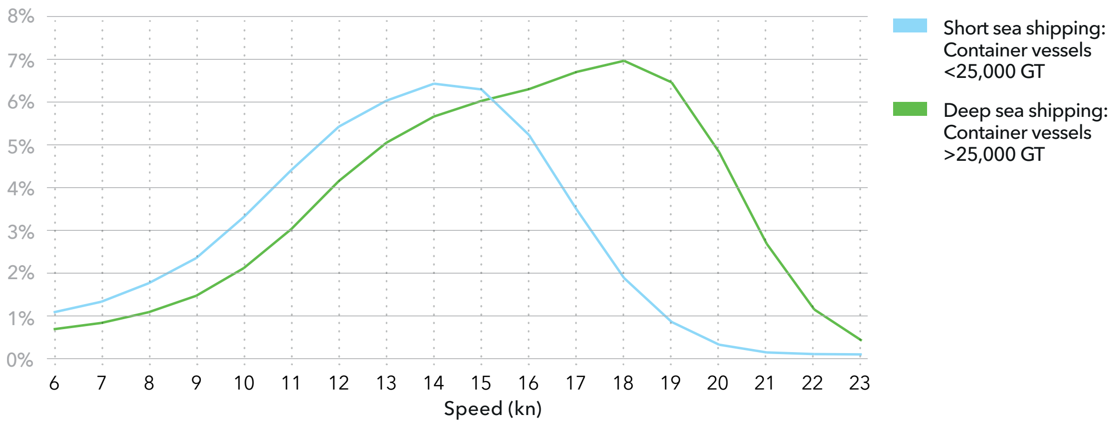


FIGURE 2.3.3

Operational speed profile for container vessels in 2017

Units: Share of time



2.4 FUEL CONSUMPTION BY MODE OF OPERATION

Fuel consumption is not proportional to the time spent in different operational modes. Figure 2.4.1 shows how fuel consumption by operational mode varies between major ship types: 15% is consumed while stationary; only 1% while manoeuvring; and, 84% when cruising.

Figure 2.4.2 shows how fuel consumption by mode of operation varies with ship size. The smallest vessels consume most of their fuel in non-cruising mode, while the largest ships consume less than 10% in non-cruising mode.

FIGURE 2.4.1

Share of fuel used in each operation mode in 2017 by cargo vessel segment

Units: Percentages

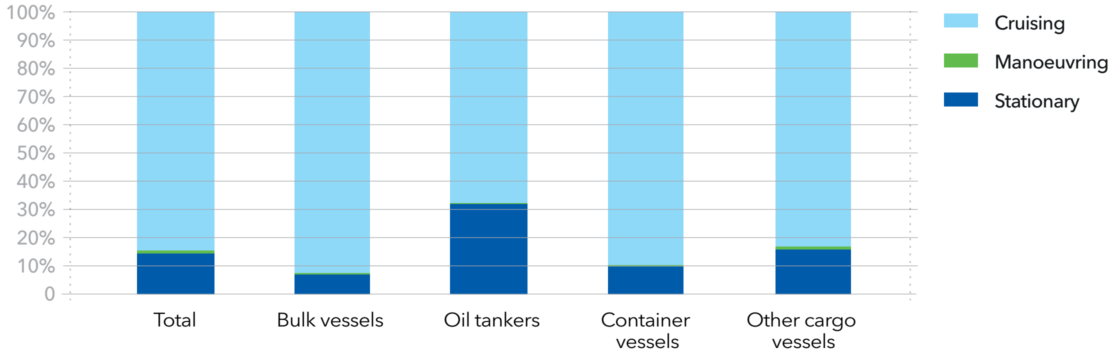
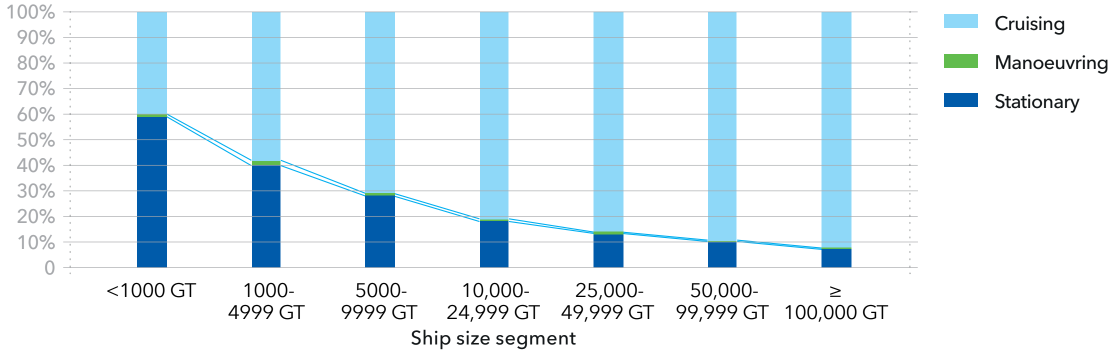


FIGURE 2.4.2

Share of fuel used in each operation mode in 2017 by ship size segment

Units: Percentages



2.5 GEOGRAPHICAL DISTRIBUTION OF SHIP FUEL CONSUMPTION

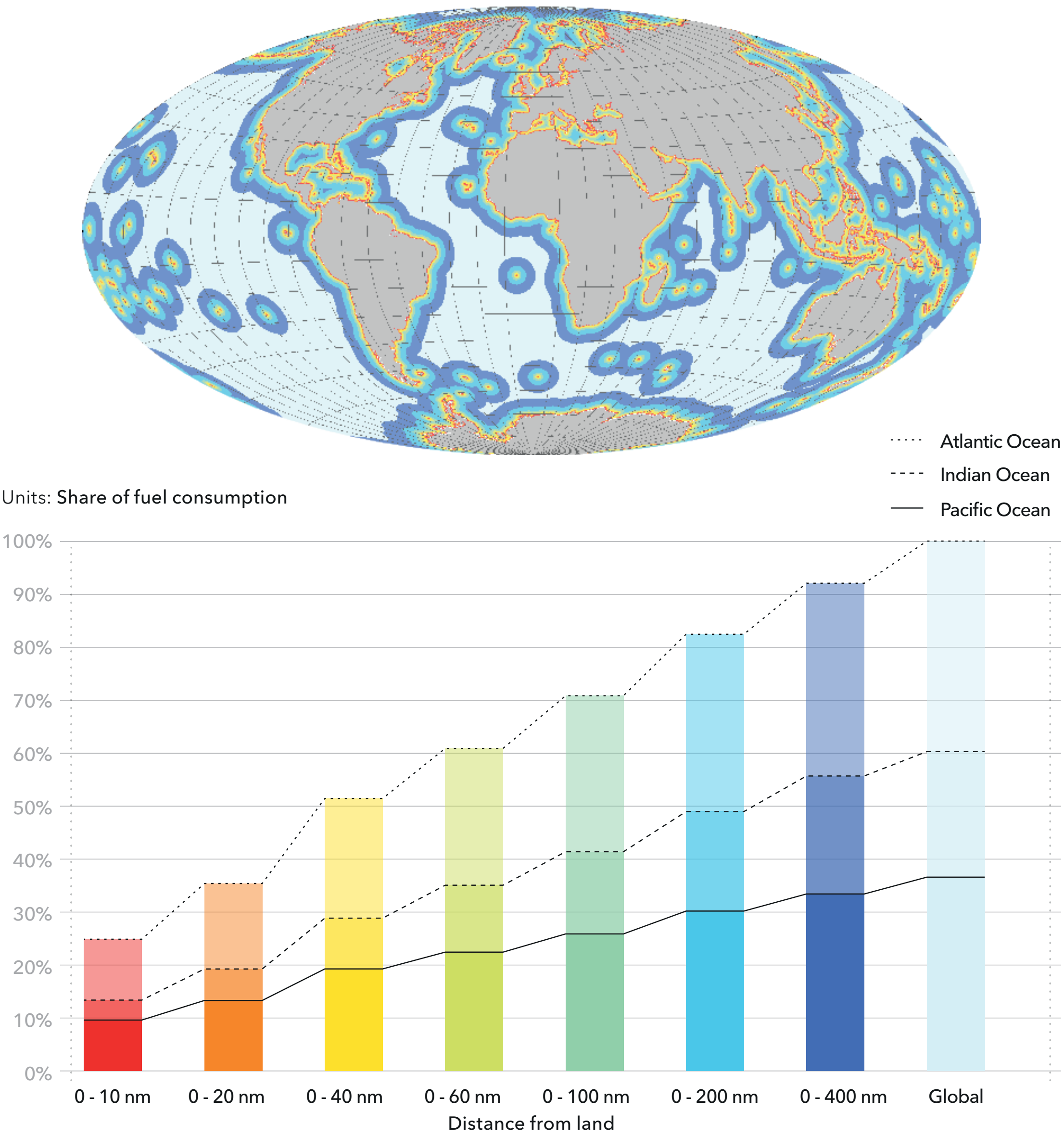
Most ship fuel is consumed in the northern hemisphere within a well-defined system of international sea routes (Figure 2.1.2). Also, large percentages of total maritime fuel consumption happen close to shore or to coastal communities, meaning that much of the emissions of harmful substances such as particulate matter (PM), nitrogen oxides (NOx), and sulphur oxides (SOx) also happen close to shore, impacting on the environment and human health (Endresen et al, 2003; Corbett et al, 2008; Sofive et al, 2018).

Figure 2.5.1 shows the accumulated fuel consumption by shipping by its distance from land. Approximately 25% is consumed by ships being stationary in port or operating closer than 10 nautical miles (nm) from shore. The results confirm an expected gradual increase in the share of consumption with proximity to land. More than 50% of the fuel consumed is by vessels closer than 40 nm from shore. By sea area, the largest share (40%) of fuel consumption relates to ship traffic in the Atlantic Ocean and Mediterranean Sea, followed closely by the Pacific Ocean (36%) and Indian Ocean (24%).

Introducing cleaner fuels and new technologies will reduce total fuel consumption and related emissions (chapter 5). It should be noted that ship emissions are not directly proportional to fuel consumption. Reasons include the fact that several emission control areas have been established (see chapter 4), and different fuels and technologies applied onboard have different emission footprints (chapter 5).

FIGURE 2.5.1

Share of maritime fuel consumption in 2017 by distance from land



CHAPTER 3

SEABORNE TRADE OUTLOOK: THE ENERGY TRANSITION

3 SEABORNE TRADE OUTLOOK: THE ENERGY TRANSITION

Economic activity is the main driver of maritime transport, be it transportation of fuels, agricultural products, raw materials for manufacturing industries, or manufactured products for final use.

This chapter provides an outlook for the maritime industry based on volumes to be transported, focusing on crude oil, oil products, gas, bulk, and containerized cargo. Our forecast is based on DNV GL's updated model, which is described in detail in the main report, DNV GL Energy Transition Outlook 2018 (DNV GL, 2018a). Here, we provide a short description of the approach and the transport needs, before presenting our updated predictions for the maritime industry and its operations.

3.1 MODELLING APPROACH

Our Energy Transition Outlook (ETO) model is designed to forecast the energy transition in 10 global regions (Figure 3.1.1). It is a system dynamics feedback model implemented with Stella software and covering the energy system from source to sink.

Our global energy forecasting approach quantifies trade in commodities between and within the 10 regions. This enables forecasts that reflect dynamics, such as growth and decline of the fossil-fuel trade in coming decades. These dynamics are influenced by several factors:

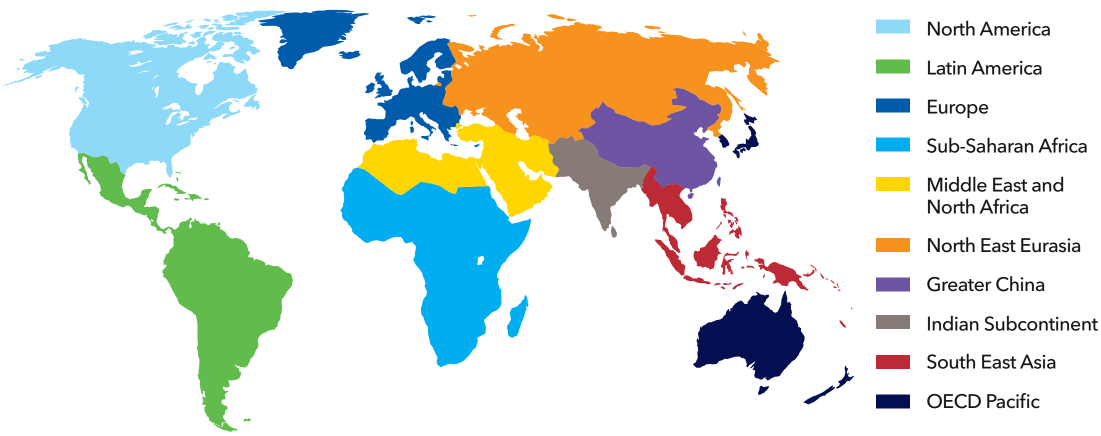
– The energy transition through decarbonization and electrification
– New fossil-fuel production methods such as hydraulic fracturing
– Increased conversion of gas to liquefied natural gas (LNG)
– Regional shifts in fossil-fuel demand and supply
– Geopolitical changes.

DNV GL has built a demand-driven model (DNV GL, 2018a), in which the main drivers of energy demand are energy efficiency, population, and GDP. Key demand sectors, such as buildings, feedstock, manufacturing, and transport, are analysed in detail.

Energy supply is characterized by a decarbonization push, helped by regional energy policies favouring some energy carriers over others. Technology learning curves and corresponding cost developments are driving down costs of all energy sources, while resource availability constraints might drive up costs. Differences between these cost developments help to determine the future energy-supply mix. The model captures several technologies and quantifies their uptake.

FIGURE 3.1.1

Regions analysed in the Energy Transition Outlook



The ETO modelling also includes non-energy trade, relevant for ship segments such as bulk and containers. A more complete overview of the modelling approach, drivers, barriers, and expected technology and cost developments is in the main report (DNV GL, 2018a).

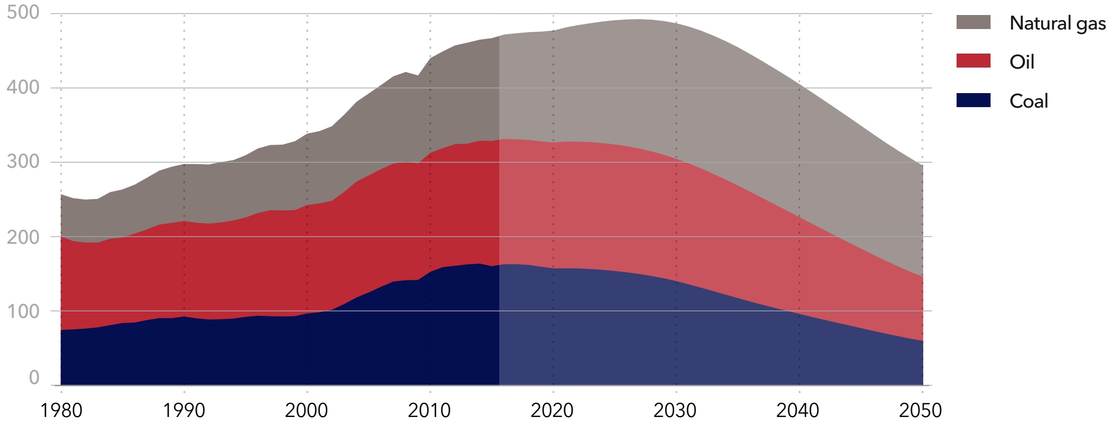
In the main report, we provide more details of our approach and resulting regional forecasts for energy demand and supply. We forecast that global final energy demand will peak in 2035, at a level 16% higher than today, and will then decline slowly. Energy supply peaks around the same period, and consumption of fossil fuels is reduced, impacting maritime transport of coal and oil. Seaborne fossil-fuel trade within and between regions is a major component of the forecast. Figure 3.1.2 illustrates the global forecast for primary energy supply from fossil sources.

> "Energy supply is characterized by a decarbonization push, helped by regional energy policies favouring some energy carriers over others.

FIGURE 3.1.2

World primary fossil fuel supply

Units: EJ/yr



3.2 MARITIME TRANSPORT NEEDS

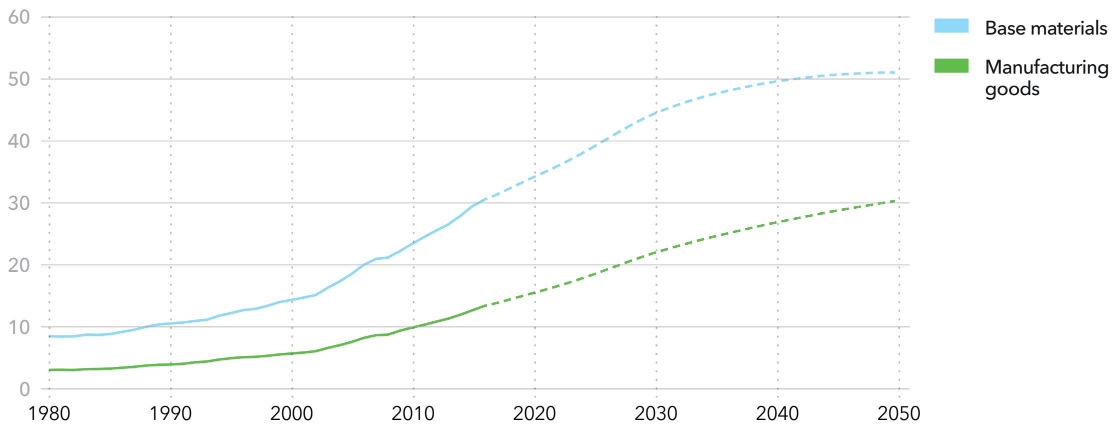
Trade in crude oil is determined by differences between regional production and regional demand. On the crude-oil supply side, we model production capacity as a cost-driven global competition between regions. We consider three segments; offshore, onshore, and unconventional oil. The gap between a region's crude oil production and refinery input determines the surplus for export or a deficit to be met by imports, which are mainly transported on keel. The destinations of crude oil imports are based on the most recent Automatic Identification System (AIS) data of crude oil tankers, adjusted for ballast movements. We adopt a similar approach for shipment of oil products, where we use oil products demand and refinery output as the determinants of regional trade.

To determine seaborne gas trade, we deduct the current share of gas transported by pipelines. This reasoning is supported by historical data and trends in gas production. For gas in the form of LNG and liquid petroleum gas (LPG), transportation costs – including piping, liquefaction, and regasification – are a significant component of the final consumer price to end users. We first determine the fraction of gas demand to be supplied from the region's indigenous sources. This fraction varies between regions due to geographic, political, and economic differences, and over time. Any shortfall in meeting demand from regional production is allocated to exporting regions according to their current shares as gas-trading partners. Intra-regional trade is determined as a constant multiplier of regional gas demand.

FIGURE 3.2.1

World manufacturing supply

Units: Gt/yr



Coal use is derived from sectors such as buildings, manufacturing, and power, with demand for brown coal confined to its combustion for electricity. Each region's hard-coal supply reflects its mining capacity, which expands as demand increases and is limited by its geologically available reserves. As in the case of natural gas, we assume a stable mix and shares of trade partners for coal. Regions with domestic shortfalls import coal from regions with surpluses.

Looking at the non-energy trades, we model regional manufacturing of finished goods (e.g., construction equipment, electronics, food, machinery, and textiles) and the use of raw materials (e.g., chemicals, iron and steel, other metals, paper, pulp, and wood) to produce these. Taking account of surplus and excess regional production levels, provides the baseline for non-energy trade on keel. Figure 3.2.1 shows the global manufacturing demand towards 2050 by broad sector.

Trade in iron ore is also driven by base-material production. Global minor bulk trade is correlated with worldwide production of base materials, such as metals, paper, steel and wood, but uses a different trade multiplier than iron ore. We assume that grain-production dynamics will follow population and GDP-per-capita growth of existing and potential grain-importing regions. Similarly, we define a relationship between container trade and the global supply of manufactured goods. A similar relationship exists between manufactured goods, production, and other cargo trade, including shipping of dry cargo unaccounted for in other categories.

We estimate future distance of cargo by multiplying each region pair's trade volume with a sailing distance estimated by AIS data, then taking a weighted average. Because this approach utilizes regional imports and exports, the effect of new routes, such as the US emerging as a new crude oil exporter, is also reflected in tonne-miles.

The future trade will be impacted by the emerging technology landscape. Notably, digitalization will impact trade volumes and distances in various ways. First, robotization will mean labour costs becoming a less significant cost component, making relocation of manufacturing from high labour-cost countries to emerging economies less attractive. This will reduce trading volumes compared to a less robotized world (Backer and Flag, 2017), as relatively more manufacturing will happen close to market. Similarly, within-region trade will increase, and average voyage distances will decline. The exact effect has been hard to estimate, and with a 0.1% per year decline in distance modelled for all ship segments, this impact is dwarfed by the effects of other trade changes on trade distances.

3.3 TRADE TOWARDS 2050

We summarize our seaborne trade forecast by cargo type in Tables 3.3.1 and 3.3.2, and present a wider picture over the forecasting period 2016–2050 in Figures 3.3.1 and 3.3.2., where trade is measured either in Gt/yr (gigatonnes – i.e., billion tonnes per year) or in Tt-nm/yr (trillion tonne-nautical miles per year).

We forecast a 39% rise in seaborne trade measured tonnes over the period 2016–2030, and a 2% rise for 2030–2050. We project increased seaborne transportation for all trade segments except crude oil and oil products, which peak around 2030 (Table 3.3.1). The largest relative growth in transportation demand is for gas and container cargo, both growing about 120% to mid-century.

For bulk, the combination of an increase in non-coal bulk trade with eventual reductions in coal transportation implies sustained growth to 2050, when trade will be 41% higher than it is now.

Variations in sailing distances explain differences in the relative scale of trade by cargo type seen in Tables 3.3.1 and 3.3.2. Consequently, the growth in annual transport of goods in tonne-miles for 2016–2030 will be 32%, less than the 39% projected growth in tonnes.

TABLE 3.3.1
World seaborne trade – tonnes

	Trade (million tonnes/yr)			
Cargo type	**2016**	**2030**	**2040**	**2050**
Crude oil	1,950	2,280	1,850	1,270
Oil products	1,070	1,320	1,250	1,020
Natural gas	360	640	770	790
Bulk	4,890	6,730	6,940	6,910
Container	1,730	2,850	3,400	3,740
Other cargo	1,150	1,630	1,860	2,010
Total	11,130	15,460	16,080	15,730

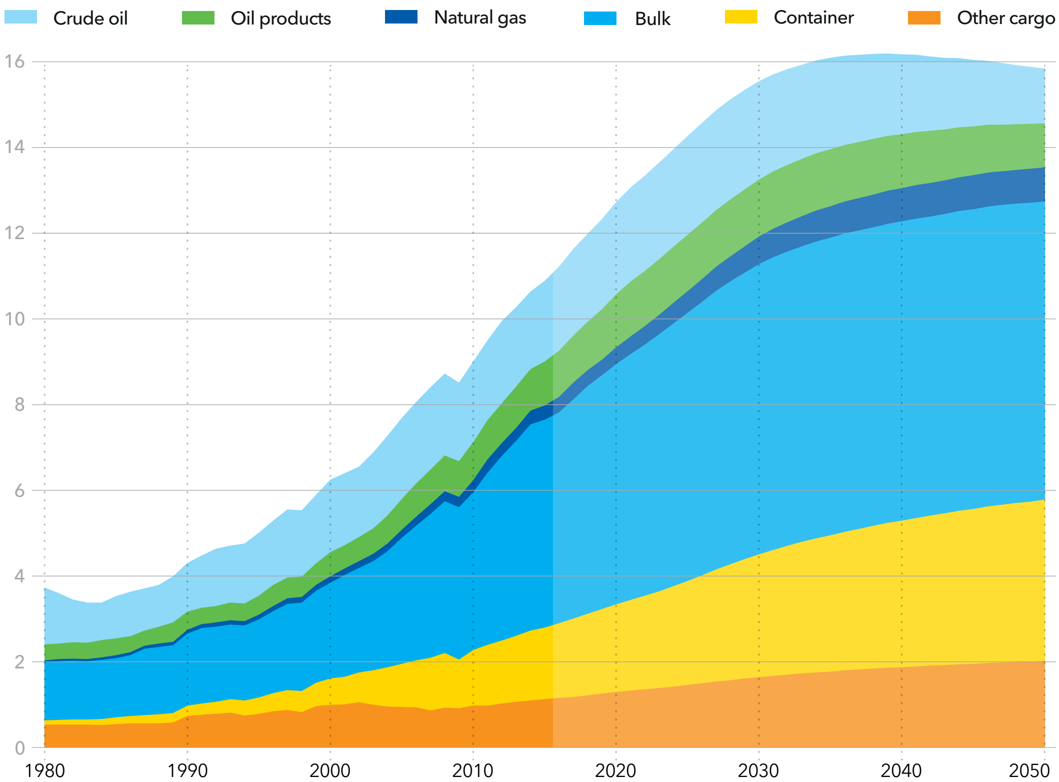
TABLE 3.3.2
World seaborne trade – tonne-miles

	Trade (billion tonnes/nm/yr)			
Cargo type	**2016**	**2030**	**2040**	**2050**
Crude oil	9,580	11,380	9,600	6,570
Oil products	3,040	3,760	3,500	2,800
Natural gas	1,460	3,670	4,620	4,520
Bulk	27,200	34,320	36,970	37,890
Container	8,580	12,690	14,950	16,250
Other cargo	5,190	6,680	7,590	8,140
Total	55,060	72,510	77,230	76,150

FIGURE 3.3.1

World seaborne trade: tonnage

Units: Gt/yr



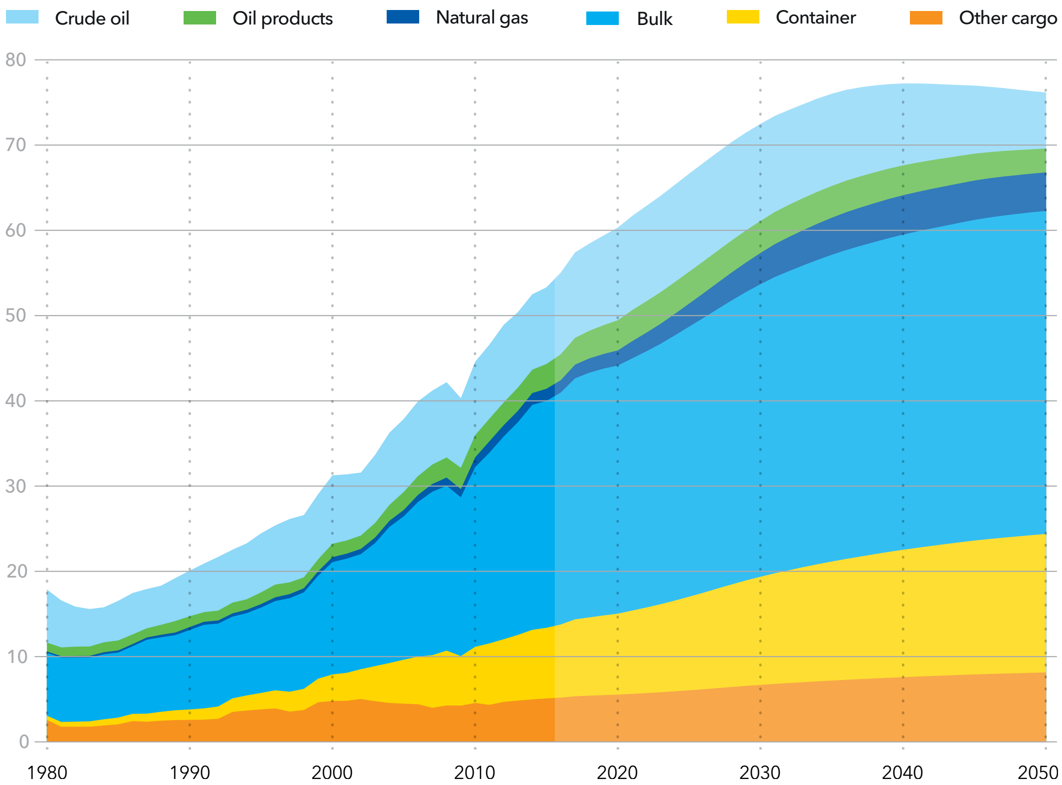
Sources: forecast - DNV GL; historical data - Clarkson Research, 2017

Average annual growth rate in %	2010-2016	2016-2030	2030-2050
Crude oil	0.7	1.1	-2.9
Oil products	3.3	1,5	-1.3
Natural gas	4.3	4.3	1.0
Bulk	4.9	2.3	0.1
Container	5.0	3.6	1.4
Other cargo	5.0	3.6	1.0
Average	3.8	2.4	0.1

FIGURE 3.3.2

World seaborne trade: tonne-miles

Units: Tt-nm/yr



Sources: forecast - DNV GL; historical data - Clarkson Research, 2017

Average annual growth rate in %	2010-2016	2016-2030	2030-2050
Crude oil	1.8	1.2	-2.7
Oil products	2.7	1.5	-1.5
Natural gas	4.1	6.8	1.0
Bulk	4.4	1.7	0.5
Container	4.5	2.8	1.2
Other cargo	4.5	2.8	1.0
Average	3.7	2.0	0.2

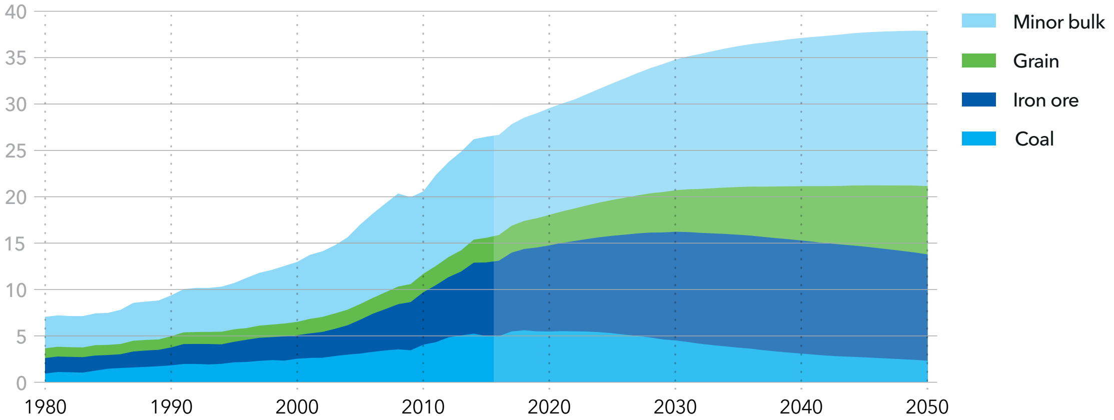
Slower growth in tonne-miles than in tonnes to 2030 results mostly from improved route planning and thus better-optimized voyages. Route distances increase for crude oil and decrease for bulk; average voyage length cancels out globally. Conversely, the tonne-miles growth for 2030–2050 will be 5% in contrast with a mere 2% growth in tonnes, as changing trade patterns more than outweigh voyage optimization.

Summarizing, traded tonnes and related tonne-mile shipping demand will both peak within two to three decades. The peak is not marked. It could better be termed a plateau because the combined need for trade and maritime cargo will stabilize as trade in oil and coal decreases, while growth of other cargoes slows in line with decelerating growth in both global population and GDP.

FIGURE 3.3.1.1

World seaborne bulk trade

Units: Tt-nm/yr



Sources: forecast - DNV GL; historical data - Clarkson Research, 2017

Average annual growth rate in %	2010-2016	2016-2030	2030-2050
Coal	3.5	-0.7	-3.3
Iron ore	6.3	2.6	-0.1
Grain	5.6	3.5	2.5
Minor bulk	3.3	1.9	0.9
Average	4.4	1.9	0.4

3.3.1 BULK

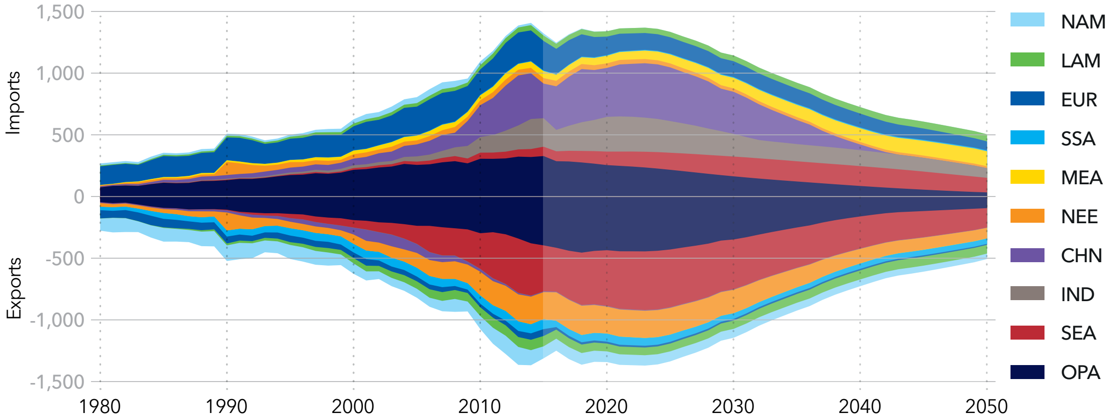
Because we distinguish energy commodities from other cargoes, we separate bulk trade into coal and non-coal. The latter includes grain, iron ore, and minor bulk (Figure 3.3.1.1). Non-coal bulk dominates the picture, growing 2.8%/yr to 2030, and 0.7%/yr thereafter. Growth in iron ore and minor bulk trade will be solid for the first decades, but will then slow down. For iron ore, this growth will decline after 2030 due to the slower growth of base-material output. Grain trade will continue to grow, although the pace of growth will reduce towards 2050. Grain trade increases reflect greater increases in population than in indigenous agriculture production. Climate change and water scarcity in developing countries are also influencing agricultural production and raising the need for grain imports.

Global seaborne coal trade is currently dominated by hard-coal being exported from Australia and Indonesia to China, India, Japan, and Korea (Figure 3.3.1.2). We forecast that current Chinese coal imports will remain high for the coming decade. Thereafter, they will enter decline amid decarbonization of the country's power and manufacturing sectors, which will allow indigenous coal production to catch up with demand. In contrast, the Indian Subcontinent will see sustained growth in coal consumption, but its production will also expand to enable self-sufficiency towards 2050.

FIGURE 3.3.1.2

Coal imports and exports by region

Units: Mt/yr



3.3.2 OIL

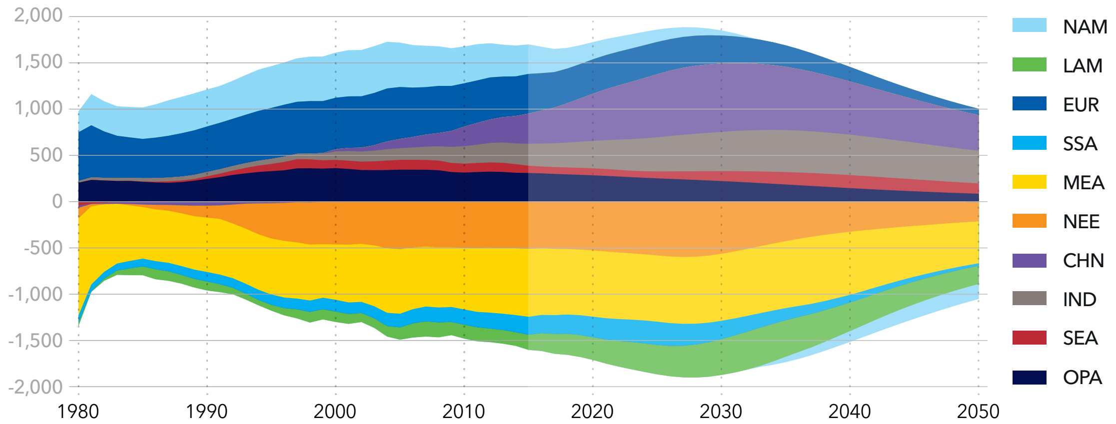
Transport is the largest consumer of oil. As explained in detail in the main report (DNV GL, 2018a), oil demand is set to peak in the 2020s and then decline as vehicle electrification speeds up. Manufacturing is the second-largest consumer of oil, including its use for feedstock, an application that will peak in the late 2020s.

With more than 90% of crude oil trading on keel, changing production and consumption patterns impact seaborne trade directly. Regional patterns for this trade are changing. Europe and OECD are already experiencing a reduction in oil consumption. This will continue, while China's consumption will continue to grow, peaking around 2030, followed somewhat later by India. Production will continue to be dominated by Middle East and North Africa, with Latin American production increasing, and levels in North East Eurasia and North America remaining stable until the mid-2030s, then decreasing.

FIGURE 3.3.2.1

Net crude oil imports by region

Units: Mt/yr



Latin America, Middle East and North Africa, and North East Eurasia will continue as major exporters. For North America, the pattern is already shifting because of its strong increase in shale oil (Figure 3.3.2.1).

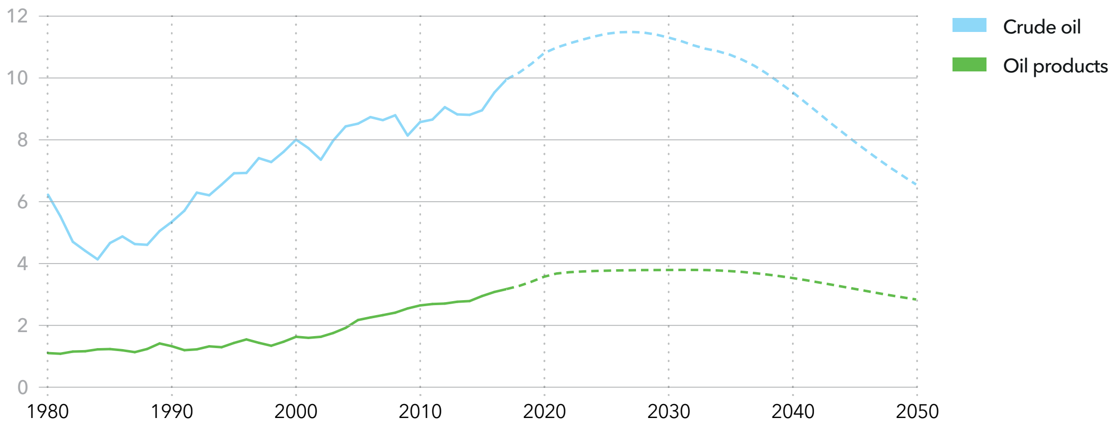
More than 85% of global seaborne crude oil trade is currently inter-regional, and the remaining 15% intra-regional, within regions. Seaborne crude-oil trade will plateau some 21% higher than now within the next decade, thereafter trending down after 2027 to reach around 6.5 trillion tonne-miles in 2050 (Figure 3.3.2.2).

In forecasting trade in oil products as a function of regional refineries' output and demand, we conclude that it will first level off and eventually decline. Regional developments, such as expansion in refining capacities in Russia and the Middle East and West Africa, will have a significant impact in the near future. The seaborne oil products, trade in tonne-miles is around one third of the crude oil trade in 2016. In the future, the reduction in the former will be less than for crude oil, partly due to increased trade in biofuel, which we define as oil products in our maritime trade analysis.

FIGURE 3.3.2.2

World seaborne crude oil and products trade

Units: Tt-nm/yr



Sources: forecast - DNV GL; historical data - Clarkson Research, 2017

3.3.3 NATURAL GAS

Natural gas is mostly used in power stations, followed by direct use in buildings and manufacturing. While gas consumption in power stations, and as a whole, peaks in 2033 in our modelling, its use in manufacturing increases throughout the forecast period to 2050. More details of production, supply, and demand can be found in the ETO main report (DNV GL, 2018a).

The main gas-producing regions are and will remain Middle East and North Africa, North America, and North East Eurasia. Driven by manufacturing sector growth, China's rising need for natural gas sees it become the leading gas importer by 2021. It remains so for the rest of the forecasting period. Europe will remain a large gas importer, and the Indian Subcontinent and Sub-Saharan Africa will see growing imports. This is illustrated in Figure 3.3.3.2, where the thickness of the lines represents trade volume in tonnes, although the paths do not represent detailed trade routes. The main feature of the comparison for 2016–2050 is the strong growth in exports from North America, specifically the US.

Trade in natural gas as LNG and LPG will continue to increase (Figure 3.3.3.1). Most gas exports are currently through pipelines, Russia to Europe being the prime example. This will change as inter-regional trade, and North American exports in particular, grows towards 2050. We predict that the share of piped natural gas trade between countries will decrease to less than 50% in mid-century.

FIGURE 3.3.3.1

World seaborne natural gas trade

Units: Tt-nm/yr

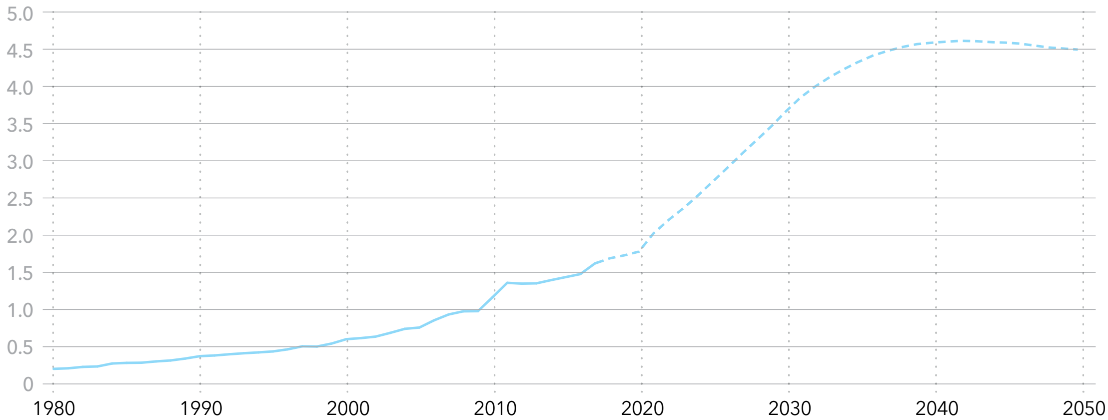
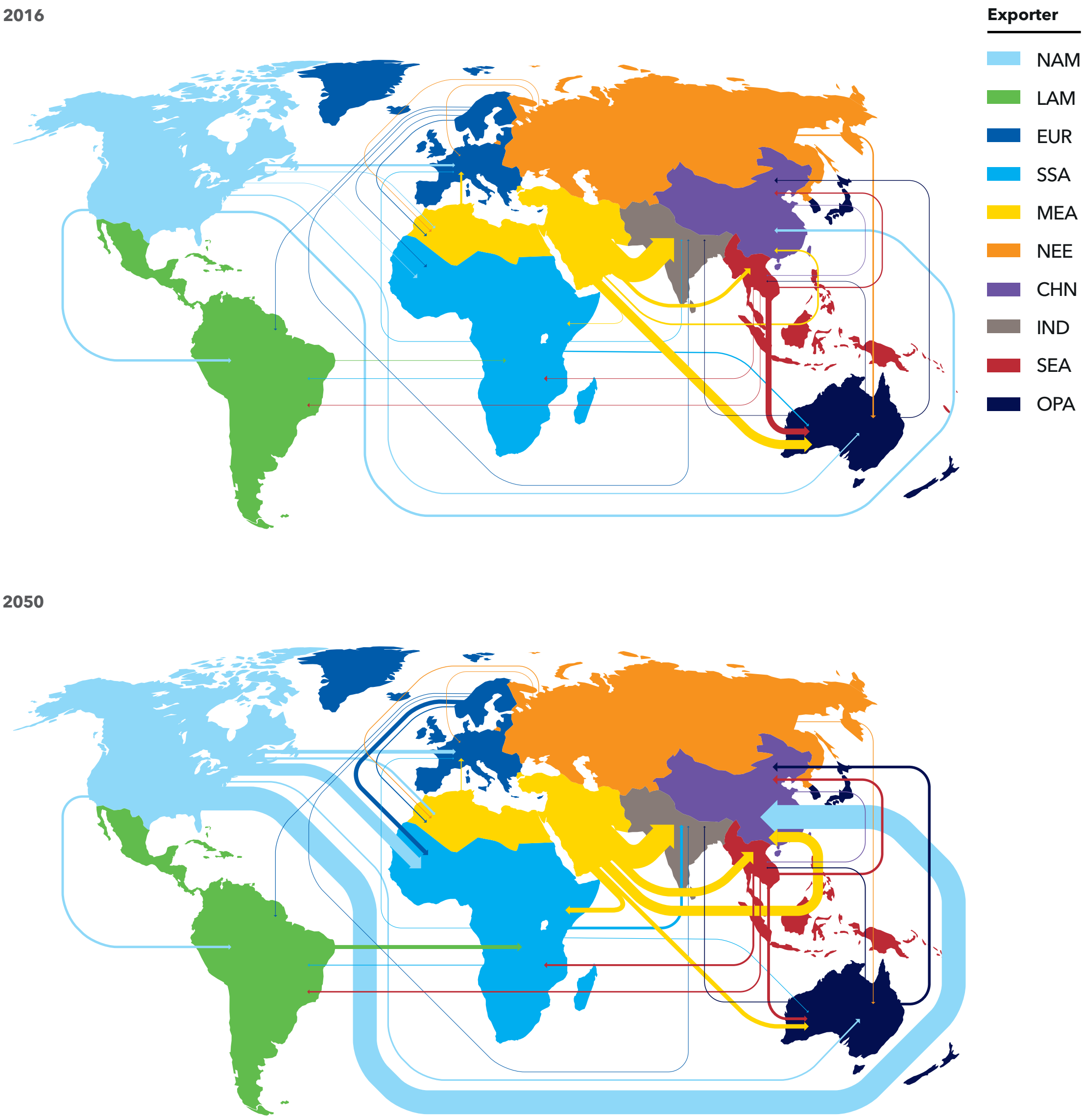


FIGURE 3.3.3.2

Illustration of global seaborne natural gas trade in 2016 and 2050



3.3.4 CONTAINERS

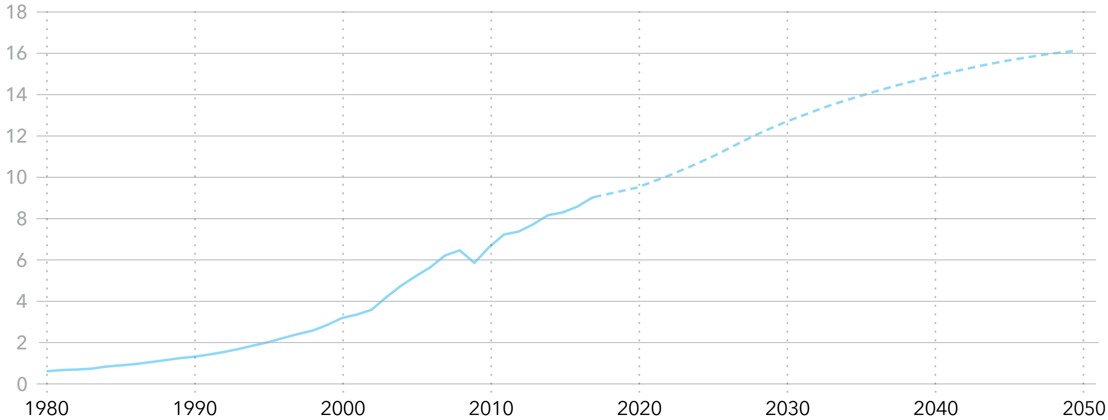
Container trade has grown strongly for decades, outpacing global seaborne trade. Containerization of more and more commodities will likely continue, while some other factors – like additive manufacturing (3D printing; see section 7.2.2), automation, and robotization – will reduce the container-trade multiple (container trade versus GDP growth). We forecast that container-trade tonnage will broadly mimic manufacturing goods and increase by 3.4%/yr to 2030 and 1.4%/yr thereafter (Figure 3.3.4.1).

Container trade growth will be highest in regions with the greatest growth in manufacturing output. China will dominate growth for another decade. Thereafter, the Indian Subcontinent will take over as the main growth region. Asian and African regions will increasingly dominate as economic growth moves south and east.

FIGURE 3.3.4.1

World seaborne container trade

Units: Tt-nm/yr



3.3.5 OTHER CARGO AND OFFSHORE SHIPPING

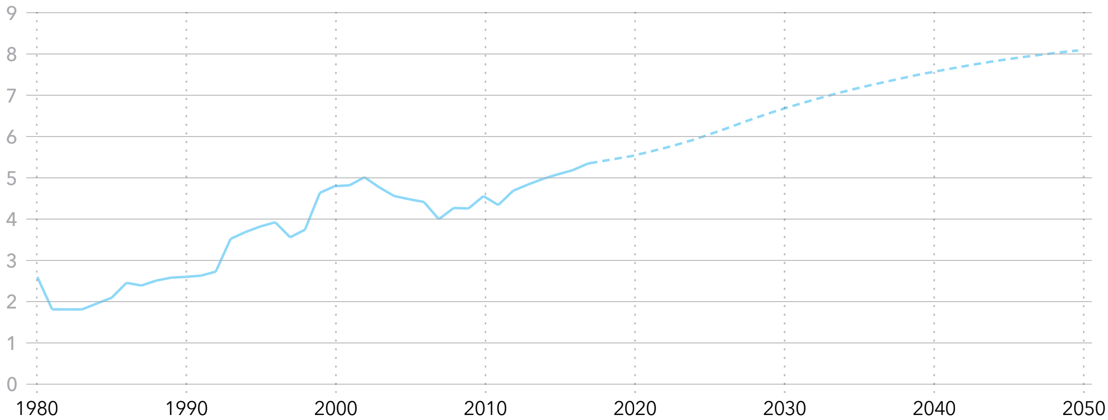
Other cargo is a category encompassing all types not described above. It includes general cargo, and most chemicals carried on tankers. Parts of the other cargo segment will move to containers over time. This is one main reason why the segment will see annual growth rates decline towards 2050 (Figure 3.3.5.1). Seaborne other cargo trade will increase 2.4%/yr on average until 2030, and 1%/yr thereafter. Our analysis does not track geographical change in this trade, but we foresee a slow eastward shift in line with the growth of Asia's share in the world economy.

Offshore shipping is a sizeable shipping segment, and is expected to undergo significant changes in the coming decades. While declining production of offshore oil and gas will reduce the need for related shipping, this will be compensated for in part by growth in other offshore segments, such as wind energy generation. For a more thorough discussion on the shipping implications, see our 2017 forecast (DNV GL, 2017b).

FIGURE 3.3.5.1

World seaborne other cargo trade

Units: Tt-nm/yr



CHAPTER **4**

REGULATORY AND STAKEHOLDER OUTLOOK

4 REGULATORY AND STAKEHOLDER OUTLOOK

To ensure compliance and optimize business decisions in shipping, it is vital to understand existing and future regulatory frameworks and the expectations of external stakeholders. In this chapter, we consider major global and regional regulations that will impact on shipping in the coming decades, then discuss stakeholders' expectations on sustainability.

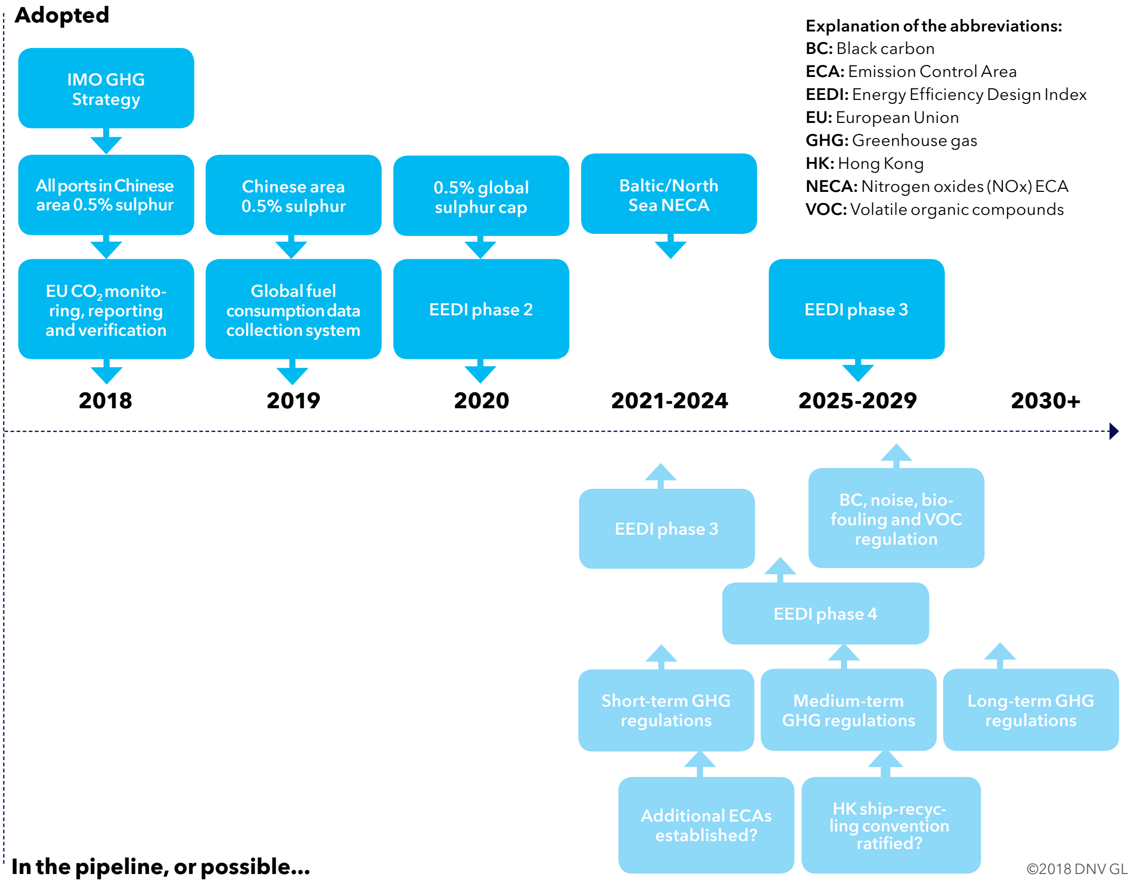
4.1 REGULATORY TIMELINE

Shipping has experienced a surge in environmental regulations over the past decade. Those emanating from agreements reached under the auspices of the International Maritime Organization (IMO) include the global sulphur limit on ship fuel; nitrogen oxides (NOx) Tier III requirements in Emission Control Areas (ECAs); and the ballast water management regulation. All will impact on shipping in the next five years, while greenhouse gas (GHG) emissions will be the main challenge in the decades to 2050 (Figure 4.1.1). The timeline pictured does not include all local regulations that have been adopted or may be in the future.

We also expect safety regulations to improve incrementally. Their main thrust will be to ensure that new environmental technologies and fuels can be applied safely, and to address challenges related to digitalization, such as autonomy, control systems, and cyber risk.

FIGURE 4.1.1

Timeline of adopted and possible environmental regulations towards 2030



Explanation of the abbreviations:
BC: Black carbon
ECA: Emission Control Area
EEDI: Energy Efficiency Design Index
EU: European Union
GHG: Greenhouse gas
HK: Hong Kong
NECA: Nitrogen oxides (NOx) ECA
VOC: Volatile organic compounds

4.2 EMISSION OF SULPHUR OXIDES

Emission of sulphur oxides (SOx) from shipping is being regulated at global and regional levels (Figure 4.2.1). The IMO has decided that the 0.5% global sulphur cap for ship fuel will be implemented from 1 January 2020. The decision is final, will not be subject to re-negotiation, and has thus provided certainty to the maritime and bunker industries on regulatory conditions.

Uncertainty remains over the means of compliance, however. Ship operators will need to decide on their preferred compliance strategies, decisions that will have significant operational and financial implications. There is no one-size-fits-all solution on the table. Sulphur scrubbers, liquefied natural gas (LNG), and 'hybrid' fuels are all realistic options, but most vessels are expected, at least initially, to target 0.5% sulphur fuel (distillates or low-sulphur fuel oil) as a default position. Local availability issues and price volatility are expected consequences of the unfamiliar fuel-demand picture that will materialize on 1 January 2020. Cases of non-compliance will likely be significant in number during a transitional period, due in particular to insufficient tank cleaning at bunker facilities and on ships.

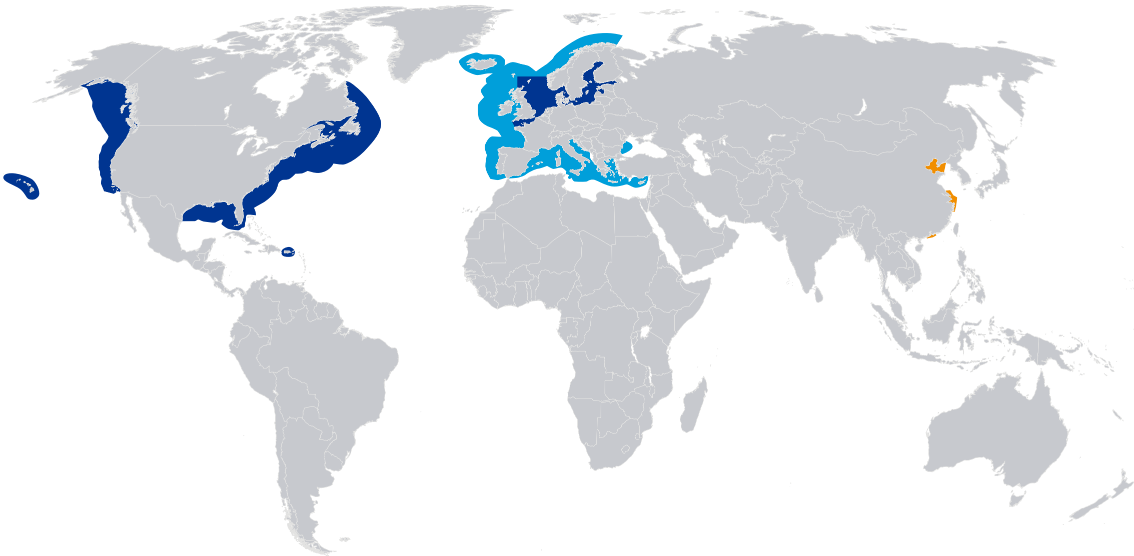
On a regional and domestic level, the European Union's Water Framework Directive (2000/60/CE) is constraining the discharge of scrubber water. Belgium and Germany prohibit its discharge in most areas, allowing only closed-loop scrubbers. Similar restrictions apply in parts of the US, such as Connecticut.

In Asia, China is taking a staged approach to rolling out regulations governing domestic requirements for SOx controls similar to emission control areas (ECAs). These apply to the sea areas off Hong Kong/Guangzhou and Shanghai, and in the Bohai Sea. The government is initially enforcing a maximum 0.5% sulphur content for fuel burned in key ports in these areas, gradually expanding coverage, and culminating in applying the requirements to all fuel used in the sea areas from 2019 onwards. It is possible that the requirement for the sea areas will be tightened to no more than 0.1% sulphur in 2020, and that a formal ECA application may be submitted to the IMO.
In DNV GL's view, there is a real possibility of such zones being extended to cover additional Chinese sea areas.

> "Ship operators will need to decide on their preferred compliance strategies, decisions that will have significant operational and financial implications.

FIGURE 4.2.1

Global and regional sulphur regulations



- 0.5% Global limit (MARPOL, 2020)
- 0.1% Emission Control Areas (MARPOL, 2015)
- 0.1% EU ports (EU Sulphur Directive, 2010)
- 0.5% Selected areas in China/Hong Kong (2016-2019)*

*Note that China and Hong Kong may go down to 0,1% before 2020.

Area	Sulphur limit	Scrubbers
Global	0,5% (2020)	yes
Sulphur	0,1% in all ports	yes
EU	0,1% in selected areas	open-loop restricted in some countries
China	0,5% in selected areas	yes
California	0,1% within 24 nm	no, only through research exemption

4.3 EMISSION OF NITROGEN OXIDES

The IMO's NOx Tier III requirements are in force in the North American ECAs for ships constructed on or after 1 January 2016. Tier III also applies for engine retrofits (non-identical) and major conversions on existing ships from this date. Tier III requirements can be met by using LNG as fuel (depending on engine type) or by installing selective catalytic reactors (SCR) or exhaust gas recirculation systems (EGR).

Anyone constructing a ship today needs to consider whether operation in the North-American ECAs will be part of the operational pattern upon delivery, or might be at any time in the future. If so, NO_X-control technology will be required on board. When choosing such technology, operators should also consider how they intend to ensure compliance with the IMO's 2020 sulphur cap. Using LNG will ensure compliance with both NOx and SOx caps. EGR and SCR are NOx-specific reduction technologies.

IMO has also placed NOx Tier III requirements on ships operating in the North Sea and the Baltic ECAs. This will apply to ships constructed on or after 1 January 2021, and to engine retrofits and major conversions. There are presently no indications of other NOx ECAs being in the pipeline, but China is considering requiring Tier II for their domestic fleet.

4.4 BALLAST WATER MANAGEMENT

The Ballast Water Management Convention ('the Convention') entered into force on 8 September 2017, more than 27 years after the start of negotiations and 13 years after its adoption in 2004. It mandates treating ballast water before its release into the sea, in order to avoid transfer of harmful invasive species. Typically, this can be achieved through cavitation, chemicals, deoxygenation, electrolysis, ozonation, or ultraviolet light.

The Convention's revised implementation schedule currently obliges every ship in international trade to comply sometime between 8 September 2017 and 8 September 2024, depending on the vessel's gross tonnage (GT). For ships of 400 GT and more, the compliance date is linked to renewal of the International Oil Pollution Prevention certificate, whereas ships of less than 400 GT must comply by 8 September 2024. In practical terms, the entire international world fleet must be compliant within 2024.

In the US, the domestic ballast water management regulations entered into force in 2013. New ships must comply upon delivery. Since 1 January 2016, all existing ships must comply by the time of their first scheduled dry-docking.

4.5 GREENHOUSE GAS EMISSIONS

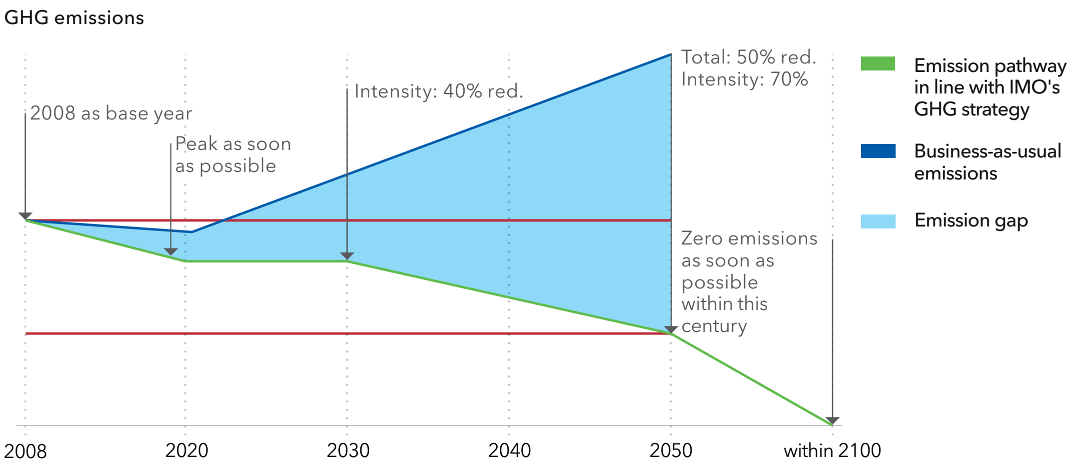
When the COP 21 Paris Agreement on climate change mitigation was adopted in 2015 as a response to the global-warming threat, shipping was not included. Instead, the IMO was expected to come up with their own contributions to reducing GHG emissions.

In April 2018, the IMO adopted a strategy to achieve this in shipping. Taking 2008 as a baseline year, this aims to reduce total GHG emissions from shipping by at least 50% by 2050, and to reduce the average carbon intensity (CO_2 per tonne-mile) by at least 40% by 2030 while aiming for 70% in 2050 (Figure 4.5.1). The IMO's ultimate vision is to phase out such emissions as soon as possible within this century. It will review strategy and targets in 2023, based on information gathered from its Data Collection System and from a fourth IMO GHG study, to be undertaken in 2019.

The EU has established general decarbonization goals suggesting a target of GHG emissions 80% below 1990 levels by 2050. Along the way, there are milestones to achieve a binding target of 40% cuts by 2030 and, indicatively, 60% by 2040. All sectors are expected to contribute. For shipping this has, for example, led to the EU monitoring, reporting, and verification system, operational from 2018. It also means that shipping could potentially be brought into the EU Emissions Trading System (ETS) unless the IMO establishes adequate measures by 2023. We expect IMO actions by then to be sufficient to avoid this.

FIGURE 4.5.1

IMO GHG strategy



Carbon intensity is measured as CO_2 emission per tonne-mile, while Total is the absolute GHG emission from international shipping.

As shipping activity will continue to grow towards 2050, the IMO's 50% reduction target is ambitious. It will require application of currently immature energy-efficiency technology and solutions, acceptance of lower speed, and deployment of large volumes of carbon-neutral sustainable fuels. Such fuels are presently unavailable in sufficient quantities. A concerted effort is needed to develop them and make them available in the necessary volumes and at acceptable prices.

Achieving its GHG ambitions will require the IMO to develop new policy measures and regulations. While nothing is yet agreed, its current strategy contains a long list of possible measures. They include, among others, strengthening the IMO's energy efficiency design index (EEDI), which is mandatory for new ships; application of operational indicators; speed optimization/reduction; market-based measures; and, development of carbon-neutral fuels. Work on establishing an action plan, thus kick-starting work on the actual measures, will start in autumn 2018.

Although we expected the immediate impact on ships to be limited, efforts required to achieve the goals will need to be built up over the coming years, with the real impact starting to materialize in the 2020s. Taking a long-term perspective, we expect implementation of the IMO strategy (see fact box page 60) to fundamentally change how ships are designed, operated, and fuelled. Chapter 5 of this report outlines possible technologies and fuels that will be needed, and chapter 8 discusses how this can impact fleet investment and ship designs today.

> "The IMO's emission-reduction targets are ambitious. It will require application of currently immature energy-efficiency technology and solutions, acceptance of lower speeds, and deployment of large volumes of carbon-neutral sustainable fuels.

REGULATING GREENHOUSE GAS EMISSIONS

Meeting International Maritime Organization (IMO) targets for reducing greenhouse gas (GHG) emissions from shipping will necessitate mandatory requirements for individual ships, as well as other policy measures to support development and implementation of new technologies and fuels. The IMO will next prioritize and decide which measures to pursue, then develop an action plan.

Short-term and medium-term measures to see emissions peak as soon as possible and reach the IMO's 40% carbon-intensity reduction target in 2030

These must target existing vessels and ships built by 2030. Only adjustments to the IMO's Energy Efficiency Design Index (EEDI) requirements are likely to be ready in time, 2022 at the earliest. Given a ship scrapping rate of 3% per year, about 40% of emissions in 2030 will be from ships built in 2022–2030.

Given the usual timeframe for developing new regulations, it is unlikely that any other requirement can be in place before 2023. From that date, further regulation may be based on input from the fourth IMO GHG study, and from fuel consumption data collected by the data collection system mandated by MARPOL Annex VI. The key will be to address existing ships, and to further improve energy-efficiency requirements for newbuilds. The IMO is looking at the following key measures and ideas:

- Further improvement of the existing energy-efficiency framework with a focus on the EEDI and IMO's Ship Energy Efficiency Management Plan.
- Development of technical and operational energy-efficiency measures for both new and existing ships, including consideration of indicators.
- Consideration and analysis of the use of speed optimization and speed reduction.

Medium-term and long-term measures to reach the 70% carbon intensity and 50% absolute emission reduction in 2050

In the medium and long term, large-scale use of carbon-neutral fuels is required. These are unavailable in large quantities today. Regulation for individual ships is needed to force implementation as these fuels are not expected to be competitive, at least in the first years. Supportive policy is required to promote and develop them to the point where they are available, and at acceptable prices.

In 2050, more than 70% of the fleet will have been built since 2030, after which date ships will have a larger impact on emissions levels in 2050, and extensive retrofits of engine or fuel systems should be avoided.

Standards based on lifecycle assessment will be needed to evaluate the carbon intensity of fuels. This will enable biofuels and synthetic fuels to be accounted for as carbon-neutral. Such standards will prevent use of zero-carbon fuels made by carbon-intensive processes; hydrogen produced from natural gas, for example.

The IMO is also considering new emission-reduction mechanisms, possibly including market-based measures.

4.6 EMERGING ENVIRONMENTAL ISSUES

Several environmental issues are under consideration at the IMO and domestically in various countries. They include topics such as plastics, pollution from ships, the impact of underwater noise on cetaceans, particle emissions, hull biofouling, and banning heavy fuel oil (HFO) in the Arctic. New Zealand introduced biofouling regulations in May 2018. The IMO is looking at plastics and a potential ban on HFO in the Arctic. In our view, there is a distinct possibility that most, if not all, of these issues will become subject to further domestic or international regulations sometime in the next decade.

4.7 CYBER RISK AND SECURITY

Recent years have brought rapid growth in the reach and complexity of cyber attacks in the maritime industry. Cyber risk and security have become a concern, and should be considered as integral parts of overall safety management in shipping and offshore operations.

With the increasing use of systems with embedded software, cyber security is becoming critical not only for data protection, but also for reliable operations. It is not just a matter of firewalls and antivirus software; up to 90% of all cyber-security incidents can be attributed to human behaviour. Phishing and social engineering, unintentional downloads of malware, and other threats, are common issues. Most crews and onshore staff are insufficiently prepared for handling cyber attacks, resulting in behaviour that fails to contain the threat. The issues need to be addressed in a holistic approach that looks at systems, software, procedures, and the human factor.

With increasingly complex control systems and software on board, managing cyber risks also includes addressing weaknesses in software. This typically stems from misconfiguration of equipment and software, as well as from software design or updates containing undetected weaknesses due to insufficient verification and validation.

IMO has developed a guideline providing high-level recommendations on maritime cyber-risk management (MSC-FAL.1/Circ.3, July 2017). As a non-mandatory requirement, it recommends that cyber risk is addressed in safety management systems after 1 January 2021.

“ With the increasing use of systems with embedded software, cyber security is becoming critical not only for data protection, but also for reliable operations.

4.8 AUTONOMOUS SHIPS

Autonomous and unmanned surface ships (smaller ships and navy vessels) have been in use for some years, but with exemptions from international maritime regulations. There are currently several planned projects with larger autonomous ships (unmanned and remotely-controlled). These are all in national waters and national authorities will allow them to sail as trials.

The IMO has been conducting a scoping study since 2017 on international regulations. Due for completion in 2020, the study is intended to identify 'showstoppers' for autonomous ships. Further scoping is needed on the various international conventions as this work is in its early stages.

The amendment of current instruments, or the development of new ones, will begin when scoping is complete. Bear in mind, however, that it took 17 years from the first LNG-fuelled ship sailing in national Norwegian waters until the IMO's International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels entered into force. Consequently, it may be optimistically assumed that international regulations for autonomous ships could be in place by 2035.

That said, some autonomous ships may be sailing in national waters under national requirements during the next decade.

4.9 STAKEHOLDER EXPECTATIONS

Irrespective of the regulatory environment, companies and the public sector are attempting increasingly to 'green' their value chains, reducing their carbon footprints. This is driven by factors such as consumer preferences and pressure from investors, non-governmental organizations, politicians, and the general public.

Adopting higher standards could increase visibility and represent a competitive advantage. We are already seeing stakeholders in the maritime industry heightening their focus on climate concerns. In one example, public procurement of ferry services in Norway now requires low- or zero-emission technology. Finance-sector requirements on climate-risk assessment and disclosure may become common in a few years. If so, carbon performance and climate-risk exposure will be required information.

In recent decades, sustainability has changed from being a subject discussed by non-governmental organizations and academics to become a key topic in boardrooms and the financial media. Achieving long-term value for shareholders and stakeholders through sustainable environmental, social, and governance measures is now a central focus for many companies.

In 2015, the UN adopted the 2030 Agenda for Sustainable Development, a global framework that includes an ambitious set of 17 Sustainable Development Goals (SDGs) and 169 associated targets. The goals and targets will stimulate action towards 2030 in areas of critical importance for people, the planet, and prosperity. The SDGs present an extraordinary opportunity for companies to align strategies and business models with global sustainable development needs. As a global industry, shipping has a critical role to play in meeting many of the goals (DNV GL, 2017e).

For the shipping industry, it is expected that the significance of sustainability challenges will increase over the next decades. The recent international agreements concerning reduction of GHG emissions, combined with increased local, national, and regional focus on harmful local emissions, will place environmental sustainability high on the agenda.

Shipping companies have an opportunity to respond strategically to these signals and create business benefit and value. The successful implementation of a sustainability strategy in shipping will require measuring many relevant aspects and applying new technologies and practices for improving performance and reducing footprint and risks. This is reflected in chapter 8 of this report, where ship and fleet performance is evaluated for various alternative fuels and technologies.

“The SDGs present an extraordinary opportunity for companies to align strategies and business models with global sustainable development needs.


HYDROGEN
ENERGY STORAGE

CHAPTER 5

FUEL & TECHNOLOGY OUTLOOK

5 FUEL & TECHNOLOGY OUTLOOK

Reduction of greenhouse gas (GHG) emissions will be the main challenge for shipping in the next decades. The IMO target for shipping to reduce GHG emissions by at least 50% of 2008 levels by 2050 is ambitious.

In addition to energy-efficiency measures, reaching the IMO target for reducing GHG emissions from shipping will most likely require widespread uptake of fuels with a high GHG-reduction potential; for example, bio-fuels, electricity, synthetic fuels, electrofuels[4], and non-carbon-based fuels. This will fundamentally change how ships are designed, operated, and fuelled.

A range of alternative fuels and technologies are available for ships to reduce CO_2 emissions. Their potential for this purpose varies widely, depending on the primary energy source, the fuel processing, the engine type/converter, and the supply chain (Figure 5.0.2). Alternative fuels that expend a lot of energy and produce extensive emissions in their production and processing phases are likely to be expensive and to have high lifecycle-GHG emissions. Their cost could also be impacted substantially by future GHG and environmental regulations. Such energy-intensive fuels will require access to low-price renewable energy to be competitive.

In this chapter, we describe a selection of carbon-neutral fuels that can be crucial to achieving the IMO targets (ection 4.5) when combined with important energy-efficiency measures (section 5.2). Carbon-neutral fuels refer to a variety of energy fuels or energy systems that have no net GHG or carbon footprint. The term covers fuels with no carbon emissions at the stack, such as hydrogen (H_2) and ammonia (NH_3), provided that the energy used for producing them emits no GHGs. Examples include nuclear, renewable, or using carbon capture and storage (CCS). It also covers fuels with carbon emissions at the stack, such as biofuels, provided that the carbon contained in the fuel is sustainably sourced and part of the natural carbon cycle, so that combustion does not lead to added CO_2 in the atmosphere. In addition, energy used for producing such a fuel must, itself, be without GHG emissions.

We also highlight the main barriers to widespread implementation of new technologies and fuels (section 5.3), and propose a structured approach to compare and rank fuels (section 5.1.7).

We focus on novel solutions. Information on more mature fuels, such as liquefied natural gas (LNG), liquid petroleum gas (LPG), and methanol is available in several recent reports (OECD 2018; IEA 2014; DNV GL 2014b; DNV GL 2017a; DNV GL 2018f) and summarized in the text box on page 69–70. Information about different energy-efficiency measures can be found in various studies (Buhaug et al, 2009; IMO, 2011; Eide et al, 2011, 2013; DNV GL 2017i; Smith et al, 2016; OECD, 2018).

4 Electrofuels is an umbrella term for carbon-based fuels such as diesel, methane, and methanol, which are produced from CO_2 and water using electricity as the source of energy

LIQUEFIED NATURAL GAS, LIQUID PETROLEUM GAS, AND METHANOL

Liquefied natural gas (LNG): the main component of LNG, methane (CH_4), has more or less the same composition as the natural gas used in households, for power generation, and in industrial processes. Because the boiling point of LNG is approximately -163°C at 1 bar of absolute pressure, it must be stored in insulated tanks made of cryogenic materials.

- The maximum achievable reduction in CO_2 emissions during combustion of LNG is 25%, when compared with using heavy fuel oil (HFO). Accounting for methane release ('slip'), the GHG saving may be lower, or even negative, depending on engine technology.
- In practice, when considering the complete lifecycle for LNG, the GHG savings amount to roughly 0–18% compared with traditional marine fuels.
- LNG significantly reduces or eliminates emissions of sulphur oxide (SOx) and particulate matter (PM). The reduction of nitrogen oxide (NOx) emissions depends on engine technology, but is typically well within the strictest International Maritime Organization (IMO) NOx Tier III requirements in Emission Control Areas (ECAs).
- The volume of a tank of LNG is typically twice to three times as big as one with the energy equivalent amount of oil-based fuel (Figure 5.0.1)

Liquid petroleum gas (LPG): any mixture of propane and butane in liquid form can be called LPG. In the US, the term LPG is generally associated with propane. Propane is a gas under ambient conditions, but has a boiling point of -42°C. Consequently, applying moderate pressure allows it to be handled as a liquid at room temperature. At pressures above 8.4 bar at 20°C, propane is a liquid. Butane can take two forms, n-butane and isobutane, with boiling points at -0.5°C and -12°C, respectively. Since both isomers have higher boiling points than propane, they can be liquefied at lower pressures.

- LPG combustion results in CO_2 emissions approximately 16% lower than those of HFO.
- The combination of low production and combustion emissions yields an overall GHG- emission reduction of about 17% compared with HFO or marine gasoil (MGO).
- LPG significantly reduces or eliminates SOx and PM emissions. The level of reduction of NOx emissions depends on the engine technology.
- The volume of a tank of LPG is typically twice to three times as big as one with the energy-equivalent amount of oil-based fuel (Figure 5.0.1).

There are two main sources of LPG; as a by-product of oil and gas production or as a by-product of oil refining. It is also possible to produce LPG from renewable sources; for example, as a by-product of renewable diesel production.

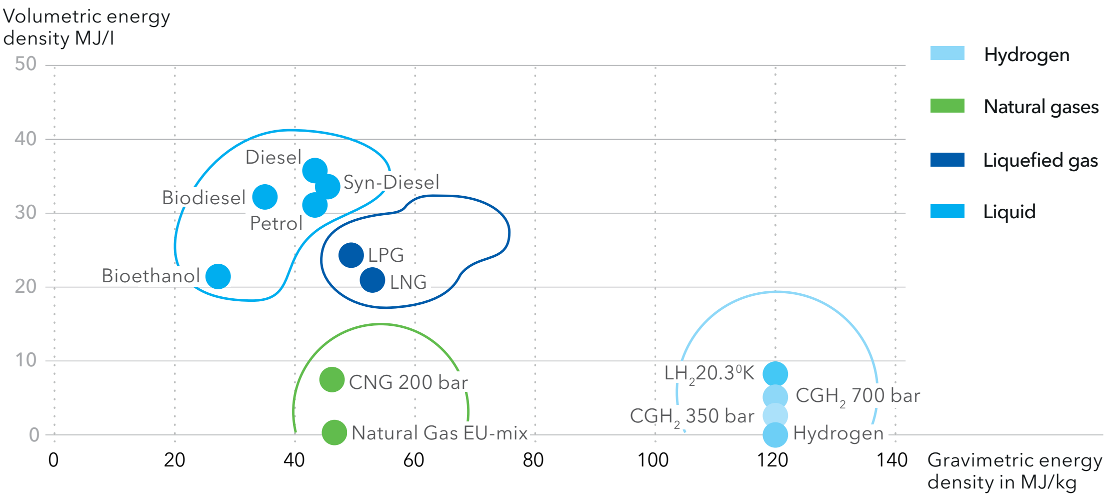
Methanol: with its chemical structure CH_3OH, methanol is the simplest alcohol with the lowest carbon content and highest hydrogen content of any liquid fuel. It is a basic building block for hundreds of essential chemical commodities and is also used as a fuel for transport. It can be produced from several different feedstock resources, like natural gas or coal, or from renewable resources, such as biomass, CO_2, and hydrogen.

Methanol is a liquid from 176–338 Kelvins (-93°C to +65°C) at atmospheric pressure.

- Using methanol in an internal combustion engine reduces CO_2 emissions by approximately 10% compared with oil. The exact value may differ, depending on whether the comparison is with HFO or distillate fuel.
- When considering the complete lifecycle, including production of the fuel from natural gas, the total CO_2 emissions are equivalent to, or slightly higher than (in the order of 5%), the corresponding emissions of oil-based fuels.
- The lifecycle emissions of methanol from renewable sources (biomass) are significantly lower than from production from natural gas.
- Using methanol virtually eliminates SOx emissions and meets the IMO sulphur emission cap. It is also expected that PM emissions will be significantly lower. The reduction in NOx emissions depends on the technology used.
- Methanol fuel tanks are typically twice the volume of oil tanks with the same energy content.

FIGURE 5.0.1

Energy density of fuels



Source: Shell hydrogen study 2017

5.1 CARBON-NEUTRAL FUELS

A wide range of alternative fuels can contribute to reducing CO_2 emissions, though applicability, cost, and availability currently restrict their use. The potential for alternative marine fuels will depend on factors related to meeting emission and safety requirements, physical and chemical characteristics, availability, cost, safety, and local and global environmental footprint (Chryssakis & Stahl 2013; DNV GL, 2014a, 2015, 2017a). There is no 'magic bullet' solution. In most cases, selection will be based on a compromise between benefits and drawbacks of various fuel options (DNV GL, 2015).

For alternative fuels, it will be important to have a lifecycle perspective that includes emissions arising from production and transport of the fuel (e.g., Bengtsson et al, 2011; DNV GL, 2014a, Gilbert et al, 2018), avoiding carbon- and energy-intensive solutions. A distinction should be made between primary-energy sources/feedstocks and energy carriers for use on board ships (Figure 5.0.2). Examples of the first category include fossil (e.g., oil, gas, coal), bio-derived (e.g., waste oil, wood, palm oil), renewable (e.g., wind, solar, hydropower) and nuclear sources. Examples of energy carriers for use on board include the following:

- Fuel oil (HFO, vegetable oils) and diesel (e.g., MGO, biodiesel)
- Gases (e.g., LNG, LPG, liquefied biogas (LBG), dimethyl ether (DME), H_2, and NH_3
- Alcohols (e.g., methanol, ethanol)
- Solid fuels (e.g., coal)
- Electricity.

To be carbon-neutral, zero-carbon fuels such as H_2, NH_3, electrofuels, and electricity must themselves be produced with zero emissions, either from renewable energy sources or from fossil sources with CCS. A future option for carbon-based fuels could be to install CCS on board ships. Such a system has been investigated in a Eurostar project. The results showed that the concept was technically feasible and capable of reducing CO_2 emissions by 65%[5]. High cost and space requirements will probably limit its applicability, however.

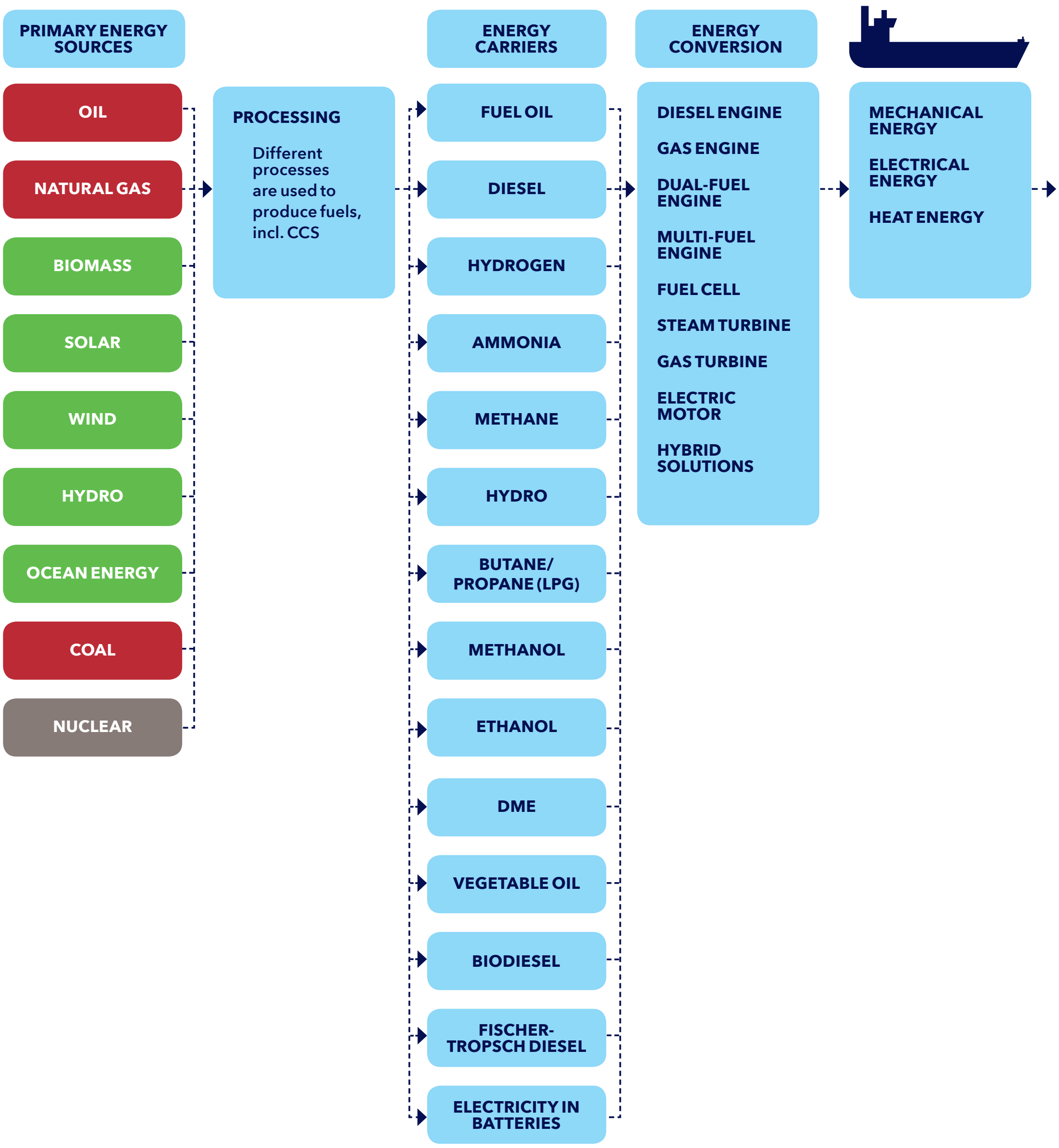
Handling different fuels will require different propulsion systems (energy converters). Alternative propulsion systems for shipping include gas, dual, multi-fuel engines, marine fuel cells, battery electric propulsion systems, and gas and steam turbines. LNG was introduced as ship fuel (other than for LNG carriers) around 2000. Although it has mainly been used by small-sized short-sea ships, there have been recent orders for large vessels selecting LNG as a fuel. A few LPG-fuelled vessels, as well as methanol- and ethane-fuelled ships, have also been introduced. Two-stroke dual-fuel engines have increased fuel flexibility significantly because they may use fuels such as methanol, ethanol, and LPG, in addition to LNG and HFO/MGO[6]. Promising steam- and gas-turbine concepts, are also being considered. Marine fuel cells are emerging, providing a higher efficiency, and thereby lower fuel consumption and associated emissions, compared with combustion engines.

While focusing on GHGs, it is vital to recognize the footprint of other types of emission from alternative fuels and technologies; mainly NOx, SOx, and PM.

5 https://www.psenterprise.com/news/news-press-releases-dnv-pse-ccs-report
6 https://marine.mandieselturbo.com/docs/librariesprovider6/technical-papers/the-man-b-amp-w-duel-fuel-engines-starting-a-new-era-in-shipping.pdf?sfvrsn=2

FIGURE 5.0.2

Simplified illustration of the chain from energy resources to mechanical energy for marine propulsion (inspired by Brynolf, 2014).

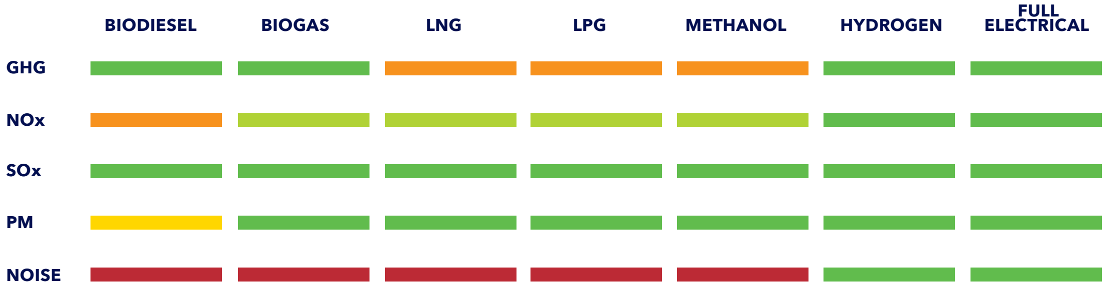


These impacts can be both positive and negative, and vary between fuels and technologies. Direct emissions from the ship (tank-to-propeller) for selected fuels/energy carriers vary as indicated in Figure 5.0.3. For example, using LNG as a marine fuel significantly reduces SOx and PM emissions, potentially cuts GHG emissions by 10–20%, and diminishes emissions of NOx by 85–90% in the case of low-pressure engines. Among the fuels shown here, only electricity and H_2 (marine fuel cells) deliver zero tank-to-propeller emissions.

In the following sections, we describe fuels offering high GHG-reduction potential, and address the current uptake, maturity, availability, and cost aspects. These fuels, as well as currently-used fossil fuels are employed as input to our outlook on world fleet energy use (chapter 6).

FIGURE 5.0.3

Diverse fuels and technologies differ in their potential to reduce various components of tank-to-propeller emissions from ships. The reductions illustrated are relative to using traditional fuels (HFO/MGO). Green indicates high potential. Red indicates low potential.



5.1.1 ELECTRIFICATION

On an all-electric ship, all power for the propulsion and auxiliaries comes from batteries charged from an on-shore electric grid while at berth. However, it is likely that most electric-powered ships will be built as hybrid-electric. For these, the amount of electric energy supplied from shore varies greatly and can often be zero (charging and discharging only to the on-board power system). The amount depends on operational requirements for the ship, and on the on-shore power available. This section will focus on electrification and charging from shore, and section 5.2.3 will further detail potential benefits and opportunities for hybrids.

Electrification of ships will reduce the tank-to-propeller emissions according to the degree of electrical energy used. The reduction will clearly be up to 100% when all ship operations are powered by electricity. To obtain true zero emission, the electricity must itself be produced by a zero-emis-

FERRIES TO THE FUTURE

The first full-electric car ferry, MF Ampère, has been in service between Lavik and Oppedal on the west coast of Norway since 2015[7] The next all-electric car ferry started operating between Pargas and Nagu in Finland in 2017[8] About 40 car ferries, hybrid-electric solutions with a very high share (90–100%) of electrification, are currently contracted for future ferry contracts in Norway, and several more are anticipated. The technological solutions are, with few exceptions, hybrid-electric with diesel/gas engines as back-up. This provides flexibility for future use on other routes/trades with different premises for electrification. The back-up provision covers, for example, charging system down-time and yard visits. The Norwegian car ferries typically operate at fjord crossings over distances up to 10 kilometres and consume 200–1,000 kilowatt hours (kWh) of energy per trip. The ferries are mainly charged on each docking.

Two of HH Ferries' four ferries operating between Helsingborg, Sweden, and Helsingör, Denmark, have been converted to all-electric ships[9]. This combined installation of 8,320 kWh battery capacity will more than halve total GHG emissions for the ferry link.

The innovative hybrid-electric sightseeing ship, Vision of the Fjords, which can carry 400 passengers, was introduced by the Norwegian marine transportation company The Fjords in 2016[10]. An all-electric passenger ship, Future of the Fjords, was delivered to the same operator in April 2018[11].

7 Teknisk ukeblad: http://www.tu.no/artikler/denne-fergen-er-revolusjonerende-men-passasjerene-merker-det-knapt/222522

8 Teknisk ukeblad: http://www.tu.no/artikler/eksporterer-batteriteknologi-til-finland/278058

9 https://new.abb.com/marine/references/hh-ferries

10 https://www.tu.no/artikler/ingen-har-noensinne-bygget-et-slikt-skip/358454

11 https://www.skipsrevyen.no/helelektriske-future-of-the-fjords-klar-i-april-2018/

sion technology; for example, from renewable energy sources, nuclear, or by using CCS.

The amount of electrical energy which can be transferred from shore to ship depends on several factors, including on-shore electric grid capabilities; battery-charging facilities; and time spent alongside. Together with the installed battery capacity on board the ship, these define the potential of electric operations. The short-sea shipping segment currently has the highest potential for electric operations. Within this segment, ships on short routes, with regular schedules and long contracts, have the greatest potential of all. Ships operating on routes with frequent port calls may also utilize more on-shore electricity. Deep-sea shipping looks unlikely to exhibit much electrification any time soon, but such vessels can already install batteries for energy optimization during cruising, or as a low-emission solution when operating in sensitive areas or near harbours.

Figure 5.1.1.1 illustrates the rapid development of all electric and battery-hybrid ships (Maritime Battery Forum, 2018). More than 200 all-electric and battery-hybrid ships are currently operating or on order. That said, installing battery systems on board, including replacements, after typically 8–10 years, is significantly costlier than for traditional diesel engines. In addition, infrastructure investment is required to provide electricity from land. There are large geographical variations in electricity prices and in suitable infrastructure. It will likely be challenging to pay back investment through only the price difference between electricity and marine fuels.

FUTURE DEVELOPMENTS

Although the core technology and architecture of the lithium-ion battery have not changed drastically since it entered the market almost 30 years ago, development has greatly increased its capability. Improved knowledge and understanding of the electrochemical processes have led to significant advancements in design and chemical engineering, particularly for selecting cathode materials. Opportunities for advancement in manufacturing processes have also yielded performance benefits.

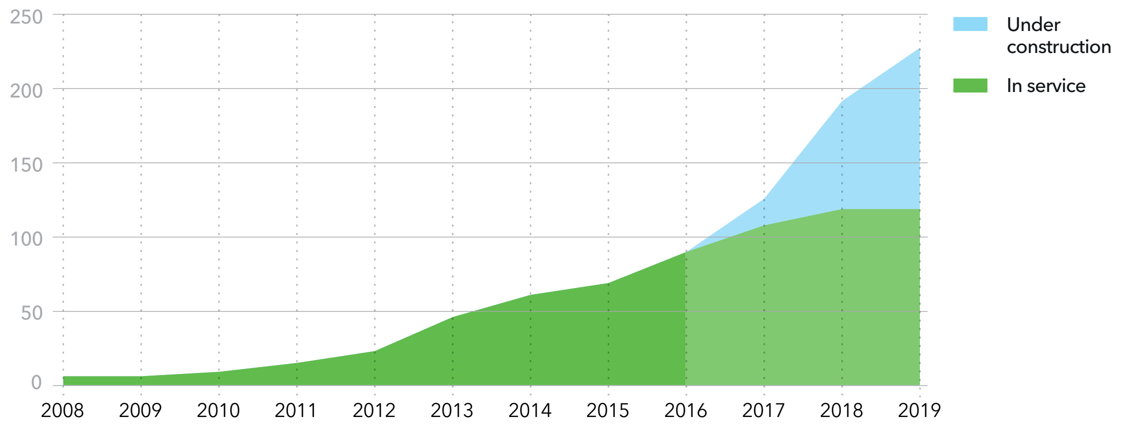
Aside from these incremental improvements to the core technology, new elements are now being used on the anode side. Silicon-based anodes are now found in commercial products, bringing benefits through energy density and lower costs. Products with titanate-based anodes are also available and offer significantly higher power and battery lifetimes.

On the immediate horizon, there will most likely be more changes to the cathode material, but these are unlikely to vary significantly from current technology. Cathodes made using cobalt-based

FIGURE 5.1.1.1

Development of all-electric and battery-hybrid ships currently operating or on order (Maritime Battery Forum, 2018)

Units: Number of ships



chemistries presently comprise most of the market; specifically, nickel-manganese-cobalt or nickel-cobalt-aluminium. Cobalt is the costliest item on the lithium-ion battery materials list, so reducing its use is of keen interest. Such alternatives would utilize higher amounts of nickel. This would yield improvements to energy density and reduce cost, but would likely mean sacrifices on cycle life and thermal stability. Like most aspects of lithium-ion technology development, the motivation comes primarily from the automotive sector and consumer electronics. Consequently, the direction of technology development is not always towards systems ideally suited to maritime applications. However, as cost is the primary driver in all markets, these technologies, as they progress, willmost likely find their way into maritime systems, particularly as maritime customers maintain pressure on costs.

Further down the line, but currently on the laboratory bench, is perhaps the most significant potential change in the fundamental architecture of the lithium-ion battery: solid-state electrolytes. Lithium-ion batteries as we know them must use a special kind of liquid electrolyte, which is flammable. Solid state in this context refers to the use of glass-like materials in place of the liquid electrolyte. This would eliminate much of the safety concerns presently surrounding the technology. However, it is still unclear what other performance benefits may be realized when the battery cell is engineered to meet the challenges and potential benefits of solid-state electrolyte. The technology must also overcome manufacturing challenges and be able to offer solutions that are cost competitive with current forms of lithium-ion, which have seen a significant cost decrease in the past few years.

Power electronics are vital to making batteries work. They also account for a significant amount of volume, weight, and cost, with prices often similar to those for the batteries they support. Technological advancements in this area are moving slowly, but significant benefits could be realized through alternative approaches to the fundamental architecture used. This could involve greater use of direct current (DC) power distribution systems, a development already in operation. Similarly, battery-charging technologies and hardware are currently receiving much focus and development effort. Fully automated systems and wireless (induction) charging are already in the market. Although their capabilities can be expected to keep improving, it is unclear whether any game-changing technology is on the horizon. Because charging systems are already capable of high power, limitations due to charge time come primarily from the battery system itself; hence, advancements in battery technology will be a key enabler of charging capability.

DNV GL first issued Class Rules for the use of lithium-ion batteries on ships in 2012[12]. These rules cover fundamental aspects, such as location, fire protection, ventilation, and other key aspects for integrating a battery system. Specific testing requirements have also been developed to ensure the level of safety required in the maritime environment. DNV GL continues to push the level of safety of these systems by leading the currently ongoing Maritime Battery Safety Joint Development Project, in collaboration with representatives from the entire maritime battery-vessel value chain, including the authorities.

12 https://www.dnvgl.com/maritime/dnvglrules/innovate.html
https://rules.dnvgl.com/docs/pdf/DNVGL/RU-SHIP/2018-01/DNVGL-RU-SHIP-Pt6Ch2.pdf

5.1.2 BIOFUELS

Biofuels are derived from converting primary biomass or biomass residues into liquid or gaseous fuels. Many processes exist for producing conventional (first-generation) and advanced (second- and third-generation) biofuels. They involve a variety of feedstocks and conversions, producing a range of energy carriers including diesel, CH_4, and methanol.

Biofuels do not reduce carbon emissions directly. Instead, lower GHG contributions are normally attributed to biofuels compared with fossil fuels. CO_2 from the combustion of biological material leads to added CO_2 in the atmosphere in the same way as fossil fuels. However, bio-CO_2 is traditionally considered to be part of the CO_2 that would otherwise have been in circulation through natural cycles, although this depends on the timeframe over which reduction targets and climate impacts are considered.

The emission-reduction potentials of biofuels vary widely depending on the feedstock, the generation method, the engine type/converter, and the supply chain. CO_2 reductions of up to 80–90% are possible for certain types of biofuel when calculated on a lifecycle basis. The highest reduction potential is reported for advanced biofuels.

Biofuels can be blended with conventional fuels or used as drop-in fuels substituting for conventional fossil fuels. Advanced biofuels are mostly compatible with existing infrastructure and engine systems, although modifications are sometimes required. The operational costs for biofuel systems, excluding fuel costs, are expected to be comparable with those for HFO/MGO-fuelled vessels. However, since biofuels, and especially advanced biofuels, will be more expensive than fossil fuels, the associated fuel costs are expected to be higher.

Land-use aspects of biofuel production are frequently cited as an obstacle. This comes largely from looking at the effects on the overall carbon budget when comparing the outcomes of allocating land for growing crops for biofuel production and alternative uses, primarily food production or biodiversity. This is an issue in the case of first-generation biofuels. Later types of biofuel, and advanced biofuels based on different bio-waste streams, are considered more sustainable, although concerns persist about the overall sustainability of biofuels. These include environmental and socio-economic issues, and the carbon footprint from producing and transporting biofuels must also be considered.

The most promising biofuels for ships are biodiesel (for example, hydrotreated vegetable oil, HVO); biomass-to-liquids (BTL); fatty-acid methyl esters (FAME); and, liquefied biogas (LBG). Biodiesel is most suitable for replacing marine diesel oil or marine gas oil. LBG is the best replacement for LNG. Straight vegetable oil (SVO) can substitute HFO. Global production data indicate that 32 million tonnes per year (Mt/yr) of biodiesel and 170 Mt/yr of SVO are produced (Maritime Knowledge Centre, TNO & TU Delft, 2017).

Renewable HVO biodiesel is a high-quality fuel in which the oxygen has been removed using H_2, which results in long-term stability. It is compatible with existing infrastructure and can be used in existing engines, subject to approval by the manufacturer. The GHG emissions from a lifecycle perspective have been assumed to be about 50% less than for diesel, and PM emissions are also lower. There are no sulphur emissions. NOx emissions may also be somewhat reduced, but non-compliant with IMO Tier III requirements without additional NOx-abatement technology.

Since 2006, several demonstration projects have tested the technical feasibility of various FAME biodiesel blends in shipping. Challenges reported for FAME biofuels include fuel instability, corrosion, susceptibility to microbial growth, and poor cold-flow properties. Some ferries operating in Norway have recently started to use HVO biodiesel.

The ISO 8217:2017 standard does not allow for blending of FAME with regular marine distillate or residual fuels, but the sixth edition introduces the DF (Distillate FAME) grades DFA, DFZ and DFB. These grades allow up to 7% FAME content by volume (ISO, 2017). Other than this allowance, these grades are identical to the traditional grades for all other parameters. Such limitations do not apply to HVO, which is classified as DM (distillate) under the ISO standard, under certain conditions.

FUTURE DEVELOPMENTS

In most cases, advanced biofuels will be more expensive than fossil fuels. The potential for reducing biofuel costs is expected to be higher for second-generation fuels than for first-generation fuels (Festel et al, 2014; Van Eijk et al, 2014). IIn 2017, the International Energy Agency (IEA) estimated the price of second-generation biofuels, taking into account technical development and biomass-derived products (IEA, 2017).

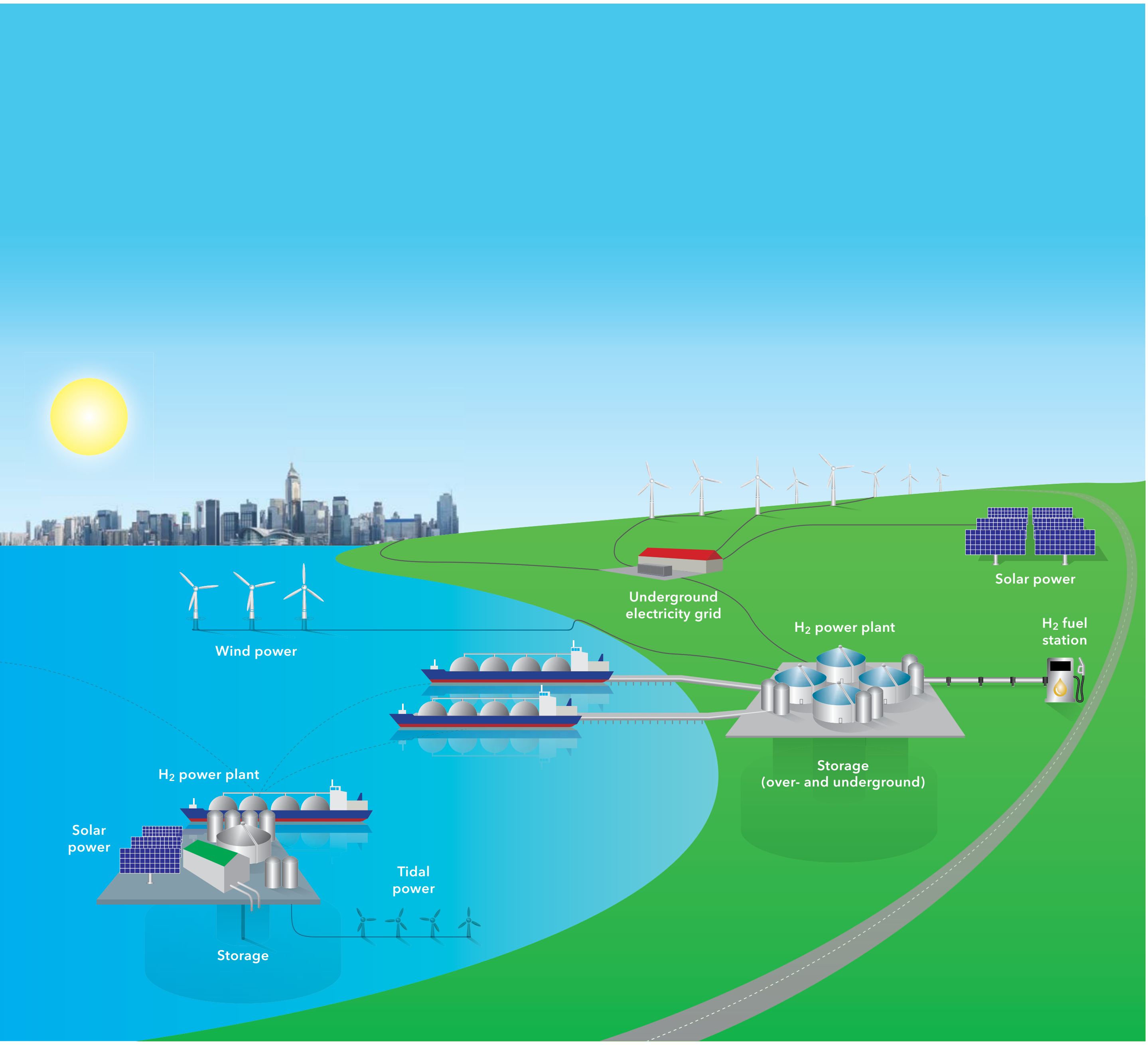
Third-generation, algae-based biofuels are still at the research and development stage, but were tested in 2011 on the container ship Maersk Kalmar. The US navy has also conducted some testing.

5.1.3 HYDROGEN

Hydrogen is an energy carrier. It is possible to obtain zero-emission ship solutions if H_2 is used in marine fuel cells. If the gas is produced from renewable energy sources, or from natural gas with CCS, zero-emission value chains can be created. Even though its lifecycle emissions may be zero, it is important to note that producing H_2 for use as a fuel requires considerable energy. Consequently, even if the energy efficiency of H_2 converted to electrical energy in fuel cells may be high (see below), the lifecycle energy efficiency is significantly lower due to the energy loss in H_2 production.

Fuel cells were previously used mainly for special purposes, such as in outer space and submarines. The technology has matured and is in commercial use in applications such as forklifts, standby generators/uninterruptible power supply, and combined heat and power systems. Fuel cells have advanced to near commercial use for cars, buses, trucks, and rail applications. They provide higher efficiencies and thereby reduce fuel consumption and emissions. Depending on fuel-cell type, electrical efficiency of 50–60% is expected, which is slightly higher than marine diesel generators (DNV GL 2017d). With heat recovery, the efficiency can increase to 80%. Noise and vibrations are insignificant, and fuel cells are also expected to require less maintenance than conventional combustion engines and turbines.

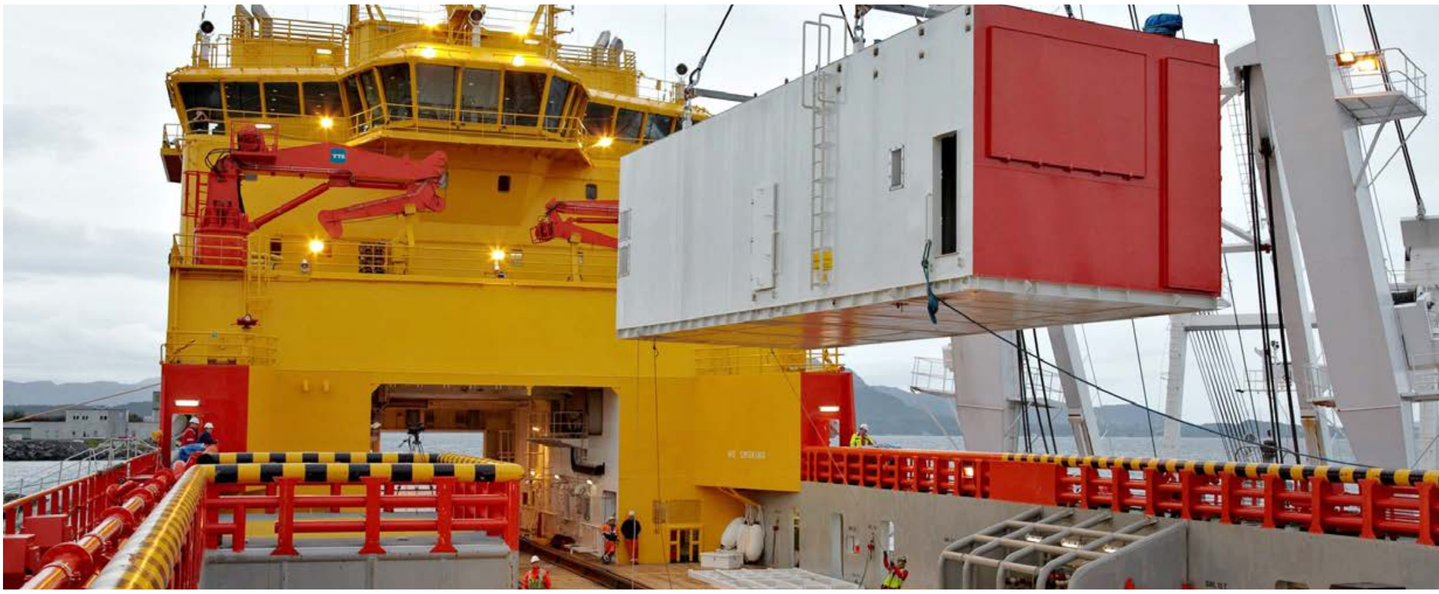
The cell converts the chemical energy of the fuel to electrical power through electrochemical reactions. For simplicity, the energy conversion can be considered as being similar to that in batteries, but with continuous fuel and air supplies. Different fuel-cell types are available, and their names reflect the materials used in the electrolyte membrane. The properties of the membrane


Underground
electricity grid
Solar power
Wind power
H2 power plant
H2 fuel
station
Storage
(over- and underground)
H2 power plant
Solar
power
Tidal
power
Storage

affect the permissible operating temperature, the nature of electrochemical reactions, and fuel requirements. DNV GL (2017d) evaluated seven fuel-cell technologies and concluded that the solid-oxide fuel cell, the proton-exchange membrane (PEM) fuel cell, and the high-temperature PEM, are the most promising for marine use. Depending on fuel-cell type, they can also be powered by carbon fuels such as natural gas, an option that, in particular, reduces NOx, SOx, and PM emissions.

Driven by the expected improvement in performance and efficiency, fuel cells for ships have become a subject of development and large-scale testing during the last decade, although their application in shipping is still in its infancy. Several demonstration projects have been conducted, some of which are described in DNV GL (2017d). The FellowSHIP project, which was managed by DNV GL, was the first large-scale installation and demonstration of a fuel cell in a merchant vessel, the offshore supply vessel, Viking Lady (DNV 2012a). By 2012, the project had reached 18,500 hours operation of its 320 kW LNG-fuelled molten-carbonate fuel cell (DNV GL, 2017d). A dynamic and multi-dimensional model of the molten-carbonate fuel cell was also developed (Ovrum and Dimopoulos, 2011). The model was calibrated and validated with measured performance data from the prototype installation. The FellowSHIP project also tested hybrid energy-storage/battery systems (e.g., DNV 2013).

Fuel cells are currently an expensive option compared with traditional power, due to significantly higher investment and operational costs; for example, high fuel price, fuel storage costs, and a need for stack replacement. The cost of H_2 produced by electrolysis is closely related to the price of electricity. When produced by steam methane



reforming, the cost is closely related to the price of gas, as well to the scale of the production plant. Currently, H_2 produced by natural gas reforming, and as a by-product from industrial processes, is typically expected to be cheaper than H_2 from electrolysis. If using natural gas, the resulting carbon must be captured using CCS for the resultant H_2 to be considered a zero-emission fuel.

The fuel distribution chain is another significant cost element. Production and distribution costs vary greatly with local conditions[13] In the near future, the typical fuel cost of H_2 is expected to remain higher than the cost of the fossil alternatives.

More than 50 Mt/yr of H_2 are produced globally; roughly equal to the energy content of 150 Mt of ship fuel. Nearly all H_2 is produced from natural gas. But as it can also be produced by electrolysis of water, there are no major limitations to production capacity, except the energy source, that could restrict the amount of H_2 available to the shipping industry.

FUTURE DEVELOPMENTS

The Norwegian Public Roads Administration has initiated a development project aiming to have the first hybrid H_2 fuel cell-electric ferry in commercial operation in 2021[14]. Two vessels are to be built for Royal Caribbean Cruise Lines featuring a new generation of cruise ships with LNG-fuelled propulsion and H_2 fuel cells for powering the ship's hotel functions. In addition, one hydrogen-powered ferry will be built in Scotland and one in California[15].

When battery electric solutions become very large due to high energy demand, or suffer from insufficient charging capacity/availability, H_2 might contribute to more weight-efficient and cost-efficient solutions than battery electric solutions alone. Hydrogen can be used most efficiently in fuel cells, but it is also possible to use it in adapted combustion engines. Some initiatives are considering blending H_2 with other fuels to improve combustion and emission properties. It has also been reported that an electrolysis system for producing H_2 is being tested on two inland water barges (Zincir & Deniz, 2018). Hydrogen is produced on board by electrolysis of purified water, and there is no need for H_2 fuel bunkering. Testing is meanwhile underway for 100% H_2 fuelling of a combustion engine[16]; some combustion products, such as NOx, will arise from the combustion process when H_2 is used in this way.

Hydrogen offers almost three times higher energy density on a weight basis than commonly used liquid hydrocarbon fuels (Figure 5.0.1). However, there are challenges to find volume-efficient ways to store hydrogen. Most commonly, it is stored either as a compressed gaseous hydrogen (CGH)

13 Indicated production cost range today from USD3.5–8.3 per kilogramme (/kg) for production by electrolysis, and from less than USD2/kg (e.g. https://idealhy.eu) up to more than USD6.5/kg for production from natural gas/biogas. Cost estimates typically include production, compression, storage and transport, and can include CCS, but typically not costs for liquefaction in the case of storage and transport of hydrogen as a cryogenic liquid. The price of electrolysers is expected to fall in the near future, reducing the CAPEX and consequently the production cost of hydrogen. Similarly, the growth in intermittent renewable energy supply is expected to be a source of cheaper hydrogen.

14 https://www.tu.no/artikler/skal-utvikle-verdens-forste-hydrogenferge-tre-rederier-kvalifisert/409140

15 https://lloydslist.maritimeintelligence.informa.com/LL1123165/US-to-develop-first-hydrogenpowered-ferry
https://worldmaritimenews.com/archives/255096/fergusonmarine-to-build-worlds-first-renewables-powered-hydrogen-ferry/

16 https://www.cmb.be/en/new/antwerp-maritime-group-cmb-pioneers-environmentally-friendly-shipping-the-hydroville-is-hydrogen-powered
http://www.cheetahmarine.co.uk/en/deliveries/worlds-first-hydrogen-powered-boat-smashes-targets
https://www.governmenteuropa.eu/hydrogen-powered-zero-emission-combustion-engine/86777/

or as cryogenic liquid hydrogen (LH). For storage of large quantities of H_2, it is possible to achieve lighter and more volume-efficient storage on board by using LH rather than CGH, to which storage pressures of 350–700 bar are commonly applied; for example, in hydrogen cars. The penalties with LH are the energy requirement for liquefaction (uses typically about 30% of the energy for liquefaction)[17,18], and the losses due to boiloff during fuel transfer and storage, and the need for well-insulated, purpose-made storage, tanks and equipment. The benefits of more volume-efficient transport can compensate for the liquefaction losses. A range of material-based H_2-storage methods are also being explored. This includes storage in metal hybrids, in liquid organic H_2 carriers, and in various sorbents. In some instances, other H_2-rich energy carriers, like NH_3 or methanol, are considered together with a reformer for end use in fuel cells.

Storage and bunkering of H_2 for use on ships will require specially-designed storage tanks and bunkering systems. Development of a bunkering infrastructure is therefore needed in parallel with the development of H_2 as a ship fuel.

Hydrogen and fuel cell-specific requirements are lacking and are currently not covered by the IGF Code. According to Part A of this Code, an Alternative Design approach must be carried out to demonstrate an equivalent level of safety.

DNV GL has issued Class Rules for Fuel Cell Installations (DNV GL, 2017d)[19]. These rules set requirements for fuel-cell power systems, as well as design principles for fuel-cell spaces, fire safety, and control and monitoring systems. There is currently limited experience with marine storage and use of H_2, but storage technologies are available from land-based applications.

5.1.4 AMMONIA

Safety and regulatory challenges and space/weight considerations related to storing large quantities of H_2 on ships have generated interest in exploring alternative H_2-based energy carriers. Ammonia (NH_3), sometimes called 'the other hydrogen', is carbon-free and liquefies at a higher temperature than H_2 (-33°C versus -253°C). Ammonia is over 50% more energy-dense per unit of volume than liquid H_2 (Maritime Knowledge Centre, TNO & TU Delft, 2017). Storage and distribution can therefore be easier than for hydrogen. A recent study claims that it can be less costly to use NH_3 for long-term storage of liquid H_2 (0.5 USD/kg for H_2 in NH_3 versus 15 USD/kg for H_2 stored as LH, when estimated for half-year storage)[19]. This indicates that there might be significant cost savings associated with storing LH as ammonia, including in ship applications. Costs and processing to make the H_2 available for use in fuel cells must be considered.

17 Source: 'Well-to-wheels analysis of future automotive fuels and powertrains in the European context', JRC Technical Reports (http://iet.jrc.ec.europa.eu/about-jec). Energy losses for liquefaction are reported to be in the range of 21–40%, with 30% considered a representative value for today's technology. Typically, current liquefaction plants are designed for minimal investment cost rather than minimal energy consumption.

18 Source: Integrated Design for Efficient Advanced Liquefaction of Hydrogen, http://idealhy.eu
Today's standard technology uses about 36% of the energy for liquefaction, but it is possible to design liquefaction plants where the loss is reduced by almost 50%.

19 https://rules.dnvgl.com/docs/pdf/DNV/rulesship/2011-07/ts623.pdf
https://rules.dnvgl.com/docs/pdf/dnvgl/ru-ship/2017-01/DNVGL-RU-SHIP-Pt6Ch2.pdf

20 IEA 2017, Producing ammonia and fertilizers: new opportunities from renewables, source: https://www.iea.org/media/news/2017/Fertilizer_manufacturing_Renewables_01102017.pdf

In addition to H_2 fuel cells, there are several fuel cells designed to use ammonia directly (Maritime Knowledge Centre, TNO & TU Delft 2017). It is reported that the first utilization of liquid anhydrous ammonia as a fuel for motor-buses took place in the 1940s, and that the bus fleet logged thousands of kilometers with no difficulties[21]. Combustion of ammonia is reported to have enhanced power output compared to traditional fuels and H_2 (Maritime Knowledge Centre, TNO & TU Delft, 2017). In 2007, a vehicle drove across America, from Detroit to San Francisco, powered by a mix of NH_3 and gasoline[22].

More than 170 Mt/yr of NH_3 are produced globally, most of it from natural gas. Ammonia's advantages as a storage technology may make it an option for transporting large amounts of energy over long distances from remote renewable sources.

FUTURE DEVELOPMENTS

Ammonia engines are being developed, and major industrial projects will soon demonstrate the environmental benefits of NH_3 in dual-fuel combustion[23]. The use of NH_3 gas as a fuel source in dual-fuel engine applications is a relatively novel idea, where it can be used as a substitute for natural gas. The first NH_3-specific maritime fuel data is expected be published by researchers in the UK this year, while the Japan 'Energy Carriers' programme expects to have results in 2020[24]. Studies have also started to investigate non-CO_2 emission levels when NH_3 is used as a fuel[25].

As for other energy carriers, the level of CO_2 emissions from producing NH_3 depends on the production path. Most NH_3 plants today are producing from 300,000 t/yr of NH_3 upwards, and production costs decrease significantly for larger plants. Ammonia can also be produced from naphtha, heavy fuel oil, and coal, but this will generate greater CO_2 emissions.

5.1.5 ELECTROFUELS

"Electrofuels" is an umbrella term for carbon-based fuels such as diesel, methane, and methanol, which are produced from CO_2 and water using electricity as the source of energy (Hansson & Grahn, 2016; Brynolf et al, 2018). Electrofuels are also known as e-fuels, power-to-gas/liquids/fuels, or synthetic fuels. The CO_2 can be captured from various industrial processes, the air, or seawater (Figure 5.1.5.1). This is referred to as carbon recycling, as carbon can be taken from industrial exhaust gases or even from ambient air. Electrofuels are carbon-neutral, if produced using nuclear power, renewables, or with CCS. The shipping company Stena Line has started to run on methanol and is considering e-methanol as a future renewable option.

Studies have assessed the potential role of electrofuels as marine fuel and reported that it is not unlikely that they will be able to compete with other fuel options in the shipping sector in the near term (Hansson & Grahn, 2016). They also report that H_2 is more cost-effective than e-methanol in the shipping sector, under the chosen assumptions.

21 https://www.agmrc.org/renewable-energy/renewable-energy/ammonia-as-a-transportation-fuel/

22 https://nh3fuelassociation.org/introduction/

23 http://www.ammoniaenergy.org/bunker-ammonia-carbon-free-liquid-fuel-for-ships/

24 http://www.hellenicshippingnews.com/the-maritime-industry-begins-assessment-of-ammonia-as-a-fuel/

25 http://www.hellenicshippingnews.com/the-maritime-industry-begins-assessment-of-ammonia-as-a-fuel/

A comprehensive review of the production costs of electrofuels is reported by Brynolf et al (2018). They are costlier than fossil fuels and biofuels, and the competitiveness depends mainly on the capital cost of the electrolyser, the electricity price, and the capacity factor. Other cost aspects reported to be less important are CO_2-capture costs, and cost of water. Brynolf et al (2018) do not compare costs for H_2 and electrofuels as this would require additional information related to the costs for propulsion and storage systems. They expect that cost is higher for H_2-fuelled fuel cells (need fuel storage systems) than for the (drop-in) electrofuel options used in combustion engines.

FUTURE DEVELOPMENTS

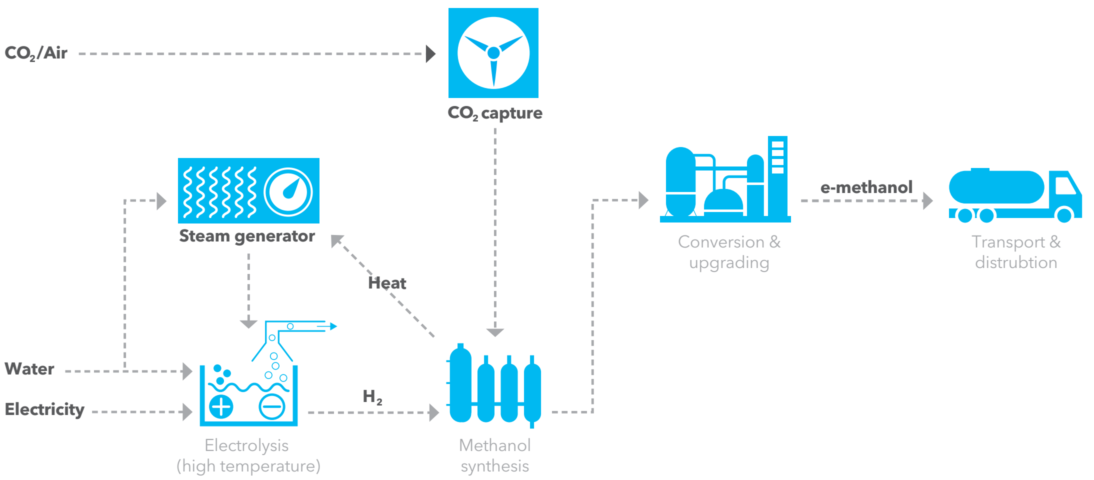
Electrofuel is an emerging fuel, with several demonstration-scale facilities in Europe. The first commercial electrofuel plant was built in Iceland in 2012, with a capacity to produce more than five million litres of e-methanol per year. Iceland produces e-methanol using geothermal energy and CO_2 from the same source (Hansson & Grahn, 2016). It is reported that Audi has invested in a 6-megawatt electrofuel plant in Germany (Brynolf et al, 2018). A test facility in Germany has shown that it is possible to produce high-quality drop-in electrofuels, producing diesel from renewable electricity and CO_2 captured from the air (Brynolf et al, 2018).

5.1.6 NUCLEAR

The International Atomic Energy Agency (IAEA) defines nuclear materials as uranium, plutonium, and thorium. Nuclear power is currently a controversial technology that can be used for propulsion on very large ships, or on vessels that need to be self-supporting for longer periods of time. The extent of its actual use will depend on technology developments and social acceptance. To avoid the possibility of unwanted use of nuclear

FIGURE 5.1.5.1

Production process of e-methanol (including the option of using high-temperature electrolysis).



material, nuclear-powered ships would need to run on low-enriched nuclear material. While limited resources of nuclear material mean that is not considered a truly sustainable energy alternative, it has an obvious advantage in that nuclear generation does not emit GHGs, except for emissions related to handling of the nuclear materials.

The Russian ice-breaker fleet operating on the Northern Sea Route is an example of fully marine-adapted nuclear power. Several nuclear-powered navy vessels operate today. Three experimental nuclear-powered merchant ships have been built and operated, so far without commercial success; Savannah (US); Otto Hahn (West Germany); and, Mutsu (Japan) (Schøyen & Steger-Jensen, 2017). These ships were independently developed and operated in the 1960s and 1970s for technology demonstration and learning. A fourth ship, Sevmorput (Soviet Union/Russia, 1988–to date), was built and operated, a pioneer in respect of its logistics, functions and propulsion system.

Electricity produced from nuclear power plants on land can also be used for shore powering, for charging batteries of electric ships, or for providing energy for producing other fuels, such as biofuels, electrofuels, NH_3, or hydrogen.

FUTURE DEVELOPMENTS AND PERSPECTIVES

Several concepts for compact nuclear reactors are being studied, ranging from 30–200 MW electrical power output, and all with more than 10 years of service life. An important barrier that needs to be overcome is related to safe storage and recycling of spent fuel.

The use of thorium as a nuclear fuel – instead of uranium or plutonium, which are utilized today – can also offer significant advantages: higher fuel availability, greater efficiency, and reduced nuclear-waste production.

Given the public opposition to nuclear power in most countries, and the fears related to potential consequences from accidents and misuse, it seems very unlikely that nuclear propulsion will be adopted in shipping within the next 10–20 years. This is supported by a recent study reporting that it is unlikely that further merchant nuclear-fuelled ships for ocean cargo transport will be built, unless their lifecycle costs and corresponding infrastructure are improved relative to conventionally powered ships (Schøyen & Steger-Jensen, 2017). They also point out that there may be potential for nuclear ships, including non-military, only in nations where there is some strong political reason for investing in nuclear ship propulsion. This picture could change after 2030, provided that societal acceptance increases and other efforts to reduce GHGs do not prove as effective as desired.

5.1.7 RANKING OF ALTERNATIVE FUELS

The many alternative fuels, and their diverse characteristics, make it difficult to clearly identify ‘winners and losers’. For different stakeholders – shipowners, investors, cargo owners, regulators, and others – a systematic and practical framework for analysis is needed to aid decision making (Figure 5.1.7.1).

We therefore introduce a concept for ‘ranking alternative marine fuels’, describing a multi-objective approach to evaluate promising options. Utilizing detailed information about alternative fuels, combined with the concept’s assessment criteria and weighting factors, ranking of promising fuels can be achieved. The proposed method is inspired by the work of DNV GL (2014b, 2015), Brynolf (2014), Deniz & Zincir (2016), Månsson (2017), and Hansson et al (2017).

The approach assesses how well an alternative fuel performs compared with traditional fuels or other alternative fuels. The main criteria are environment, economy, and scalability, and these are divided into sub-criteria that DNV GL expect to be the most important to consider (Figure 5.1.7.1). The criteria developed are qualitative and measurable.

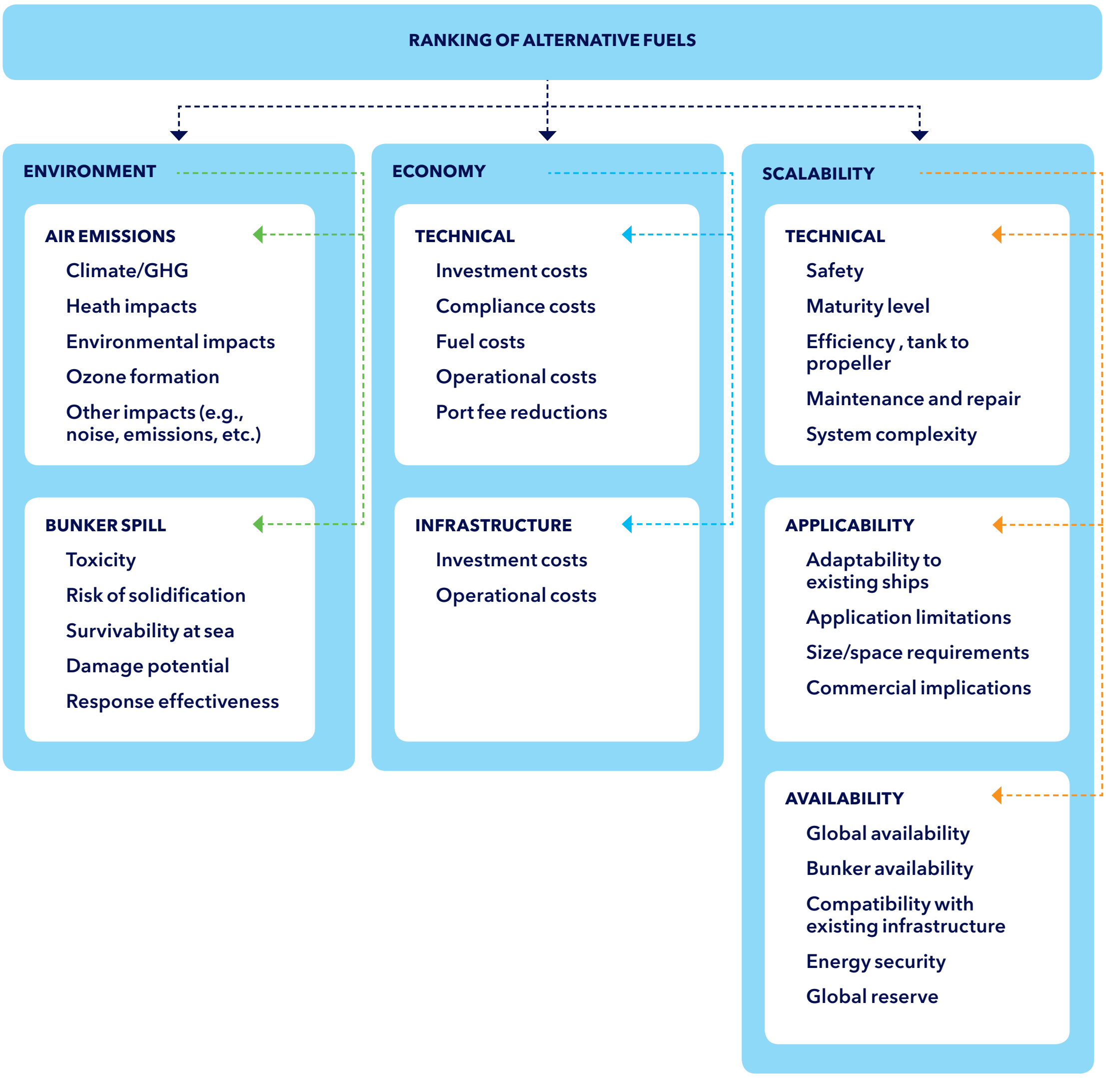
With the involvement of relevant stakeholders, weighting factors can be assigned to reflect different priorities and views. Stakeholders may include national and local authorities, shipowners, cargo owners, ship builders, manufacturers, and technology providers, classification societies, industry associations, academia, non-governmental organizations, and financial institutions. The proposed approach allows promising alternative fuels to be ranked after assessment based on the defined criteria (Figure 5.1.7.1).

To illustrate a potential use of the ranking method, consider hydrogen (H_2) and biodiesel. For one of the main criteria, 'environment', Figure 5.0.3 indicates that H_2 has a better score on air emission compared with biodiesel, due to NOx emissions. Hydrogen also outperforms biodiesel on bunker spill, as H_2, will not form any slick at the sea surface. For the main criterion 'economy', advanced biodiesel drop-in fuels will have a higher score than H_2, given the latter's high investment and operational cost. Regarding 'scalability', advanced biodiesel and H_2 will have relatively low scores for maturity, infrastructure, and availability. However, biodiesel will score higher for scalability due to its easy adaptability to existing ships, and its lesser need for additional safety measures. If the three main criteria are equally weighted, biodiesel will receive a higher score than hydrogen. However, applying a higher weighting to the criterion 'environment' could potentially shift the ranking in favour of hydrogen.

The method is suitable for making assessments today, and for forecasting by making assumptions about technology and infrastructure developments. Use of the ranking method is expected to provide additional support to shipowners and policy makers. Different actors will have different priorities and perspectives, which can be reflected by changing the weighting of the different criteria. Policy makers will focus on introducing policy and adopted strategies, to reduce emissions and impacts from a societal perspective. The shipowner perspective is to design competitive future ships of certain sizes, types, cargo capacities and flexibility, operations and speed, while complying with current and upcoming regulations. In all cases for the shipowner, the cost associated with machinery, as well as expected fuel prices, will play the dominant role. Safety will also be a primary concern and can be translated into monetary terms once a design has been established and the necessary safety measures identified.

FIGURE 5.1.7.1

A multi-objective method for ranking alternative fuels



5.2 TECHNICAL AND OPERATIONAL ENERGY-EFFICIENCY MEASURES

Several technical and operational measures are available for reducing shipping's energy use and emissions. Mitigation measures range from easily achievable operational measures to capital-intensive technical solutions. This section provides an overview of energy-efficiency measures, and points towards some next-generation energy-efficiency measures.

5.2.1 OVERVIEW OF ENERGY-EFFICIENCY MEASURES

Improved energy efficiency means that the same amount of useful work is done, but using less energy (Buhaug et al, 2009). Such improvements can be achieved by reducing propulsion energy demand (e.g., hull and propeller efficiency), reducing the energy use of other on-board consumers (e.g., cargo-handling systems, deck machinery) and improving energy production (e.g., waste-heat recovery and machinery-system optimization). The energy-efficiency measures can be divided into the following groups (DNV 2010; DNV GL 2017i; Eide et al 2011, 2013):

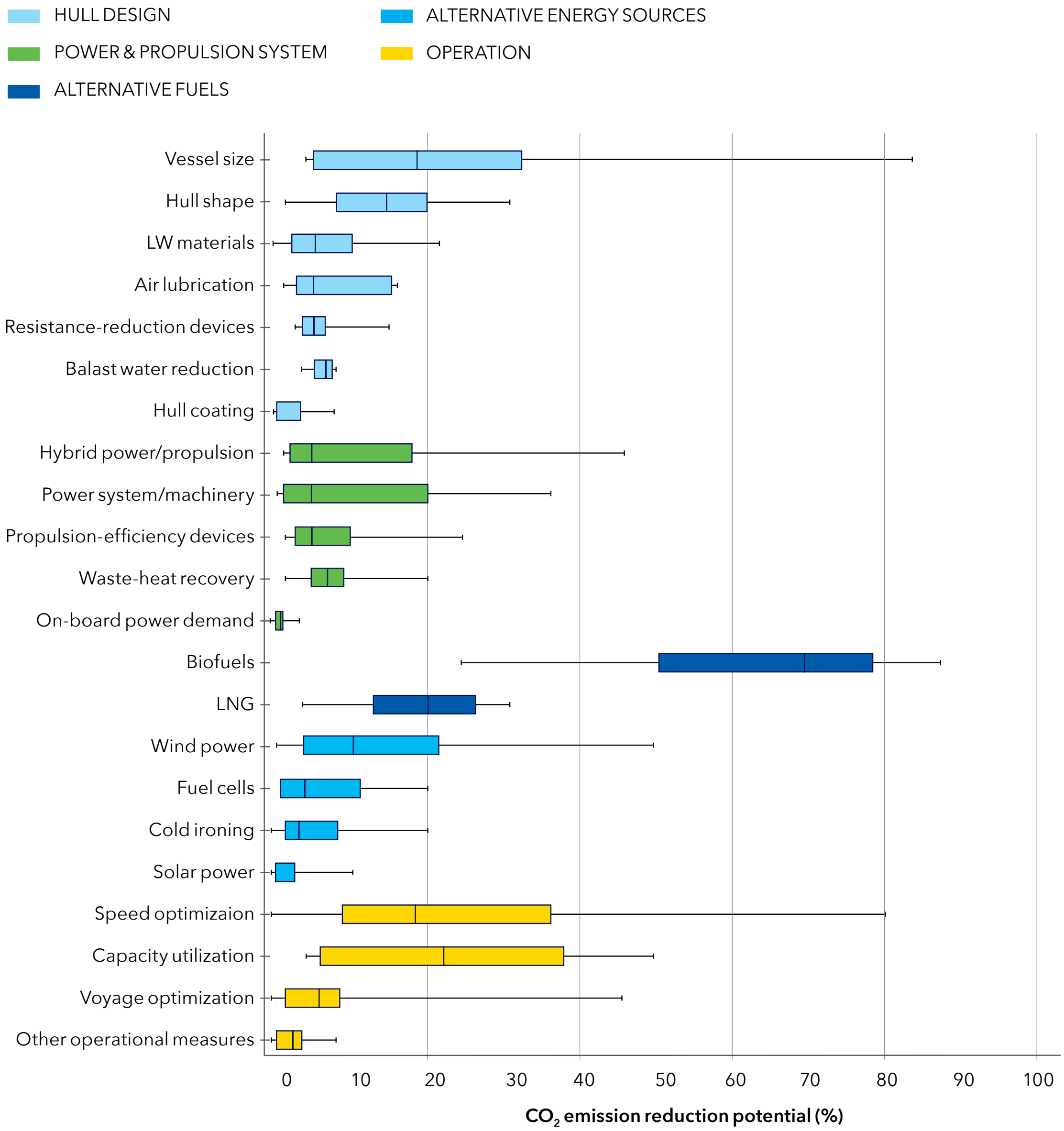
- **Technical measures** generally aim at either reducing the power requirement to the engines or improving fuel efficiency. They are linked to the design and building of ships (e.g., hull design), to optimization of the propulsion system, to the control and efficient operation of the main and auxiliary engines, and to retrofits on existing ships. These measures generally have a substantial investment cost and potentially very significant emission reduction effects. Many technical measures are limited to application on new ships, due to the difficulties or high costs of retrofitting existing ships.
- **Operational measures** relate to the way in which the ship is maintained and operated. They include measures such as optimized trim and ballasting, hull and propeller cleaning, better engine maintenance, and optimized weather routing and scheduling. Operational measures do not require significant investment in hardware and equipment. They generally have low investment costs and moderate operating costs. Implementation of many of these measures,many of which are attractive for purely economic reasons, requires execution of programmes involving changes in management and training.

One effective operational measure that has large fuel-saving potential is to reduce vessel speed (e.g., Lindstad et al, 2015; DNV GL, 2017i; CE Delft, 2012; 2017a; DNV GL 2018 c,d). Part of the speed reduction can be absorbed in current transport systems through reduced time in port and improved coordination and synchronization between ship and port to avoid waiting in port, with the extra time being used to slow steam (Longva, 2011; Andersson, 2017). Otherwise, timetables and schedules must be changed, and more ships deployed to maintain the total transport capacity. The fuel consumption of a vessel increases exponentially with the speed. Even when considering the energy and emissions related to building and operating more vessels, total fuel consumption and emissions are reduced by slow steaming.

Extensive speed reduction of up to 50% is a very complex measure that would require changing logistics chains and building more vessels. Legacy industry practices, culture, and established supply chains are resistant to 'quick fixes'; and, coordinat-

FIGURE 5.2.1.1

CO_2 emission-reduction potential of individual measures within five main categories (Bouman et al, 2017, their Figure 2)



ing action or synchronizing behaviour represents a significant challenge for a system involving so many stakeholders (Røsæg, 2009). Digital technologies are expected to facilitate improved information flow (Andersson, 2017). However, extensive speed reduction will require different ship designs to be optimal. Reducing the need for energy could also enable other solutions, such as using electricity, batteries, or hydrogen.

A recent literature review of 60 studies provides quantitative estimates of the CO_2 emission-reduction potential for different measures (Bouman et al, 2017). Figure 5.2.1.1 presents the main results, indicating large variability. For example, studies have reported typical reductions of 2–10% from using lightweight materials, such as high-strength steel and composites (LW materials, see Figure 5.2.1.1.). The reduction potential for each measure strongly depends on factors such as ship type, size, operational profile, technical conditions/status, and age (e.g. DNV GL, 2016; DNV GL, 2017c).

Several studies have reported medium- and long-term projections for decarbonization in shipping (Buhaug et al, 2009; IMO, 2011; Eide et al, 2011, 2013; DNV GL 2017i; Smith et al, 2016; OECD, 2018). The results indicate that the cost-effective CO_2 emissions-reduction potential for technical and operational measures, excluding fuel choices, is in the range 20–30%, rising to about 50–60% if the more expensive and novel technologies and solutions are included. These studies also provided information on various existing and upcoming energy-efficiency measures. Such measures are included in our fleet outlook in chapter 6.

“ Part of the speed reduction can be absorbed in current transport systems through reduced time in port and improved coordination and synchronization between ship and port, with the extra time being used to slow steam.

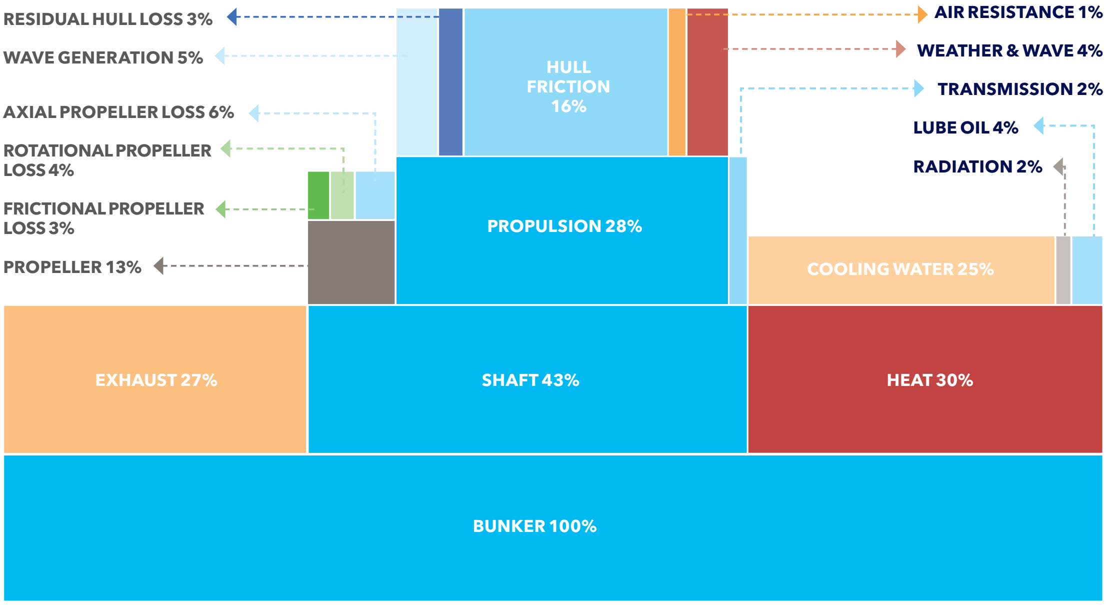
5.2.2 ATTACKING ENERGY LOSSES AND IMPROVING OVERALL PERFORMANCE

Technological developments in materials science, drag reduction, propulsion, and energy efficiency will provide the basis for the key specifications of new ship concepts. They will tackle energy losses and improve overall performance. Such losses are currently substantial. Only a fraction of the fuel energy entering a ship's main engines generates propulsion thrust. In a case study illustrated in Figure 5.2.2.1, 43% of fuel energy is converted into shaft power, the rest being lost in the engine exhaust or as heat (Buhaug et al, 2009). Further losses in the propeller and transmission mean only 28% of the energy from the fuel is fed to the main engine and generates propulsion thrust. There is potential for improvement in the areas of greatest energy loss; for example, by reducing hull friction and recovering energy from the engine exhaust and cooling water.

We expect to see a drive towards mapping energy losses and preventing them. Using advanced thermodynamics methods, such as exergy analysis, reveals insights about the potentially recoverable energy lost in a ship's energy cycle. Such analysis

FIGURE 5.2.2.1

Use of propulsion energy on board a small well-maintained cargo ship, head sea, Beaufort 6 (Buhaug et al, 2009). The bottom bar in the diagram represents the energy input to the main engine from the fuel.



also assists the prototyping of novel mature and immature technologies to close energy-efficiency gaps (Dimopoulos et al, 2014, 2016).

COSSMOS[26] modelling and simulation projects are of direct relevance here. They have been conducted for more than 70 ships, with each project indicating ways to improve energy efficiency and reduce relevant emissions. For ships in operation, COSSMOS can be a novel energy-management framework, capable of simulating the effects of implementing promising operational and technical measures. Simulation-based approaches can be, and are being, used for performance assessment and optimizing operation (Stefanatos et al, 2014), and for the potential optimal re-configuration of existing assets (Stefanatos et al, 2015).

Emerging power systems, such as electric batteries, marine fuel cells, and renewable auxiliary sources will result in more complex configurations and designs. To manage the complexity and risk inherent in innovative solutions, there is a drive towards using advanced, model-based techniques for assessing technical and economic performance from a life-cycle perspective. Model-based techniques, such as 'digital twin' real-time virtual representations of physical assets, combined with sensor data are emerging. They will provide safe and energy-effective operations for ships. Energy savings will come through learning from the past; real-time optimization of key parameters; minimizing system degradation; and, through maintaining high performance via optimized cleaning/maintenance, benchmarking, and targeting. Well-calibrated maritime digital twins will enhance the ability to analyse the past and improve present and future performance (see chapter 7).

The high focus on decarbonization and general 'greening' of shipping will trigger innovation and the introduction of new technologies and concepts in the world fleet. A fast, accelerated path from idea to commercial application of novel technologies will be required. Advanced modelling tools will help to assess and optimize new technologies and operational practices.

5.2.3 THE FUTURE IS HYBRID

Hybridization is about taking advantage of the benefits of two or more engine configurations. A hybrid electrical ship could contain alternative diesel engine configurations, marine fuel cells, battery packages, solar panels, and retractable wind turbines. Increasing the level of electrification can improve the overall efficiency and enable incorporation of many types of renewable sources. The large number of embedded components will increase the system complexity and require carful design, performance monitoring, and power management. The complexity increases if the future hybrid ship is also autonomous and ballast-free. For all these solutions, software and controls become an increasingly important aspect and difficult challenge. These challenges are faced at the commissioning and integration phase and thus digital simulation and analysis practices can greatly benefit not only the design phase, but also the implementation.

Hybrid battery-electric configurations represent perhaps the greatest opportunity in terms of potential applications within the maritime sector, with the capability to benefit a wide range of ship types. We expect that on the near horizon every new build vessel will utilize a battery in some way.

26 DNV GL has developed COSSMOS, a computer platform for modelling, simulation, and optimization of complex ship energy systems (Dimopoulos et al, 2014)

The introduction of batteries enables selection of smaller engine sizes that can operate at optimal loads for a larger proportion of the time due to additional power being obtained from the batteries when required (peak loads). When power requirements are low, the batteries can be charged using the excess energy generated by keeping the engine running at the optimal load. Further, batteries can provide redundancy (spinning reserve) to increase vessel safety and performance while also decreasing fuel consumption and emissions. In addition, batteries can greatly augment the stability and controllability of the ship power distribution system, better enabling other technologies and arrangements. Batteries can also introduce significant benefits for vessels with electric cranes and other cargo equipment with transient peak loads and options for regenerating power. The introduction of a hybrid system is expected to reduce fuel consumption by up to 20%, depending on the ship type and its operational profile. Hybrid operations with batteries for a supply ship have shown, in practice, 15% fuel consumption reduction (the FellowSHIP project).

Shore-side electricity is emerging in some ports[27], and is also referred to as 'cold ironing' and 'shore power'. This allows for the ship's on-board generators to be shut down, reducing its corresponding emissions in port. It also allows ship batteries to be recharged from shore power, for later use during manoeuvring and low sailing speeds.

Auxiliary powering by renewables, which avoids fuel costs, is also emerging:

- Various sail arrangements – such as sails, kites, fixed wing, and Flettner rotors – have been tested on merchant vessels over the years. A research ship, a ro-ro vessel, and a ro-lo one, currently have wind rotors, and another 'sail'-enabled vessel is being planned (CE Delft, 2017b). In addition, two multi-purpose ships and a bulk carrier are each equipped with a towing kite. It is also reported[28] that the first modern auxiliary wind-propulsion technology has been retrofitted on a ferry in 2018. More radical concepts[29] claiming large fuel and emission savings have also been reported.
- Wave-powered ships, with foils that convert the vertical motion in waves into propulsive thrust, have been studied and demonstrated (Bøckmann, 2015). Such wavefoils could save fuel, typically by 2–15%, but up to 40%, depending on parameters including foil span, wave direction, and ship speed. They could also reduce the most violent vessel motions. Development related to wave energy in a battery-hybrid configuration have also been reported[30].
- Solar power on ships is not very common, but solar panels were recently installed on a vehicle carrier. The solar panels installed will be used only as a 'small' supplement to the diesel generators, thus reducing the power required from the generators. The solar power units can produce energy both at sea and in port, but only

27 http://coastalconservationleague.org/wp-content/uploads/2010/01/EERA-Charleston-Shoreside-Power-Report-.pdf
https://www.zero.no/wp-content/uploads/2016/05/landstrom-i-norge.pdf
http://cruising.org/docs/default-source/research/environment-research-2017.pdf

28 Viking Grace: https://www.lr.org/en/latest-news/viking-grace-installs-rotor-sail/

29 Vindship: http://www.ladeas.no/

30 https://marineenergy.biz/2017/09/18/uksnoy-inks-deal-with-hydrowave-for-green-power-solution/
https://www.marineinsight.com/future-shipping/a-ship-with-energy-harvesting-system-to-generate-power-from-waves/

during daylight. It is reported[31] that Auriga Leader, a ro-ro ship, is fitted with more than 300 solar arrays. An innovative hybrid concept[32] has been proposed. It incorporates various elements, including solar panels, energy-storage modules, computer control systems, and an advanced rigid-sail design. The claimed fuel savings are forecast to be 40% or more.

Using renewables as auxiliary power could be an attractive option for autonomous and unmanned hybrid ships. Such vessels are expected anyhow to reduce energy requirements; for example, by allowing the removal of a ship's bridge, thus decreasing wind resistance, and through reduced manning. Smaller complements mean lower energy demand for personal needs, and less equipment for supporting people on board will save space and weight. The relative effect of these effects will depend on the type of ship and operation (DNV GL, 2018e).

Ship draft is a function of ship weight. Avoiding ballast water and its required treatment can reduce energy consumption and emissions on a hybrid ship. Innovative ballast-free ship concepts have been proposed[33]. They include ships designed to allow a continuous flow of seawater through specifically-designed tanks and/or trunks, and vessels that do not use water ballast at all, such as the DNV GL Triality concept ship. It was reported recently that South Korean shipbuilder, Hyundai Mipo Dockyard, has developed a ballast-free ship design that will first be applied to a 7,600 cubic metres-capacity LNG bunkering vessel[34]. This, the world's first ballast-free LNG bunkering vessel, is under construction.

Alternative and radical propulsion technologies may also emerge for the hybrid ship. For example, a demonstration ship, YAMATO 1[35], was built and tested in the 1990s, demonstrating superconducting electro-magnetohydrodynamic propulsion.

> "The introduction of a hybrid system is expected to reduce fuel consumption by up to 20%, depending on the ship type and its operational profile.

31 Auriga Leader, a RoRo Ship: http://www.marineinsight.com/types-of-ships/auriga-leader-the-worlds-first-partially-propelled-cargo-ship/

32 Aquarius Eco Ship: http://www.ecomarinepower.com/en/aquarius-eco-ship

33 http://www.maritime-executive.com/article/moving-towards-a-ballast-free-future

34 https://mobile.worldmaritimenews.com/archives/243838/hyundai-mipo-develops-ballast-free-ship-design/

35 https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19960000249.pdf

5.3 BARRIERS TO OVERCOME

All alternative fuels face challenges and barriers (e.g., DNV GL 2014b, 2015, 2017i; Brynolf, 2014). The cost associated with machinery, expected fuel prices, and availability of bunkering infrastructure, will be key barriers. Safety will also be a primary concern and can be translated into monetary terms once a design has been established and the necessary safety measures are identified. The need for infrastructure development, such as bunkering facilities and supply chain, is another hurdle. Uncertainty regarding long-term availability is also a concern. In addition, storage of certain alternative fuels will require more space on board compared with traditional fuels (Figure 5.0.1).

Several studies have investigated barriers to uptake of energy-efficiency technologies in shipping (DNV 2012b; DNV GL, 2017c; Acciaro et al 2013; Rehmatulla et al 2015; Rehmatulla & Smith 2015). Findings indicate the importance of financial and technical barriers, managerial practices, and legal constraints. For each energy-efficiency technology, very specific challenges and barriers will need to be identified and considered if the solution in question is to be a viable alternative for a significant part of the world fleet.

Based on current technology, a distinction should be made between short-sea and deep-sea shipping regarding the applicability of, and barriers to, various fuels. Deep-sea vessels have fewer options compared to the short-sea segment:

– **Short-sea shipping** includes vessels typically operating in limited geographical areas, on relatively short routes, with frequent port calls. Energy demand, sailing schedules, and bunkering patterns for such vessels may be suitable for applying new fuels, such as H_2 and biofuels. Some segments have an operating profile suitable for the use of batteries, either exclusively or in hybrid-propulsion configurations. For instance, the Norwegian ferry sector is currently being electrified, with phasing in of about 60 battery electric ferries over the next few years. The use of H_2 is also technically feasible. Norway has an ongoing development project aiming to put a new ferry with H_2 power on board into service in 2021[36].

– **Deep-sea shipping** includes mostly large, ocean -going vessels covering long routes and often, except for container ships, without a regular schedule. These vessels require fuel that is globally available, and fuel energy-density is important to maximize the space available for cargo transport over long distances. Sustainable biofuels can be used if they are available in the right quantities and will not create fuel-compatibility problems. Based on current technological developments, electricity cannot be used at large scale for these vessels in the foreseeable future (Sandia report, 2017). However, hybrid solutions can be of interest for deep-sea shipping. Nuclear propulsion is technically feasible for large vessels, but political, societal, and regulatory barriers can hinder its use. Various sail arrangements – sail, kite, fixed wing, Flettner rotors – have been tested on merchant vessels over the years and can potentially reduce fuel consumption. A recent study estimated significant saving potential from applying wind power on large tank and bulk ships (CE Delft, 2017b).

36 https://www.sjofartsdir.no/en/news/news-from-the-nma/breaking-new-ground-in-hydrogen-ferry-project/

In the future, renewable energy from offshore wind farms can be an energy supply for shipping. The could mean offshore charging stations supplying electrical power to ships in nearby shipping lanes. The direct electricity supply could be supplemented with H_2 produced offshore by conversion of some of the wind power by electrolysis. DNV GL Student Summer project 2015 looked at using offshore wind to produce sustainable hydrogen for Japan. They found that producing hydrogen offshore, by using floating offshore wind, is an attractive option. A recent study reported prospects for renewable marine fuels, considering decentralized production at seaports with electricity from renewable energy like wind and sun (Månsson, 2017). Such developments could challenge current bunkering infrastructure and practices, where around 12 ports account for 80% of today's bunker sales.

CHAPTER 6

WORLD FLEET OUTLOOK

6 WORLD FLEET OUTLOOK

This section provides an outlook for the world fleet, discussing how it may develop to meet transport demand (chapter 3) in light of expected technology developments (chapter 5) and upcoming regulations (chapter 4). We focus only on long-term developments and the fleet needed to meet forecast demand for transport; we do not model short-term cycles.

6.1 THE LOW CARBON PATHWAYS MODEL

The DNV GL Low Carbon Pathways model forms the backbone for forecasting the maritime fleet and energy transition towards 2050 (DNV GL, 2017c). It projects the uptake of a wide range of energy-efficiency measures, alternative fuels, and other emission-reduction technologies, based on investment decisions and upcoming regulations. Energy use and emission levels will depend on the availability of technological solutions applicable to each segment, their emission-reduction potential, and uptake rates.

Modelled levels of uptake depend on the expected payback time for each technology and fuel, the investment horizons of shipowners, and on regulations requiring specific technologies or specifying general levels of energy efficiency and carbon intensity.

TABLE 6.1.1
The impact of technology and fuel options on carbon and energy efficiency

		Carbon intensity reduction	Energy use reduction (main engines)	Energy use reduction auxiliary engines)
Fuel	Baseline: switch to low sulphur fuel	–	–	–
	Heavy fuel oil with scrubbers	–	3%	3%
	Liquefied natural gas	20%	–	–
	Electricity	100%	50%	50%
	Carbon-neutral fuels	100%	–	–
Energy efficiency	Hull form – new buildings	–	12–17%	–
	Hydrodynamics – retrofit	–	13–20%	–
	Machinery improvements	–	4–8%	12–23%
	Waste heat recovery	–	0–8%	–
	Hybridization	–	3–15%	–
	Operational measures	–	3–11%	–
	Cold ironing	–	–	30–70%
	Renewable energy (wind, solar)	–	0–10%	0–2%
	Air cavity lubrication	–	3–5%	–
Logistics and speed	Speed reduction (5%)	–	10%	5%
	Vessel utilization	–	3–20%	–
	Increase vessel sizes	–	4–14%	–
	Alternative sea routes	–	0–20%	–

Fleet growth and scrapping rates determine the possible penetration rate of new technologies and fuels. Old vessels are scrapped first; new vessels are added to match expected demand, taking into account changes in speed, utilization, and ship size.

Possible technologies and solutions to reduce energy use and CO_2 emissions (see chapter 5 for more details) are grouped into three main categories: alternative fuels; energy-efficiency measures; and logistics and speed reduction. Measures evaluated in this study, and their expected individual impacts, are listed in Table 6.1.1. The forecast percentage changes are relative to the performance of an 'average ship' built in 2015, but running on low-sulphur fuel, as this will be the default from 2020 with the introduction of global low-sulphur requirements.

We cannot currently predict with any confidence which of the possible types of carbon-neutral fuels will be preferred. The uptake is very sensitive to price and local/global availability, which are, in turn, dependent on cost of production and infrastructure development. We have therefore grouped biofuels, electrofuels, hydrogen (H_2), and ammonia (NH_3) into a single category called carbon-neutral fuels. Although the carbon-neutrality of biofuels is debated, those used in the future will be different from those available today. Third- and fourth-generation biofuels will likely be closely examined to see if they can be approved for use and labelled as carbon-neutral and sustainable (see DNV GL 2017g, pp 141, for a more detailed discussion on this topic).

In line with the Intergovernmental Panel on Climate Change and Greenhouse Gas-(GHG) accounting procedures, this study assumes that combustion of biofuels and electrofuels, and use of electricity, is carbon-neutral. Any emissions due to production are accounted for elsewhere in our Energy Transition Outlook (ETO) analysis and are not double-counted in this maritime outlook. The IMO has yet to decide how such fuels will be accounted for when measuring progress towards each its GHG-reduction targets and, on individual ships, for complying with regulations such as the IMO Energy Efficiency Design Index (EEDI).

For Liquefied Natural Gas (LNG), we assume a 20% reduction in CO_2 emissions, though emissions of unburnt methane ('methane slip') may mean GHG emissions are cut by only about 10%.

The IMO's global 0.5% sulphur limit from 2020 will shift fuel use to low-sulphur types. In the shorter term, ships will still use heavy fuel (residual) oil (HFO) and will be fitted with scrubbers, but this solution will be phased out in the longer term. Such exhaust-gas cleaning will incur a fuel consumption penalty, typically about 3%, for the affected ships, but will not impact on the forecast energy consumption in 2050.

6.1.1 IMPACT OF THE INTERNATIONAL MARITIME ORGANIZATION STRATEGY FOR REDUCING GREENHOUSE GAS EMISSIONS

In April 2018, the IMO adopted its GHG-reduction strategy, including specific targets. Whether we can expect these targets to be achieved is a key question for the projections in this study, as it will impact on the uptake of new technologies and fuels. The IMO GHG-reduction strategy needs to be implemented through regulatory and other policy measures still under discussion.

In our projection, DNV GL assumes that regulations will be in place on individual ships to incentivize the necessary emissions reduction. We have not modelled specifically which regulations and policy measures will be put in place, but have set a requirement in the model that the IMO GHG targets should be met using the most cost-effective solutions. The Low Carbon Pathway model will assess which are the most-likely technologies and solutions that can take shipping emissions down to the target levels.

See section 4.5 for a discussion on what type of regulations can be expected in the short and long term.

6.2 WORLD FLEET PROJECTIONS

Including these measures and related reduction factors in our investment decision model, DNV GL predicts the following trends over the period 2016–2050:

- The projected transport demand in 2050 is 76 trillion tonne-miles, about 38% more than in 2016 (chapter 3). With expected efficiency gains, the fleet, as measured in deadweight tonnes (DWT), will grow by 35%.
- The number of ships and total fleet size (DWT) will grow differently from demand (tonne-miles). Speed reduction, vessel utilization, and vessel size will impact directly on the relationship between tonne-miles to be transported and the corresponding deadweight tonnage. Lower speed requires higher deadweight tonnage to handle the same transport work, while better utilization and larger ships reduce the deadweight tonnage needed.
- Vessel utilization will increase in all segments; by about 25% for deep-sea trades except bulk, approximately 5% for deep-sea bulk, and some 20% for short-sea ships.
- The average size of deep-sea vessels will rise 40% for LNG tankers (due to more deep-sea vessels), 30% for container and other cargo ships, and 10% for bulkers.

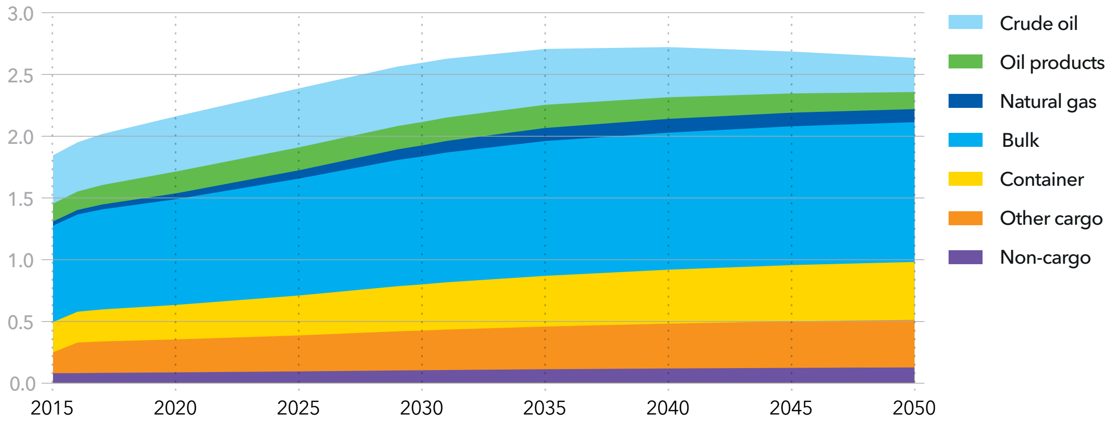
The development forecast by segment is shown in Figure 6.2.1. We predict that the crude oil fleet will decrease by almost a third (30%) come mid-century, peaking around 20% greater than today in 2030, before it shrinks towards 2050. The product tanker fleet will decrease by 8% by 2050.

High demand growth for LNG tankers will see the fleet size triple (205%) by 2040, but then slip back for a total increase of 190% by 2050. The bulk segment will remain relatively stable, with moderate long-term growth of 32% to 2030 and 44% to 2050. The greatest increase after gas carriers will be in the container segment where fleet size grows with GDP and rises 52% to 2030 and 88% to mid-century. For other cargo vessels and non-cargo vessels, we predict a 55% increase of the fleet by 2050.

FIGURE 6.2.1

Fleet development by segment

Units: Billion dwt



6.3 ENERGY MIX

Fuel consumption per tonne-mile will decline 30% on average due to energy-efficiency measures, mainly hull and machinery improvements and speed reduction. Vessel speeds will be adjusted to meet regulatory requirements and further varied according to market conditions and energy cost. DNV GL assumes a speed reduction on cargo vessels of about 5%, on average.

Total energy use and energy efficiency vary considerably between segments depending on typical sizes and speeds. Product tankers are generally smaller and less energy efficient than crude oil carriers, but there are a larger number of product tankers. The total energy use is about the same for each of the two segments.

The container and bulk segments will account for the largest shares of total shipping energy use in 2050, 28% and 19% respectively. We predict that total energy use in international shipping will increase from about 11 exajoules (EJ) in 2016 to a peak of almost 13 EJ in 2035 and then decrease to 11 EJ in 2050 (Figure 6.3.1).

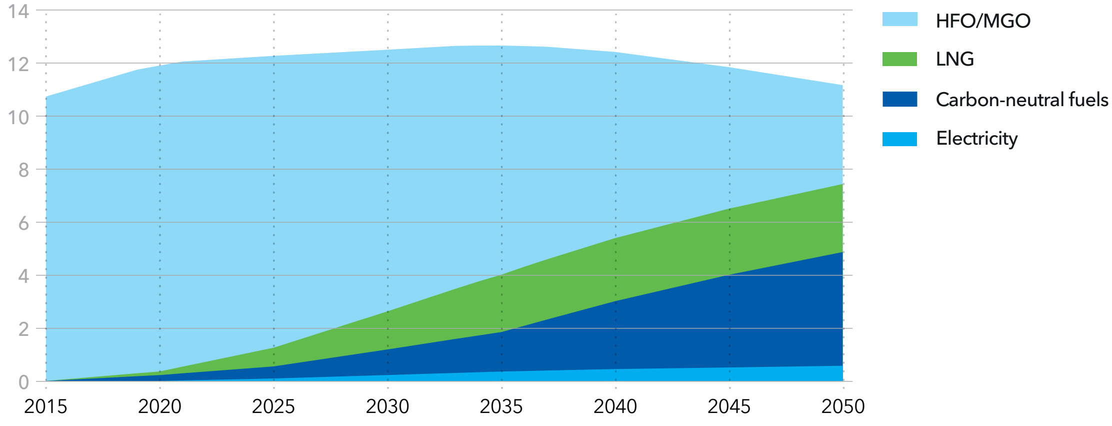
We forecast that by 2050, 39% of shipping energy will be supplied by carbon-neutral fuels, slightly surpassing liquid fossil fuels such as MGO (Marine Gas Oil) and HFO, which together will supply 33% of the energy. LNG and liquid petroleum gas (LPG) will together account for 23% of the energy use. Electric batteries charged from shore will be an energy source on a third of ships from mid-century. Together with cold ironing, shore-based electricity will provide about 5% of the total energy for shipping (Figure 6.3.2).

The total energy use equates to 270 million tonnes of oil equivalent (Mtoe) in 2050, of which 90 Mtoe is supplied by HFO/MGO, 60 Mtoe by LNG, 100 Mtoe by carbon-neutral fuels, and an additional 160 terawatt hours (TWh) of electricity[38].

FIGURE 6.3.1

Shipping energy mix

Units: EJ/yr



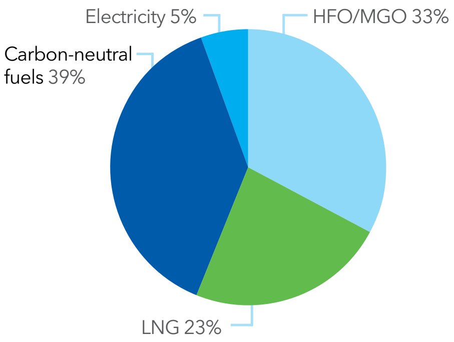
38 1 EJ = 23.9 Mtoe = 278 TWh

If we assume that all carbon-neutral fuel would be biofuels, demand from shipping would be about 30% of the total projected global biofuel demand from the transport sector in 2050. Short-sea and non-cargo shipping will use 40% of the total energy, and, in these segments, electricity can constitute more than a tenth (11%).

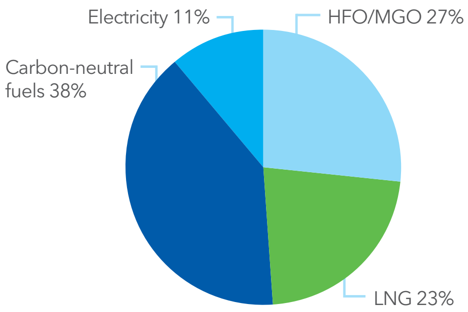
> We forecast that by 2050, 39% of shipping energy will be supplied by carbon-neutral fuels, slightly surpassing liquid fossil fuels such as MGO and HFO, which together will supply 33% of the energy.

FIGURE 6.3.2

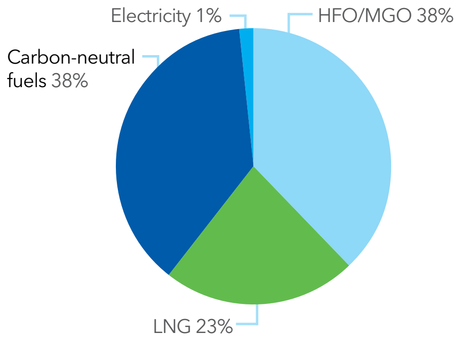
Shipping energy mix 2050, total



Shipping energy mix 2050, short sea



Shipping energy mix 2050, deep sea




LNG

6.4 CARBON INTENSITY AND CARBON DIOXIDE EMISSION DEVELOPMENT

Grouped into three categories – energy-efficiency measures, alternative fuels, and logistics improvements and speed reductions – the drivers in our model will progressively decarbonize shipping by 2050. The impact of lower speeds and other logistical measures can be achieved to full effect early in the period up to 2035, as these options can be implemented without renewing the fleet. Beyond 2035, we will see the full impact of gradually improving the energy efficiency of new ships, and of the shift to alternative fuels.

We forecast that average carbon intensity (CO_2 emitted per tonne-mile) will improve by 60% between 2016 and 2050 (Figure 6.4.1). Compared with 2008, the baseline year for the IMO GHG strategy targets, carbon intensity will improve by 51% and 74% by 2030 and 2050, respectively.

Based on projections of demand for maritime transport work, we forecast that CO_2 emissions for international shipping will fall by 45% to 441 million tonnes (Mt) by 2050 compared with 2016, or 52% compared with 2008 (Figure 6.4.2). Carbon-neutral fuels contribute 42% of the total CO_2 reduction by mid-century.

> “Beyond 2035, we will see the full impact of gradually improving the energy efficiency of new ships, and of the shift to alternative fuels.

FIGURE 6.4.1

Shipping average carbon intensity

Units: gCO_2/t-nm

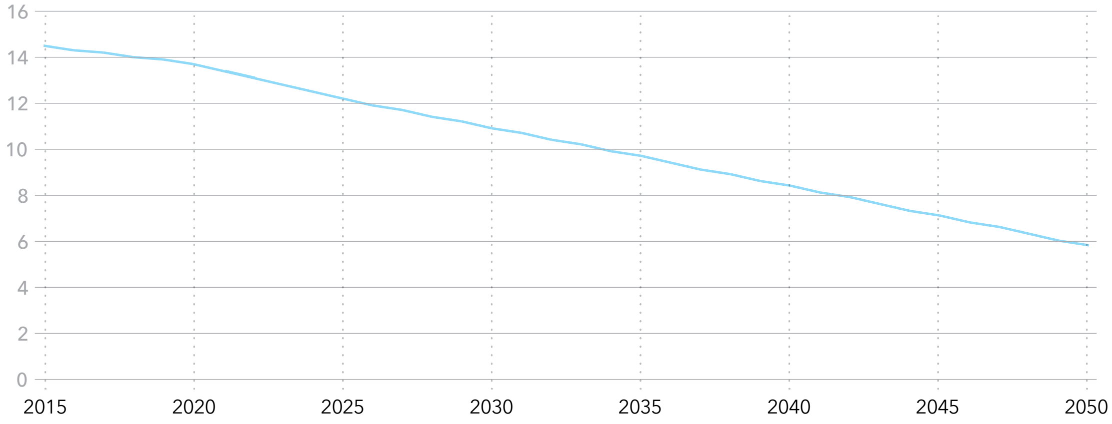
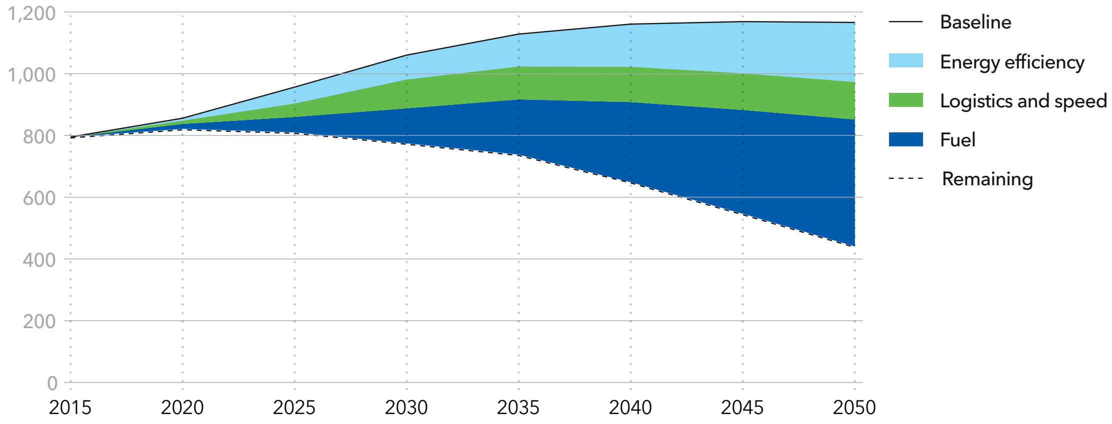


FIGURE 6.4.2

International shipping: emissions pathway 2015-2050

Units: $MtCO_2$/yr



6.5 COMPARISON WITH THE 2017 ENERGY TRANSITION OUTLOOK AND OTHER PROJECTIONS

Based on the projections in the global ETO model, expected transport demand in 2050 is reduced compared to our 2017 modelling, down from 84 to 76 trillion tonne-miles. This also reduces the energy use, assuming the same energy efficiency, from 12 to 11 EJ.

The Low Carbon Pathways model has undergone several amendments prior to the publishing of this report, to reflect the latest regulatory development, technology research and advances, and knowledge of the abatement measures and alternative fuels. In this year's modelling, the impact and cost of plug-in hybridization and cold ironing have been updated. The share of electricity in global shipping has increased due to cold ironing.

The main change comparing the 2017 and 2018 projections is the impact of the IMO GHG strategy. The model forces implementation of the most cost-effective solutions to reach the strategy's targets for emission levels and carbon intensity. The uptake of carbon-neutral fuels in 2050 is increased from 18% uptake of biofuels in last year's projections to 39% uptake of any carbon-neutral fuel in this report, while the uptake of energy-efficiency measures does not significantly increase. This indicates that alternative fuels are preferred to more expensive energy-efficiency measures.

Several other studies have looked at possible CO_2 pathways, and the same CO_2 emission levels can be achieved with various combination of technologies, alternative fuels, and operational measures (e.g., Eide et al 2013; DNV GL 2017i; Smith et al, 2014; 2016; OECD, 2018). While the details and assumptions of the different pathways vary considerably, the main findings formulated by DNV GL (2017i) are robust.

These findings were, and are, as follows:

- To halve CO_2 emissions, the shipping industry must apply energy-efficiency measures to the fullest possible extent.
- Even then, other tactics will be required: carbon-neutral fuels in substantial volumes, as shown in the current report, and/or reducing speed by up to 50% compared with today.
- The emerging pathway to low or no carbon emissions in shipping will depend on preferred solutions, which, in turn, hinge on their cost, availability, and effectiveness.


Powerdock

CHAPTER 7

KEY ISSUES TO MONITOR

7 KEY ISSUES TO MONITOR

This section addresses some key issues to monitor over the next five years in different ship segments, and discusses factors that could shift our projections in the long run towards 2050.

7.1 THE NEXT FIVE YEARS

The main ETO report devotes a separate chapter to key issues that are important to monitor over the next five years, and which will indicate where our projections might diverge from actual outcomes. Some of these are particularly important to maritime transport, and some are key for all maritime market segments. The world fleet development is driven by many factors, such as newbuilding activity, scrapping, deliveries, and changes to newbuild, second-hand, and scrap prices. We will also be keeping a close watch on speed, congestion, and lay-ups, as well as port and logistic-capacity developments.

All these elements will shape the future size and productivity of the fleet, and will thus influence the capacity utilization that ultimately drives earnings. All need close monitoring. Specific regional initiatives, such as 'One Belt, One Road' in China, and the expansion of the Northern Sea Route, could also factor into changing trade patterns and fleet requirements.

Key issues to watch in the bulk, container, gas, and oil tanker shipping segments over a five-year horizon are discussed below.

BULK

Fundamentals in the dry bulk segment have improved significantly. We observe a stronger seaborne trade growth within both major and minor bulk cargoes. Coal trade remains robust and demonstrates continuous growth. It is important to note that increased seaborne coal volumes are not only driven by increased consumption. We often see high-grade coal imports that offset a lower grade, domestic coal. In countries like China, despite relentless efforts to reduce GHG emissions, demand for power rises and, in the short-term perspective, coal-based energy seems to be the only option. Elsewhere, strong industrial production in both OECD and non-OECD countries is well reflected in non-coal trades such as iron ore, steel, or scrap. All these factors persuade us that the dry bulk sector will experience continuous growth in demand for transportation in the energy and other commodity sectors.

CONTAINERS

Positive developments in the world economy have influenced containerized trade. There are notable improvements in the mainline and regional trades. The biggest gains are observed in the trans-Pacific route as well as in the North-South and intra-Asian trade. The new Panama locks opened the way to increase the size of vessels being deployed in the Pacific, pushing the smaller, old Panamaxes out of their original trade patterns to regional trades. Intra-Asian trade continues to expand, backed by the strong economic development in China. Overall, we remain positive about near-term trade developments, although we do appreciate the strong influence of the recent rapid growth of GDP. That said, any slowdown in the coming years will have a negative influence on the box trade. Finally, the trade is likely to suffer from the proposed tariffs on trade between China and the US. Currently, we see only marginal losses. Should there be a bigger 'trade war' in the future, the container trade will be disrupted to a much greater degree.

GAS

The LNG trade is undergoing structural change. Substantial additions of new natural gas liquefaction capacity, combined with rapidly growing demand, have led to double-digit growth of the trade. It is expected to maintain this momentum in the next few years. Rapidly increasing export capacity in Australia, Russia, and the US meets a very strong increase in demand for LNG, particularly in China.

We observe a growing number of countries joining the LNG-consumer group, importing through either land-based re-gas facilities or using Floating Storage Regasification Units. As gas proves to be the cleanest fossil fuel, its future use will only grow, with the seaborne LNG side gaining in importance compared with pipelines. New LNG exporters, particularly the US, will have a strong impact on the future growth of the LNG seaborne trade, adding both new tonnes and new miles to the world trade. We remain extremely optimistic in our expectations for expansion of the trade over the next five years. It is also worth noting that the rapid expansion of shale gas also drives the LPG sector in the US, which, despite its current temporary weakness, is expected to start growing rapidly in the next few years.

OIL TANKERS

Lower oil prices from 2014 onwards created substantial growth in the oil trade, both in the crude and products sector. The uncontrolled rapid increase of supply from OPEC countries and Russia, and from US shale and tight oil production, led to sharply lower oil prices, reaching to below USD27 per barrel (/b) at the bottom in early 2016. Importers, particularly in Asia, were very quick to take advantage, and the trade grew substantially. Latterly, OPEC production limits have led to increased drawing on oil inventories, helping oil prices to recover to some USD75/b for benchmark Brent crude at the time of writing.

Although the seaborne trade growth has been reduced, we remain relatively optimistic concerning the near-term trade forecast. We do not expect OPEC's production limits to remain in place for much longer, and thus expect the oil trade to expand further. We also see the upcoming International Maritime Organization 2020 sulphur regulations for shipping as a positive driver, particularly for the products tankers, as more diesel fuels will need shipping around the world. Regarding downside risk, we are concerned about the future of Venezuela, with its rapidly deteriorating political and economic situation causing, among other effects, a rapid decline in the country's domestic oil production. We also see the collapse of the Iranian nuclear deal, combined with the US reinstating sanctions on Iran, as a possible drag on oil-trade expansion in the short term.

> "The LNG trade is undergoing structural change. Substantial additions of new natural gas liquefaction capacity, combined with rapidly growing demand, have led to double-digit growth of the trade.

7.2 POTENTIAL GAME-CHANGERS TOWARDS 2050

While the ETO model forecasts our best estimate of the development of the energy transition, based on our current assumptions and data sets, the actual pathways and outcomes in 2050 will remain subject to changed premises. Highlighting uncertainty in energy forecasting, other studies have predicted stronger growth in transportation demand (Fang et al, 2013; OECD/International Transport Forum (ITF), 2017; Sharmina et al, 2017; OECD/ITF, 2016; OECD, 2014). This is partly explained by their expectations of higher economic growth, fossil-fuel use, and trade multiples when compared with the levels factored into our ETO analysis. Comprehensive analysis of sensitivities related to our modelling is available in the main report (DNV GL, 2018a).

Last year's Maritime Forecast outlined three main areas of uncertainty that could impact on our projections:

- Decarbonization and environmental awareness
- Major shifts in transport demand
- Digitalization and innovation.

These areas are still valid for this year's report; but with the uncertainty concerning decarbonization reduced from last year with the IMO's strategy clarified. We see major disruptions due to the impact of digitalization related to the ship or fleet of ships, but also potential changes in transport demand.

7.2.1 DIGITALIZATION

In the next decade, virtual ships will become the standard method for commissioning, designing, operating, and maintaining vessels and whole fleets. The virtual vessel, a 'digital twin' of the real one, is a simulator containing all on-board equipment and machinery, networks and control systems; all of it connected and integrated in cyberspace, just as if it was on the physical vessel (DNV GL, 2017f). The digital twin's copy of the control system can be tested in simulated conditions, identical to those encountered in reality.

Better computerized design tools have already enabled optimization of hull design to accommodate lower hydraulic drags. Marine energy systems have similarly been improved through use of advanced simulation techniques. Indeed, the use of digital twins now enables the re-use of such design tools during ship operation, with the aim of improving propulsion efficiency once afloat. In addition to optimizing the speed for wave conditions, route wave forecasts may be entered into such algorithms to provide a more accurate view of the economics of going slowly through adverse weather conditions, or navigating around them.

A digital twin and virtual engine rooms could help to evaluate promising measures and cost-effective reduction strategies. Improving the understanding of GHG emissions over the lifetime of assets allows companies to manage GHG-related risks better. Where a digital twin includes real-time or near real-time information from many sources, it can enable improved energy and safety management and can help to optimize scheduling of costly maintenance.

In a digital ecosystem of many vessels, we can integrate applications and data models and leverage the cloud, Big Data, and the Internet of Things to create exciting opportunities that will harness the power of advanced predictive analysis. This can be used to optimize fleet performance, improve information integrity, and deliver energy and cost savings. Indirectly, digitalization can enable new business models and better ship and fleet operations, with a positive impact on energy use.

Shipowners will increasingly use Automatic Identification System-based systems in more intelligent ways, augmented with similar data from ports. With knowledge of exact port availability, waiting times will be reduced, speed can be optimized, and fleet utilization improved. This will reduce tonnage needs and enable fuel saving from slow steaming when more exact knowledge of port slots allows for that. Such improved planning will also enable improved scheduling and logistics, further increasing fleet utilization.

7.2.2 NEW COMMODITIES AND SHIFT IN TRADE DEMAND

As societies, new technology, and the world climate develop in the coming decades, new commodity value chains will emerge and existing ones will become less prominent.

Use of biomass for energy production will increase. It will change from being a local, inefficient commodity, to becoming an important feedstock for power generation and liquid fuels for heavy road transport, shipping, and aviation. Regions with insufficient capacity for producing energy from biomass will increasingly need to import biofuels. Japan is among those countries with comprehensive plans to invest in biomass power plants. Its government has approved 12 gigawatts of installed capacity[39]. This will require substantial shipping capacity.

New energy carriers may become relevant in the later part of the forecast period. One example is hydrogen (H_2), which we predict will start to see firmer uptake from about 2030. Although initial volumes will be limited, there will be a need for developing storage, transport, and handling technology. Currently, it looks likely that long-distance ship transport will involve H_2 in liquid state at 20 Kelvin (-253°C). There is a plan to pilot this in a project producing liquid H_2 from brown coal with carbon capture and storage in Australia, then shipping it to Japan[40].

Water scarcity is expected to worsen for some regions due to the combined effects of increased consumption, climate change, and uneven geographical distribution of water resources. This may lead to a need for seaborne transportation of water, in addition to energy-intensive desalination and water purification plants. This trade has the potential to become significant in volume, and may also be combined with ballast voyages, but the uncertainty surrounding it is currently very high.

The type of products produced globally will certainly change in the coming decades. Additive manufacturing (3D printing; see fact box) can lead to more raw materials being transported or recycled locally at the expense of finished goods. The increased use of robots and automation could enable relocation of production back to developed countries, shortening global value chains. With a strong trend towards electrification of the energy system, there will be a shift from transporting energy towards transporting goods supporting the transition, such as electric vehicles, batteries, and solar photovoltaic and wind turbine technologies.

39 http://www.reuters.com/article/us-japan-biomass/japan-fires-up-biomass-energy-but-fuel-shortage-looms-idUSKCN1BX0IT

40 http://www.abc.net.au/news/2018-04-12/coal-to-hydrogen-trial-for-latrobe-valley/9643570

ADDITIVE MANUFACTURING SET TO IMPACT SUPPLY CHAIN LOGISTICS

Additive manufacturing, otherwise known as 3D printing, progressively builds up products from raw materials such as metal-powder feedstock or a wire. It can transform the business models of many industries, with consequences for supply-chain logistics, and hence demand for transport or components, equipment, and structures by various means, including shipping. Being able to source replacement parts more rapidly through on-site manufacture can also reduce the downtime of vessels, with the potential for positive consequences for the profitability and efficient operation of fleets and individual ships.

The technology could allow organizations to access an archive of digital designs for immediate on-site printing, rather than maintaining physical inventories of spare parts and/or waiting for them to be made and transported to where they will be used.

Activity in this field is in its infancy, but is starting to pick up. Worldwide shipments of 3D printers of all types more than doubled in 2016 to exceed 450,000 and are expected to reach 6.7 million in 2020[41].

There are now 3D printers in many ports and industry hubs around the world. Parts ranging in size from screw pins and bearing shells to box heat exchangers and even propellers have been printed successfully.

In one example, the Port of Rotterdam, Netherlands, is establishing an Additive Manufacturing FieldLab with 3D metal printers[42]. Its vision is for companies, researchers, and students to collaborate in what will be a centre for developing knowledge of metal printing, 3D scanning, 3D design, and certification.

In another sector, a financial case can be proved for using 3D printing for components and equipment used offshore in oil and gas production, and there is potential to scale up additive manufacturing for larger structures.

These, and other industries, are at the start of an emerging market for selling digital rights and licences to print parts, repair and refine obsolete parts, and establish a wider supply chain. Add in Blockchain technology for secure, private traceability, and the digital aspect of additive manufacturing is where the scalability and disruptive power of it resides.

DNV GL has been looking into the potential of 3D printing for the maritime and oil and gas sectors since 2010. The technical advisory team has released research and innovation papers, undertaken pilot studies, and collaborated in joint development projects. For example, it has been part of an industry collaboration working to assess the repair and reconditioning of turbochargers with laser cladding 3D-printing technology[43].

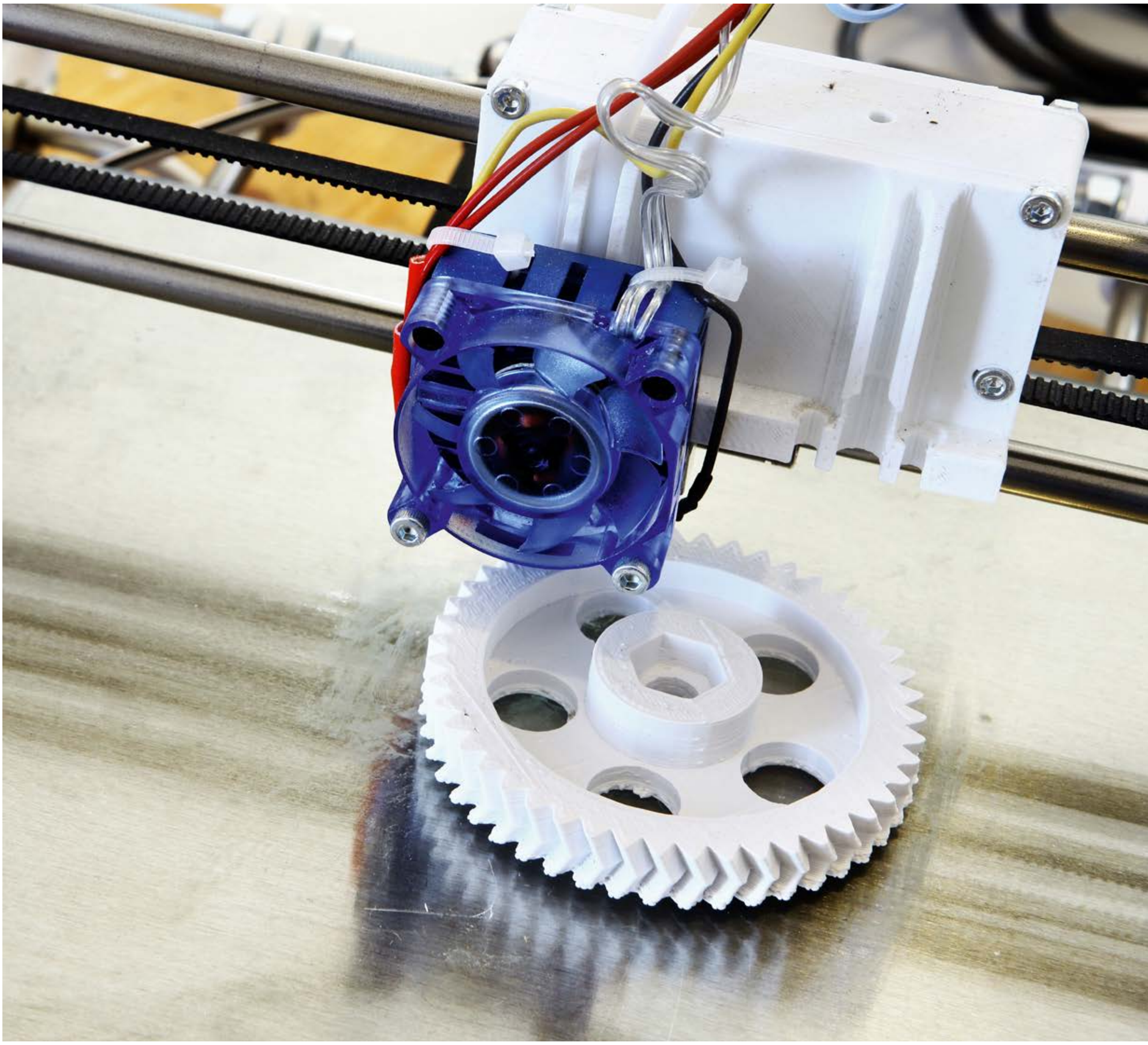
DNV GL's new Global Additive Manufacturing Technology Centre of Excellence in Singapore, established in February 2018, will dismantle barriers to the spread of the technology in industry. Obstacles include whether 3D-printed parts can be qualified and certified to standards applied to traditionally-made goods[44].

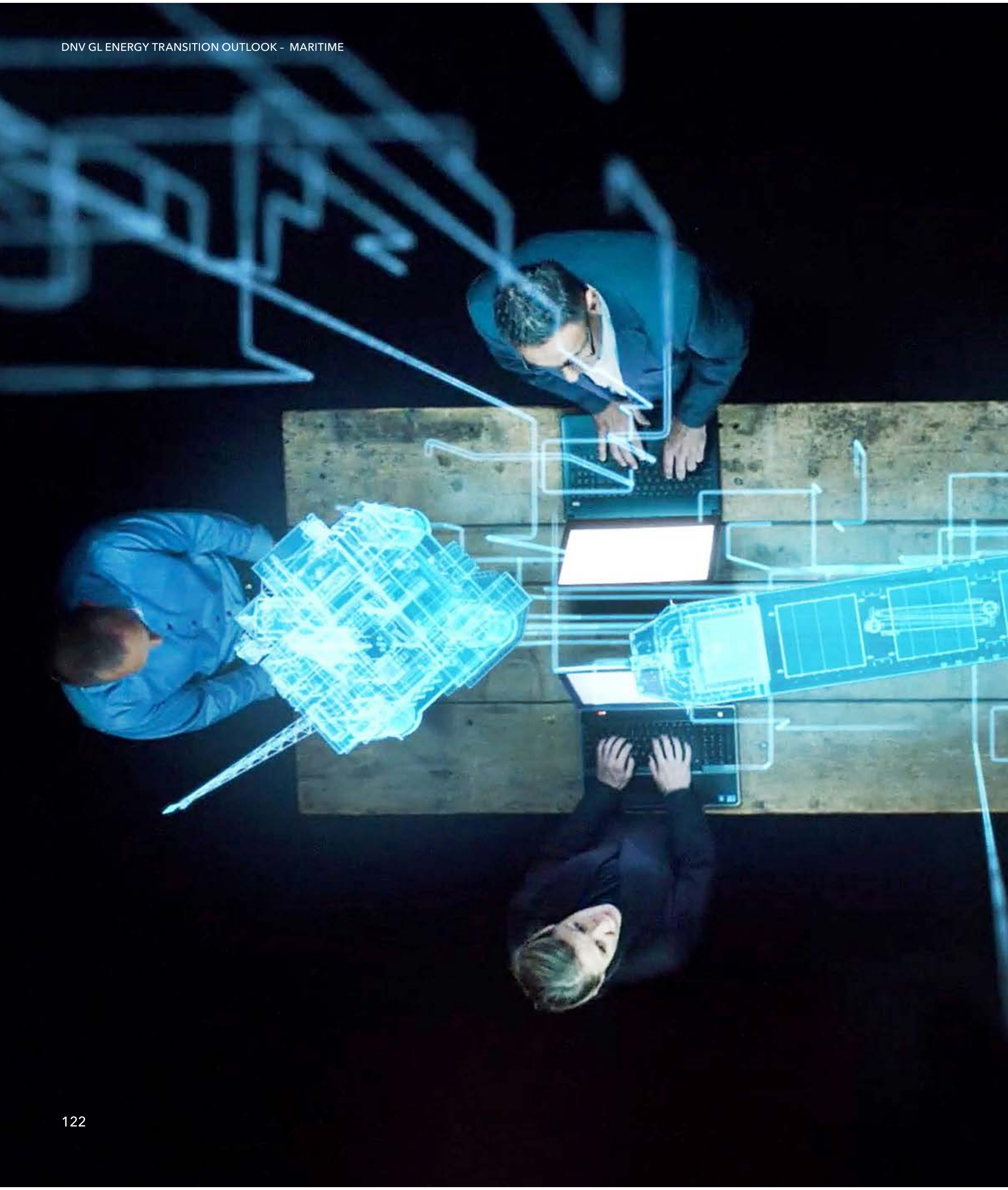
41 'Information economy report 2017', UNCTAD

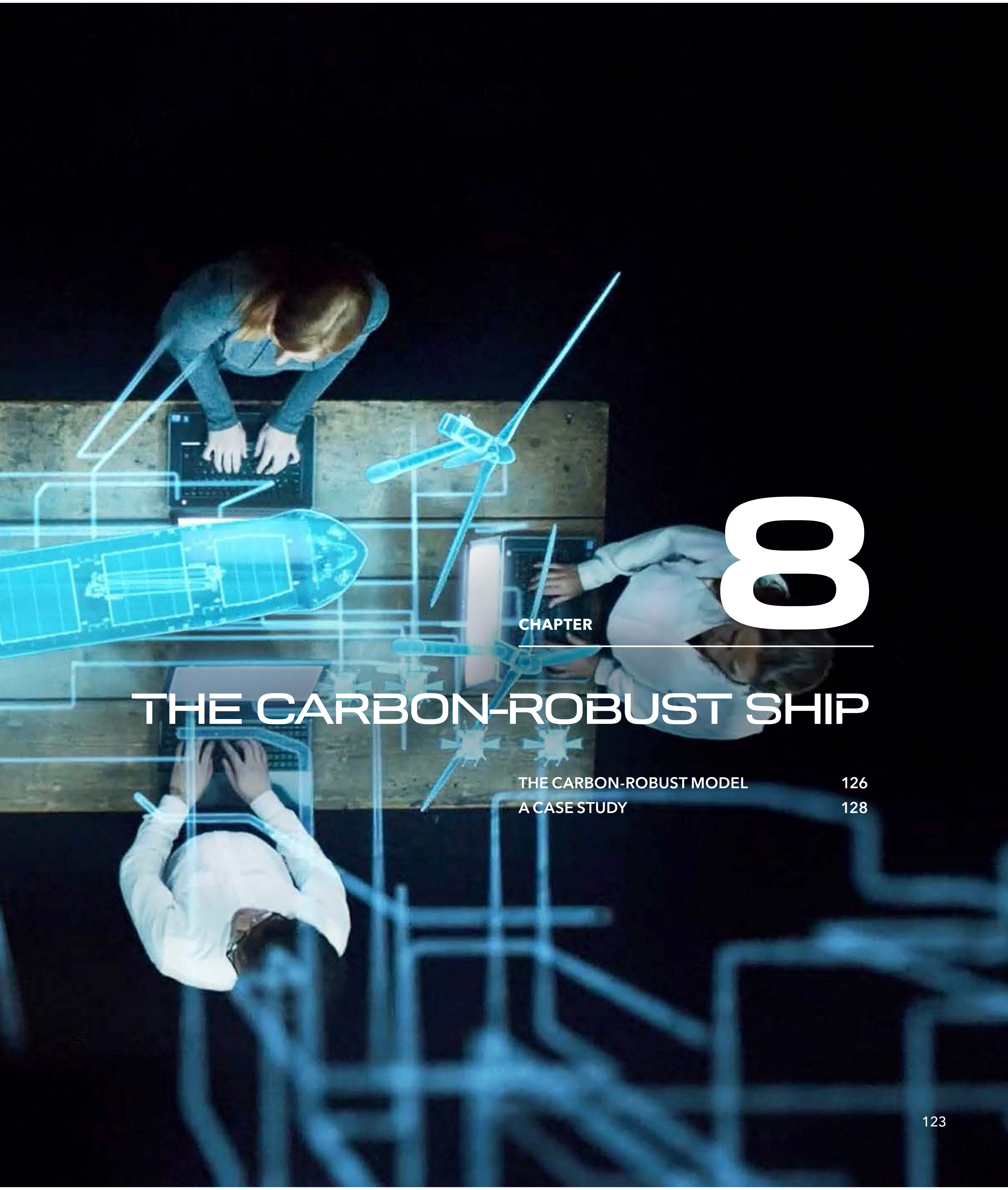
42 '3D printing in the Port of Rotterdam', www.portofrotterdam.com

43 'A new dimension in manufacturing', DNV GL, Maritime Impact, Issue 02-17

44 'New centre to boost 3D printing in oil and gas industry', DNV GL PERSPECTIVES, www,dnvgl.com







CHAPTER

8

THE CARBON-ROBUST SHIP

8 THE CARBON-ROBUST SHIP

Shipowners have always managed risk and uncertainty as a vital part of business. On top of the well-known cyclical ups and downs of shipping markets, history is rich with examples of external shocks or events that have caused significant changes to the industry.

These include commercial game-changers like containerization, technological break-throughs like the transition from sail to steam power, or radical regulations such as the double-hull requirments imposed on tankers. We have seen winners and losers in this ever-evolving business.

Moving forward, the uncertainty facing the industry seems only to increase. As we have seen in the previous chapters, global regulations on CO_2 and local regulation of harmful sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM), are poised to shape the future fleet (chapter 4).

Simultaneously, fuels and technology are developing rapidly, with potential game-changing consequences (chapter 5). Add in 'traditional' worries over market cycles, trade demand (chapter 3), and supply, and there are many uncertainties to consider when investing in new tonnage.

Looking back 50 years, we find very recognizable ships. The main changes have been to ship size and cargo types, and not to design or fuel. But given the trends and drivers mentioned above, it is natural to ask whether ships built 20 or even just 10 years from now will be as similar to today's ships as those built 10-, 20-, or even 50-years ago.

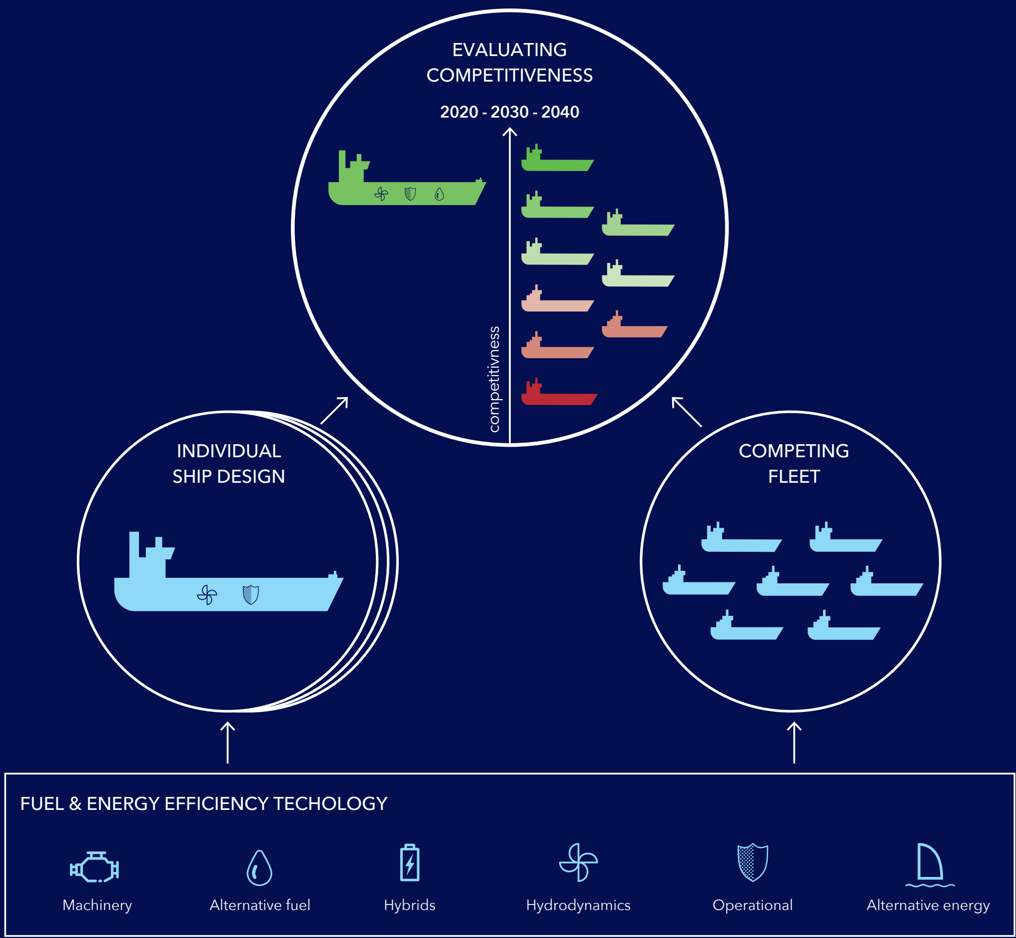
To help navigate this future, and manage the uncertainty, we proposed a carbon-robust ship concept in our 2017 publication (DNV GL, 2017b). The concept was launched as a model for developing ships able to withstand regulatory, fuel, technological, and market shifts. A carbon-robust ship should be designed to be competitive and survive given any decarbonization scenario. Commenting on this concept, the Norwegian Shipowners' Association (2018) states: 'Simply put: managing climate risk, put into in practice.'

In this section, we present a significantly developed version of the concept. The new model evaluates fuel and technology options by comparing the break-even costs of a design to that of the competing fleet of ships. The DNV GL model is named the 'Carbon-Robust Model'. The model's structure is outlined, in Figure 8.0.1, and is briefly described in section 8.1. Going forward, DNV GL aims to use this 'Carbon-Robust Model' to assist shipowners to future-proof their vessels, ensuring long-term competitiveness and profitability as the industry decarbonizes.

In section 8.2 we showcase the model to gain insight into what a carbon-robust bulk carrier would look like under possible future CO_2 regulations and explore a selection of likely scenarios and design options. We draw on our deep knowledge in a number of key areas for this analysis: the future regulatory landscape (chapter 4); fuel and technology options (chapter 5); and fleet development (chapter 6).

FIGURE 8.0.1 OUTLINE OF THE CARBON ROBUST MODEL

Competitiveness of selected individual ship designs is evaluated against the competing fleet of ships at a given point in time (e.g., 2030 or 2040) by comparing the break-even cost or CO_2 emissions as a measure. The user can draw on a pool of fuel and technology options in creating the individual ship designs. For the competing fleet, fuel and technology uptake are governed by pre-set scenarios.



8.1 THE CARBON-ROBUST MODEL

A future-proof, or carbon-robust, ship design is one that performs well both today and in an uncertain low- or zero-carbon shipping industry of the future. Given the level of uncertainty, we have developed a scenario-based model through which we can explore design options and stress-test them for ship or fleet competitiveness for a range of possible carbon and energy futures.

Competitiveness is evaluated by comparing the break-even cost of a proposed ship design to that of the competing fleet of ships at a selected point in time (e.g., 2030 or 2040). The break-even cost is the minimum rate that a ship must secure to cover all costs. Rates above the break-even cost will leave the ship owner with a profit.

The break-even rate is composed of three elements.

- **Capital cost:** This covers the daily costs of financing the vessel. Newbuilding costs and optional technology costs are included. For simplicity, we assume 30% equity, and 70% loan, standard terms, and 20-year repayment. The capital costs reduce over time as the loan is repaid.
- **Operational cost:** This covers the daily cost of crew, maintenance and repairs, stores, etc. Crew cost is assumed to be constant. Maintenance cost increases with age.
- **Voyage cost:** The annual cost of fuel, and port and canal dues. Fuel consumption is calculated, and adjusted for the energy-efficiency level of ships. Fuel price depends on fuel type. Port costs are kept constant.

The model is populated using data from various sources including DNV GL proprietary databases, Stopford (2009), IHS Markit, Clarkson Research, and Drewry (various editions).

8.1.1 INDIVIDUAL SHIP-DESIGN SELECTION AND EVALUATION

The model compares the break-even cost of individual vessel designs to the break-even cost of the competing fleet of ships at a given point in time (e.g., 2030 or 2040). It is designed to allow for easy exploration of different possibilities. In the model front-end, the user selects a set of fuel and technology choices for a vessel to be built in 2020, and the model estimates the CO_2 emission levels and total annual costs. Fuel prices and CO_2 tax levels can be changed from pre-set levels. For simplicity, local emissions to air are not considered to have a cost.

Results for two future scenarios can then be examined. The results are shown for the period between 2020 and 2050. The performance of the vessel is compared with the performance of the rest of the fleet. The break-even distribution for the fleet is utilized in the comparison.

8.1.2 THE COMPETING FLEET

The future competing fleet is constructed for two possible scenarios, each describing a plausible and consistent narrative for the development of the key external drivers and their impact on fleet development (see section 8.2 for examples).

The competing fleet of ships consists of ships currently operating, and ships being added to the fleet in the years to come. As time progresses, the future fleet is constructed by scrapping ships and building new ones. The number of ships to be scrapped and built is governed by the scenario description. Towards 2040 and 2050, the fleet composition is dominated by vessels built after 2020. Each new vessel is allocated an energy-efficiency level, and a fuel type (see the Fuel and Energy-Efficiency Technology module of the model).

The uptake of technology/fuel types is outlined in the scenario description (section 8.2). The two scenarios differ primarily in the implementation of the IMO GHG-reduction strategy, and the resulting uptake of technologies and fuels for new ships. It has been assumed that none of these measures can be installed on existing vessels (i.e., no retrofitting). Other trends could have been included in scenarios; for example the introduction of autonomous ships, or more regulations on local pollution such as SOx, NOx, and PM. However, the number of variables has been kept low to maintain focus on some key issues.

A CO_2 emission level and a break-even cost constructed as described above is assigned to every vessel in the competing fleet.

8.1.3 FUEL AND ENERGY-EFFICIENCY TECHNOLOGIES

A repository of fuels and energy-efficiency measures is available for application in the model. Fuels and energy-efficiency measures are applied to the individual ship designs to be evaluated, and to the ships in the competing fleet.

Each technology element affects the total cost level, ultimately resulting in a total cost distribution for the fleet and the selected vessel designs. The voyage costs depend on the fuel prices, which can be altered in the front-end. CO_2 emissions depend on the selected fuel, and the energy efficiency level. Additional investment costs are added to the capital costs for scrubber technology, battery hybridization, and LNG. The energy-efficiency measures affect the fuel consumption (and thus the voyage costs) and the total CO_2 emissions (and thus the carbon cost). Learning curves are employed to reflect how the investment costs for fuel technologies reduce with time.

8.2 A CASE STUDY

To showcase our model as a framework for analysis, we now explore some possible designs for the bulk carrier segment. The design alternatives include several possible fuel and energy-efficiency technologies. Our reference vessel is a 55,000 deadweight tonnage (DWT) Handy Max bulk carrier, also known as a Supramax. Using the model, we aim to shed light on some key questions for a ship designed today and built in 2020:

- How will an individual design perform relative to the fleet over its lifetime?
- How is the individual design exposed to carbon risk?

THE SEGMENT

Our reference vessel is part of a segment of ships that typically transport minor bulks, grain, and coal. Their main dimensions allow them to call at a vast number of ports and to reach terminals that are often inaccessible for larger ships.

In our model, we make the simplified assumption that all bulk vessels of 50,000–55,000 DWT belong to this segment. At the time of writing this report, there are 603 bulkers in this size segment, corresponding to 31.6 million DWT. The average age of these vessels is 12.4 years, which is one year older than the average age of the entire dry bulk fleet. We model the development of this fleet to assess the competitiveness of our reference vessel, and assume that the fleet will run mainly on MGO (or Low-Sulphur HFO, LSHFO) in 2020, with 10% using HFO in combination with scrubbers.

THE DESIGNS

In our modelling for the reference vessel, we consider ships to be delivered in 2020, which means that no fuel option described in chapter 5 is available. We do not consider electrification or the use of hydrogen. We consider most energy-efficiency measures described to be available, at a cost.

From this menu of options, we consider three easily-distinguishable designs to illustrate the use of the model:

Design A: The standard ship
- Running on MGO/LSHFO
- Standard newbuild energy-efficiency levels; no additional investment

Design B: The LNG-powered ship
- Running on LNG with investment in engine, fuel tanks, and systems
- Standard newbuild energy-efficiency levels; no additional investment

Design C: The fuel-efficient ship
- Running on MGO/LSHFO
- Enhanced levels of energy efficiency, with additional investment.

THE FUTURE FLEET

Scenario: Dull Blue

After adoption of the IMO GHG-reduction strategy, the development of further regulations and measures comes to a standstill, and shipping will not reduce GHG emissions to meet the set targets for 2050. The EEDI is slightly strengthened and only a few policy measures for developing carbon-neutral fuels are initiated.

The delayed introduction of binding regulatory measures from the IMO weakens the incentive for shipowners and providers of technology alike to invest in R&D, piloting, and early-phase market introduction of low-emission technologies.

From 2030, alternative fuels are available in small quantities at a reasonable price. There is a limited uptake, first in short-sea and then, from 2040, in deep-sea. Scrubbers will remain a popular choice, with a significant market share.

Scenario: Bright Green

The IMO's decarbonization vision and 50% GHG emission-reduction ambition for 2050 is followed up by strengthening the EEDI, which impacts increasingly on new designs from 2025. In 2030, the IMO introduces a market-based measure, a fuel levy of USD50 per tonne (/t) of CO_2.

The global IMO regulations are accompanied by a massive R&D and implementation effort to make carbon-neutral fuels available from 2030 onwards. Traditional oil-based fuels are replaced, first by LNG and then by carbon-neutral alternatives. The shift to alternative fuels makes exhaust scrubbers redundant from 2030.

Fuel substitution starts in the coastal and short-sea segment from 2025. Availability of alternative fuels develops first regionally, then globally for the deep-sea segments. Increasing demand for low-carbon transport results from regulation, market pull, and reduced costs due to R&D. It is followed by a scale-up of the application of 'green' ship technology and fuel production and distribution, driving prices even lower for alternative fuels.

Resulting fleet: 2040
A growth rate of 2.6% has been applied in both scenarios, which gives a total of 986 vessels in 2040.

Fuel and energy efficiency in 2040 (Dull Blue)

MGO/LSHFO	75%
HFO + scrubber	17%
LNG	8%

Note: Almost all vessels have baseline energy efficiency

Fuel and energy efficiency in 2040 (Bright Green)

MGO/LSHFO	55%
HFO + scrubber	3%
Battery hybridization	4%
LNG	18%
Biofuels	19%

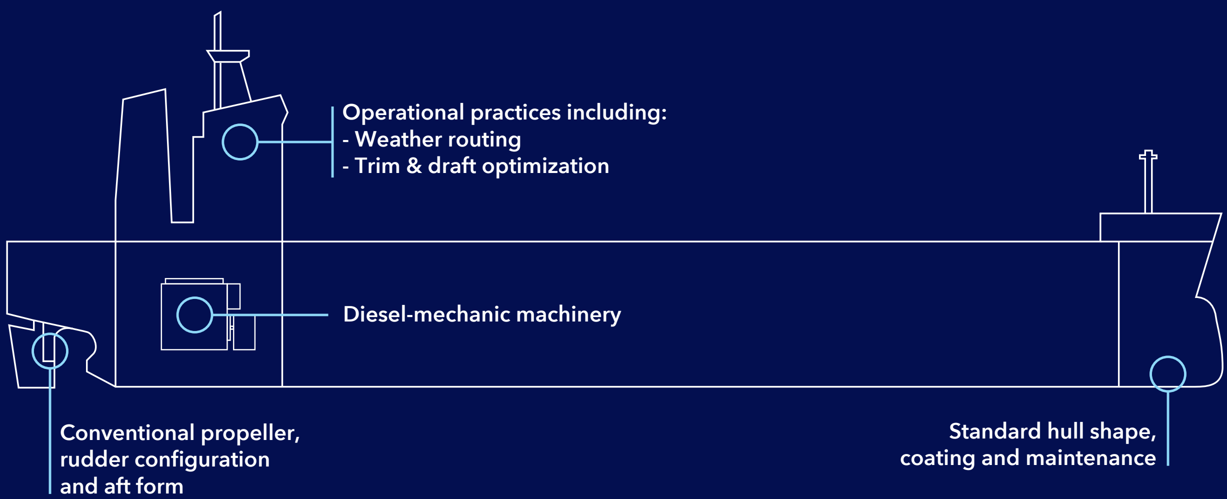
Note: Some 20% of ships have energy-efficiency levels beyond baseline

THE BULK CARRIER CASE STUDY: THREE POSSIBLE DESIGNS

To showcase the carbon-robust model, three bulk carrier design alternatives are presented. These are variations over the same 55,000 DWT Handymax vessel, featuring different fuel and energy-efficiency technology options. The competitiveness of the three designs is assessed using the model, capturing changes to the investment and fuel costs associated with the fuel and technology options.

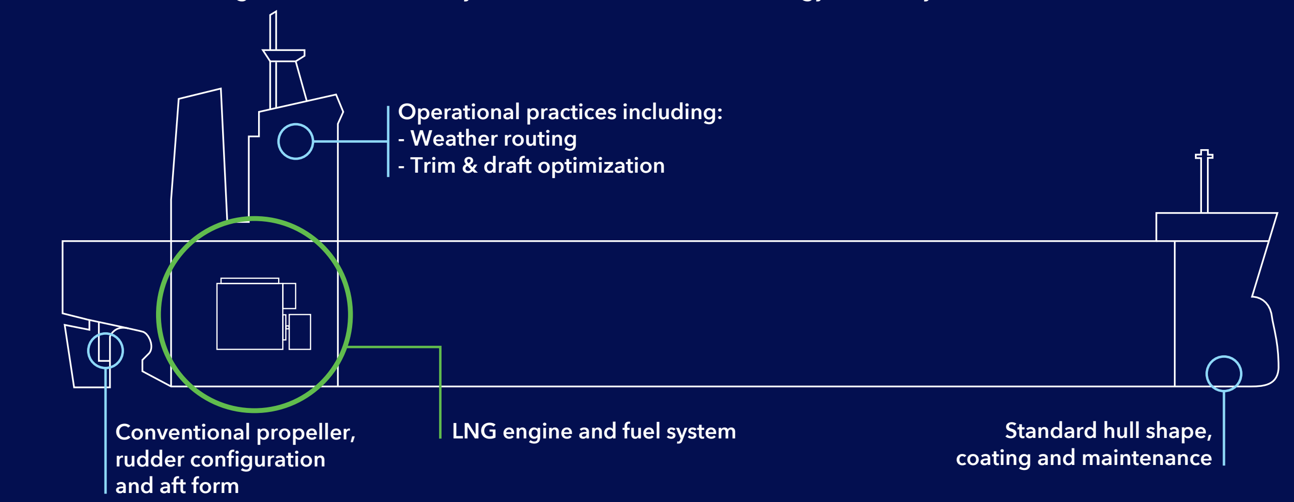
Design A The standard ship

Running on MGO/LSHFO
Standard newbuild energy-efficiency levels, no additional investments



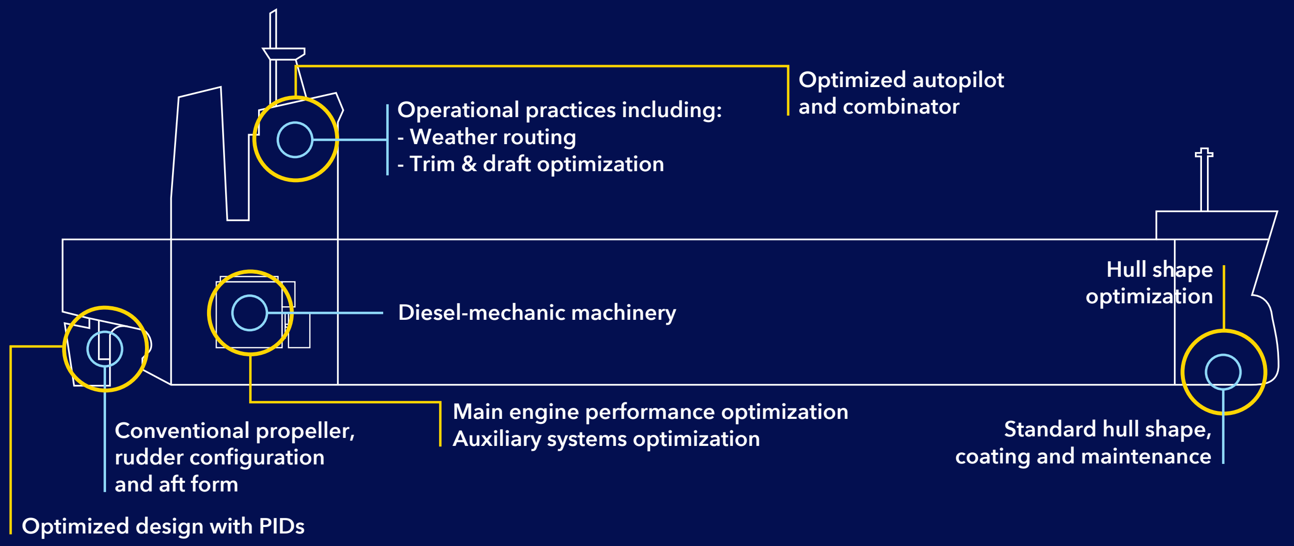
Design B The LNG-powered ship

Running on LNG
Investment in engine, fuel tanks, and systems, standard newbuild energy-efficiency levels, no additional investments



Design C The fuel-efficient ship

Running on MGO/LSHFO
Enhanced levels of energy-efficiency, with additional investments.



RESULTS: DESIGN EVALUATION

We apply the model to the three designs described above for our reference vessel, exploring performance under two different scenarios (see table page 129) that result in different future fleets.

The following fuel and carbon-price assumptions have been applied:

– MGO/LSHFO – USD600 per tonne (/t)
– HFO – USD400/t
– LNG – USD700/t
– CO_2 – USD50/t in the 'Bright Green' scenario, with implementation in 2030

Figure 8.2.1 shows the fleet break-even rate distribution for 2020. For any break-even rate, we show the number of ships in the fleet to which this rate applies. The 2020 distribution is the same in both scenarios as it based on the current fleet. The lower the break-even rate, the higher the potential for profit. The figure shows that most vessels need about USD23,000 per day (/d) (including fuel) to break-even. Some poorly-performing ships need USD25,000/d. The best vessels in the fleet need less than USD18,000/d.

The figure also shows the performance of the three designs for our reference vessel: A, B, and C. In 2020, they are found in the high-cost range of the distribution, reflecting the capital burden of financing new vessels. The standard ship (A) and the fuel-efficient ship (C) perform similarly in 2020, although the more energy-efficient design's break-even rate is slightly better. The LNG-powered ship (B) is struggling with higher costs.

Figure 8.2.2 and 8.2.4 show the fleet changes over time in the 'Dull Blue' scenario. In 2030, the distribution curve has shifted to the left as it now includes more ships with lower break-even rates. The number of ships with rates close to USD25,000/d has declined. In 2040, the curve has shifted even further to the left.

The performance of our reference vessel designs also change with time. In 2030, the energy-efficient ship (C) is performing best, with designs A and B trailing. In 2040, with their debts repaid, our reference-vessel designs are all competing in the low-cost range of the fleet.

Figure 8.2.3 and Figure 8.2.5 show the changes in the fleet over time in the 'Bright Green' scenario. There are significant differences compared to the 'Dull Blue' scenario. The 2030 distribution has shifted to the right, reflecting the USD50/t CO_2 levy that our model imposes on the fleet in 2030. However, in 2040 the distribution shifts back to the left as energy-efficient designs enter the fleet in greater numbers, compensating for the CO_2 levy.

FIGURE 8.2.1

Fleet brake-even rate distribution and break-even daily rate for the three reference vessels, 2020 – both scenarios

Units: Number of vessels

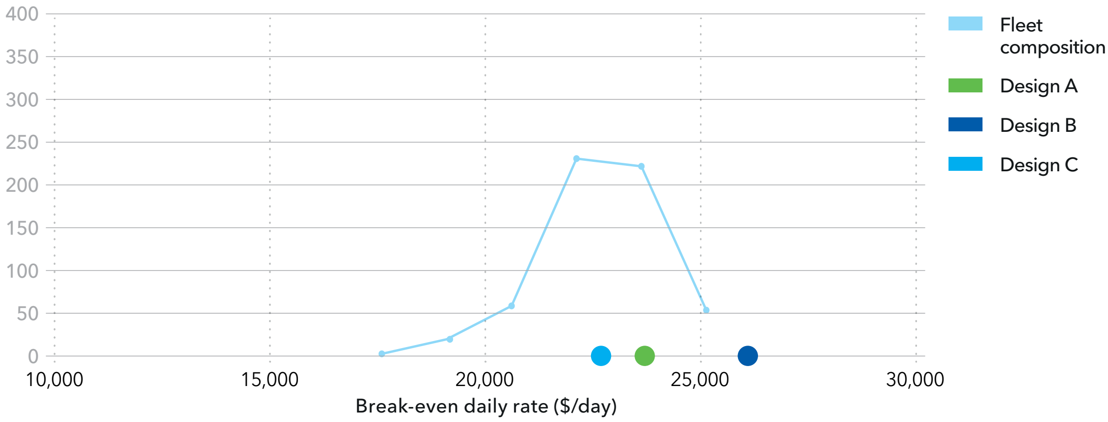


FIGURE 8.2.2

Fleet brake-even rate distribution and break-even daily rate for the three reference vessels, dull blue 2030

Units: Number of vessels

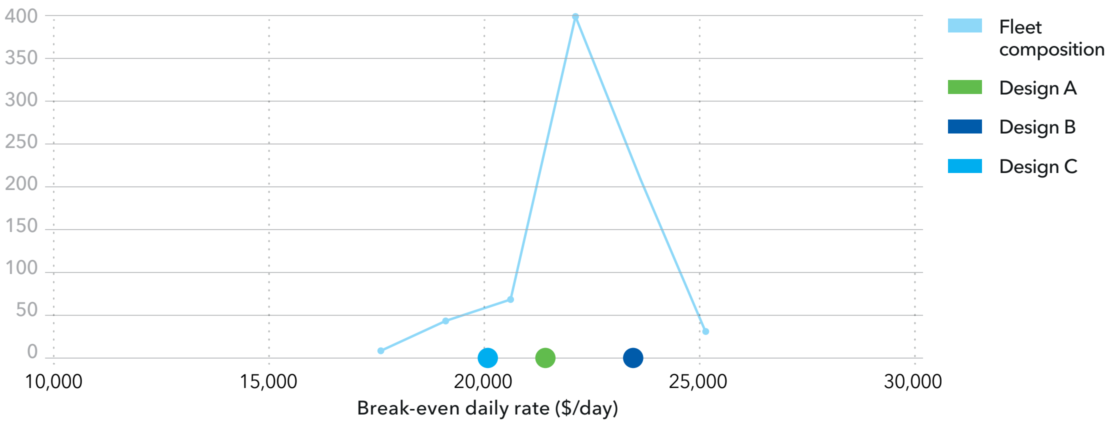


FIGURE 8.2.3

Fleet brake-even rate distribution and break-even daily rate for the three reference vessels, bright green 2030

Units: Number of vessels

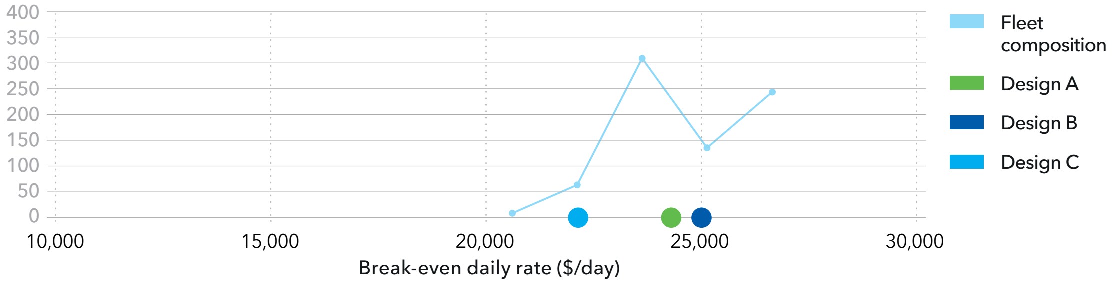


FIGURE 8.2.4

Fleet brake-even rate distribution and break-even daily rate for the three reference vessels, dull blue 2040

Units: Number of vessels

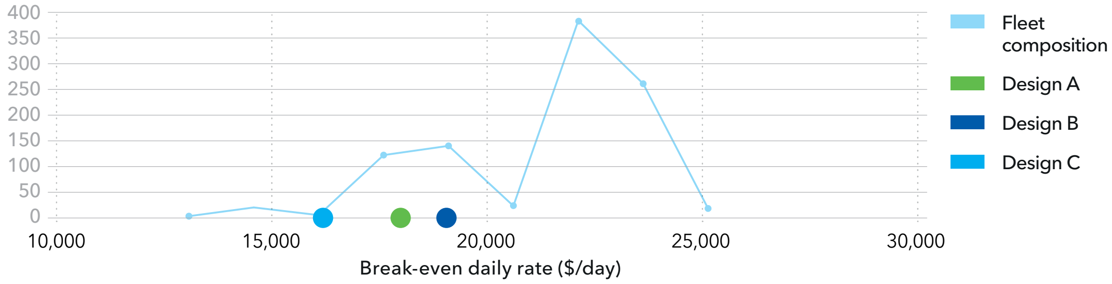


FIGURE 8.2.5

Fleet brake-even rate distribution and break-even daily rate for the three reference vessels, bright green 2040

Units: Number of vessels

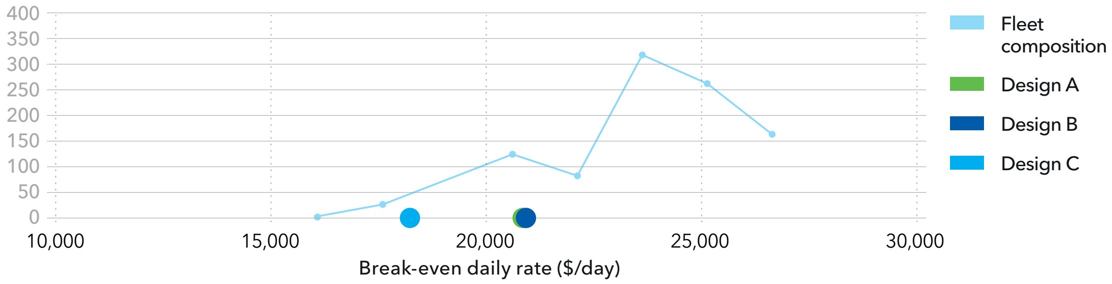


Figure 8.2.6 provides further details for the two scenarios. Here the percentage of the fleet that performs better than our designs are given for 2020, 2030, and 2040. Performance is ranked both on break-even rate and CO_2 emissions.

For the break-even rates, we see the same as in the figures on page 133-134; our vessels struggle to compete in 2020, but the relative performance improves with time. For the LNG-powered ship (B), we see marked improvement in 2030 under the 'Bright Green' scenario.

The numbers for CO_2 performance tell a slightly different story. All three designs perform very well in 2020, competing with older, less efficient ships. In 2040, our designs still perform well in the 'Dull Blue' scenario. However, in the 'Bright Green' scenario, only the LNG-powered vessel (B) is still performing well in 2040, when it is outperformed by only 24% of the competition. At that point, the standard ship (A) has higher emissions than half the fleet, and the energy-efficient ship (C) is not much better.

The modelling of the two scenarios and three designs in Figure 8.2.6 provides a first glimpse of the model's capabilities, and generates useful insights. However, there are numerous other interesting possibilities to explore in relation to the three reference-vessel designs and the development of the fleet.

In the following pages, we use the model to explore some of these options, asking 'what if?' questions to investigate how the designs perform in competition with the fleet throughout their lifetime, and how they are exposed to carbon risk. The answers are compared against the base-case results shown in Figure 8.2.6.

FIGURE 8.2.6

Relative performance of three designs under two scenarios, showing the percentage of the whole fleet that performs better in 2020, 2030, and 2040: performance is ranked both on break-even rate and CO_2 emissions.

	BREAK-EVEN DAILY RATE						CO_2 EMISSIONS					
	Scenario: Dull Blue			Scenario: Bright Green			Scenario: Dull Blue			Scenario: Bright Green		
	2020	2030	2040	2020	2030	2040	2020	2030	2040	2020	2030	2040
Design A	60%	16%	3%	60%	16%	3%	5%	7%	10%	5%	28%	51%
Design B	100%	80%	21%	100%	54%	16%	1%	1%	1%	1%	10%	24%
Design C	52%	8%	3%	52%	7%	3%	1%	4%	9%	1%	19%	38%

WHAT IF THE COST OF FUEL INCREASES?

Fuel prices are highly volatile. Predicting prices two decades ahead is impossible, but how do our designs perform if we assume substantially higher fuel prices? Here, we explore an alternative price scenario in which MGO increases by 25% above our base-case to USD750/t, HFO by 37.5% to USD550/t, and the LNG price is kept constant at USD700/t.

At these higher prices for MGO and HFO, the energy-efficient ship (C) reaps the reward for improved energy efficiency and gains competitiveness under both scenarios, most notably in the short term (Figure 8.2.7). The LNG-powered ship (B) also becomes more competitive as the LNG price is lower in relative terms, and the design outperforms the standard ship (A) in both scenarios. The CO_2 ranking is unchanged.

FIGURE 8.2.7

Relative performance – assuming high fuel prices – of three designs under two scenarios, showing the percentage of the whole fleet that performs better in 2020, 2030, and 2040: performance is ranked both on break-even rate and CO_2 emissions

	BREAK-EVEN DAILY RATE						CO_2 EMISSIONS					
	Scenario: Dull Blue			Scenario: Bright Green			Scenario: Dull Blue			Scenario: Bright Green		
	2020	2030	2040	2020	2030	2040	2020	2030	2040	2020	2030	2040
Design A	60%	16%	3%	60%	28%	11%	5%	7%	10%	5%	28%	51%
Design B	53%	10%	3%	53%	14%	3%	1%	1%	1%	1%	10%	24%
Design C	29%	7%	3%	29%	6%	1%	1%	4%	9%	1%	19%	38%

WHAT IF WE USE HEAVY FUEL OIL WITH EXHAUST SCRUBBERS INSTEAD OF MARINE GAS OIL?

Our reference designs A and C are assumed to run on MGO. How do our results change if the vessels use HFO and exhaust scrubbers, instead of MGO? With fuel prices reset to their original levels as in our base case, we see from Figure 8.2.8 that using HFO substantially improves the break-even performance of A and C in 2020, both ships now being outperformed by only 9% of the competition (compared to 60% for A and 52% for C in the base case). The downside to this is a significantly reduced performance for CO_2 emissions, increasing the exposure to market risk if demand for low-emission vessels increases.

FIGURE 8.2.8

Relative performance – assuming HFO with exhaust scrubber instead of MGO – of three designs under two scenarios, showing the percentage of the whole fleet that performs better in 2020, 2030, and 2040: performance is ranked both on break-even rate and CO_2 emissions.

	BREAK-EVEN DAILY RATE						CO_2 EMISSIONS					
	Scenario: Dull Blue			Scenario: Bright Green			Scenario: Dull Blue			Scenario: Bright Green		
	2020	2030	2040	2020	2030	2040	2020	2030	2040	2020	2030	2040
Design A	9%	1%	1%	9%	1%	1%	64%	75%	81%	64%	82%	95%
Design B	100%	80%	21%	100%	54%	16%	1%	1%	1%	1%	10%	24%
Design C	9%	1%	1%	9%	1%	1%	3%	6%	9%	3%	25%	47%

WHAT IF WE ADD MORE ENERGY-EFFICIENCY MEASURES TO OUR DESIGN?

Investment in energy efficiency is often a good business proposition, but not in all circumstances. What if we further increase investment in energy efficiency for our already energy-efficient ship (C)? And how does the competitiveness of our LNG-powered ship (B) change if energy-efficiency levels increase? Here, we model what happens when we apply all available measures to design C (with default fuel price and fuel choice settings) and we increase the energy efficiency of design B (Figure 8.2.9).

For the modified design C, break-even competitiveness changes little, as the additional capital expenditure is balanced by fuel savings. However, the long-term CO_2 competitiveness is improved. For the LNG-powered ship (modified design B), the impact on break-even competitiveness is clearer, with significant improvements in 2030 and 2040. CO_2 competitiveness is only marginally improved. For both ships, the improvements are more pronounced under the Bright Green scenario.

FIGURE 8.2.9

Relative performance – assuming greater energy-efficiency – of three designs under two scenarios, showing the percentage of the whole fleet that performs better in 2020, 2030, and 2040: performance is ranked both on break-even rate and CO_2 emissions

	BREAK-EVEN DAILY RATE						CO_2 EMISSIONS					
	Scenario: Dull Blue			Scenario: Bright Green			Scenario: Dull Blue			Scenario: Bright Green		
	2020	2030	2040	2020	2030	2040	2020	2030	2040	2020	2030	2040
Design A	60%	16%	3%	60%	16%	3%	5%	7%	10%	5%	28%	51%
Design B	91%	50%	3%	91%	10%	3%	1%	1%	1%	1%	7%	19%
Design C	53%	8%	3%	53%	1%	1%	1%	1%	1%	1%	9%	23%

WHAT IF WE SELECT A LNG-READY CONCEPT?

An LNG-ready concept implies building the ship with conventional MGO/HFO fuel technology, but preparing the vessel to allow a less-costly LNG retrofit later. In the model, we recast the energy-efficient ship design (C) as an LNG-ready vessel. An initial investment of 1% of the newbuild price is added, and, in 2030, when the vessel is retrofitted, the cost of the LNG technology and a 20% retrofit extra cost is added. This investment takes into account the fuel technology learning curve mentioned in Section 8.1.3. The LNG price is set to the default USD700/t in 2020 but 29% lower at USD500/t in 2030 and 2040, thus incentivizing the switch to LNG.

From Figure 8.2.10 we see that the LNG-ready vessel (design C modified) is placed at a disadvantage compared with the standard ship (design A) when judged by break-even rates in 2020, but performs better than the LNG-powered vessel (design B). In 2030, with the LNG price now lower, the LNG-ready vessel performs better or equal to design A, but not as well as design B, the LNG-powered ship. In terms of CO_2 emissions, design C performs similarly to design A (fuelled by MGO) before the implementation of LNG technology in 2030, after which it performs similarly to design B (LNG-powered). In 2040, large parts of the competitive fleet have paid off their debts and become more competitive relative to the LNG-ready vessel.

FIGURE 8.2.10

Relative performance – assuming LNG-ready Design C with baseline energy-efficiency technology – of three designs under two scenarios, showing the percentage of the whole fleet that performs better in 2020, 2030, and 2040: performance is ranked both on break-even rate and CO_2 emissions

	BREAK-EVEN DAILY RATE						CO_2 EMISSIONS					
	Scenario: Dull Blue			Scenario: Bright Green			Scenario: Dull Blue			Scenario: Bright Green		
	2020	2030	2040	2020	2030	2040	2020	2030	2040	2020	2030	2040
Design A	60 %	16 %	3 %	60 %	28 %	5 %	5 %	7 %	10 %	5 %	28 %	51 %
Design B	100 %	10 %	3 %	100 %	8 %	1 %	1 %	1 %	1 %	1 %	10 %	24 %
Design C	81 %	16 %	21 %	81 %	13 %	18 %	5 %	1 %	1 %	5 %	10 %	24 %

CASE SUMMARY

Although limited to a specific ship segment, the case study presented offers some valuable insights. We see significant differences in competitiveness over the life of a vessel under varying scenarios. The results indicate that the energy-efficient ship (design C) is the most robust choice in terms of break-even competitiveness, striking a balance between short-term and long-term interest. The design performs adequately under both scenarios.

In comparison, the standard ship faces the risk of being outperformed under several likely conditions. The LNG vessel struggles with high investment costs, and fuel prices that are advantageous only under certain conditions. The LNG-ready case seems to be economically feasible only if emphasis is placed on the Bright Green scenario.

Adding exhaust scrubbers make sense, given the HFO/MGO price, but risks creating a ship with relatively low CO_2 performance. The case study also reveals that vulnerability to CO_2 ranking is potentially high, and could easily expose an owner to significant market and carbon price risk in 2030 and 2040. In this respect, the LNG vessel (design B) is a safer choice, although design C – the energy efficient ship – perhaps performs adequately.

The above conclusions come with some important caveats. First, the sensitivity to fuel prices is high, and should be rigorously examined. Also, only a limited set of technologies and fuels have been applied in the specifications of the reference vessels. Thus, further exploration of additional scenarios and designs is needed to reach firm conclusions.

Second, this case study only explores a bare minimum of two fleet scenarios, leaving out several highly relevant scenarios. To properly manage the risk of becoming a stranded asset, more scenarios should be explored to assess the probability and consequences of these. Several relevant aspects have not been considered in this case study. This includes the potential game-changers outlined in section 7.2, shifts in transport demand, and the impacts of digitalization and innovation. Future studies should be shipowner specific, and could further explore;

- The impact of local, national, and regional requirements to reduce harmful emissions to air
- Impacts on the fleet from various forms of regulation, including ship speed limits
- The possibilities for designing vessels with speed flexibility
- Scenarios that vary trade volumes and fleet growth rates
- Ship designs with high degrees of automation/autonomy
- Scenarios that assume different carbon prices.

In addition, the results presented here apply to a narrow fleet segment, the bulk fleet of 50,000–55,000 DWT used in the case study. Extrapolating to other segments should be done with caution. Further studies should be case-specific and explorative rather than trying to cover all possible scenarios.

Different stakeholders could be interested in analysing separate cost items, not only the total break-even rate. Many shipowners do not pay the fuel bill for their vessel; the charterer does. This makes it more interesting for owners to keep the capital and operational costs low, as these are the items that must be covered by the rate they receive. Investments in fuel and energy-efficiency technology is only of interest if the additional investment is recouped by receiving premium freight rates, or if it makes the vessel first pick, thus avoiding off-hire. Various perspectives can be explored with the model to investigate individual cost items in detail. It can also be used for stake-holders wishing to analyse barriers to the uptake of alternative fuels and technologies. Robustness costs and certainty on future expectations and requirements are powerful drivers for uptake.

The case study outlined above provides important new knowledge. However, it is worth re-emphasizing that the scenarios described are limited in complexity and variability, and that additional parameters could be included to gain even more insights for making informed business or policy decisions.

In this report, we have explored the implications of a global transition towards an increased use of renewable energy and a diminishing use of fossil fuels, which is underway and will progress towards mid-century.

As discussed, uncertainty is high. However, we believe that this uncertainty is manageable.
By applying a structured, knowledge-based approach, supported by modelling tools and expert assessment, stakeholders can stay ahead of industry developments and remain competitive moving forward.

REFERENCES

1 Acciaro et al. (2013), 'The energy efficiency cap in maritime transport, Journal of Shipping and Ocean Engineering', Vol.3, No. 12, 2013, pp1–10
2 Andersson P. (2017), 'Green approaches at sea – The benefits of adjusting speed instead of anchoring', Transportation Research Part D: Transport and Environment, Vol.51, March 2017, pp240–249
3 Bengtsson, S. et al. (2011), 'A comparative life cycle assessment of marine fuels liquefied natural gas and three other fossil fuels', Department of Shipping and Marine Technology, Chalmers University of Technology, Gothenburg, Sweden, 2011
4 Bouman E.A. et al. (2017), 'State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review', Transportation Research Part D: Transport and Environment, Vol.52, Part A, May 2017, pp408–421
5 Brynolf S. (2014), 'Environmental assessment of present and future marine fuels, thesis for the degree of doctor of philosophy', Chalmers University of Technology, Sweden
6 Brynolf S. (2018), 'Electrofuels for the transport sector: A review of production costs', Renewable and Sustainable Energy Reviews, Vol.81, 2018, pp1887–1905
7 Buhaug Ø. et al., 'Second IMO GHG study 2009, International Maritime Organization (IMO)', London, UK, April 2009
8 Chryssakis C., Stahl S. (2013), 'Well-to-propeller analysis of alternative fuels for maritime applications', Paper No. 265, CIMAC Congress 2013
9 Corbett et al. (2008), 'Mortality from ship emission: A global assessment', Environmental Science and Technology, Vol.41 (24):8512-8,·January 2008
10 CE Delft (2012), 'Regulated slow steaming in maritime transport, An assessment of options, cost and benefits', CE Delft, February 2012
11 CE Delft (2017a), 'Regulating speed: a short-term measure to reduce maritime GHG emissions'
12 CE Delft (2017b), 'Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships'
13 De Backer K. and Flaig D. (2017), 'The future of global value chains: 'Business as usual or 'a new normal'?', OECD Science, Technology and Industry Policy Papers, No. 41, 2017, OECD Publishing, Paris
14 Deniz C. and Zincir B. (2016), 'Environmental and economical assessment of alternative marine fuels', Journal of Cleaner Production, Vol.113, 1 February 2016, pp438–449
15 Dimopoulos G.G., Stefanatos I.C. and Kakalis N.M.P. (2016b), 'Exergy analysis and optimisation of a marine molten carbonate fuel cell system in simple and combined cycle configuration', Energy Conversion and Management, Vol.107, pp10-21, January 2016
16 Dimopoulos G.G., Georgopoulou C.A., Stefanatos I.C., Zymaris A.S., Kakalis N.M.P. (2014), 'A general-purpose process modelling framework for marine energy systems', Energy Conversion and Management, Vol.86(0), 2014, pp325-339
17 DNV GL (2018a), 'Energy Transition 2018: A global and regional forecast of the energy transition to 2050', DNV GL, August 2018
18 DNV GL (2018c), 'The effect of reducing cruise ship speed in the World Heritage fjords', DNV GL rep. 2018-0260, Rev. 2
19 DNV GL (2018d), 'ASEAN ship emission inventory', DNV GL rep., 2018-0260, Rev. 0
20 DNV GL (2018e), 'Towards unmanned ships?', DNV GL position paper
21 DNV GL (2018f), 'Assessment of selected alternative fuels and technologies', DNV GL position paper
22 DNV GL (2017a), 'LPG as a marine fuel', DNV GL position paper https://www.dnvgl.com/technology-innovation/sri/maritime-transport/publications.html

23 DNV GL (2017b), 'Energy Transition Outlook 2017: Maritime forecast to 2050, DNV GL, December 2017' https://eto.dnvgl.com/2017/maritime
24 DNV GL (2017c), 'Low carbon shipping towards 2050, DNV GL, June 2017' https://www.dnvgl.com/publications/low-carbon-shipping-towards-2050-93579
25 DNV GL (2017d), 'Study on the use of fuel cells in shipping', for European Maritime Safety Agency (EMSA), Publ. online at www.emsa.europa.eu, 2017
26 DNV GL (2017e), 'Sustainable Development Goals: Exploring maritime opportunities, Report for the Norwegian Shipowners' Association', 2017. Available at: https://www.rederi.no/globalassets/dokumenter-en/all/fagomrader/smi/dnv-gl-sdg-maritime-report.pdf
27 DNV GL (2017f), 'Digital twins at work in maritime and energy: Tackling real world costs, tight margins and safety challenges with virtual tools', DNV GL, February 2017
28 DNV GL (2017g), 'Energy Transition Outlook 2017: A global and regional forecast of the energy transition to 2050', DNV GL, September 2017
29 DNV GL (2017i), 'Navigating a low-carbon future, DNV GL report 2017-0205 for the Norwegian Shipowners' Association', 2017
30 DNV GL (2016), 'Teknologier og tiltak for energieffektivisering av skip [in Norwegian]', DNV GL report 2016-0511
31 DNV GL (2015), 'The fuel trilemma: Next generation of marine fuels', DNV GL position paper 03-2015
32 DNV GL (2014a), 'AIS ship movement data: Creating a bird's-eye view on shipping', DNV GL maritime white paper, 2014
33 DNV GL (2014b), 'Alternative fuels for shipping, DNV GL strategic research and innovation position paper 1-2014'
34 DNV (2013), 'Hybrid ships', DNV position paper 15, 2013
35 DNV (2012a), 'Fuel cells for ships', DNV position paper 13, 2012
36 DNV (2012b), 'Identifying and overcoming barriers to the implementation of emission reduction measures in shipping', DNV Report No. 2010-1800
37 DNV (2010), 'Assessment of measures to reduce future CO_2 emissions from shipping', DNV Position Paper 05.
38 Eide, M.S., Chryssakis, C., and Endresen Ø. (2013), 'CO_2 abatement potential towards 2050 for shipping including alternative fuels', Carbon Management, June, Vol.4, No.3, pp275–289
39 Eide, M., Longva T., Hoffmann P., Endresen Ø., Dalsøren S. (2011), 'Future cost scenarios for reduction of ship CO_2 emissions (2011)', Maritime Policy & Management, Vol.38:1, pp11–37
40 Endresen, Ø., Sørgård E., Sundet J. K. , Dalsøren S. B., Isaksen I. S. A., Berglen T. F., and Gravir G., (2003), 'Emission from international sea transportation and environmental impact', Journal of Geophysical Research, 108 (D17), 4560, doi:10.1029/2002JD002898, 2003
41 Fang I. et al (2013), 'Global Marine Trends 2030', Lloyd's Register, QinetiQ and University of Strathclyde, 2013
42 Festel G. et al. (2014), 'Modelling production cost scenarios for biofuels and fossil fuels in Europe', Journal of Cleaner Production Vol.66, 2016, pp242–253
43 Gilbert P. et al. (2018), 'Assessment of full life-cycle emissions of alternative shipping fuels', Journal of Cleaner Production, Vol.172, 20 January 2018, pp855–866
44 Hansson J. and Grahn M. (2016), 'The potential role of electrofuels as marine fuel: A cost effective option for the future shipping sector?', Conference proceedings, Shipping in Changing Climates (SCC), Newcastle, UK, 10–11 November 2016
45 Hansson J., Grahn M. and Månsson S. (2017), Assessment of the possibilities for selected alternative fuels for the maritime sector, Conference proceedings, Shipping in Changing Climates (SCC), London, September 2017

46 IEA (2017), 'Biofuels for the marine shipping sector: An overview and analysis of sector infrastructure, fuel technologies and regulations', IEA Bioenergy: Task 39, 2017
47 IEA (2014), 'Alternative fuels for marine applications', IEA, 2014
48 IMO (2011), 'Reduction of GHG emissions from ships: Marginal abatement cost and cost effectiveness of energy-efficiency measures', IMO, MEPC 62/INF.7, 2017
49 ISO (2017), 'International standard 8217, Petroleum products – Fuels (class F) – Specifications of marine fuels', Sixth edition, ISO 8217:2017(E)
50 Lindstad. H and Eskeland G.S. (2015), 'Low carbon maritime transport: How speed, size and slenderness amounts to substantial capital energy substitution', Transportation Research Part D, Vol.41, 2015, pp244–256
51 Longva T. (2011), 'A new queuing policy in ports', Proceedings of MTEC2011, Singapore, 13–15 April 2011
52 Månsson S. (2017), 'Prospects for renewable marine fuels: A multi-criteria decision analysis of alternative fuels for the maritime sector', Master's thesis, Chalmers University of Technology, Göteborg, Sweden, 2017
53 Maritime Battery Forum (2018), data provided on development of all-electric and battery-hybrid ships currently operating or on order, http://maritimebatteryforum.com/
54 Maritime Knowledge Centre, TNO & TU Delft (2017), 'Framework CO_2 reduction in Shipping', 16 January 2017
55 Mjelde A., Martinsen K., Eide M., Endresen Ø. (2014), 'Environmental accounting for Arctic shipping – A framework building on ship tracking data from satellites', Marine Pollution Bulletin, Vol.87, October 2014, pp22–28
56 Norwegian Shipowners' Association (2018), 'Think Ocean', Maritime Outlook Report 2018, February 2018.
57 OECD (2018), 'Decarbonising maritime transport by 2035', OECD, 26 March 2018 https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport.pdf
58 OECD/ITF (International Transport Forum) (2017), 'ITF Transport Outlook 2017', ISBN 978-9282108000
59 OECD/ITF (International Transport Forum) (2016), 'Capacity to grow: Transport infrastructure needs for future trade growth' http://www.itf-oecd.org/sites/default/files/docs/future-growth-transport-infrastructure.pdf
60 OECD (2014), 'International freight and related CO_2 emissions by 2050: A new modelling tool'
61 Ovrum E., Dimopoulos G. (2011), 'A validated dynamic model of the first marine molten carbonate fuel cell', Applied Thermal Engineering, Volume 35, March 2012, Pages 15-28
62 Rehmatulla et al. (2015), 'The diffusion of energy efficiency technologies in shipping', International Conference on Shipping in Changing Climates, Glasgow, UK, 2015
63 Rehmatulla N. & Smith T. (2015), 'Barriers to energy efficiency in shipping: A triangulated approach to investigate the principal agent problem', Energy Policy, Vol. 84, September 2015, pp44–57
64 Røsæg E. (2009), 'A system for queuing in ports', Scandinavian Institute of Maritime Law Yearbook 2008, Sjørettsfondet 2009
65 Sandia report (2017), 'Practical application limits of fuel cells and batteries for zero emission vessels', Sandia National Laboratory, United States: N. p., 2017. Web. doi:10.2172/1410178
66 Sharmina et al. (2017), 'Global energy scenarios and their implications for future shipped trade', Marine Policy, Vol.84, 2017, pp12–21

67 Schøyen H. and Steger-Jensen K. (2017), 'Nuclear propulsion in ocean merchant shipping: The role of historical experiments to gain insight into possible future applications', Journal of Cleaner Production, Vol.169, 2017, 152–160
68 Shell (2017), 'Energy of the Future? Sustainable Mobility through Fuel Cells and H2', Shell/ Wuppertal Hydrogen Study. https://epub.wupperinst.org/frontdoor/deliver/index/docId/6786/file/6786_Hydrogen_Study.pdf
69 Sofive I, Winebrake J.J. et al. (2018), 'Cleaner fuels for ships provide public health benefits with climate tradeoffs', Nature Communications, Vol. 9, Article number 406, February 2018
70 Smith T., Raucci C., Haji Hosseinloo S., Rojon I., Calleya J., Suárez de la Fuente S., Wu P., Palmer K (2016), 'CO_2 emissions from international shipping: Possible reduction targets and their associated pathways', Prepared by UMAS, October 2016, London, UK
71 Smith T., et al (2014), 'Third IMO GHG Study 2014'; International Maritime Organization (IMO) London, UK, June 2014.
72 Stefanatos I.C. et al. (2014), 'Modelling and simulation of crude-oil tankers discharge operations', In Proc. 26th International Conference on Energy, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS), 15–19 June 2014, Turku, Finland
73 Stefanatos I.C. et al. (2015), 'Model-based thermoeconomic assessment and selection of alternative configurations for crude-oil tankers discharge systems', 28th International Conference on Energy, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS), 29 June–3 July 2015, Pau, France
74 Stopford M. (2009), 'Maritime economics – 3rd edition', Publ. Routledge, ISBN 978-0415275583
75 van Eijck J., Batidzirai B., Faaij A. (2014), 'Current and future economic performance of first and second generation biofuels in developing countries', Applied Energy, 2014, Vol. 135, issue C, 2014, pp115–141
76 Zincir B. and Deniz C. (2018), 'Maritime industry developments related to alternative fuels', 3rd International Naval Architecture and Maritime Symposium (INT-NAM 2018), 23–25 April 2018, Istanbul, Turkey

HISTORICAL DATA

This work is partially based on the World Energy Balances database developed by the International Energy Agency, © OECD/IEA 2016, 2017, 2018 but the resulting work has been prepared by DNV GL and does not necessarily reflect the views of the International Energy Agency.

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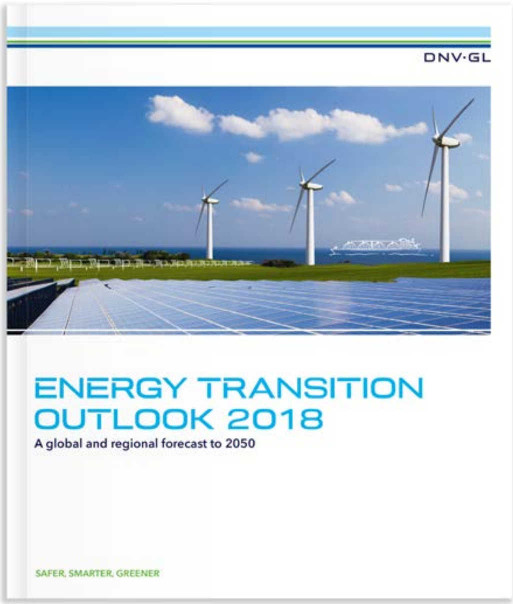
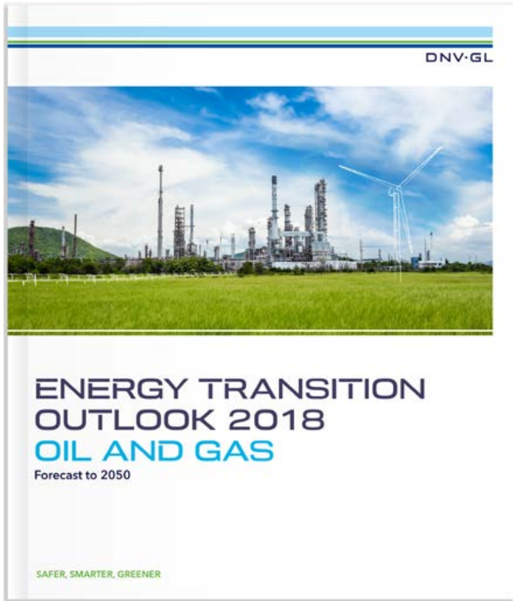
ENERGY TRANSITION OUTLOOK 2018 REPORTS OVERVIEW





ENERGY TRANSITION OUTLOOK

Our main publication deals with our model-based forecast of the world's energy system through to 2050. It gives our independent view of what we consider 'our best estimate' for the coming energy transition. The report covers:

The DNV GL Model and our main assumptions, on population, productivity, technology, costs and the role of policy and governments.

Our outlook for global energy demand for transport, buildings and manufacturing, energy supply for each energy carrier, energy efficiency and expenditures.

Regional energy outlooks for each of our 10 regions.

The climate implications of our outlook and an assessment of how to close the gap to 2°C.

OIL & GAS

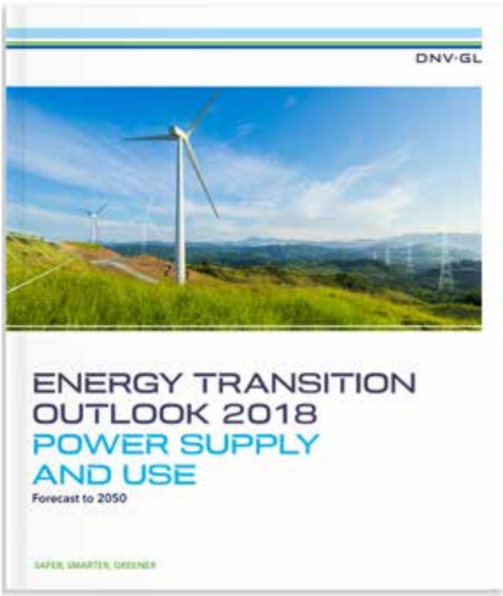
Our oil and gas report underlines the continued importance of these hydrocarbons for the world's energy future. It forecasts several trends:

Gas will overtake oil to become the largest energy source in 2026, and industry efforts will be directed accordingly.

Production is likely to come from a greater number of smaller, more technicallychall-enging reservoirs, with shorter lifespans.

Investment in pipeline and LNG infrastructure will increase to connect new sources of supply with changing demand centres.

New gases will enter distribution networks, and lifecycle performance will come under increasing focus for the refining and petro-chemical industries.



POWER SUPPLY AND USE

This report presents implications of our energy forecast for key stakeholders in the power industry, including electricity generation, which includes renewables; electricity transmission and distribution; and energy use. Amidst electricity consumption increasing rapidly and production becoming dominated by renewables, the report details important industry implications. These include:

Deep and widespread change involving established energy industry players.

The need for increased use of market mechanisms and changes to the electricity markets and regulation.

Massive expansion and automation of transmission and distribution network.

Rapid expansion of electric vehicles.

MARITIME

In our Maritime Forecast to 2050, we present our wider outlook for the maritime industry.
The report details:

– Outlooks for seaborne trade; for regulatory development; as well as fuels and technology
– Implications for the world fleet, including future energy mix and greenhouse gas emissions.

The report ends by presenting a significant development of the 'carbon robust ship concept'; a structured, knowledge-based approach to handling uncertainty – supported by modelling tools – which allows stakeholders to stay ahead of industry developments and remain competitive moving forward.

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