COURSE TO ZERO

Handbook for decarbonization of shipping

Maritime Bergen

Project name:		DNV AS Maritime
Report title:	Handbook for decarbonization of shipping	Environment Advisory
Customer:	Maritime Bergen, Olav Kyrresgate 11, 5014 Bergen	Veritasveien 1
Customer contact:	Siv Remøy-Vangen	1363 Høvik
Date of issue:	2021-11-26	Norway
Project No.:	10292878	Tel:
Organisation unit:	Environment Advisory	
Report No.:	2021-0975, Rev. 0	
Document No.:		

Applicable contract(s) governing the provision of this Report:

Objective:

Development of a decarbonization handbook

Prepared by:	Verified by:	Approved by:
Øyvind Sekkesæter Environmental Consultant	Øyvind Endresen Senior Principal Consultant	Terje Sverud Head of Section
Ola G. Skåre Environmental Consultant	Magnus S. Eide Principal Consultant	
Jon Leonhardsen Environmental Consultant		

DNV Distribution:

☐ OPEN. Unrestricted distribution, internal and external.

☒ INTERNAL use only. Internal DNV document.

☐ CONFIDENTIAL. Distribution within DNV according to applicable contract.*

☐ SECRET. Authorized access only.

*Specify distribution:

Keywords:
Handbook
Decarbonization of shipping
Carbon risk

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
0	2021-11-26	First issue	Øyvind Sekkesæter	Magnus S. Eide	Terje Sverud

Table of contents

EXECUTIVE SUMMARY

The topic of sustainability is rising rapidly up the agenda for governments, businesses, and the public. Greater regulatory and business focus on sustainability is increasingly affecting core operations in every industry, and shipping is no exception. This *Handbook for Decarbonization of Shipping* ('the Handbook') is intended to enhance a shipowner's ability to navigate this evolving and complex landscape, with a special focus on decarbonization. It can also help other stakeholders in the maritime value chain – including financial institutions and investors – to understand and adapt to forthcoming trends and technological changes.

The Handbook provides practical guidance on how to manage decarbonization risk in a structured way, ensuring that individual ships comply with their respective target carbon intensity trajectories over their lifetimes. To our knowledge, a practical handbook like this has never before been published for this purpose.

The Handbook starts by elaborating on the term 'sustainability', and on shipping's environmental footprint, providing clarity on a range of terms and expressions that are often used, but too often misunderstood causing confusion and uncertainty. There are also references to relevant literature sources and standards that could provide deeper insight.

We then narrow the scope and focus on key drivers of decarbonization in the sector. Three of these can incentivize decarbonization in different ways:

- First, regulations and policies will place direct requirements on ships and shipping companies.
- Second, expectations from cargo owners, and access to investors and capital, will increasingly favour environmentally friendly shipping – for example, through higher chartering fees or access to low-cost financing.
- Third, in response to the increasing pressures to decarbonize, shipowners must apply low- and zero-emission technologies and fuels.

This handbook describes the solutions available or under development which may enable the necessary greenhouse gas emission reductions. These abatement measures for a ship can be categorized into four groups:

1) Energy-efficiency measures, either technical or operational
2) Alternative fuel technologies
3) 'Harvesting' energy from the surroundings -– reducing power demand
4) After-treatment – onboard carbon capture and storage

Again, we provide references to relevant literature sources and databases that could provide deeper insight. It is important to keep in mind that the technical applicability of various abatement measures will vary greatly for different ship types and trades. Newbuilds will have more options available than ships in operation.

Crucially, the Handbook presents a practical framework for assessing and mitigating decarbonization risk for ships, incorporating the insights presented previously on the drivers for decarbonization, and on the technologies and fuels available to achieve specific decarbonization ambitions. Figure 1 illustrates our three-step framework for managing decarbonization risk for either newbuilds or existing vessels.

Figure 1 A three-step framework for managing decarbonization risk, building on previously presented approaches (DNV GL, 2018a, 2019a; DNV, 2021a), and related DNV services[1].

Figure 2 visualizes steps 1 and 2 of our framework for assessing decarbonization risk. First, a target (GHG) trajectory is selected, a baseline vessel is defined, and the compliance status of the vessel can be seen as the period before the vessel intersects with the target trajectory. Second, different compliance strategies are developed (*Strategy 1* and *Strategy 2*), and the most robust strategy is used as the basis for developing a roadmap with one or more decarbonization measures included.

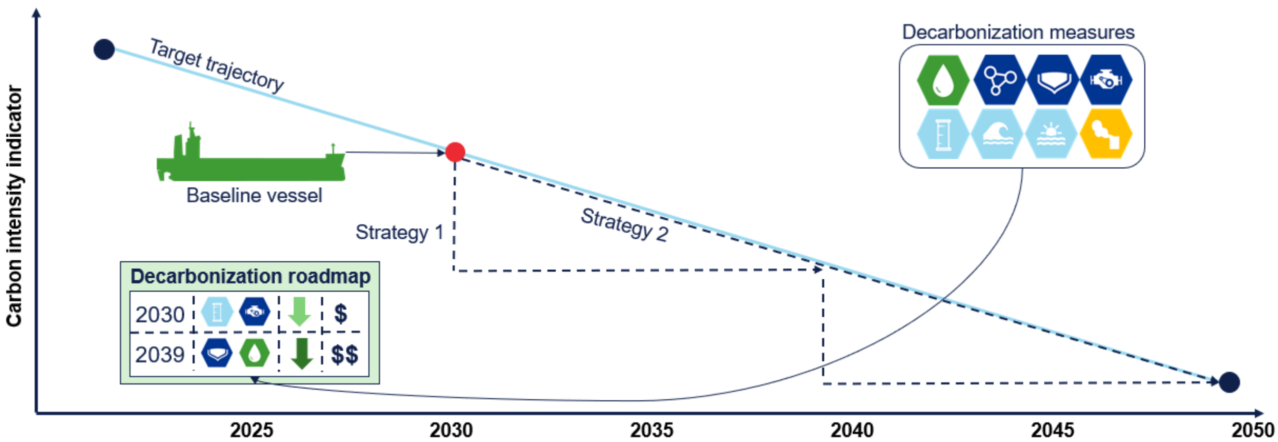

Figure 2 Visualization of steps 1 and 2 in DNV's framework for assessing decarbonization risk. A baseline vessel and target carbon intensity trajectory must be defined, and compliance strategies assessed, before a decarbonization roadmap is developed.

In the final part of the Handbook we exemplify the use of this framework using three example cases, shown in Table 1. Each decarbonization roadmap developed in the case studies is a long-term plan needed to successfully implement the chosen strategy to achieve a given carbon intensity target trajectory. In general, the roadmap should be continuously updated so that the most robust compliance strategy is reflected at any given time. Once complete, the roadmap will provide important guidance and an implementation timeline for different decarbonization measures. Note that these cases are simplified for illustration purposes, and all have been developed in dialogue with industry actors. Prerequisites for conducting a full analysis include expert tools; detailed input data (e.g. fuel prices); and competence on the drivers for decarbonizing shipping and relevant decarbonization technologies.

[1] https://www.dnv.com/maritime/insights/topics/decarbonization-in-shipping/advisory-services.html

Table 1 Overview of generic cases investigated. For each generic ship case, two compliance strategies have been assessed.

Case name (Ship type and size)	Newbuild or existing vessel	Name of target carbon intensity trajectory[1]	Assumed operational lifetime	Compliance strategies
Bulk carrier (~60k dwt)	Newbuild	Decarbonization by 2050	2024–2054	1. Future blend-in of carbon-neutral marine gas oil (MGO) 2. Future conversion to ammonia, along with blend-in of carbon-neutral MGO (pilot fuel)
Chemical tanker (~10k dwt)	Existing vessel	Decarbonization by 2050	2019–2049	1. Future blend-in of carbon-neutral MGO 2. Conversion to liquefied natural gas (LNG) and future blend-in of carbon-neutral LNG
General cargo vessel (~4k dwt)	Existing vessel	Decarbonization by 2070	2008–2046	1. Future blend-in of carbon-neutral MGO 2. Retrofit of Flettner rotors along with future blend-in of carbon-neutral MGO

[1] Target carbon intensity trajectory specified in more detail in relevant subsections.

NOMENCLATURE

AIS	Automatic Identification System
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CII	Carbon Intensity Indicator
DWT	Deadweight tonnage
EE	Energy efficiency
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ships Index
GHG	Greenhouse gas
GT	Gross tonnage
IMO	International Maritime Organization
LHV	Lower heating value
MACC	Marginal abatement cost curve
MEPC	Marine Environment Protection Committee
NPV	Net Present Value
OPEX	Operational expenditure
SEEMP	Ship Energy Efficiency Management Plan
SR	Speed reduction

1 INTRODUCTION

Sustainability is rising rapidly up the agenda for governments, businesses, and the public. While the potential consequences of neglecting it have been known for a long time, the gravity of the challenge has in recent years caught the attention of a broader audience. Scientific evidence, communicated for example as Earth Overshoot Day[2], marking the date humanity's demand for ecological resources exceeds what Earth can regenerate in a year, is making it clear that we are on an unsustainable path. Climate change driven by greenhouse gas (GHG) emissions is acknowledged as the most critical subset of the sustainability challenge. In August 2021, the Sixth Assessment Report[3] of the UN-sponsored Intergovernmental Panel on Climate Change (IPCC) reinforced and significantly strengthened the most urgent warnings that have emerged from 30 to 40 years of climate science, stressing that global GHG emissions need to be cut dramatically and fast.

Responding to scientists' repeated warnings, 196 governments pledged in 2015 to the Paris Agreement to limit global warming to well below 2 degrees Celsius, subsequently setting or strengthening targets and developing plans to reduce GHG emissions. International collaboration on climate action has also reached shipping. In 2018, the International Maritime Organization (IMO) adopted its initial GHG strategy, envisaging a 40% reduction in carbon intensity of international shipping by 2030, and that total annual GHG emissions should be reduced by at least 50% and carbon intensity by 70% by 2050, compared with in 2008. What has emerged over the past few years, however, is that private stakeholders are also formulating targets, expectations, and requirements on GHG emissions – and often on wider sustainability performance. Greater regulatory and business focus on sustainability is increasingly affecting core operations in every industry, and shipping is no exception.

DNV's *Handbook for Decarbonization of Shipping* ('the Handbook') is intended to enhance a shipowner's ability to navigate this evolving and complex landscape, with a special focus on decarbonization. It can also help other stakeholders in the maritime value chain – including financial institutions and investors – to understand and adapt to forthcoming trends and technological changes. The Handbook provides guidance on how to manage decarbonization risk in a structured way, ensuring that individual ships comply with their respective target carbon intensity trajectories over their lifetimes. To our knowledge, a practical handbook like this has never before been published for this purpose.

The Handbook starts off by elaborating on the sustainability term and shipping's environmental footprint (Chapter 2). We next narrow the scope and focus on the key drivers for decarbonization of the sector, describing regulations and discussing expectations from the financial sector and cargo owners (Chapter 3). We then present promising low- and zero-emission technologies and fuels available and under development, which may enable the necessary GHG emissions reductions (Chapter 4).

Chapter 5 covers a practical framework for assessing and mitigating decarbonization risk for ships, incorporating elements such as drivers for decarbonization (Chapter 3) and cost-efficient technologies and fuels to achieve specific decarbonization ambitions (Chapter 4). We demonstrate the framework through three different generic ship cases in Chapter 6.

Figure 1-1 illustrates the structure and contents of the Handbook, which builds on previously published DNV approaches to managing the carbon risk of ships[4].

2 https://www.overshootday.org/

3 https://www.ipcc.ch/report/ar6/wg1/

4 DNV GL (2018a; 2019a, 2020b); (DNV, 2021a), and related DNV services: https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/advisory-services.html

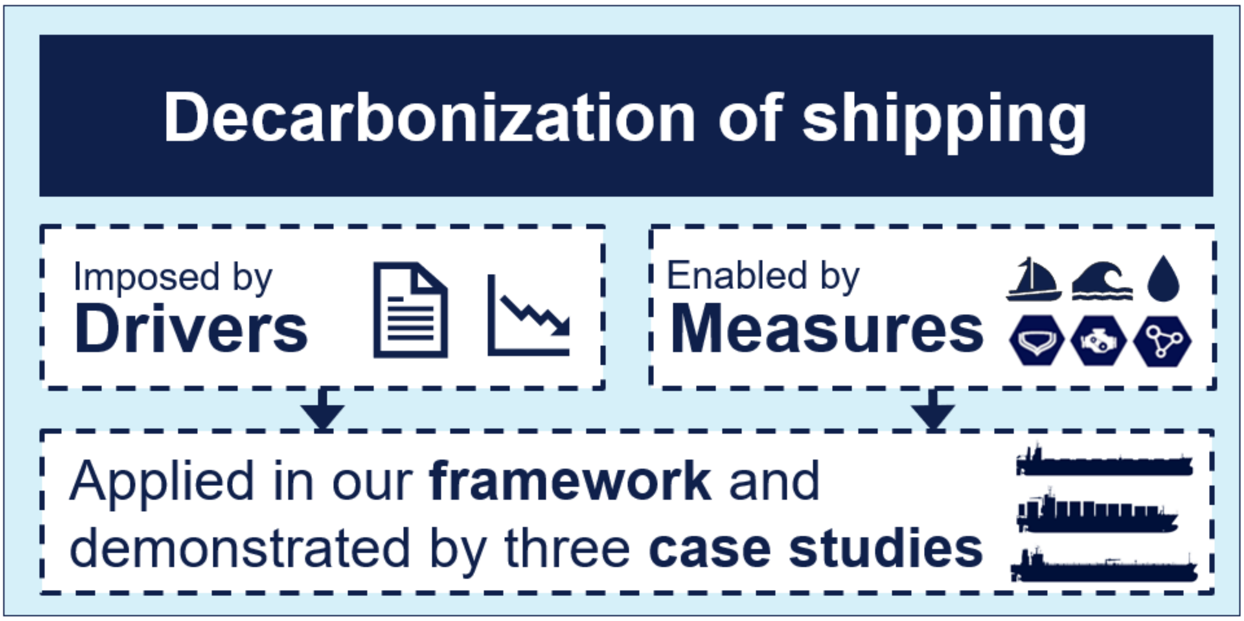

Figure 1-1 Structure and content of the *Handbook for Decarbonization of Shipping*.

2 SUSTAINABILITY IN SHIPPING

This chapter of the Handbook elaborates on terms used in discussing sustainability and environmental, social, and corporate governance (ESG), and shipping's environmental footprint. We also provide references to relevant literature sources and standards that could provide deeper insight.

Just like any other industry, shipping is having an impact on the world around it. Be it the impact on the environment, the hundreds of thousands of people employed in the industry, or the economic impact on global value chains, shipping is leaving a mark – and not all of it is for the better. An entity – such as an industry, company, or asset – that is negatively impacting on the world is leaving it in a worse state than before the entity was introduced, implying that it is not *sustainable* – or in other words, it is *unsustainable*. The Brundtland Commission (WCED, 1987) defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs". This definition captures the essence of sustainable development: improving the lives of populations around the world, without compromising on environmental concerns. As a vital part of global value chains, and consequently contributing to social and economic development, shipping is an essential part of the sustainable future – but only if there are major improvements in the industry.

Following the definition, we can argue that sustainability is binary: you are either compromising the ability of future generations to meet their needs, or you are not. In reality, moving from unsustainable to sustainable is a lengthy and stepwise process, with grades of sustainability between the start and finish. Amid industrialization and globalization over the last century, economic growth has been prioritized over environmental concerns. Moreover, the world's economy and energy system today are so interconnected and complex that it is simply impossible for most industries to become sustainable overnight. Consequently, we need a *transition* to a sustainable society.

In 2016, the UN introduced the Sustainable Development Goals (SDGs)[5], a blueprint for achieving such a transition by 2030. The SDGs consist of 17 Goals and 169 targets addressing current global challenges ranging from poverty and hunger to climate change. Shipping has enormous potential to contribute to achieving the SDGs and is already contributing to reaching many of the targets. A report for the Norwegian Shipowners' Association (DNV GL, 2017b), identifies seven SDGs[6] as having high potential for shipping to contribute to. Four of these – climate action, life below water, good health and well-being, and life on land – are directly linked to a ship's emissions. These four also stand out because the potential for shipping is linked solely to minimizing harm, not maximizing benefits. The environmental aspect of sustainability is arguably where shipping, through its emissions, has the most significant direct negative impact.

Sustainability as a topic is already weighing heavily on shipowners' decision making and day-to-day operation, and the pressure will grow going forward. Extensive reports and roadmaps on the topic include, among others, the Sustainable Shipping Initiative's 'Roadmap to a sustainable shipping industry' (SSI, 2016).

2.1 ESG

In the corporate context, 'sustainability' is sometimes used interchangeably with the term *Environmental, social, and governance* (*ESG)*, also known as *Environmental, social, and corporate governance.* While sustainability and ESG are closely related, there are significant differences. ESG is a set of varied factors that can be measured and reported to evaluate the sustainability of a company, and is a term often used in the context of investments. It is a subset of non-financial performance indicators, enabling analysts and investors to take sustainability factors into account in a systematic approach. Figure 2-1 provides an overview of typical topics under the ESG umbrella.

[5] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[6] The shipping industry has the greatest potential to contribute to the Goals on climate action, affordable and clean energy, sustainable cities and communities, life below water, good health and well-being, decent work and economic growth, and life on land (DNV GL, 2017b).

Environmental	Social	Governance
▪ GHG emissions	▪ Human rights	▪ Corruption
▪ Climate risk	▪ Labour conditions	▪ Leadership
▪ Energy efficiency	▪ Product safety	▪ Executive pay
▪ Air pollution	▪ Equality and diversity	▪ Board composition
▪ Water pollution	▪ Data privacy and security	▪ Audit and internal controls
▪ Waste management	▪ Supply-chain transparency	▪ Independence
▪ Water management		▪ Tax
▪ Deforestation, land use		▪ ESG

Figure 2-1 Overview of typical topics under the *Environmental, social, and governance* umbrella.

Each topic has a set of indicators (or metrics) that are often industry-specific, quantifiable, and possible to report objectively. In its Guidelines for ESG reporting in the shipping and offshore industries, the Norwegian Shipowners' Association (NSA, 2020) recommends ESG indicators for shipping companies. Under the 'Environment' heading of ESG, NSA lists GHG intensity; Sulphur emissions; other air emissions; responsible ship recycling (number of ships recycled responsibly); sailing duration in marine protected areas; and number of spills to the environment. Under the ESG heading 'Social', the list includes lost time incident rate (LTIR)[7]; workforce diversity; management and board; marine casualties, and more. For reporting 'Governance', the NSA recommends (to cite just two examples) corruption risk, as assessed against Transparency International's Corruption Perception Index, and the number of incidents where bribes have been requested. Echoing that environment is shipping's greatest sustainability challenge, the NSA puts most weight on 'Environment' within ESG, recommending 11 indicators compared with 6 under the heading 'Social', and 4 under 'Governance'.

While ESG may come across as a relatively new concept due to the rapid rise in attention in recent years, sustainability and corporate responsibility have actually been on the public agenda for many years. The term CSR (Corporate Social Responsibility, ESG's precursor) was coined and introduced in 1953 to focus on companies' responsibilities for society and the environment (Bowen, 1953). Being more of a management philosophy rather than a structured approach for measuring sustainability efforts, CSR has never become more than an add-on to core business activities, with minimal focus in the day-to-day operation. Being focused on measuring and reporting on these non-financial performance indicators, ESG is more tangible and has gained foothold as a core part of business activities and reporting. A key reason for this is that public reporting on sustainability practices and performance is increasingly tied to financial and legal reporting requirements, and the maritime industry should prepare for more stringent ESG reporting. The World Economic Forum stresses the importance of sustainability reporting in a June 2021[8] article presenting five ways that companies should start preparing for stronger reporting mandates.

Several standards for sustainability reporting have been released over the years; in 2020, there were more than 230 reporting initiatives (NSA, 2020). Albeit with some differences, the existing standards aim to provide a reusable framework for reporting on sustainability and ESG performance by listing a set of different accounting metrics and key performance indicators. The NSA (NSA, 2020) points to four initiatives as landmarks in the global reporting landscape. Applicable regardless of industry and geography, these are outlined in Figure 2-2.

7 LTIR is a metric that calculates the number of incidents that result in time away from work.

8 https://www.weforum.org/agenda/2021/06/sustainability-reporting-five-ways-companies-should-prepare. Accessed 16 August 2021.

Global Reporting Initiative (GRI)

GRI is the most widely used international reporting framework for sustainability reporting, with over 90% of the largest companies in the world using this standard. GRI is based on international standards such as the UN Guiding Principles of Business and Human Rights, UN Global Compact and OECD Guidelines for Multinational enterprises.

The Sustainability Accounting Standards Board (SASB)

SASB aims to help businesses identify, manage and report on the sustainability topics that matter most to their investors. SASB has developed 77 globally applicable industry-specific standards which identify the minimal set of financially material sustainability topics and their associated metrics for the typical company in an industry.

The International Integrated Reporting Framework (International IR Framework)

The International IR framework is a format for reporting on how six capitals - financial, manufactured, human, social and relationship, intellectual and natural – are utilized to create value. The purpose of the Framework is to establish Guiding Principles and Content Elements that govern the overall content of an integrated report, and to explain the fundamental concepts that underpin them.

UN Sustainable Development Goals (SDGs)

The 17 Sustainable Development Goals (SDGs) define global sustainable development priorities and aspirations for 2030. The SDGs call for worldwide action among governments, business and civil society to end poverty and create a life of dignity and opportunity for all, within the boundaries of the planet. While not a reporting framework per se, many businesses refer to the SDGs in their reports.

Figure 2-2 Key sustainability reporting initiatives, adapted from (NSA, 2020).

Frontline (2019) and Maersk (2020) are shipping sector examples of sustainability reports that are based on such standards (both using SASB[9]). Managing ESG issues at company level using recognized sector-specific standards is key to the sustainability of the shipping industry.

2.2 Shipping's environmental footprint

The shipping industry has for decades been under scrutiny for its impact on climate and the environment. From building to scrapping, a ship produces a variety of substances and gases (referred to as *waste streams*) that are environmentally harmful to both air and sea. Many of these waste streams are regulated through the six annexes of The International Convention for the Prevention of Pollution from Ships (MARPOL), developed by the International Maritime Organization (IMO). The waste streams result from the different input factors a ship consumes over its lifetime. Simplified, the ship is ultimately an object with a set of input and output factors that are consumed and produced through construction, operation, accidents (e.g. oil spill) and scrapping. Individually, each object perhaps does not pose significant harm to the environment; but scaled up to the global fleet, the emissions add up to an amount that cannot be left unchecked. Figure 2-3 presents an overview of the input and output factors of a ship, and the international regulations implemented to minimize the latter.

[9] Sustainability Accounting Standards Board: www.sasb.org

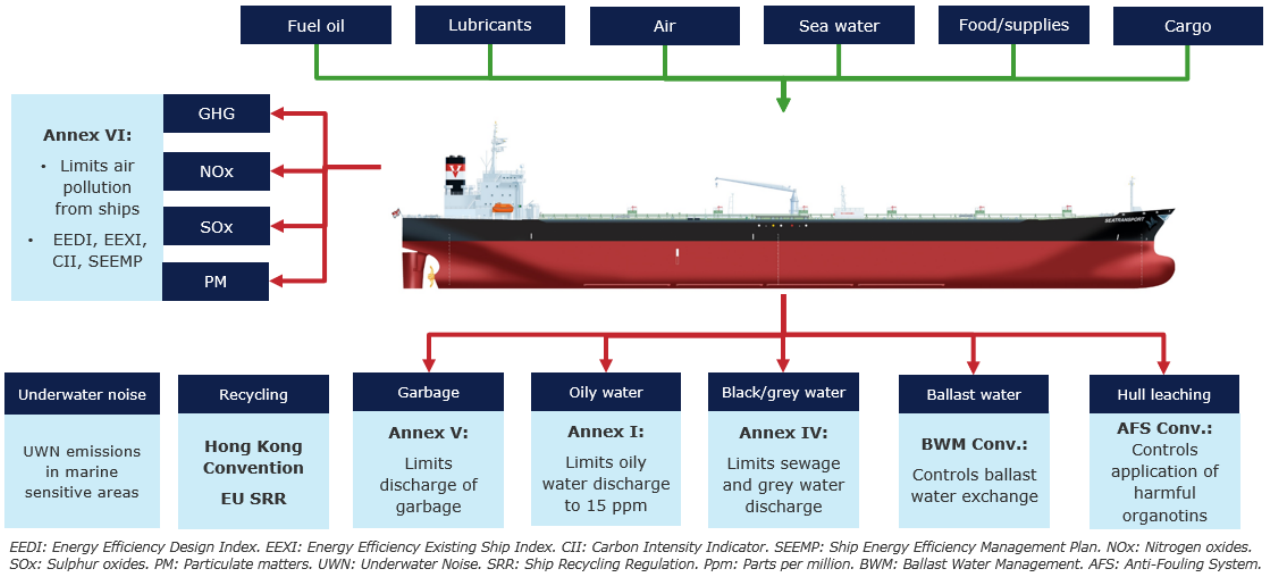

Figure 2-3: Ship waste streams and regulations. Annex numbering refers to the MARPOL convention.

All the waste streams shown in Figure 2-3 compromise ship sustainability and should be minimized. Jalkanen et al. (2021) demonstrated how these can be modelled to assess the environmental impact of shipping. Since 2008, DNV has carried our similar environmental accounting modelling, covering discharges and emission to air for Norwegian waters. The AIS-based environmental accounting model has been established in cooperation with the Norwegian Coastal Administration (NCA), where results for Norwegian waters are typically aggregated for selected ship types and size segments and presented in the NCA-owned web portal havbase.no.

A review of shipping's environmental impacts has recently been reported by Jägerbrand et al. (2019). The waste streams negatively affecting the marine environment, air quality, and human welfare can also be considered as societal damage costs. Ytreberg et al. (2021) established a conceptual framework for valuation of environmental impacts from shipping, with Baltic Sea shipping as a case study. Their findings showed that shipping in the Baltic Sea impose a total annual damage cost of EUR 2.9 billion. Of this, EUR 816 million is due to reduced air quality and EUR 768 million because of marine eutrophication, EUR 737 million from climate change, and EUR 582 million down to marine ecotoxicity.

While all ship emissions should be minimized, GHGs are widely acknowledged as the most important to cut – and urgently. Under current policies, global warming by the end of this century will be 2.7 to 3.1 degrees Celsius (°C) above pre-industrial levels, according to Climate Action Tracker.[10] In DNV's most recent *Energy Transition Outlook* (DNV, 2021b), we calculate that the carbon budget for staying below 2°C global warming will be exhausted in 2053, resulting in global warming of 2.3°C by 2100. With the vast majority of research suggesting devastating consequences if global temperatures rise above 2°C, there is a pressing need for emission reductions. In 2018, shipping accounted for 2.9% of the world's total GHG emissions (Faber et al., 2020), more than a billion tons of carbon dioxide (CO_2) or its equivalent in other GHGs. Total GHG emissions from shipping have grown by nearly a tenth (9.6%) since 2012. Despite this, shipping emits significantly less GHGs per unit of transport work than other transportation modes (see Appendix B). It is important to find technically feasible and cost-effective solutions for the deep-sea segment, comprising 30% of the world fleet in terms of number of vessels[11], but accounting for more than 80% of world-fleet CO_2 emissions (DNV GL, 2019a).

10 https://climateactiontracker.org/global/temperatures/. Accessed 8 June 2021.
11 In this context, deep-sea vessels are defined as vessels above 15 000 GT.

Deep-sea shipping consists of large ocean-going ships, and a very large proportion of their energy consumption relates to propulsion of the ship at steady speed over long distances.

2.2.1 Greenhouse gas emissions from the ship lifecycle perspective

Emissions from the operational phase dominate a ship's GHG emissions in a lifecycle perspective. Quanget al. (2020) estimated the Global Warming Potential of a general cargo ship's entire life cycle through a lifecycle assessment (LCA) and showed that the operation phase accounted for about 95%. The scrapping and building phases make up the remaining 5%. Also using the LCA approach, Chatzinikolaou et al. (2016) assessed a Panamax oil tanker and estimated the operation phase's contribution to GHG emissions to be 96%. Both studies use relatively large vessels (about 75,000 dwt) for their case analysis, and the relative significance of the phases could be different for other vessel sizes and segments.

It is still important to keep a holistic view of the ship's footprint on the climate. The operation phase is ultimately just one of the different phases of a ship's life cycle; and, as energy-efficiency technologies and alternative fuels are maturing and being adopted by the industry, the relative significance of emissions from the other phases will increase. The *sustainability lock-in* of the early phases is another argument for keeping the lifecycle perspective in mind. The lifecycle emissions of a vessel are to a large extent governed by the choices made in the design stage. Except in cases where zero-emission drop-in fuels will be available without engine modifications, deciding and designing engine system for a specific fuel could have a much larger impact than operational adjustments (e.g. slow steaming or trim optimization) on the lifecycle emissions.

3 DRIVERS FOR REDUCING GREENHOUSE GASES FROM SHIPPING

This chapter of the Handbook focuses on GHG emissions as a key sustainability issue and discusses the key drivers for decarbonizing marine transport, namely regulations, and expectations from the financial sector and cargo owners. Taken together, uncertainty over future regulatory change and other drivers, and the uncertain development of fuel and technology options, mean that shipowners considering newbuilding orders today face a complex carbon-risk picture. In this rapidly changing landscape, it is important to keep up to date with the latest decarbonization drivers.

The expected tightening of regulations in the years to come is driving decarbonization as shipowners must plan for lifecycle compliance. A ship that is compliant today is not necessarily so a few years down the road, which represents a significant financial risk. DNV GL (2020b), KLP, DNB, DNV (2021), and DNV (2021b) measured the financial risk and performance for different engine technologies under different regulation scenarios and showed that investments in conventional engine technologies yield weak financial returns in strict regulatory environments.

As outlined in the previous chapter, GHG emissions is arguably the most compromising element of a ship's sustainability and ESG performance. Shipping is under a lot of pressure to reduce its GHG footprint, which continues to grow. A range of different private and public actors have promoted initiatives and structures which serve as drivers for shipping's eventual decarbonization of shipping. Pressure is exerted by many different actors; but in principle, we expect that three fundamental key drivers will push shipping decarbonization over the current decade (DNV, 2021a): regulations and policies; access to investors and capital; and cargo owner and consumer expectations (Figure 3-1).

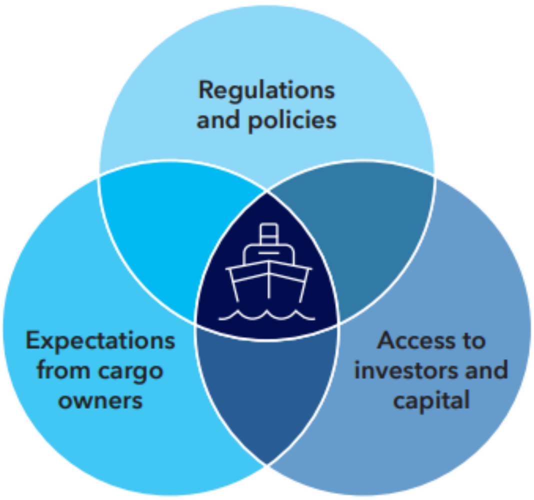

Figure 3-1 Key drivers influencing ship decarbonization (DNV, 2021a).

These three key drivers can incentivize decarbonization in different ways. Regulations and policies will place direct requirements on ships and shipping companies. Expectations from cargo owners, and access to investors and capital, will benefit environmentally friendly shipping; for example, through higher chartering fees, or access to low-cost financing. Behind all three drivers is the more climate-conscious behaviour affecting the way people act as consumers, voters, and investors, caused by the increased public awareness of climate change. Figure 3-2 shows some decarbonization milestones for key actors, which will be elaborated on in the subsequent subchapters.

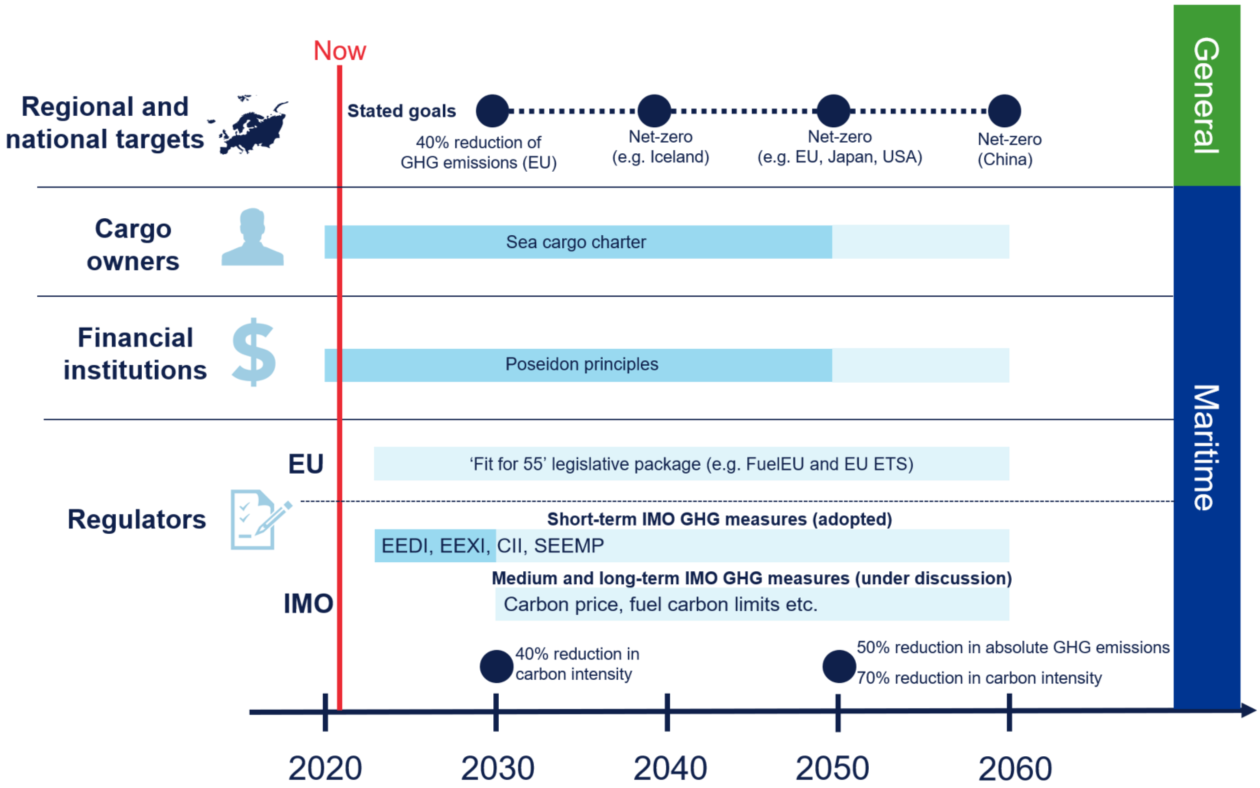

Figure 3-2 Timeline for decarbonization regulations and initiatives, and milestones for GHG targets. Inspired by DNV (2021a).

3.1 Regulations and policies

Government policies such as regulations remain a key driver for decarbonization, imposing direct requirements on ships and shipping companies. The most influential regulator for shipping is the IMO, with its concrete ambitions of at least halving absolute GHG emissions by 2050 compared with in 2008, in addition to reducing carbon intensity by 70%. Regional and national regulators are also entering the scene increasingly.

3.1.1 Global regulations – the IMO

3.1.1.1 Short-term policy measures

Extensive new CO_2 regulations applying to existing ships were adopted in June 2021. They are the Energy Efficiency Existing Ship Index (EEXI), the Carbon Intensity Indicator (CII) rating scheme, and the enhanced Ship Energy Efficiency Management Plan (SEEMP). These measures, along with already existing Energy Efficiency Design Index (EEDI), are designed to meet the target of achieving a 40% reduction in carbon intensity for shipping by 2030 relative to 2008 and are described in more detail below.

The policy measures adopted by the IMO to regulate GHG emissions from shipping may be divided into *technical*, *operational*, and those applicable for *newbuilds* and *ships in operation* (Figure 3-3). The technical policy measures (EEDI and EEXI) relate to technical design parameters for a given ship in a defined design condition. Operational policy measures (CII rating and enhanced SEEMP), on the other hand, reflect the actual operation of the vessel.

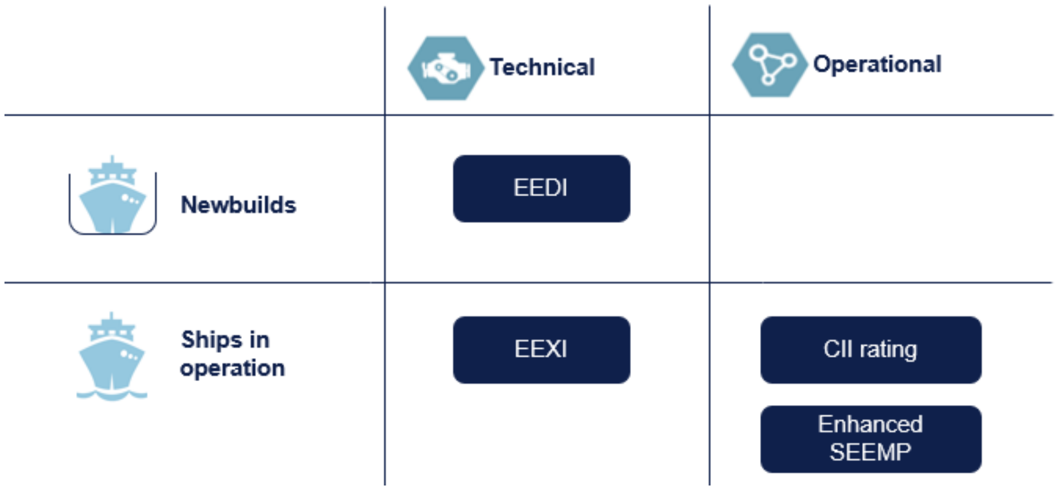

Figure 3-3 Currently adopted international policy measures to regulate GHG emissions from shipping.

EEDI, EEXI, CII, and enhanced SEEMP requirements are applicable for different ship types and sizes (Table 3-1).

Table 3-1 Vessel types and sizes subject to EEDI and EEXI reduction requirements, and CII rating and enhanced SEEMP.

<table>
<tr><th colspan="2">Ship type/characteristics</th><th>EEDI and EEXI</th><th>CII rating and enhanced SEEMP</th></tr>
<tr><td rowspan="13">Conventional propulsion[12]</td><td>Bulk carrier</td><td>>= 10 000 DWT</td><td>>= 5 000 GT</td></tr>
<tr><td>Gas carrier</td><td>>= 2 000 DWT</td><td>>= 5 000 GT</td></tr>
<tr><td>Tanker</td><td>>= 4 000 DWT</td><td>>= 5 000 GT</td></tr>
<tr><td>Containership</td><td>>= 10 000 DWT</td><td>>= 5 000 GT</td></tr>
<tr><td>General cargo ship (except livestock carrier, barge carrier, heavy load carrier, yacht carrier, nuclear fuel carrier)</td><td>>= 3 000 DWT</td><td>>= 5 000 GT</td></tr>
<tr><td>Refrigerated cargo carrier</td><td>>= 3 000 DWT</td><td>>= 5 000 GT</td></tr>
<tr><td>Combination carrier</td><td>>= 4 000 DWT</td><td>>= 5 000 GT</td></tr>
<tr><td>Ro-ro vehicle carrier</td><td>>= 10 000 DWT</td><td>>= 5 000 GT</td></tr>
<tr><td>Ro-ro cargo ship</td><td>>= 1 000 DWT</td><td>>= 5 000 GT</td></tr>
<tr><td>Ro-ro passenger ship</td><td>>= 250+ DWT
and >=400 GT</td><td>>= 5 000 GT</td></tr>
<tr><td>Cruise ship</td><td>N/A</td><td>>= 5 000 GT</td></tr>
<tr><td>Passenger ship (except ro-ro passenger and cruise)</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Other ship with conventional propulsion, (e.g. heavy load carrier, livestock carrier, offshore)</td><td>N/A</td><td>N/A</td></tr>
<tr><td colspan="2">LNG carrier with any propulsion system</td><td>>= 10 000 DWT</td><td>>= 5 000 GT</td></tr>
<tr><td colspan="2">Cruise ship with non-conventional propulsion</td><td>>= 25 000 GT</td><td>>= 5 000 GT</td></tr>
<tr><td colspan="2">Bulk carrier, gas carrier, tanker, container ship, general cargo ship (except livestock carrier, barge carrier, heavy load carrier, yacht carrier, nuclear fuel carrier), refrigerated cargo carrier, combination carrier, ro-ro vehicle carrier, ro-ro cargo ship and ro-ro passenger ship with non-conventional propulsion</td><td>N/A</td><td>>= 5 000 GT</td></tr>
</table>

[12] MARPOL Annex VI defines conventional propulsion as a method of propulsion where a main reciprocating internal combustion engine(s) is the prime mover and coupled to a propulsion shaft either directly or through a gear box.

More information on each requirement is given below.

EEDI

EEDI is a technical requirement applicable for newbuild vessels since 2013. It requires a minimum level of energy efficiency (or maximum level of CO_2 emissions) per capacity mile (e.g. dwt-mile). EEDI is calculated based on a formula using the technical design parameters for a given ship. Figure 3-4 shows the main factors for calculating EEDI. Namely, the installed power on board the vessel (for the main engine and auxiliary engines), the specific fuel consumption for propulsion and auxiliaries, the CO_2 factor of fuel being applied, as well as design speed (i.e. attained speed of design at a given design condition) and deadweight.

$$\text{EEDI} = \frac{\text{Engine load (kW)} \bullet \text{Specific fuel consumption} \bullet CO_2 \text{ factor}}{\text{Design speed} \bullet \text{Deadweight}}$$

Figure 3-4 Main factors for calculation of EEDI (simplified). kW: Kilowatts.

The required EEDI for a vessel is a function of deadweight, with larger vessels having stricter targets (quantitively). The requirements are to be tightened incrementally every five years in phases that started with an initial Phase 0. Newbuilds are now progressing to reaching Phase 3 between 1 April 2022 and 1 January 2025, depending on ship type (Table 3-2). EEDI requirements are given relative to a reference line, calculated from technical parameters for newbuild ships greater than 400 GT delivered in the 10 years to 1 January 2009[13].

Table 3-2 EEDI-phases and reduction factors.

Phase	Applicable to ships built in the period		EEDI reduction factor relative to reference line (%)
	from…	to…	
0	1 January 2013	31 December 2014	0
1	1 January 2015	31 December 2019	Up to 10%
2	1 January 2020	31 December 2024	Up to 20%
3	1 April 2022 or 1 January 2025, depending on ship type)	N/A	Up to 50%

In addition to the upcoming EEDI Phase 3, a Phase 4 is likely to be introduced later this decade, further tightening requirements for newbuilds.

[13] For Ro-ro cargo and Ro-ro passenger ships, technical parameters for ships delivered in the period 1 January 1998 to 1 January 2010 are used.

EEXI

EEXI is a technical requirement that will be applicable for vessels in operation from 2023. It will impose a requirement equivalent to EEDI Phase 2 or 3 (with some adjustments) to all existing ships (see example for container vessels in Figure 3-5). The scope is the same ship types and sizes to which the EEDI applies but includes all ships regardless of the year of build. It is a one-off certification, and the attained EEXI is to be verified, and a new Energy Efficiency Certificate issued, no later than the first annual survey on or after 1 January 2023.

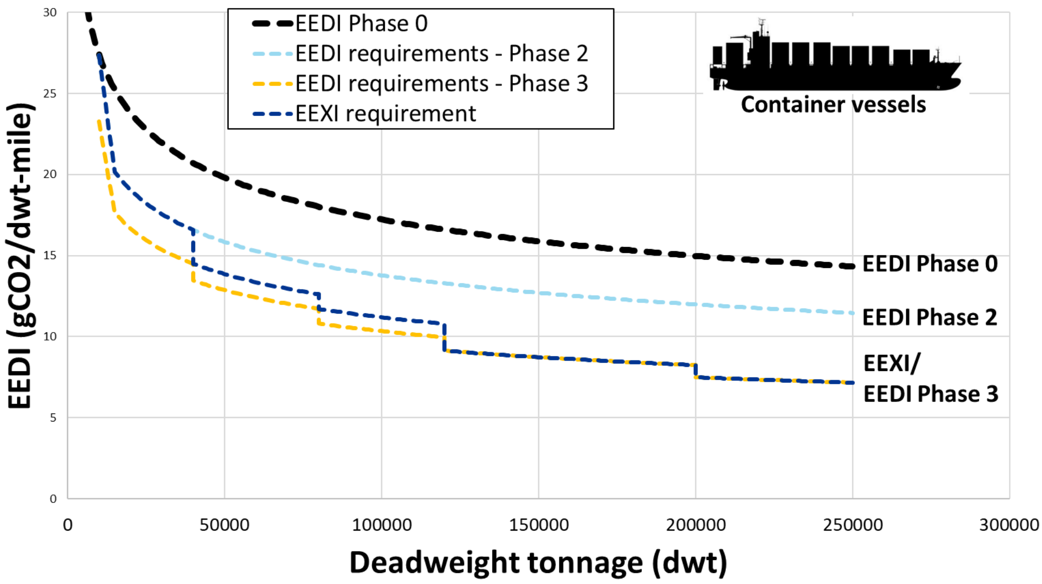

Figure 3-5 EEXI requirement and comparison with EEDI for container vessels.

CII rating

CII (Carbon Intensity Indicator) rating is an operational requirement that will be applicable for ships in operation from 2023. All cargo, RoPax and cruise ships greater than 5,000 GT will need to calculate a CII, and will be assigned an annual rating of A to E. The rating thresholds will be set relative to a 2019 baseline and will be increasingly stringent towards 2030 (Figure 3-6). Adopted GHG emissions reduction requirements cover the period leading up to 2026, with an 11% reduction in 2026 relative to the CII reference line. This reduction requirement is relative to the mid-point of the C-rating band. Typically, the A-rating is 10% to 20% lower than the mid-point of the C-rating band. For ships that achieve a D-rating for three consecutive years, or an E rating in a single year, a corrective actions plan needs to be developed as part of the SEEMP and approved.

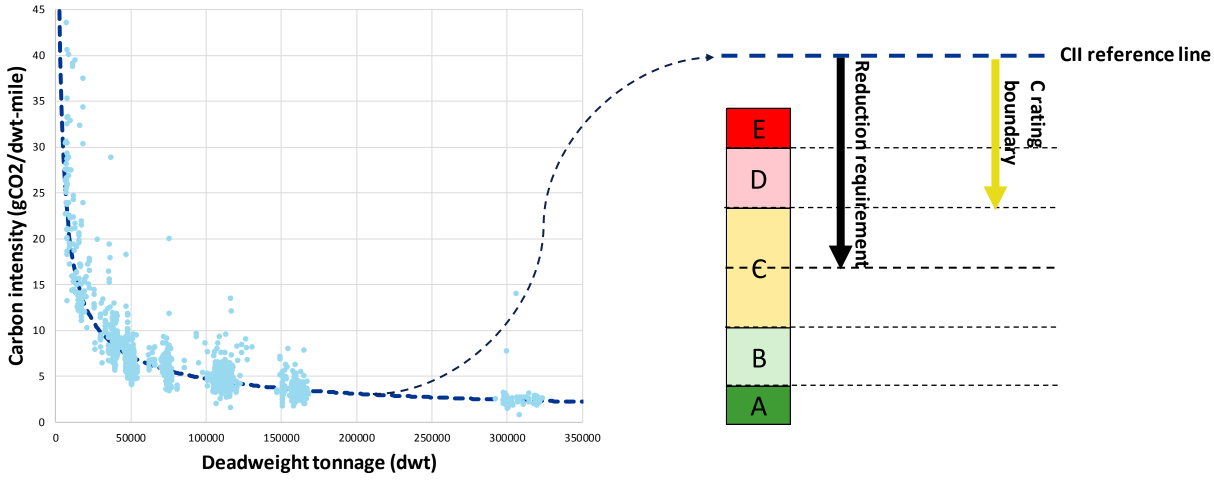

Figure 3-6 Reference line and rating thresholds for CII. Example for oil tankers.

Calculation of CII for individual ships is based on the IMO Data-collection System (DCS), requiring ships above 5,000 GT trading globally to report fuel consumption, hours underway, and distance travelled on an annual basis. It is a measure of annual CO_2 emissions per transport work capacity and is calculated from the formula in Figure 3-7. The calculation of CII is to be improved through correction factors and voyage exclusions, to be developed in 2022.

Figure 3-7 Calculation of CII. Correction factors and voyage exclusions to be developed in 2022.

A review of the CII rating requirements is to be conducted before 2026, and it cannot be ruled out that, in the future, a different measure for carbon intensity will be used for CII rating requirements, e.g. Energy Efficiency Operating Index (EEOI). Rather than calculating carbon intensity in terms of gCO_2/capacity-mile, EEOI considers the actual cargo carried by the vessel. Currently though, IMO DCS-data does not collect any information related to the cargo carried by a vessel, and such information would need to be collected and verified before being implemented into IMO policy measures.

Enhanced SEEMP

Enhanced SEEMP is an operational requirement applicable for vessels in operation by 1 January 2023. All ships subject to the CII requirements need to keep on board an approved SEEMP which must include mandatory content, such as an implementation plan on how to achieve the CII targets. The implementation of the SEEMP will also be subject to company audits, although the specific requirements to the audit are still under development and are expected to be approved by the IMO in June 2022.

3.1.1.2 Mid- and long-term policy measures

While the currently adopted short-term policy measures (EEDI, EEXI, CII, and SEEMP) may become increasingly stringent as time passes, other policy measures are also assessed to help regulate GHG emissions from shipping to achieve the IMO GHG reduction targets. It is widely acknowledged that alternative fuels will be more expensive than conventional fuels, and that a set of financial incentives or technical regulatory requirements could be necessary to achieve a significant uptake of environmentally friendly solutions. These tools could include market-based measures (MBMs), or carbon pricing, including levies, taxes, and cap-and-trade schemes, along with technical and operational requirements such as fuel carbon limits and alternative fuel drop-in requirements. There are two main variants of MBMs: introduction of a carbon levy or tax, implying a fixed price on emissions; or, introduction of a cap-and-trade scheme, implying a cap on emissions and a floating price. Prior to the June 2021 meeting of the IMO's Maritime Environment Protection Committee (MEPC 76), several submissions were raising these topics.

MBMs is on the list of candidates for mid-term measures outlined in the IMO's Initial GHG Strategy (IMO, 2018), and implementation of such measures could be agreed by the IMO between 2023 and 2030. However, the process towards implementation is expected to be lengthy. A reasonable assumption is therefore that any form of carbon pricing scheme from the IMO cannot be implemented before the latter half of this decade due to political and practical issues (DNV GL, 2020b).

Countries[14] and industry organizations[15] have made submissions to the IMO arguing for a rapid introduction of a carbon levy. Individual industry stakeholders have also voiced support for carbon levy schemes. For example, Maersk[16] has proposed a carbon price ramping up from USD 50 to USD 150 per tonne of carbon dioxide (tCO_2). Determination of a suitable price level could be approached from different angles; for example, it could be based on the Paris Agreement targets, or on the required price to levelize the cost of alternative fuels. Naturally, results will differ depending on the angle. OECD estimates that a carbon price of EUR 120 per tCO_2 is needed in 2030 to decarbonize by mid-century (OECD, 2021). While this Paris-aligned estimate is industry-generic, the major ship charterer Trafigura approaches the question from the levelized fuel cost angle. It proposes that the IMO introduces a carbon levy of between USD 250 and USD 300 per tCO_2 to make zero- and low-carbon fuels more competitive (Trafigura, 2020). Status on carbon price uptake and level can be found in the OECD report (OECD, 2021), and from the World Bank's Carbon Pricing Dashboard[17].

Several proposals regarding emissions cap-and-trade schemes, the second variant of MBMs, have also been submitted to the IMO[18]. One of the main benefits of this approach is that since the absolute emission allowed (the emission cap) is regulated, a high degree of certainty of reaching a certain reduction target can be obtained, and the decarbonization target trajectory can be met as the number of allowances decrease over time.

As an alternative, or addition, to setting a carbon price and letting market forces drive down emissions, fuel GHG/CO_2 levels per unit of energy used could be regulated. According to submissions made on the topic[19], this measure can resemble the global sulphur cap introduced in 2020, essentially setting a hard limit to how much GHG/CO_2 the fuel can release from combustion. This could also include well-to-tank emissions. For CO_2/GHG, this model will potentially require some more flexibility; for example, by allowing fleet averaging, meaning that a low-emissions fuel burned on one vessel can offset a worse-performing fuel burned on another within a defined fleet.

---

14 See for example MEPC 76/7/12, Proposal for IMO to establish a universal mandatory greenhouse gas levy, submitted by Marshall Island and Solomon Islands

15 See for example MEPC 76/7/39, *Consideration of market-based measure*, submitted by ICS, BIMCO, CLIA, INTERCARGO, IPTA, IMCA, INTERFERRY and WSC

16 https://www.bloomberg.com/news/articles/2021-06-02/shipping-giant-maersk-seeks-150-a-ton-carbon-tax-on-ship-fuel

17 https://carbonpricingdashboard.worldbank.org/resources

18 See for example MEPC 76-7-2, *Concepts for a regulatory mechanism for the effective uptake of alternative low-carbon and zero-carbon fuels* submitted by Norway. See also MEPC 76-7-15, *The importance of starting work on mid-term GHG reduction measures that incentivize the use of sustainable low-carbon and zero-carbon fuels in international shipping*, submitted by Denmark, France, Germany, and Sweden.

19 See MEPC 76-7-2, *Concepts for a regulatory mechanism for the effective uptake of alternative low-carbon and zero-carbon fuels*, submitted by Norway. See also MEPC 76-7-15, *The importance of starting work on mid-term GHG reduction measures that incentivize the use of sustainable low-carbon and zero-carbon fuels in international shipping,* submitted by Denmark, France, Germany, and Sweden.

Current IMO regulations only address onboard tank-to-propeller emissions of carbon dioxide. In order to incentivize uptake of alternative fuels in the future, it will be important that carbon-based biofuels and electrofuels are credited with GHG emissions reduction, even though they have tank-to-wake CO_2 emissions that are comparable to fossil fuels. Towards this end, it will be important to consider the lifecycle perspective of fuels. It is also important to consider other GHGs such as nitrous oxide (N_2O) and methane (CH_4). Discussions are currently ongoing in the IMO for how lifecycle GHG emissions of marine fuels can be addressed in regulations[20].

3.1.2 Regional

Beyond the IMO, the EU is one of the most influential and ambitious regulators. Its ambition is to reduce the Union's total sector-independent emissions by 55% by 2030, relative to 1990, and to become climate-neutral by 2050. In July 2021, the EU presented its 'Fit for 55' legislative package, which among other things propose to extend the EU Emissions Trading System (EU ETS) to also include maritime transport, and to introduce the FuelEU Maritime Initiative, which aims to increase the use of sustainable fuels.

The EU ETS for shipping is proposed to apply to 50% of emissions from voyages between EU and non-EU ports (both in- and outbound), and to 100% of CO_2 emissions from intra-EU voyages and when at berth in an EU port. The FuelEU Maritime Initiative is proposed to apply to 50% of energy used on inbound and outbound EU voyages, and to 100% of energy used on intra-EU voyages and when at berth in an EU port. The EU Council and Parliament will consider the draft proposals before final adoption.

Recently, major countries have also announced concrete targets. China has set a target to be carbon-neutral by 2060; the US aims to reduce GHG emissions by 50% by 2030 relative to 2005, while Japan and Canada have a similar timeline for a 40% to 45% reduction. These ambitions should be expected to impact shipping through national and international policies and action plans, which will stimulate incentives and activities to develop and implement new solutions. This is already the case in Norway, where the target of reducing GHG emissions by at least 50% by 2030 compared with 1990 levels has resulted in an action plan for green shipping (Norwegian Government, 2019).

3.2 The financial sector and the growing importance of ESG

The financial sector represents the second instrumental driver for the decarbonization of shipping. Decarbonizing shipping will require a tremendous amount of money. One estimate[21] puts a price ticket of USD 3.4 trillion on the associated capital expenditure (i.e. not including fuel costs) for eliminating global carbon emissions from the sector. Studies have indicated that the additional cost on a per unit of transportation work basis may not necessarily be too significant relative to the value of the cargo being transported (see Appendix C). In other words, banks and investors are crucial for facilitating the transition, and are also in position to dictate the direction and speed of it. By virtue of banks' ability to define terms and criteria for financing, and investors' right to choose where to invest their money, these players can stimulate decarbonization by channeling capital to 'green' companies and projects.

Access to capital

Fueled by the increasing focus on and awareness of climate change and climate risks, the financial sector's demand for specific and comparable ESG information has grown rapidly the past years. Starting as information only requested by investors managing thematic funds (e.g., ethic or environment focus), it has now become a central part of company analysis related to investments, as investors acknowledge the risks associated to poor sustainability governance. In fact,

[20] See ISWG-GHG 9/WP.1/Rev.1 (Draft report of the ninth meeting of the Intersessional Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG 9)).

[21] https://shipandbunker.com/news/world/237209-economist-martin-stopford-estimates-34-trillion-bill-for-shipping-decarbonisation. Accessed 24 June 2021.

companies with poor ESG efforts and governance are increasingly risking reduced access to capital as more and more investors channel capital away from assets and projects exposed to climate risk. Norges Bank Investment Management's (NBIM) document "Climate Change, Expectations of Companies" is an explicit example of evolving expectations in the financial sector[22]. The document outlines NBIM's expectations to its investee companies, related to how companies integrate climate-change considerations into strategy and risk management, in addition to information disclosure (reporting) and transparency.

In addition to capital markets' growing preference for sustainable companies, financing directly tied to sustainability performance has become widespread. Issuance of green bonds (see fact box) in the Nordic high-yield market accounted for 14% of the total volume in 2020, growing to 21% in the first four months of 2021 (DNB, 2021). Several shipowners, including Odfjell[23], Bonheur[24], and Fred. Olsen[25] have in recent years issued green or sustainability-linked (general corporate purpose, not "use of proceeds") bonds, or have borrowed money under green or sustainability-linked terms.

Green bonds
Green bonds were created to fund projects that have positive environmental and/or climate benefits. Most of the green bonds issued are green "use of proceeds" or asset-linked bonds. Proceeds from these bonds are earmarked for green projects but are backed by the issuer's entire balance sheet.

The Poseidon Principles[26], established by 13 leading banks engaged in the shipping industry are another example of the growing importance of the financial sector as a driver for transition. The principles establish a framework for assessing and disclosing the climate alignment of ship finance portfolios, set a benchmark for what it means to be a responsible bank in the maritime sector, and provide actionable guidance on how to achieve this.

Regulations and legal requirements for ESG reporting

In addition to the market power of the financial sector, regulations and legal requirements related to corporate reporting are increasingly pushing companies to report on their ESG performance. On a national level, The Norwegian Accounting Act §3.3.c require that large corporations – meaning primarily public limited companies (ASAs) and listed companies – to report on their practices and efforts with respect to human and social rights, equality, environment, and corruption.

Looking beyond Norway, the European Union (EU) is introducing a variety of measures and regulations in the context of sustainable finance, with the EU Taxonomy[27] as the central element. The Taxonomy is a classification system intended to direct investments to sustainable projects and activities by establishing a list of environmentally sustainable economic activities – effectively providing a definition of what is "green". From 2022, all corporations covered by EU Non-Financial Reporting Disclosure (NFRD)[28] are required to disclose how, and to what extent, their business activities are aligned with the Taxonomy. The Taxonomy will initially cover only large corporations in the EU. However, the European Commission will encourage smaller businesses to voluntarily disclose their alignment with the Taxonomy, as these companies also play an integral role in value chains. It is also expected that investors and other companies in the value chain will expect this information to be disclosed. The Taxonomy Regulation has relevance for the European Economic Area (EEA), meaning that it will eventually be included as part of the EEA Agreement.

22 https://www.nbim.no/contentassets/acfd826a614145e296ed43d0a31fdcc0/climate-change_web_2021.pdf
23 https://www.odfjell.com/about/our-stories/odfjell-se-successfully-places-shippings-first-sustainability-linked-bond/
24 https://news.cision.com/bonheur-asa/r/successful-placement-of-senior-unsecured-green-bonds,c3377216
25 https://www.offshorewind.biz/2020/06/24/fred-olsen-enters-green-loans-for-jack-up-trio/
26 https://www.poseidonprinciples.org/#about
27 https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en
28 Listed companies and companies with > 500 employees within the EU.

3.2.2 Expectations from cargo owners

> **The Sea Cargo Charter**
> Bearing many similarities to the Poseidon Principles initiative by shipping banks, the Sea Cargo Charter was launched in 2020 and is a framework for aligning chartering activities with the IMO's ambition to reduced shipping GHG emissions by at least 50% by 2050 compared with in 2008.

The third instrumental driver for the decarbonization of shipping is the cargo owner, or charterer. Cargo owners are usually the ones paying for the maritime transportation service. As such, they have significant leverage and are themselves subject to expectations throughout their own supply chains from their customers and, ultimately, the end-consumers of what is being transported. Because of this, several large cargo owners have announced ambitious decarbonization targets, in some cases aiming for carbon-neutrality by 2030 and 2040[29]. With the IMO CII rating mechanism entering into force in 2023, each ship will have an annual rating A to E, which could become an important criterion for cargo owners selecting ships to charter. A group of major bulk-cargo owners have committed to increased transparency and a carbon intensity trajectory for their chartering activity through the Sea Cargo Charter scheme (see text box). Major cargo owners such as Amazon, Unilever, and IKEA have set a goal to purchase only those ocean freight services that are using scalable zero-carbon fuels by 2040[30]. In addition to committing to targets and trajectories, some cargo owners have also proved that their efforts can result in concrete zero-emission newbuild projects. In 2020, cargo owners HeidelbergCement and Felleskjøpet Agri invited tenders for a zero-emission bulk carrier (5,500 dwt) backed by a 15-year charter contract. With complementary cargo flows (Felleskjøpet transports grain one way, HeidelbergCement transports aggregates in the other direction), the two managed to develop a sensible business case, and in March 2021 it was announced that the Norwegian shipowner Egil Ulvans Rederi won the contract and will realize a hydrogen-fuelled bulk carrier within 2023/2024[31].

We anticipate cargo owners' impact on shipping decarbonization to strengthen in the future as reporting requirements are expected to evolve to include all relevant GHG emissions from the supply chain. This means that cargo owners will need to report on the emissions from their shipping activities – for example, Scope 2 emissions from transport of fuel, and Scope 3 emissions from transport of their goods[32].

[29] See, for example, the positions of Fortescue at https://www.fmgl.com.au/workingresponsibly/climate-change-and-energy, and Anglo-American at https://www.angloamerican.com/sustainability/environment/climate-change

[30] https://www.reuters.com/business/sustainable-business/amazon-others-commit-using-zero-carbon-shipping-fuels-by-2040-2021-10-19/?s=09

[31] https://www.tu.no/artikler/norsk-rederi-bygger-verdens-forste-hydrogendrevne-lasteskip/508390?key=GkINzNPU (in Norwegian)

[32] The GHG Protocol breaks down GHG emissions into three categories: Scope 1 are defined as those caused directly by an organization's activities; Scope 2 emissions count indirect emissions resulting from an organization's energy consumption; Scope 3 is defined as all other indirect emissions caused along an organization's value chain. Read more at https://ghgprotocol.org/

4 TECHNOLOGY SPACE

This chapter of the Handbook aims to give an overview of the current technology space for ships to reduce GHG emissions. Due to the rapid developments in the maturity of technologies and availability of alternative fuels, it needs to be updated regularly. Stakeholders such as shipowners, cargo owners, and financial institutions can use this chapter of the Handbook as a standalone source of information for different GHG abatement options for ships available today and under development. The chapter also provide references to relevant literature sources and databases that could provide deeper insight.

Numerous GHG-reduction measures can potentially be applied on ships. They include, among others:

- Improving the hydrodynamic performance (e.g. hull cleaning, propeller polishing, trim/draft optimization).
- Minimizing energy consumption by improving a device or optimizing its utilization (e.g. low-energy lighting, frequency controllers, cargo handling systems).
- Improving the energy efficiency of main and auxiliary engines (e.g. optimizing heat exchangers, waste-heat recovery systems, batteries).
- Reducing power demand by ‘harvesting energy’ from the surroundings (e.g. wind powering).
- Reducing carbon emissions by using low-carbon/carbon-neutral alternative fuels.

The technical applicability of various abatement measures will vary greatly for different ship types and trades. Newbuilds will have more options available than ships in operation. Vessels in the deep-sea segment have fewer fuel options compared with those in the short-sea segment.

These abatement measures for a ship can be categorized into the following groups (and see Figure 4-1):

- Energy-efficiency measures, either technical or operational
- Alternative fuel technologies
- ‘Harvesting energy’ from the surroundings – reducing power demand
- After-treatment measure – onboard carbon capture and storage (CCS).

In addition to the GHG emissions-reduction measures applied on the ship itself, the drive for decarbonization in global industrial value chains will also drive logistics optimization, including measures such as increased fleet utilization and speed reductions – facilitated by digitalization (e.g. improved synchronization between the ship and the port). Although these measures could also have significant potential for reducing GHG emissions from ships, this chapter focuses on measures that may abate carbon emissions on individual ships. This means that measures such as logistical optimization and digitalization to improve utilization of the fleet are not covered here. Results presented in this chapter build mainly on DNV’s Maritime Forecast to 2050 study (various editions), and DNV’s abatement insight database. Other studies have also described fuels and technologies available for shipping to reduce its CO_2 footprint (e.g. McCarney, 2020; Balcombe et al., 2019; Xing et al., 2020).

The following sections of the Handbook give a high-level overview of the various measures within the above defined categories. When considering measures across these categories, it is important to maintain a holistic view of the ship’s footprint over its lifetime. The lifecycle emissions of a vessel are to a large extent governed by the choices made in the design stage. The fuel shift is underway, and there will be a transition from conventional fossil fuels to low-carbon/carbon-neutral fuels. Forecast studies indicate that in order to reach net-zero GHG emissions in 2050 for shipping, carbon-neutral fuels should make up at least 5% of the energy-mix already by 2030 (Getting to Zero Coalition, 2021; DNV, 2021e). This must go hand-in-hand with greater energy efficiency of ships, requiring rethinking both operationally and with an intensified uptake of proven energy-recovery and energy-efficiency technologies. This will place new and stronger emphasis on system-level thinking, and integration of all available technologies.

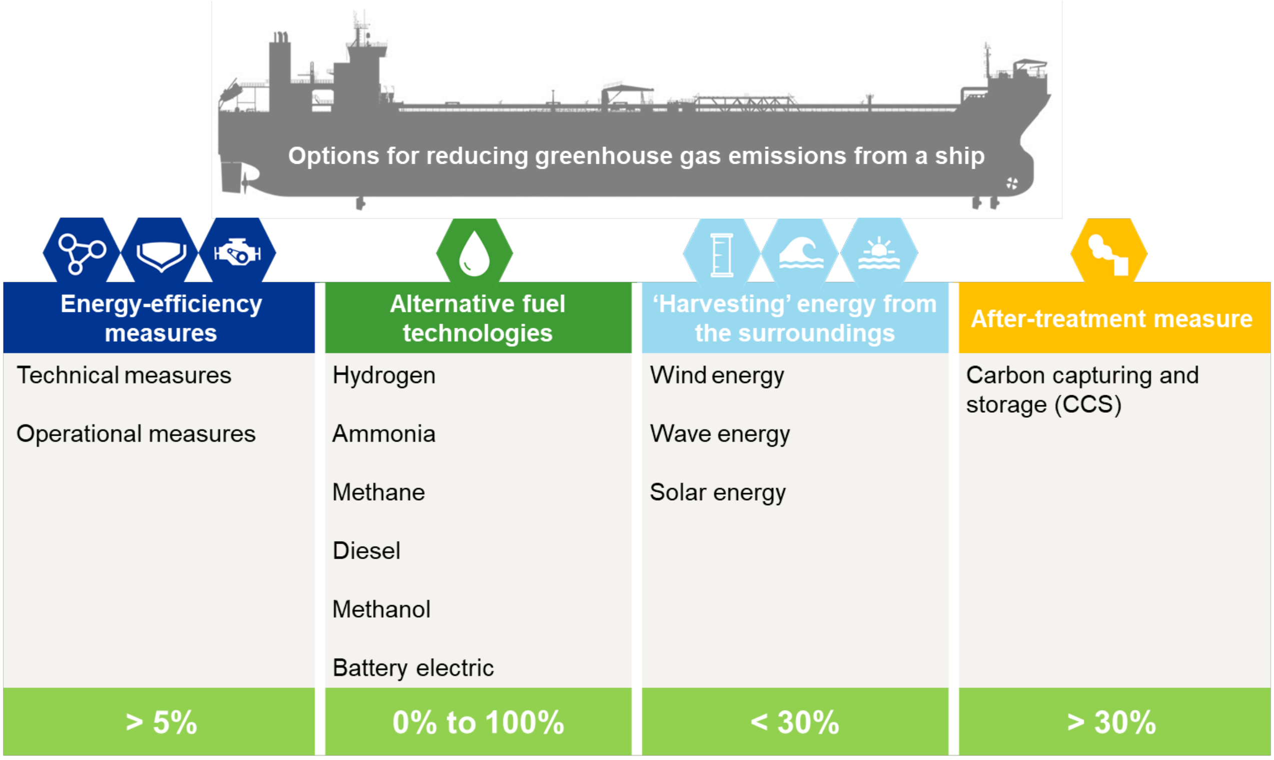

Figure 4-1 Categorization of ship GHG emissions abatement measures, including a high-level indication of the aggregate GHG emission reductions achievable by applying the measures within each category (as a percentage of baseline emissions).

4.1 Energy-efficiency measures

Improved energy-efficiency means that the same amount of useful work is done, but using less energy (Buhaug et al., 2009). Energy-efficiency measures range from easily achievable operational measures to capital-intensive technical solutions (e.g. DNV, 2010b; DNV GL, 2017a; Eide et al., 2011, 2013; Hoffmann et al., 2012; DNV GL, 2016; OECD, 2009; IMO, 2011; ICCT, 2011; Buhaug et al., 2009; Smith et al., 2014; Bouman et al., 2017; Faber et al., 2020). A literature review of 60 studies provides quantitative estimates of the CO_2 emission-reduction potential for different measures, indicating large reduction potentials but also large variability (Bouman et al., 2017). Recently, Faber et al., (2020) have provided analysis covering both technical and operational energy-efficiency measures. DNV has been involved in several projects assessing cost efficiency and marginal abatement cost curves for the world fleet (e.g. Eide et al., 2009, 2011, 2013; Longva et al., 2010; Hoffmann et al., 2012; DNV, 2009, 2010a, 2012a, 2021c; DNV GL, 2017a). The results indicate cost-effective reduction potential for technical and operational measures (not including fuels) in the range of 20% to 30 %, and higher if including more costly technologies. Based on these studies and various energy-efficiency projects and R&D projects, we have developed the in-house *DNV Abatement Insight database* of emission-reduction potential and cost for different energy-efficiency measures, and continuously update it based on new studies and projects.

Several studies have investigated barriers to uptake of energy-efficiency technologies in shipping (e.g. 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.

We next describe technical and operational measures at a high level.

4.1.1 Technical measures

Technical measures generally aim to either reduce the power requirement of the engines or to improve fuel efficiency. Such improvements can be achieved by reducing propulsion energy demand (e.g. hull and propeller efficiency); improving energy production (e.g. waste-heat recovery and machinery-system optimization); and by reducing the energy use of other onboard consumers (e.g. cargo-handling systems, deck machinery, lighting system). Technical measures generally have a substantial investment cost and potentially very significant emission-reduction effects. Some technical measures are limited to application on new ships, due to high costs or inapplicable retrofitting.

Abatement measures such as air lubrication systems, and various hull and machinery measures, are currently emerging[33]. Figure 4-2 categorizes some relevant technical measures into three main groups – energy consumers, machinery, and propulsion and hull – and gives an indicative range of CO_2-reduction potentials for each measure, based on DNV's Abatement Insight database. The emissions-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, 2017a). Consequently, ship-specific modelling and assessment will be needed to build a robust decarbonization improvement plan. Such improvement plans will be required by the enhanced SEEMP requirements, a short-term IMO policy measure to regulate GHG emissions from shipping (see Chapter 3).

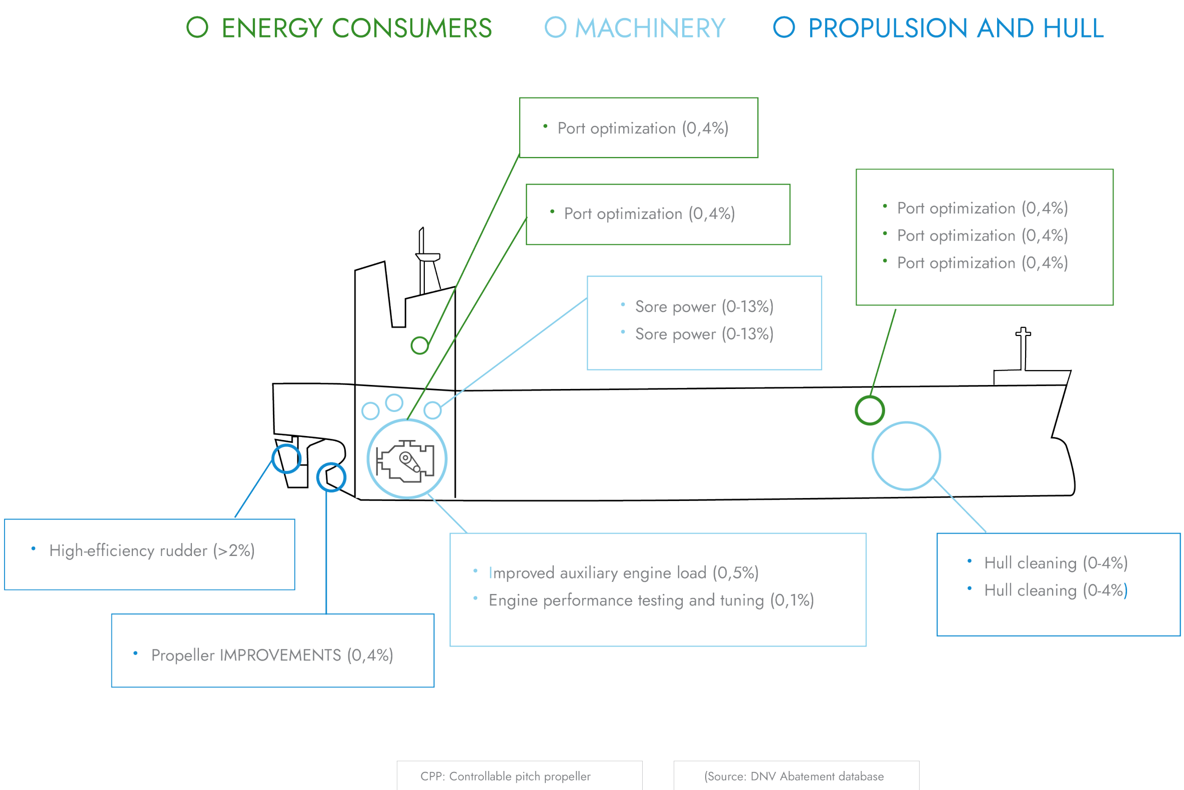

Figure 4-2 Overview of potential technical measures with indicative CO_2-reduction potentials. Note that the reduction potentials reflect an estimated annual reduction for a typical cargo ship.

[33] For instance, see "Fuelling Transition: Tracking Technology Uptake": https://www.hellenicshippingnews.com/fuelling-transition-tracking-technology-uptake/

4.1.2 Operational measures

Operational measures relate to the way in which the ship is operated and maintained. They include measures such as optimized trim and draft, hull and propeller cleaning, better engine maintenance, and optimized weather routing and scheduling. In contrast to technical measures, operational measures typically 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 is attractive for purely economic reasons, and many also require execution of programmes involving changes in management and training. Digital technologies are expected to facilitate improved information flow and be important for untapping the full potential of operational measure. One effective operational measure with a large fuel-saving potential is to reduce vessel speed (e.g. Lindstad et al., 2015; DNV GL, 2017c; CE Delft, 2012, 2017a; DNV GL 2018b,c). 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 (e.g. Longva, 2011; Andersson, 2017; Jia et al., 2017). Otherwise, timetables and schedules must be changed, and more ships deployed to maintain the total transport capacity. A large GHG-reduction potential related to better ship and port synchronization – for example just-in time arrival – has been reported (e.g. Longva, 2011, Jia et al., 2017).

Figure 4-3 presents examples of operational measures and indicative values of their corresponding CO_2-reduction potential. As for the technical measures, Figure 4-3 shows an indicative range of the CO_2-reduction potentials.

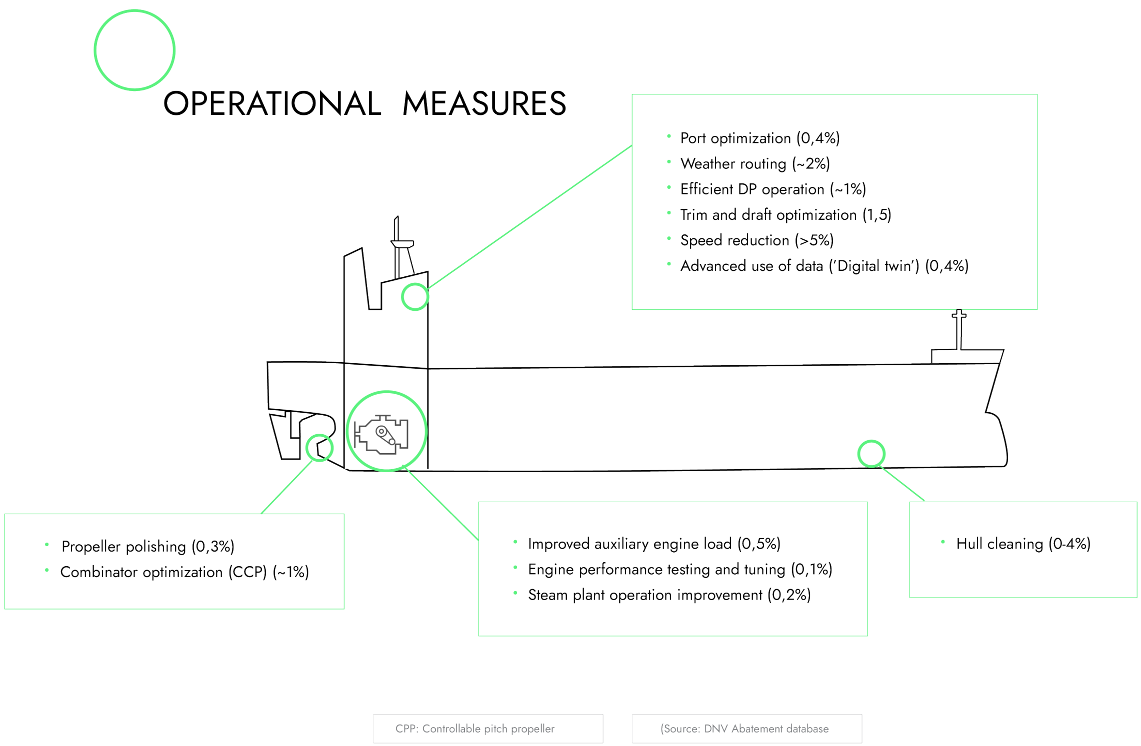

Figure 4-3 Overview of potential operational measures with indicative CO_2-reduction potentials. Note that the reduction potentials reflect an estimated annual reduction for a typical cargo ship.

4.2 Alternative fuels for shipping

Today, the world fleet is mostly powered by diesel engines running on marine fuel oils. Except for the electrification underway in the short sea segment, the current uptake is dominated by fossil fuels such as liquefied natural gas (LNG), liquefied petroleum gas (LPG) and fossil-methanol. Decarbonization of shipping will require substitution of fossil fuels by carbon-neutral fuels. Our 2020 Maritime Forecast to 2050 shows uptake of carbon-neutral fuel picking up in the late 2030s or mid-2040s, reaching between 60% and 100% of the fuel mix in 2050, depending on decarbonization scenario (DNV GL, 2020b). The term carbon-neutral refers to a variety of energy sources and energy systems that have no net GHG emissions or carbon footprint. Carbon-neutral fuels[34] can be produced from primary energy sources categorized, for example, as follows (DNV GL, 2020b):

- **Biofuels** from sustainable biomass sources
- **Electrofuels** from renewable electricity, non-fossil carbon, or nitrogen
- **'Blue' fuels** from reforming natural gas with carbon capture and storage (CCS).

Fuel types from these three families have different maturity, cost, GHG reductions, production capacity and bunkering infrastructure. Among the fossil families, liquefied natural gas (LNG) and liquefied petroleum gas (LPG) can reduce GHG emissions by up to approximately 25% (LNG) and 15% (LPG), depending on technology. Whereas many of the fuels from the other three fuel families ('blue', electro-, and bio-) have potential to provide zero or net-zero GHG emissions in a lifecycle perspective. While focusing on GHGs, it is vital to recognize the footprint of other types of emission from alternative fuels and technologies; mainly nitrogen oxides (NOx), sulphur oxides (SOx), and particulate matter (PM).

Fuels can be applied in a range of different internal combustion engines (ICEs) but also in alternative converters such as fuel cells (FC). Provided there is sufficient fuel storage onboard, vessels with dual fuel ICEs may run on different fuel substances as shown in Figure 4-4.The same fuel substance may be produced from different sources of primary energy, e.g. methanol may be produced from renewable electricity (e-methanol) and biomass (bio-methanol). Dual-fuel engines (DF) may run on more than one fuel, providing added flexibility.

Engine and fuel system	Fuel substance						
	Diesel	Methane	Propane	Methanol	Ammonia	Hydrogen	Electricity from grid
MF ICE	●						
DF LNG ICE	●	●					
DF LPG ICE	●		●				
DF methanol ICE	●			●			
DF ammonia ICE	●				●		
DF hydrogen ICE	●					●	
LNG FC		●					
Hydrogen FC						●	
Ammonia FC					●		
Battery EM							●

MF: Mono-fuel DF: Dual-fuel ICE: Internal combustion engine FC: Fuel cell EM: Electric motor
Note: There are other options not covered in this figure

[34] In the Handbook we use 'carbon-neutral fuels' as an umbrella term for zero-carbon fuels such as hydrogen and ammonia, as well as carbon-based fuels with potential to have net-zero GHG emissions in a lifecycle perspective (e.g. bio-methanol).

Figure 4-4 Technology matrix covering selected fuel, converter, and fuel system combinations. The first column gives the name of different engine and fuel systems, and columns to the right give compatible fuel substances.

Marine propulsion based on nuclear power is technically feasible for large vessels, but political, societal and regulatory barriers can hinder its implementation in the future. Therefore, this is not considered in great detail in this handbook, but for more information, consider e.g. (DNV, 2021d) and (Schøyen et al., 2017).

Importantly, shipping must carefully consider the total lifecycle impact and climate effect of the future fuels it uses. It is key that the fuels are carbon-neutral and sustainable. Current IMO regulations only address onboard tank-to-propeller CO_2 emissions from fossil fuels. However, there is ongoing work in the IMO to determine lifecycle CO_2 and GHG emission factors for all types of fuels, also including biofuels and synthetic electrofuels[35].

In the following discussion, we highlight current uptake of alternative fuels in shipping, then describe barriers preventing further uptake. Considering these barriers, we stress the importance of fuel flexibility.

4.2.1 Current uptake of alternative fuels

According to the DNV Alternative Fuels Insight platform, only 1% of ships operating today are running on alternative fuels, with a significant contribution from the short-sea segment and non-cargo ships. However, there is a fuel shift going on, and about 12% of current newbuilds are ordered with alternative fuel systems. For the deep-sea segment we see an increase in LNG-fuelled ships, and in batteries for full-electric or part-electric operations in the short-sea segment. As of June 2021, there are 79 ships using LPG as fuel and 25 ships on methanol either in operation or on order. It is worth mentioning that these ships are LPG carriers and chemical tankers, utilizing their cargo as fuel[36] (see *Gas tankers* and *Oil/Chemical tankers* in Figure 4-5). This can, however, be a steppingstone for these fuels to mature and be utilized on other ship types. Eight hydrogen propelled ships are on order or under development (see *Car/passenger ferries* in Figure 4-5). The world's first hydrogen-fuelled ferry, the MF-Hydra, is planned to be put into operation this year running on liquefied hydrogen[37]. Figure 4-5 presents an overview of the uptake in June 2021 for selected alternative fuels, including ships in operation and on order.

[35] https://www.imo.org/en/MediaCentre/Pages/WhatsNew-1603.aspx

[36] These numbers are taken for DNV's Alternative Fuel Insight platform, see https://afi.dnvgl.com/

[37] https://www.tu.no/artikler/grenser-flyttes-med-verdens-forste-hydrogenferge/507556

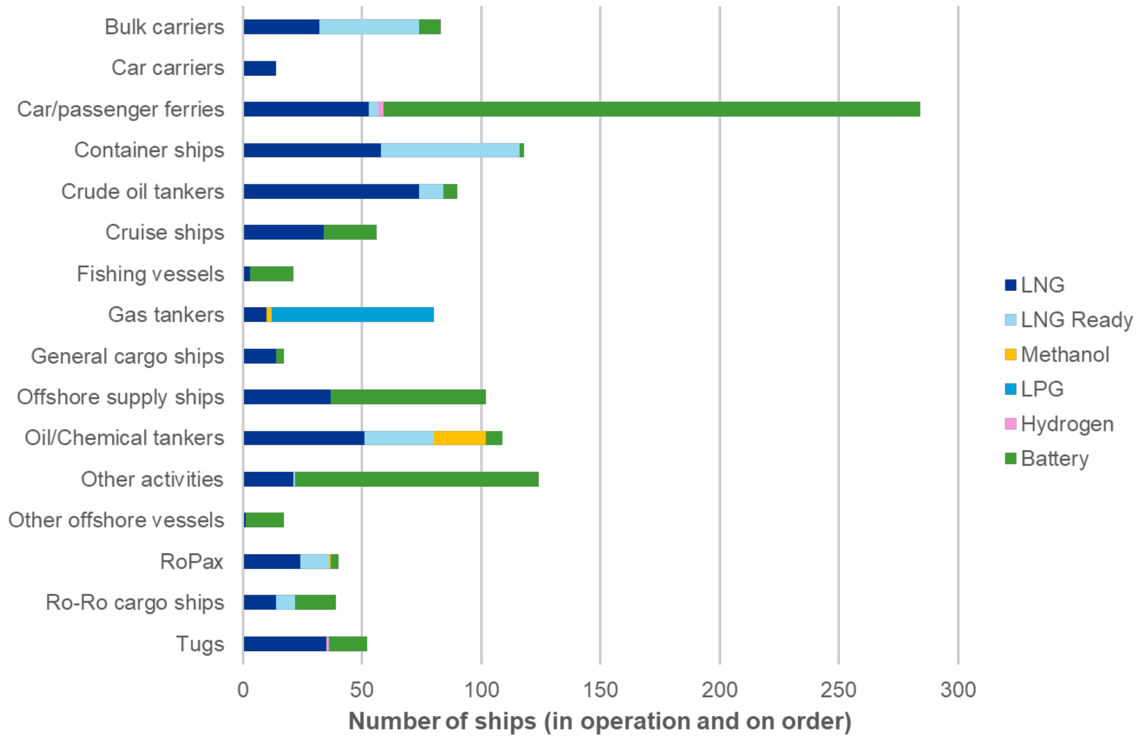

Figure 4-5 Status on uptake for selected alternative fuels in June 2021, ships in operation and on order. (Data: DNV Alternative Fuels Insight platform). 'LNG Ready' is a term used to indicate vessels that have prepared for a future retrofit to LNG as a fuel.

Battery technology is now being installed on many ships, particularly on passenger ferries in the short-sea segment as Figure 4-5 shows. On a full-electric ship, the power system for propulsion and auxiliaries is based entirely on batteries charged from the onshore electric grid while at berth (plug-in configuration), though diesel engines may be equipped for redundancy reasons. A battery-hybrid ship, on the other hand, uses diesel engines for primary propulsion, but employs batteries to optimize the engine and power systems (e.g. peak-shaving, spinning reserve in dynamic positioning mode) and thereby reduce fuel consumption. The battery-hybrid ship could be either plug-in (batteries are charged from onshore electric grid) or non-plug-in (batteries are charged by onboard power systems). There are currently 337 ships with batteries in operation, and 195 such ships on order.

There is also increasing interest in ammonia as a ship fuel, and prototyping and demonstration projects are in progress. In an ongoing EU project, demonstration of a 2-megawatt (MW) ammonia-driven solid oxide full cell (SOFC) system is planned during 2024, retrofitting an existing supply vessel, Viking Energy[38].

4.2.2 Barriers to uptake of alternative fuels

The uptake of alternative fuels in the world fleet is as mentioned increasing, with methanol, hydrogen, and ammonia emerging. In previous transitions in shipping, the industry moved from wind to coal and steam, and then to oil – and every ship made the same transition. This will most likely be different in the future transitions – all ships will probably not transition to the same fuel (DNV GL, 2020b).

The technical applicability and commercial viability of alternative fuels will vary greatly for different ship types and trades. Vessels in the deep-sea segment have fewer options compared to those in the short-sea segment. Deep-sea shipping comprises large oceangoing ships that need to store very large amounts of energy, where the main proportion of energy consumption relates to propulsion of the ship at steady speed over long distances. For deep-sea applications, the

[38] https://eidesvik.no/viking-energy-with-ammonia-driven-fuel-cell/

storage capacity is a key barrier to many alternative fuels. Current options for the deep-sea trade are therefore limited to LNG, which is not carbon-neutral, or to biofuels, which are far more expensive and not yet widely available. In the near future, we foresee ammonia and carbon-neutral methanol, to mention some, becoming viable options for deep-sea shipping.

On the other hand, decarbonization options for short-sea vessels are more diverse and include more alternative power sources and driveline configurations. For these ships, the shorter distances and highly variable power demands often make electric or hybrid-electric power and propulsion systems (including diesel-electric or gas-electric) more efficient than traditional mechanical drives. Furthermore, short-sea shipping plays an important role in the maturation of some of the fuels and technologies for later use in deep-sea shipping (e.g. LNG).

Figure 4-6 indicates the current status of typical key barriers to alternative fuels relevant for short-sea/deep-sea shipping. Key barriers mapped include fuel availability (production and infrastructure), technical maturity, cost of the required machinery and fuel-storage systems on vessels, fuel cost, and volumetric energy density. Safety will also be a primary concern for some fuels, with lack of prescriptive rules and regulations complicating their use. Moving the markers in Figure 4-6 rapidly to the right will be of paramount importance for the shipping industry to achieve its ambitions on GHG reductions. As indicated in Figure 4-6, LNG has fewer barriers towards its implementation on board ships compared with many other alternative fuels. This is due largely to the fact that LNG has been applied as a ship fuel for decades, and infrastructure is increasingly built to service the bunkering needs of the growing LNG-fuelled fleet.

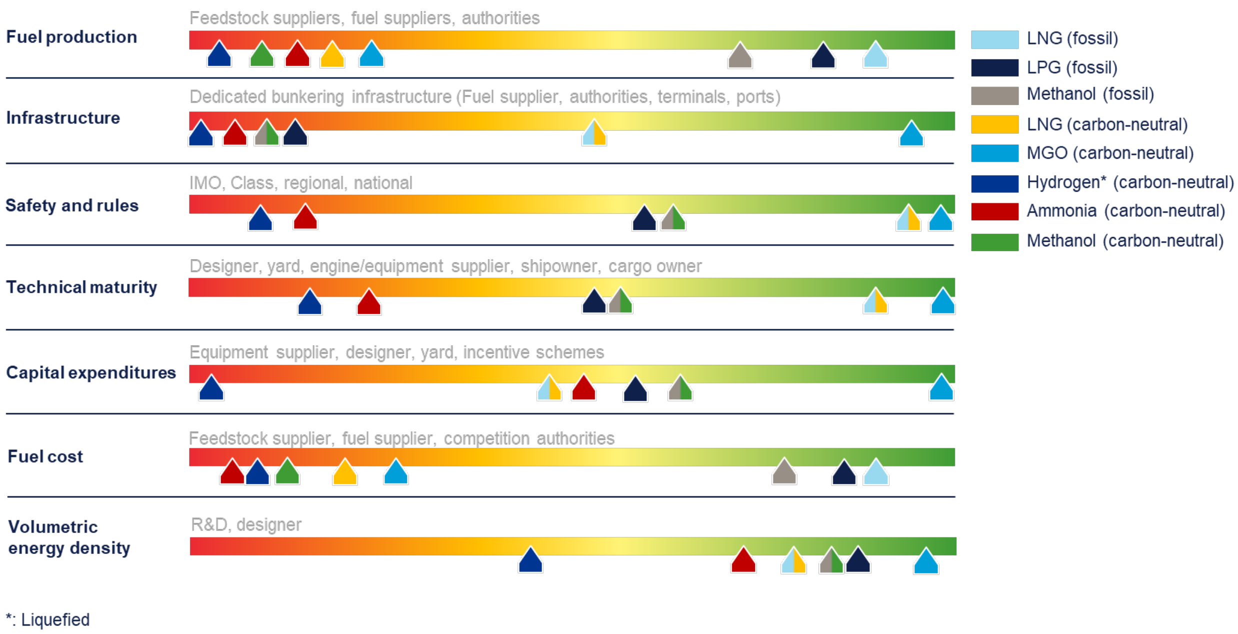

Figure 4-6 Indicative status of key barriers for selected alternative fuels (based on DNV GL, 2020b).

Generally, all the alternative fuels considered in Figure 4-6 face limitations through one or more barriers. In the following, we deep-dive on some selected barriers.

Volumetric energy density

Onboard space available for energy storage is limited on most ships, which makes low energy density a key barrier to many alternative fuels, particularly for ships in the deep-sea segment. The physical characteristics of the fuel determines how it is stored and fitted on a vessel. For example, fuel storage requirements for gases like ammonia are different than for liquid fuels such as biodiesels and methanol, which can be stored in tanks forming part of the ship structure. Figure 4-7 charts the volumetric energy density and gravimetric energy density of different fuel alternatives. The arrows indicate the decrease in energy density when also considering the weight and volume of the storage solution required for some of the alternatives. Furthermore, to get the complete picture on storage needs, efficiency of the alternative energy converters should also be considered.

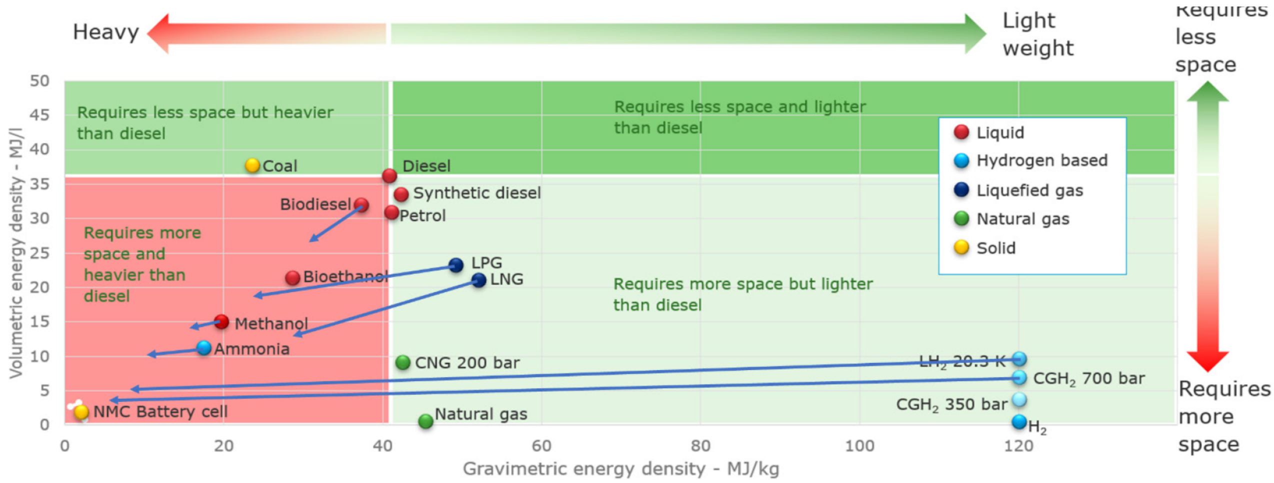

Figure 4-7 Comparison of gravimetric and volumetric storage density for fuels (DNV GL, 2019b). The arrows represent the impact on density when taking into account the storage systems for the different types of fuel (indicative values only).

Infrastructure and fuel production

Current infrastructure for using alternative fuels apart from LNG is highly limited or absent, as Figure 4-6 indicates. Similarly, the current production capacity for carbon-neutral alternative fuels is very low. Developing the necessary infrastructure and production capacity will take time, be costly, and involve many stakeholders in the land-based supply chain. New infrastructure and additional production capacity will only be developed if there is an emerging market for the expected 'winners', and if fuels have scale-up potential and long-term production capacity. Recently, we have seen bunkering infrastructure built up using regions as steppingstones towards global availability of fuels (e.g. LNG, charging of batteries).

The ecosystem for LNG as a ship fuel has matured over the years, with LNG infrastructure today at a level reflected in a significant uptake of LNG-fuelled ships in the orderbook, also in the deep-sea segment. However, as Figure 4-9 and Figure 4-9 shows, LNG availability is still not comparable with that of marine gas oil (MGO). The maps are collected from DNV's Alternative Fuels Insight (AFI) platform[39]. Launched in 2018, AFI is now the industry go-to source for information on uptake of alternative fuels and technologies in shipping, and on the related bunkering infrastructure.

The AFI platform's coverage now includes ammonia and methanol, which ships today transport globally as chemical commodities, and which several import and export terminals exist today. However, dedicated ammonia and methanol bunkering infrastructure for ships is currently limited.

Fuels built on the same molecule can potentially be used in the same bunkering infrastructure regardless of the primary energy source (as for converters and fuel systems shown in Figure 4-4). For instance, the current investment in fossil-LNG bunkering infrastructure for ships can be used in the future for e-LNG or bio-LNG bunkering.

39 DNV Alternative Fuel Insight (AFI) platform: https://afi.dnvgl.com/Map

Figure 4-8 Current LNG bunkering infrastructure (from DNV AFI platform). Different types of bunkering infrastructure are shown, including truck loading, local storage, tank to ship, bunker vessel loading and other bunkering.

Figure 4-9 Current LNG bunkering infrastructure (from DNV AFI platform). Only bunkering vessels are shown.

Technical maturity

As Figure 4-6 indicates, the technical maturity of the fuel alternatives varies substantially. For three of the most promising carbon-neutral options – ammonia, hydrogen, and methanol – maturity is low. The 2021 version of DNV's Maritime Forecast to 2050 (DNV, 2021a) presented more detailed insight into the technical maturity of the technologies needed to use these key fuels. The timeline illustrated in Figure 4-10 indicates a best estimate for when these fuels may be implemented onboard a ship, focusing on key factors such as current maturity, planned developments, and safety rules. The figure shows that key fuel technologies needed for decarbonization of shipping are four to eight years away from commercialization. Fuel cells are far less mature than ICEs for these fuels. For more details on factors such as maturity, planned developments, and safety rules, consider DNV (2021a).

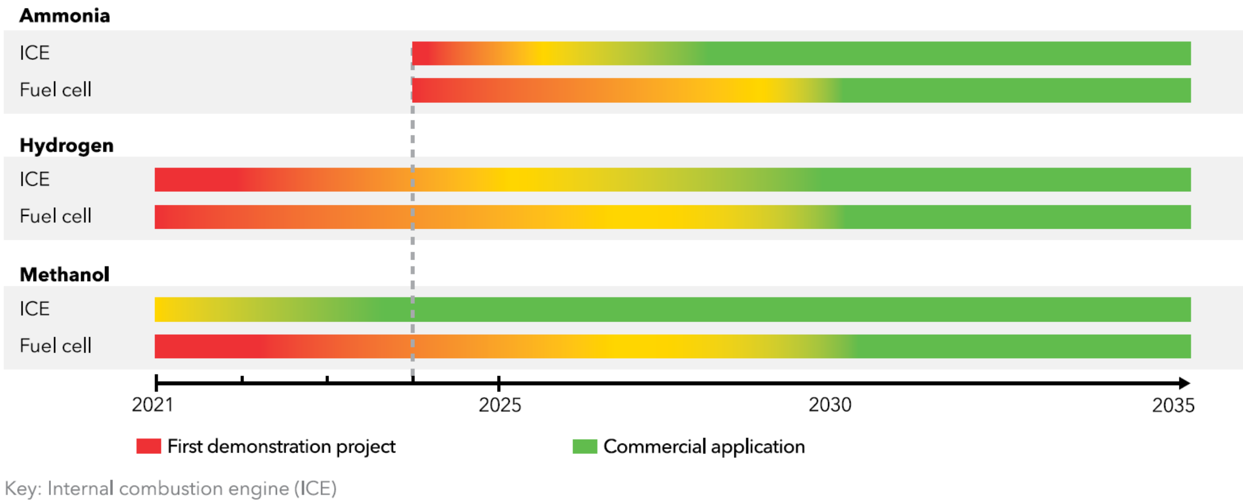

Figure 4-10 Timeline for expected availability of alternative fuel technologies - our best estimate for when these may be available for onboard use (DNV, 2021a).

4.2.3 Preparing the ship for future availability of carbon-neutral fuels

From the section above we find many barriers to the application of zero-carbon/carbon-neutral alternative fuels. Hence, planning for fuel flexibility and alternative fuel ready solutions could ease the transition and minimize risk for investing in stranded assets (DNV GL, 2019a, 2020b). Figure 4-11 illustrates this, showing that ships built with flexibility (right) have more fuel options compared to a conventional ship (left) built for one specific fuel molecule. The flexible ship (right) obtain flexibility in two ways:

1. By installing LNG dual-fuel technology, the ship has more fuel options as it may run on either bio-based or electro-based LNG/MGO as drop-in fuels in the future.
2. By preparing for a retrofit to another fuel, in this case ammonia.

The most suitable choice of vessel specifications will depend on the given ship type, size, operational profile, available fuels, and fuel prices. For more detailed information on important considerations around building a fuel flexible ship we refer to this year's Maritime Forecast to 2050 (DNV, 2021a). DNV recently introduced a "Fuel Ready" class notation offering shipowners the option to prepare for a later conversion to multiple different alternative fuels options[40].

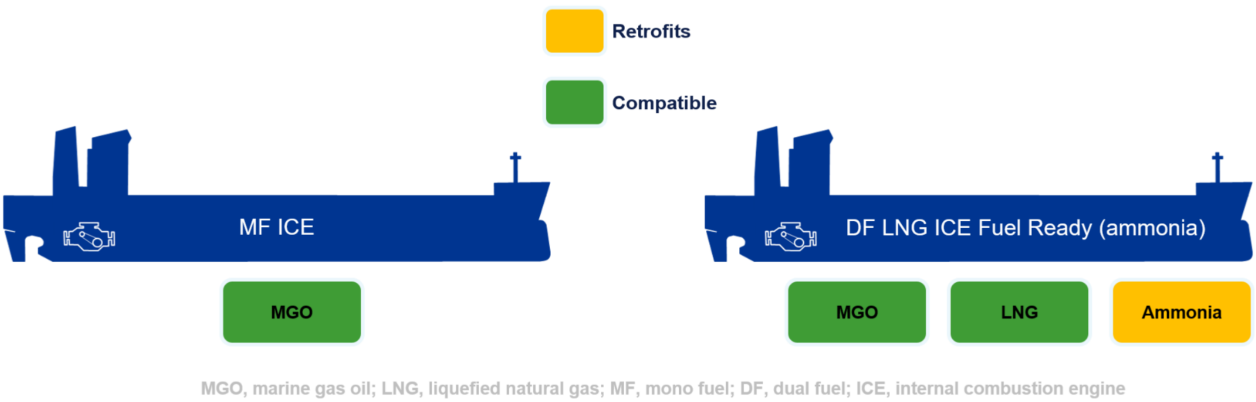

Figure 4-11 Illustrative example of the fuel options available to a standard mono-fuel (MF) ship design (left), and a ship design fitted with a dual-fuel (DF) LNG engine, and prepared for later conversion to ammonia (right).

40 For more information, see: https://www.dnv.com/news/new-dnv-fuel-ready-and-gas-fuelled-ammonia-class-notations-provide-maximum-flexibility-to-tackle-shipping-s-carbon-curve-203646

4.3 Harvesting energy from the surroundings

Ships equipped with the suitable technology can harvest energy directly from renewable energy sources in their surroundings, such as wind, waves, ocean currents, and the sun. The harvested energy can be used for propulsion or auxiliary demand, which allows the ship to decrease the power output from its primary energy sources, typically diesel engines, thus lowering emissions. Novel ship designs, with electric power systems incorporating, for example, fuel cells and batteries can ease the incorporation of energy harvesting technologies. Various technologies for this purpose are currently available, some highly mature and well-proven, others only recently introduced and less mature. There are also development projects with the intention of exploring hybrid configurations, such as solar panels installed on fixed sails. We next describe the technologies.

4.3.1 Wind energy

Various sail arrangements, such as sails, kites, fixed wing, and Flettner rotors have been tested on merchant vessels over the years. For today's ship arrangements, sails will not replace the main propulsion system but will be used as an add-on when weather conditions are favorable. Several studies have considered wind propulsion for ships (e.g. CE Delft, 2017b; ICCT, 2019, Chou et al., 2021). A new review study by Chou et al. (2021) has reported both cost and operational savings for different wind-assisted propulsion technologies. Depending on factors such as sail arrangements, ship type, and wind conditions, savings can typically range between 3% to 15% for the main engine consumption. In some special cases, a 25% reduction over time is reported for rotor sails (Sea-Cargo, 2021). More than 10 ships are operating with sails today, with the Flettner rotor being the leading technology, and several projects are underway[41, 42, 43, 44]. Weather routing to optimize the voyage is especially important for ships utilizing wind energy.

4.3.2 Solar energy

Installing solar panels (e.g. on hatches) will allow for electricity production at sea and in port. However, power production is limited to daylight hours. With solar panels, the auxiliary generators could operate at a lower output, hence reducing fuel consumption. The uptake of solar panels is currently low, mainly due to the low cost-benefit ratio, but there have been some installations[45]. To produce electricity from solar panels, a large area for the installation is required, and therefore only ships that are not dependent on deck space can utilize the system with any substantial gains (e.g. vehicle carriers)[46]. In addition, batteries will most likely be required. Over the years, solar panel technology is expected to become less expensive. The reduction potential of solar panels is typically around 1% of the auxiliary engine consumption.

4.3.3 Wave energy

Waves, normally associated with resistance and increased demand for propulsion power, can also be an energy source for ships to harvest from[47]. This can be achieved by placing foils or 'wings' in the bow of the ship to generate a thrust larger than the drag when the ship has a vertical motion relative to the water molecules, resulting in a reduction in the propulsion power (Bøckmann et al., 2018). Depending on the ship type, speed, the foil size and location, and the wave conditions, the fuel saving are reported to be typically in the range 3% to 10%, but can be as much as 40% (DNV GL, 2018a). The foils could also reduce the most violent vessel motions. The uptake of the technology is currently low.

[41] The International Windship Association: https://www.wind-ship.org/en/category/wind-propulsion-technology-providers/
[42] https://vpoglobal.com/2021/03/09/deltamarin-bar-technologies-and-cargill-present-windwings-virtual-showroom/
[43] https://www.ship-technology.com/news/wallenius-wilhelmsen-wind-powered-roro-ship/
[44] https://news.trust.org/item/20201209130140-yjblo/?utm_campaign=inDepth&utm_medium=inDepthWebWidget&utm_source=homepage&utm_content=link1&utm_itemId=20201209130140-yjblo
[45] https://www.marineinsight.com/types-of-ships/auriga-leader-the-worlds-first-partially-propelled-cargo-ship/
[46] https://glomeep.imo.org/technology/solar-panels/
[47] The wave power history: https://www.bluebird-electric.net/wave_powered_ships_marine_renewable_energy_research.htm

4.4 Carbon capture and storage (CCS)

Onboard carbon capture and storage (CCS) is another technology with potential to reduce ship CO_2 emissions, mainly in the deep-sea segment. While CCS is primarily being developed for large, stationary emission points such as factories, refineries, or power generation plants, use of the technology for onboard carbon capture and temporary storage on large oceangoing vessels is also being considered. Figure 4-12 gives a simplified illustration of the main subsystems in a maritime carbon capture system.

Until now, there has not been any large-scale demonstration of an onboard CCS system providing 100% reduction of carbon emissions from a merchant ship. Only low capture rates, approximately 20%, have been demonstrated, and concepts with up to 80% capture have been estimated based on theoretical calculations.

Interest in maritime CCS is now reviving, and the liquid absorption technology, with or without membranes, is becoming a popular option for system concepts. Past DNV studies, including hazard assessments, have showed that the marinisation of CCS systems is technically feasible. However, many barriers hinder its maritime uptake, namely the CCS system's complexity and space requirements, and the resource requirements, costs, and lack of applicable rules and regulations. Furthermore, the cost increases rapidly with increasing capture rate. It is reported that several providers are now working on developing maritime CCS technologies[48, 49, 50, 51].

Another key barrier is that infrastructure for the total CO_2 value chain must be in place for the trade in question. In other words, there must be solutions ready to handle the captured CO_2. There are ongoing initiatives to develop such value chains, e.g. the Longship project[52], aiming to develop and operate CO_2 capture, transport and storage facilities.

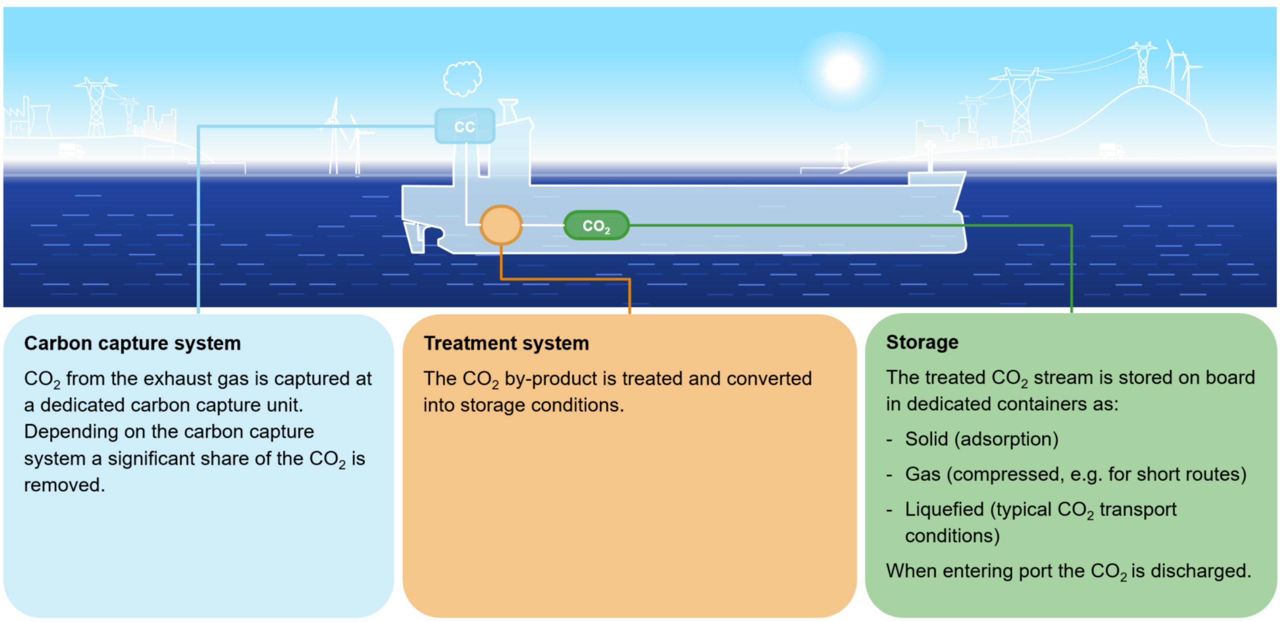

Figure 4-12 Simplified illustration of subsystems in a maritime carbon capture system based on their functionality.

48 https://www.wartsila.com/media/news/08-09-2021-wartsila-advances-carbon-capture-and-storage-in-maritime-as-part-of-linccs-consortium-2972116
49 https://www.bakerhughes.com/process-solutions/compact-carbon-capture
50 https://www.mhi.com/news/20083101.html
51 https://shipinsight.com/articles/wartsila-and-solvang-plan-ccs-retrofit-on-clipper-eos/

52 https://northernlightsccs.com/about-the-longship-project/

5 FRAMEWORK FOR ASSESSING DECARBONIZATION RISK

Chapter 3 of the Handbook described a landscape where different financial, commercial, and regulatory drivers move shipping towards decarbonization. This, in combination with an uncertain future technology space for cutting emissions covered in Chapter 4, means that shipowners today face a complex carbon-risk picture. To address this, we present in this chapter a framework for assessing decarbonization risk.

Ships were previously designed considering aspects such as technical performance, demand for seaborne transportation, earnings, oil prices and fuel consumption. Today's shipowner must, to a much larger extent, also factor in the sustainability, GHG aspects, and technology developments to ensure the ship is prepared for the future. The ship must comply with implemented and planned regulations, and efforts must also be made to ensure it remains competitive in a future where sustainability and GHG performance are closely linked to both market and financial risks. This is increasing both the amount of information needed for decision making and the number of constraints challenging the ship's design.

DNV has previously presented structured and knowledge-based approaches to manage uncertainty related to decarbonization of ships (DNV GL, 2018a, 2019a, 2021a; and related DNV services[53]). Building on this work, we present a three-step framework for managing decarbonization risk that can be applied to both newbuilds and existing vessels (Figure 5-1).

Figure 5-1 A three-step framework for managing decarbonization risk, building on previously presented approaches (DNV GL, 2018a, 2019a, 2021a; and related DNV services[53]).

Each step of the framework is described in more detail below.

Step 1

- Quantify GHG emissions, fuel consumption, and operational profile of baseline vessel. Calculate carbon intensity of the baseline vessel.
- Consider relevant commercial and regulatory decarbonization drivers and set a target carbon intensity trajectory. The carbon intensity trajectory may be minimum requirements for staying aligned with requirements, or it may be more ambitious – for example, moving towards net-zero carbon in 2040. A shipowner contends with a unique set of circumstances depending on factors such as type of cargo, charter-contract types, operational area, and financing. These factors translate into different environmental regulatory policy measures and different expectations from commercial stakeholders (e.g. cargo owners and financial institutions) to limit GHG emissions. The above elements should be reflected in the chosen target carbon intensity trajectory.

[53] https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/advisory-services.html

- Compare the GHG performance of the baseline vessel with the selected target trajectory. Identify when measures are needed to reduce carbon intensity for the vessel, in order to stay aligned with the target carbon intensity trajectory – that is, compliance status.

Step 2

- Identify applicable decarbonization measures for the baseline vessel defined in Step 1, including energy-efficiency measures, alternative fuels, and Fuel Ready options (mostly relevant for newbuilds). Conduct cost-benefit assessments for the identified measures (i.e. calculate GHG-reduction potential and cost). Abatement cost, the cost of reducing one tonne of CO_2 in terms of USD/tonne CO_2, may be used as a metric for the cost-efficiency of each measure.
- Based on the cost-benefit assessment, develop compliance strategies that meets the set target carbon intensity trajectory. A compliance strategy may include several decarbonization measures. For example, one compliance strategy could involve blending in carbon-neutral fuel, while another could include retrofit to a new fuel. In both cases, energy-efficiency measures could also be part of the picture.
- Assess each compliance strategy with respect to cost and GHG emissions, taking into account the lifetime of the vessel (and the remaining lifetime if already in operation). There are great uncertainties associated with how the drivers for decarbonization (e.g. regulations) will develop in the future, and when different decarbonization technologies will be available for commercial use. Future availability and price of alternative carbon-neutral fuels is also a big uncertainty. Because of this, it is important to evaluate each compliance strategy in many scenarios[54], each one representing a plausible future. If a compliance strategy proves to make sense financially and environmentally across many scenarios, it is a robust strategy.

Step 3

- Select the most robust compliance strategy from Step 2 and create a decarbonization roadmap. The roadmap contains a description of the elements needed to implement a selected decarbonization strategy. Before implementation, and during the implementation phase, several actions and preparations must be performed, and these must be specified in the roadmap. In the case where a roadmap contains use of alternative fuels as an action, it would be important to map out the current and future expected availability of these fuels at relevant bunkering ports.
- The roadmap should be continuously updated, so that the most robust compliance strategy is reflected at any given time.

Figure 5-2 shows a visualization of Step 1 and 2 of our framework for assessing decarbonization risk. First, a target (GHG) trajectory is selected, a baseline vessel is defined, and the compliance status of the vessel can be seen as the period before the vessel intersects with the target trajectory. Second, different compliance strategies are developed (*Strategy 1* and *Strategy 2*), and the most robust strategy is used as basis for developing a roadmap with one or more decarbonization measures included.

[54] Scenario analysis is a well-established method that can provide valuable input to strategic newbuilding plans and enhance fleet flexibility and resilience to a range of possible futures. Scenarios need to be updated so that the most recent developments in regulations, technological developments, fuel prices and availability are reflected. For more details on how to develop scenarios, consider, for example, DNV (2020b).

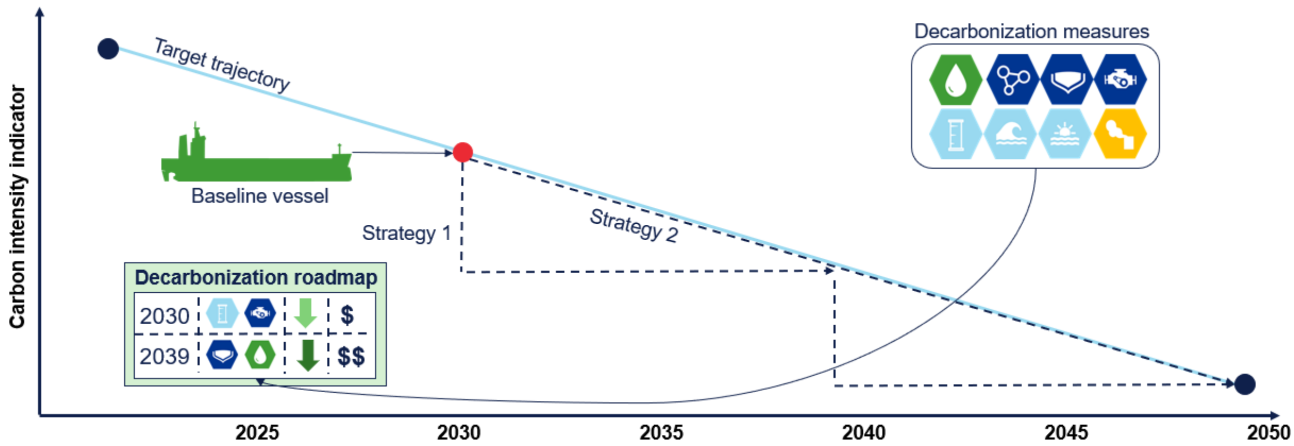

Figure 5-2 Visualization of Steps 1 and 2 in DNV's framework for assessing decarbonization risk. A baseline vessel and target carbon intensity trajectory must be defined, and compliance strategies assessed, before a decarbonization roadmap is developed (Step 3).

Chapter 6 outlines the use of this framework by using three example cases simplified for illustration purposes. To carry out a full analysis, expert tools, detailed input data (e.g. fuel prices) and competence on the drivers for decarbonization of shipping and the available decarbonization technology space are prerequisites.

6 GENERIC VESSEL CASES FOR ASSESSING DECARBONIZATION RISK

This chapter of the Handbook demonstrates the framework described in Chapter 5, using three generic vessel cases. We have looked at only two different compliance strategies per case in this study, but many more strategies could be assessed. As such, the cases do not include a full analysis of all available fuel and technology options. Nor do the cases include a robustness analysis using multiple scenarios for key variables, such as fuel prices (apart from a limited analysis of the impact from CO_2 pricing in Section 6.4). Appendix A describes input and assumptions on fuel prices, technology costs, and operational expenses used in the case studies. The cases have been developed through interaction with relevant shipowners who are members of the Maritime Bergen[55] cluster. Table 6-1 gives an overview of the generic ship cases.

Table 6-1 Overview of generic cases investigated. For each generic ship case, two compliance strategies have been assessed.

Case name (Ship type and size)	Newbuild or existing vessel	Name of target carbon intensity trajectory[56]	Assumed operational lifetime	Compliance strategies
Bulk carrier (~60k dwt)	Newbuild	Decarbonization by 2050	2024–2054	1.Future blend-in of carbon-neutral marine gas oil (MGO) 2. Future conversion to ammonia, along with blend-in of carbon-neutral MGO (pilot fuel)
Chemical tanker (~10k dwt)	Existing vessel	Decarbonization by 2050	2019–2049	1. Conversion to liquefied natural gas (LNG) and future blend-in of carbon-neutral LNG 2. Future blend-in of carbon-neutral MGO
General cargo vessel (~4k dwt)	Existing vessel	Decarbonization by 2070	2008–2046	1. Future blend-in of carbon-neutral MGO 2. Retrofit of Flettner rotors along with future blend-in of carbon-neutral MGO

For each generic ship case, we first present the baseline and target carbon intensity trajectory, followed by an assessment of each given compliance strategy before a decarbonization roadmap is developed. DNV's FuelPath Model[57] has been used for assessing all relevant compliance strategies in the generic ship case. Each generic ship case incorporates a few selected fuels and technology identified as relevant during workshops, but more could be considered (see Chapter 4 for an overview).

In the case studies, we consider tank-to-wake emissions of GHG emissions (carbon dioxide, methane, and nitrous oxide). Even though current IMO regulations on GHGs (e.g. CII rating and EEXI requirements) only cover tank-to-wake CO_2 emissions, we expect this to change in the future. We assume a GHG tank-to-wake emission reduction of 20% for LNG-fuelled vessels, compared with conventional vessels running on very low sulphur fuel oil (VLSFO). The actual reduction depends on the choice of LNG engine (technology dependent), operational profile (engine-load dependent). In the last years, reported performance data for LNG-fuelled engines indicate that an improvement in methane slip (e.g. Ushakov, 2019; GIE, 2021). We expect that this development will continue in the future. For more information about

55 https://www.maritimebergen.no/
56 Target carbon intensity trajectory specified in more detail in relevant subsections.
57 See DNV (2021a) for more information about the FuelPath Model.

methane slip, consider sources such as Lindstad et al. (2020), MAN (2019), and Sphera (2021). Apart from GHG emissions, other emission components from ships – for example, NOx and SOx emissions – should also be considered when assessing GHG compliance strategies. In particular, it is important to consider Emission Control Areas (ECAs), and local restrictions and incentives. When introducing alternative fuels, it will be vital to ensure that this will not lead to other unsustainable impacts in a lifecycle perspective. The IMO is working on guidelines to determine lifecycle CO_2 and GHG emission factors for all types of fuels, including biofuels and synthetic electrofuels. In this study, the terms *carbon-neutral MGO* and *carbon-neutral LNG* are used for fuels with similar properties to fossil MGO and LNG, but which are produced sustainably from biomass or renewable electricity. These fuels, in addition to ammonia, are assumed to have a GHG emission factor of zero in a tank-to-propeller perspective for the generic vessel cases. For more information on carbon-neutral fuels, see Chapter 4.

After a vessel enters its operational phase, its performance may become progressively worse due to factors such as hull fouling and engine performance deterioration. In the generic case studies, however, we assume that the vessel performance (in terms of energy consumption), remains constant throughout its lifetime.

6.1 Bulk carrier (60k dwt)

6.1.1 Step 1 – Define baseline, target trajectory, and compliance status

Baseline

The baseline vessel defined for this case is a 60k dwt bulk carrier, fuelled by VLSFO. This is a newbuild case, with planned delivery in 2024. Today, a modern such vessel operates with a carbon intensity in the order of ~4.7 gCO_2-eq/dwt-mile, based on reported emissions data, though the exact value will depend on factors such as operational profile of the vessel.

Target trajectory and compliance status

A target carbon intensity trajectory reaching zero in 2050 was identified as the most relevant carbon intensity trajectory[58] for this newbuild. This target trajectory reflects a market situation where cargo owners and financial institutions push for decarbonization beyond regulatory compliance (assuming the IMO's long-term GHG strategy is implemented through policy measures). In the period leading up to and including 2026, the carbon intensity trajectory is aligned with a 'C' rating according to CII rating requirements (see Chapter 3 for more information). Given this target trajectory, the baseline vessel is compliant for four years after its first year of operation, before decarbonization measures are needed (Figure 6-1).

[58] Note that even though that the adopted CII rating requirements only considers tank-to-wake CO_2 emissions, we are considering tank-to-wake GHG emissions in the generic vessel cases – including, for example, methane slip.

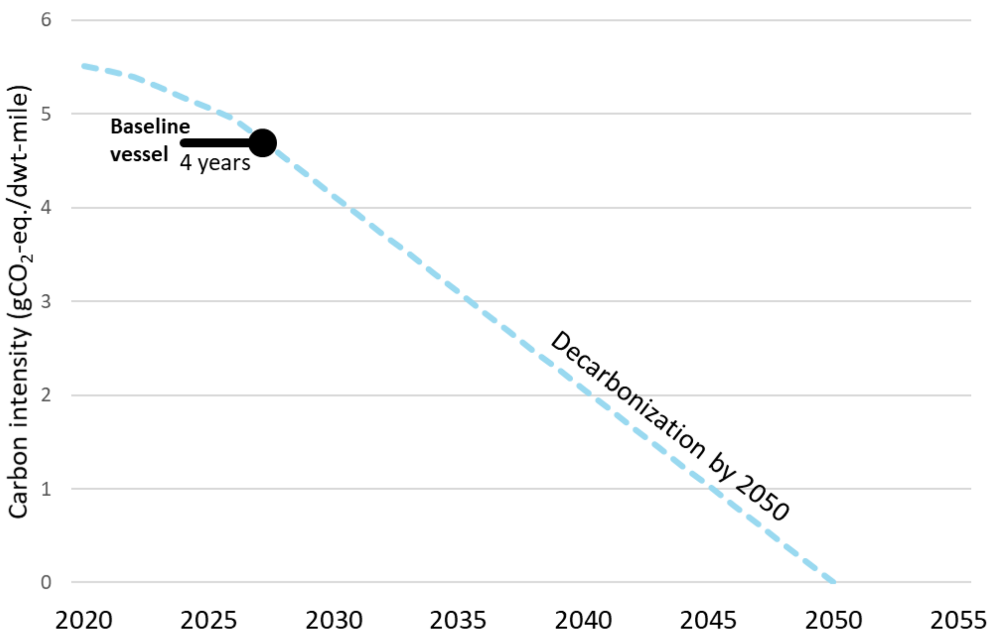

Figure 6-1 Target carbon intensity trajectory and compliance status of the baseline vessel in the bulk carrier (60k dwt) case.

6.1.2 Step 2 – Assessment of compliance strategy

Relative to the baseline presented earlier, Table 6-2 shows CO_2-eq reduction potential, and CAPEX for each of the measures deemed most relevant for the baseline vessel. The gate rudder and Air Lubrication System (ALS) are relatively immature measures, with few examples of real-life implementations on board ships. Therefore, both CO_2-eq reduction potential and additional CAPEX are uncertain.

Table 6-2 CO_2-eq reduction potential and additional CAPEX by measure.

Measure	CO_2-eq reduction potential (%)	Additional CAPEX (million USD[59])
LNG as fuel **(Including ammonia-readiness[60])**	20%	6.0
Gate rudder	5%	0.5
Slow steaming optimization	5%	0.0
ALS	4%	0.8

Based on this, we consider two newbuild options:

1. A conventional (fuelled by VLSFO) newbuild bulk carrier optimized for slow steaming, with an ALS, and a gate rudder.

[59] USD = US dollars
[60] Compatibility of LNG tank material with ammonia storage.

2. *DF LNG Fuel Ready (ammonia)*. A dual-fuel LNG newbuild bulk carrier optimized for slow steaming, with an ALS, and a gate rudder. The vessel has been prepared for a future retrofit to ammonia – a status described in the Handbook as Fuel Ready (ammonia).

For each of the newbuild options, one compliance strategy is identified and assessed, as described in Table 6-3.

Table 6-3 Description of compliance strategies explored in the bulk carrier (60k dwt) case.

Compliance strategy *Newbuild option*	Description of compliance strategy
Strategy 1 *MF conventional*	Future blend-in of carbon-neutral MGO to ensure compliance with carbon intensity trajectory.
Strategy 2 *DF LNG Fuel Ready (ammonia)*	Future conversion to ammonia, along with blend-in of carbon-neutral MGO (pilot fuel) to ensure compliance with target carbon intensity trajectory.

Figure 6-2 shows the annual cost for the two compliance strategies. Although *Strategy 2* has the highest CAPEX costs, both for the newbuild and later retrofit to ammonia, it has a significantly lower fuel expenditure as the vessel reaches its end of lifetime. Figure 6-3 shows the total discounted[61] cost associated with each compliance strategy (left), and total lifetime CO_2-eq emissions (right). Under the current economic assumptions, given in Appendix A, *Strategy 2* has a ~5% lower total discounted cost and 10.3% less total lifetime CO_2-eq emissions compared to *Strategy 1*. As a result, selecting *Strategy 2* as the compliance strategy makes the most sense from an economic and environmental perspective. This conclusion is subject to the given economic assumptions, and a prerequisite is that *Strategy 2* is a technically feasible compliance strategy and that ammonia and carbon-neutral MGO are available at bunkering locations in the future (this has not been assessed in detail for this case study). In order to determine the robustness of the strategy, its total discounted costs should be determined over many different fuel-price scenarios.

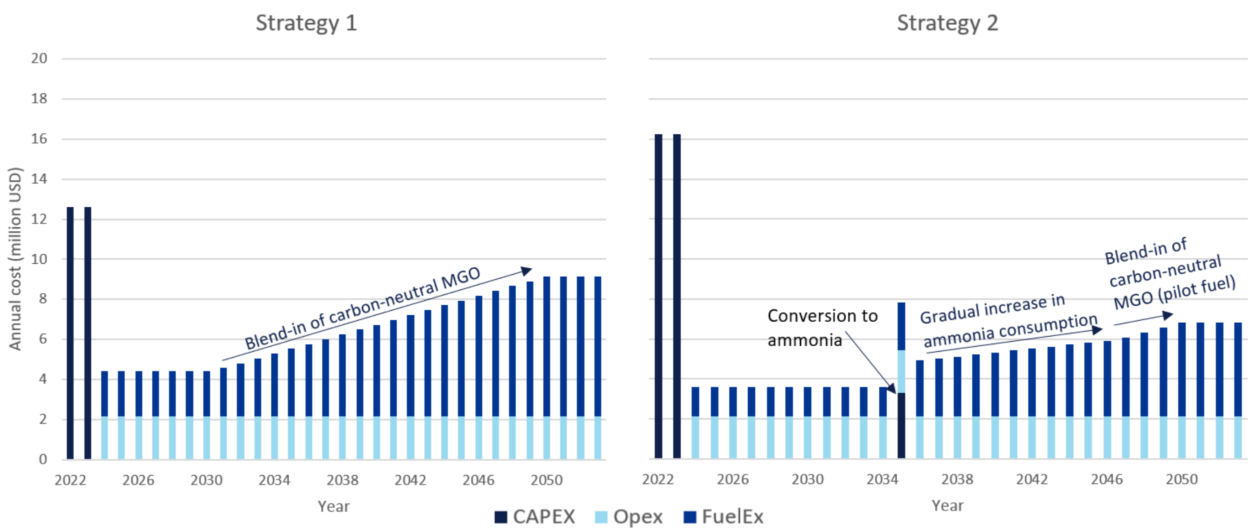

Figure 6-2 Break-down of annual cost for *Strategy 1* (left) and *Strategy 2* (right).

[61] Discount rate of 8% applied for all future cash flows.

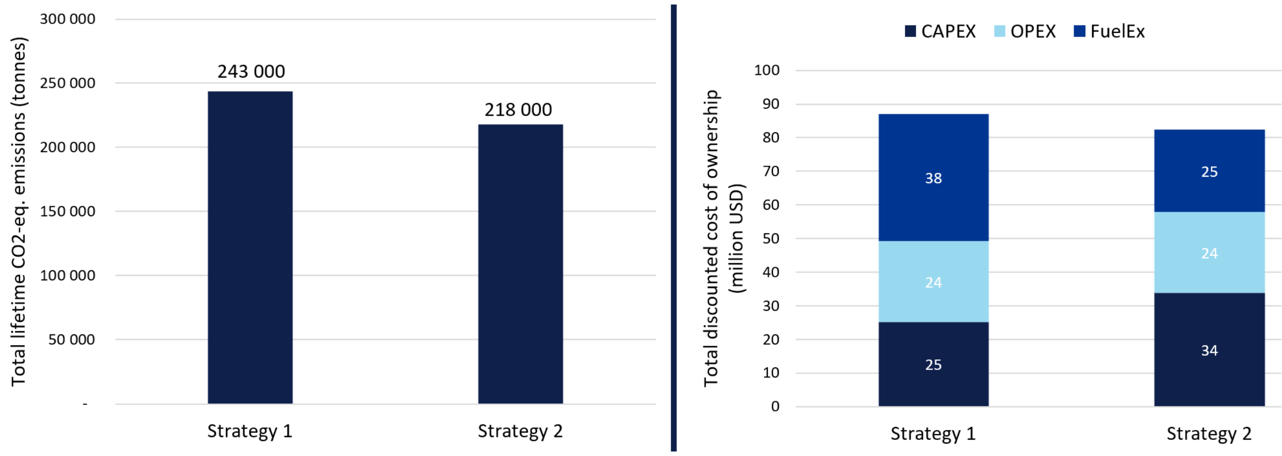

Figure 6-3 Lifetime CO_2-eq emissions (left) and break-down of total discounted lifetime cost (right), by compliance strategy.

6.1.3 Step 3 – Ship-specific roadmap for future carbon intensity compliance

Given the results from the previous section (assessment of compliance strategies), *Strategy 2* is the compliance strategy of choice. Figure 6-4 shows the carbon intensity pathway of the selected compliance strategy, until the ship's end of lifetime.

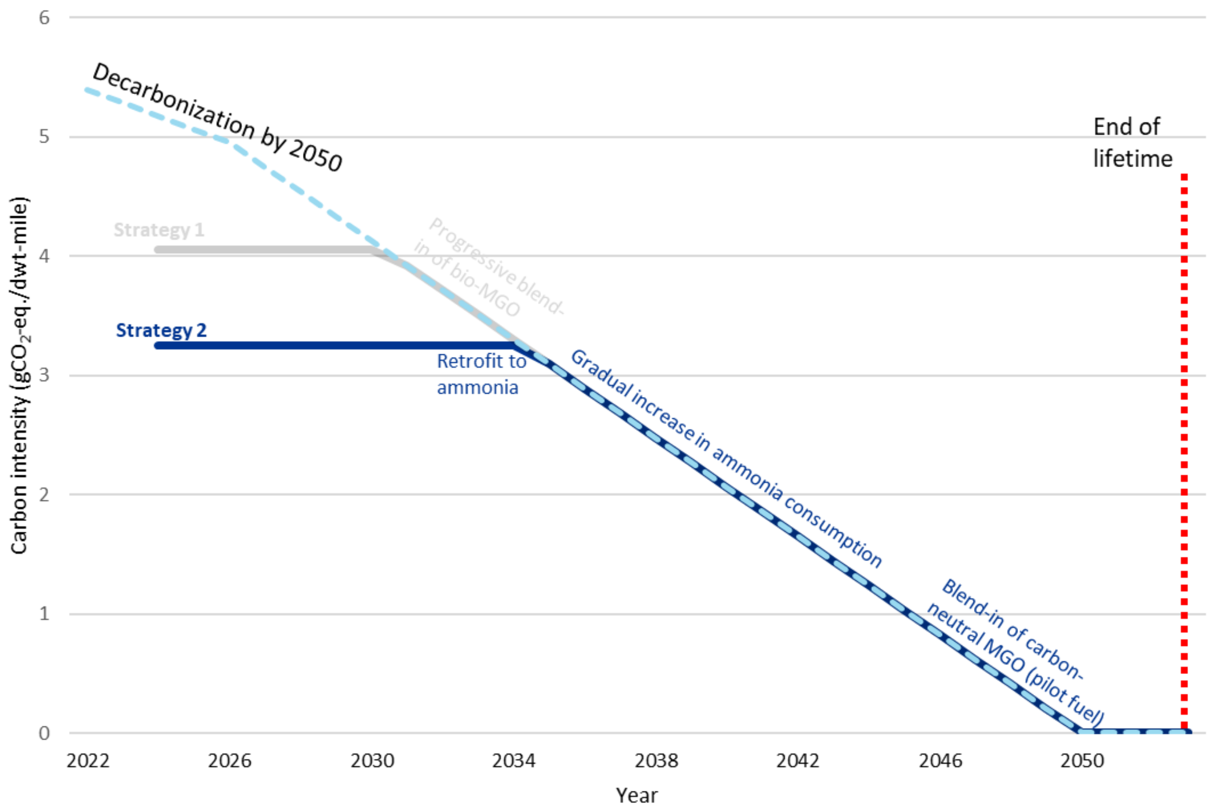

Figure 6-4 Illustration of carbon intensity for the selected compliance strategy (Strategy 2).

The shipowner must perform several actions and preparations to implement the selected decarbonization strategy. These are outlined in the decarbonization roadmap presented below, in the form of two items:

- Table 6-4 gives the decarbonization measures and time of implementation necessary to follow the carbon intensity pathway from Figure 6-4. Cost (CAPEX) and CO_2-eq reduction potential of each measure is also given. The volume of ammonia (and carbon-neutral pilot fuel) needed is also provided.
- Figure 6-5 gives a timeline with preparatory actions needed before implementation of decarbonization measures on board the vessel.

The roadmap looks far ahead into the future, until the vessel's expected end of lifetime. Therefore, it is recommended that the roadmap is kept up to date with the current drivers for decarbonization and the relevant technology space.

Table 6-4 The different measures and time of implementation needed for chosen compliance strategy.

	Measures to be implemented at newbuild stage (2024)	Measures to be implemented in 2034	Measures to be implemented in 2047
Hydrodynamics	ALS, gate rudder	-	-
Machinery	Slow steaming optimization	-	-
Fuel	DF LNG Fuel Ready (ammonia)	Retrofit to ammonia (Up to 8 000 t ammonia needed annually from 2047)	Blend-in of carbon-neutral MGO (pilot fuel) (Up to 800 t carbon-neutral MGO needed annually from 2050)
CO_2-eq reduction potential (%)	**~31%**	**~ 0%–76%**	**0%–100%**
Additional CAPEX (million USD)	**~ 7 million USD**	**~3 million USD**	**-**

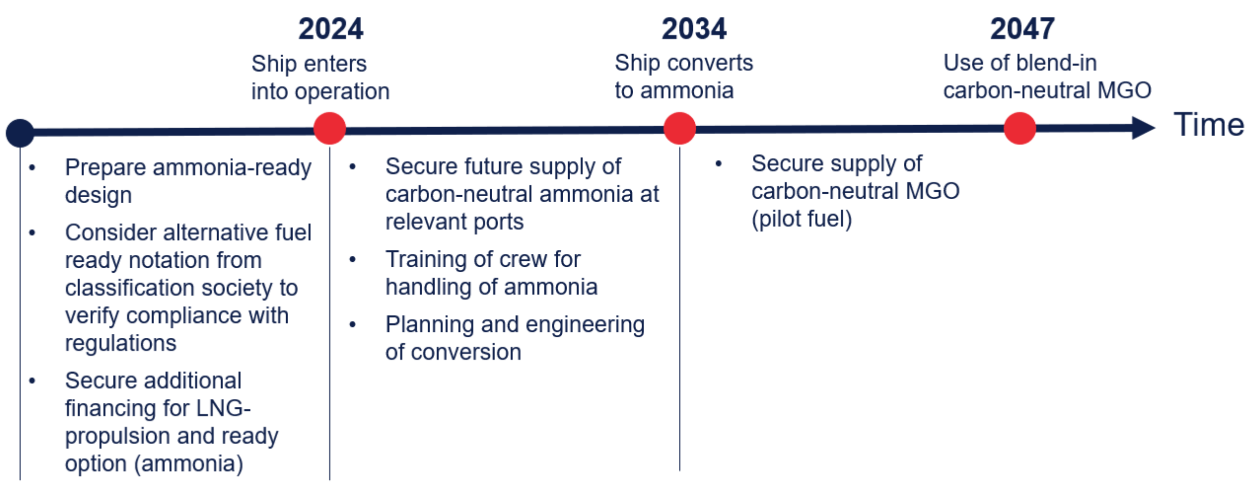

Figure 6-5 Timeline for important preparatory actions needed for implementation of strategy.

6.2 Chemical tanker (~10k dwt)

6.2.1 Step 1 – Define baseline, target trajectory, and compliance status

Baseline

The baseline vessel is an existing ship built in 2019 and running on VLSFO, but has been designed to facilitate a future conversion to LNG (i.e. LNG-ready). The vessel has already implemented several decarbonization measures, including draft optimization, weather routing, autopilot, and combinator optimization.

Today, the vessel has an operational carbon intensity in the order of ~15.9 gCO_2-eq/dwt-mile.

Target trajectory and compliance status

A target carbon intensity trajectory reaching zero in 2050 was identified as the most relevant for this generic ship case (see Figure 6-6), as this is in-line with the decarbonization ambitions of the shipowner involved in developing the generic vessel case. This target trajectory reflects a market situation where cargo owners and financial institutions push for decarbonization beyond regulatory compliance (assuming the IMO's long-term GHG strategy is implemented through policy measures). In the period leading up to and including 2026, the carbon intensity trajectory is aligned with a 'C' rating according to CII rating requirements (see Chapter 3 for more information). Given this target trajectory, the generic case vessel will be compliant until 2029, at which point decarbonization measures are needed.

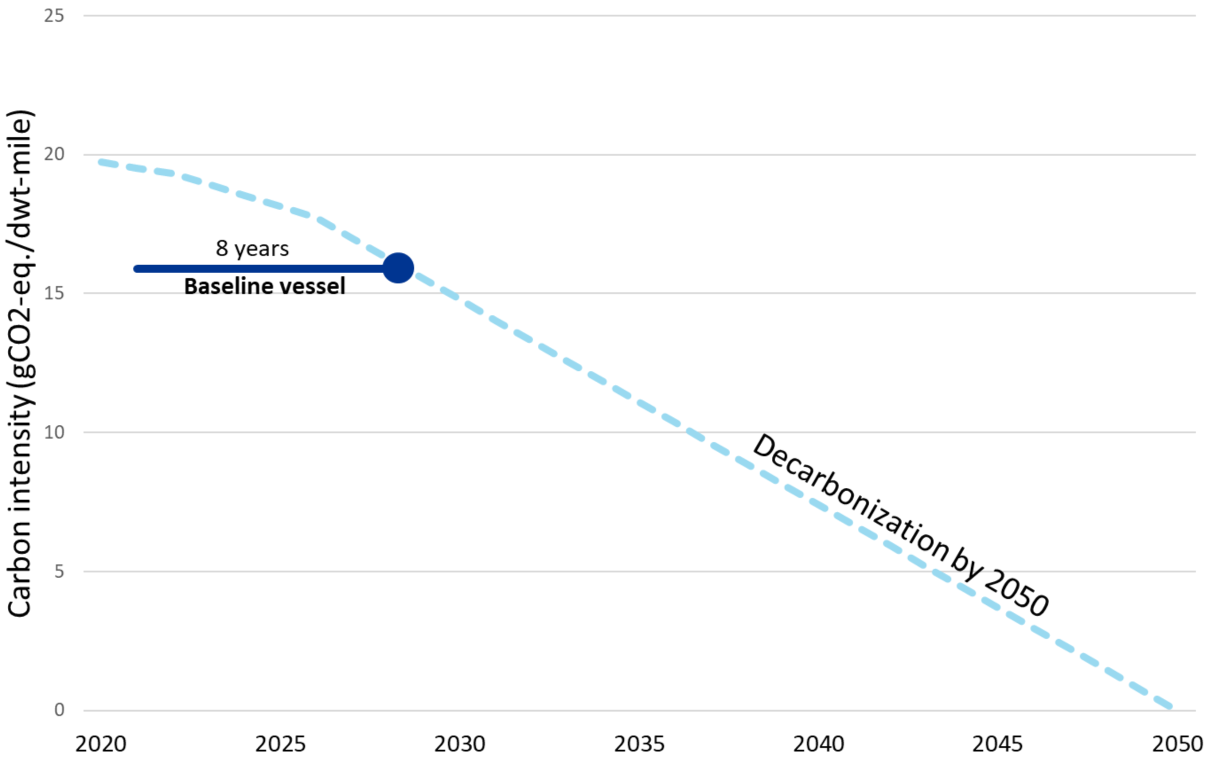

Figure 6-6 Target carbon intensity trajectory and compliance status of baseline vessel (~10k dwt chemical tanker).

6.2.2 Step 2 – Assessment of compliance strategy

As the baseline vessel has taken steps at the newbuilding stage to prepare for future conversion to LNG (i.e. LNG-ready), such a conversion is seen as a natural decarbonization measure. For simplicity, this is the only decarbonization measure considered in this case, apart from blend-in of carbon-neutral fuel (see Table 6-5). In reality, energy-efficiency measures could be considered either in combination with conversion to LNG or as standalone measures.

Table 6-5 CO_2-eq reduction potential and additional CAPEX by measure.

Measure	CO_2-eq reduction potential (%)	Additional CAPEX (million USD)
LNG as fuel	20%	3.2

Based on the above, two compliance strategies are identified and assessed as described in Table 6-6.

Table 6-6 Description of compliance strategies explored in the chemical tanker case.

Compliance strategy	Description of compliance strategy
Strategy 1	Conversion to LNG in 2022. Future blend-in of carbon-neutral LNG to ensure compliance with target carbon intensity trajectory.
Strategy 2	Future blend-in of carbon-neutral MGO to ensure compliance with carbon intensity trajectory.

Figure 6-7 shows the break-down of annual cost for the two compliance strategies. Although *Strategy 2* has the highest CAPEX costs, due to the conversion to LNG-propulsion, it has a significantly lower fuel expenditure as the vessel reaches its end of lifetime.

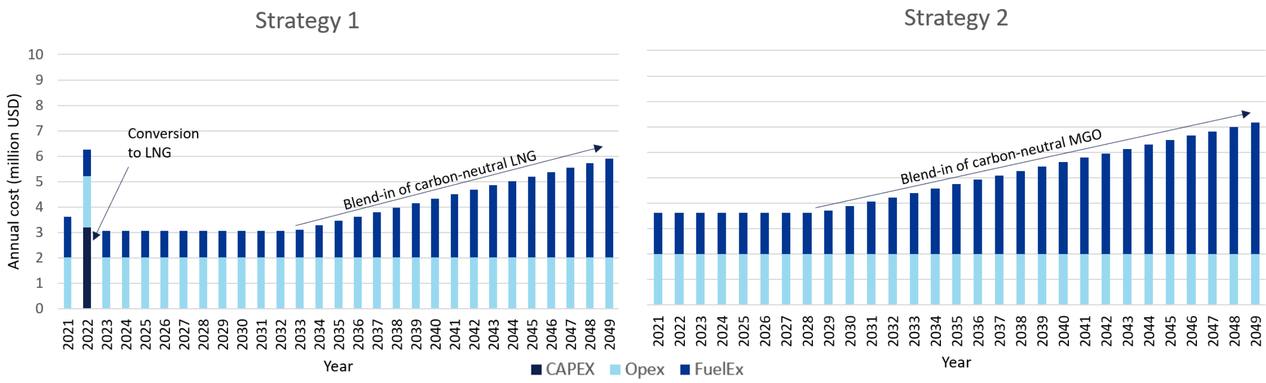

Figure 6-7 Break-down of annual cost for *Strategy 1* (left) and *Strategy 2* (right).

Figure 6-8 shows the total discounted[62] cost associated with each compliance strategy (left), and total lifetime CO_2-eq emissions (right). Under the current economic assumptions, given in Appendix A, *Strategy 1* has a ~13% lower total discounted cost and 9% less total lifetime CO_2-eq emissions compared with *Strategy 2*. As a result, selecting *Strategy 1* as the choice of compliance strategy makes the most sense from an economic and environmental perspective. This conclusion is subject to the given economic assumptions, and sensitivity studies should be performed to make this decision more robust.

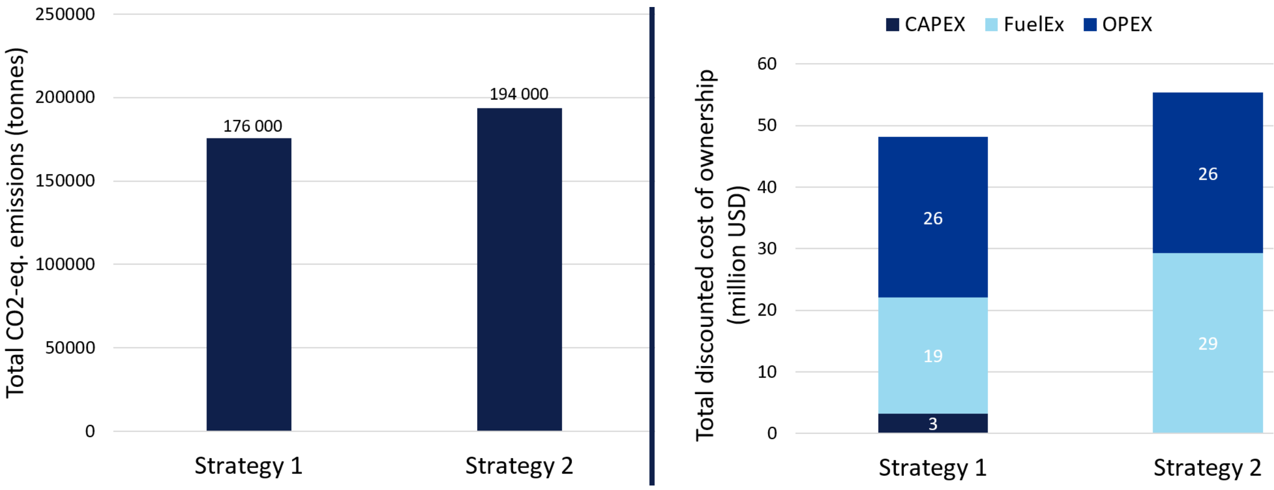

Figure 6-8 Lifetime CO_2-eq emissions (left) and break-down of total discounted lifetime cost (right), by compliance strategy.

[62] Discount rate of 8% applied for all future cash flows.

6.2.3 Step 3 – ship-specific roadmap for future carbon intensity compliance

Given the results from the previous section (assessment of compliance strategies), *Strategy 1* – converting to LNG - is the compliance strategy of choice. Figure 6-9 shows the carbon intensity pathway of the selected compliance strategy, until the ship's expected end of lifetime.

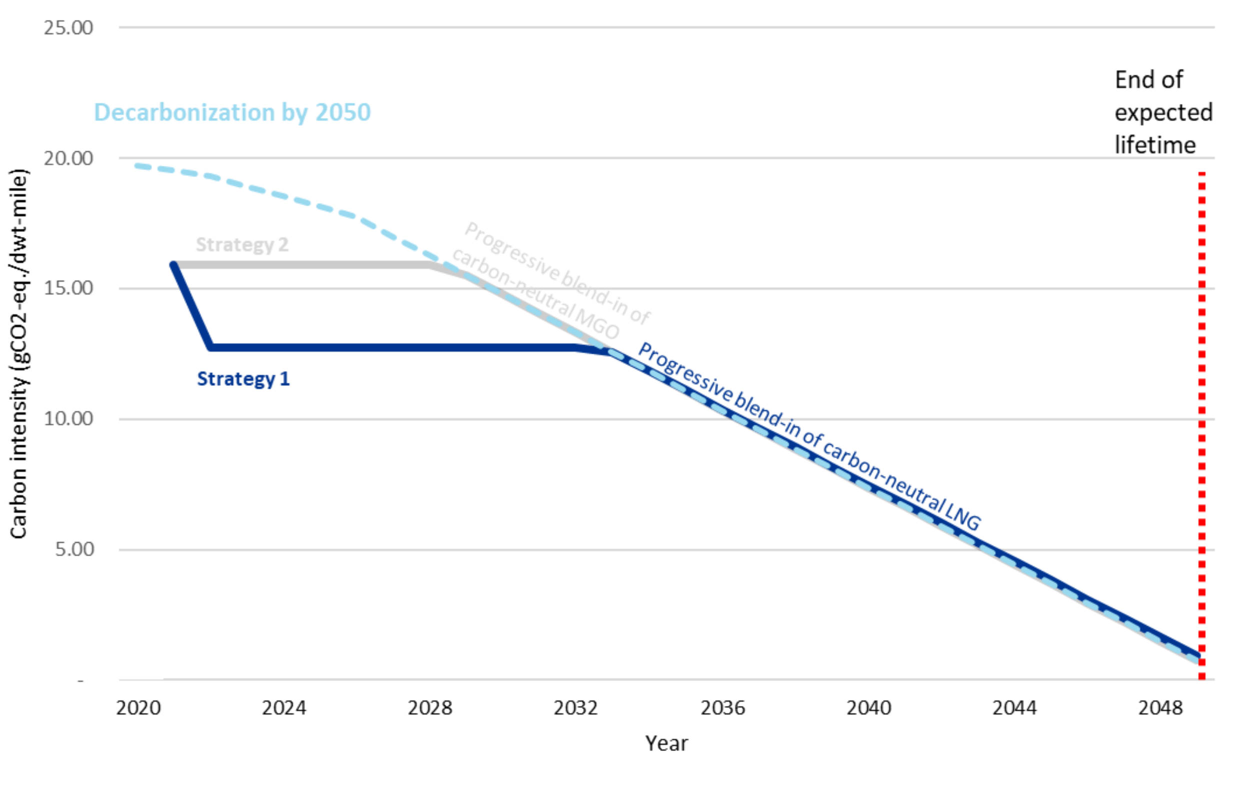

Figure 6-9 Illustration of carbon intensity for the selected compliance strategy (*Strategy 1*).

The shipowner must perform several actions and preparations to implement the selected decarbonization strategy. These are outlined in the decarbonization roadmap presented below, in the form of two items:

- Table 6-7 gives the decarbonization measures and time of implementation necessary to follow the carbon intensity pathway from Figure 6-9. Cost (CAPEX) and CO_2-eq reduction potential of each measure is also given. The volume of carbon-neutral LNG needed is also provided.
- Figure 6-10 gives a timeline with preparatory actions needed before implementation of decarbonization measures on board the vessel.

The roadmap looks far ahead into the future, until the vessel's expected end of lifetime. Therefore, it is recommended that the roadmap is kept up to date with the current drivers for decarbonization and the relevant technology space.

Table 6-7 The different measures and time of implementation needed for selected compliance strategy.

	Measures to be implemented in 2022	Measures to be implemented in 2033
Fuel	Conversion to LNG	Substitution of fossil LNG with carbon-neutral LNG (Up to 2 500 t carbon-neutral LNG needed annually in 2049)
CO_2-eq reduction potential (%)	**∑~ 20%**	**0%–93%**
Additional CAPEX (million USD)	**∑~ 3 million USD**	-

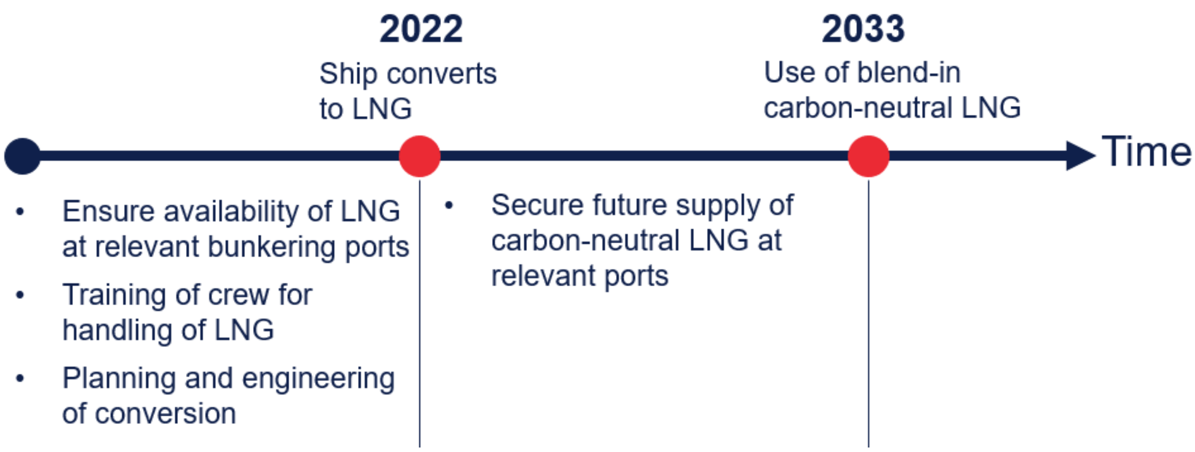

Figure 6-10 Timeline for important preparatory actions needed for implementation of roadmap.

6.3 General cargo vessel (4k dwt)

6.3.1 Step 1 – Define baseline, target trajectory, and compliance status

Baseline

The baseline vessel is an existing ship built in 2008 and running on VLSFO. The vessel is already operating at a low speed (<10 knots (kn)), and further speed reduction is likely not feasible from a technical and commercial perspective. Today, the vessel has an operational carbon intensity in the order of ~19.3 gCO_2-eq/dwt-mile.

Target trajectory and compliance status

A target carbon intensity trajectory reaching zero in 2070 (although the vessel is expected to have its last operational year in 2046) was identified as the most relevant carbon intensity trajectory for this newbuild (see Figure 6-11). This trajectory can represent a minimum regulatory compliance trajectory assuming the IMO's current long-term GHG strategy is implemented through policy measures. This trajectory was picked since the vessel is below 5,000 GT and is hence not subject to CII rating and enhanced SEEMP requirements (reference to Chapter 3, Table 3-1). Consequently, as far as international decarbonization policy measures are concerned, the regulatory driver for this vessel is not as strong as for other ships above 5,000 GT. The given target trajectory, *Decarbonization by 2070*, is based on the CII reference line for bulk carriers and is aligned with a 'C' rating between 2023 and 2026, before going linearly towards zero in 2070. It should be noted that the CII reference line has been constructed based on data for vessels of 5,000 GT and above. As such, the CII reference line is not necessarily representative of the performance of the general cargo vessel assessed in this generic ship case. Under the given target carbon intensity trajectory, the baseline vessel is compliant until 2034.

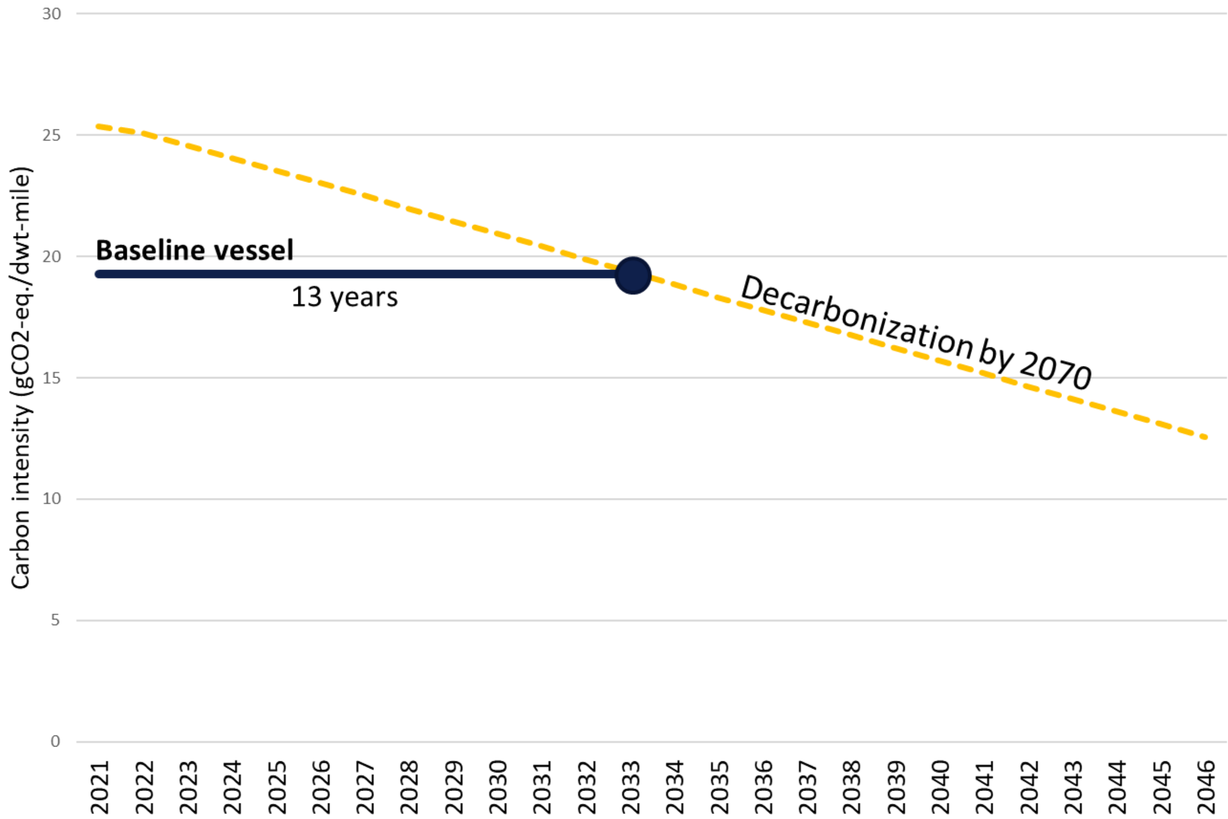

Figure 6-11 Target carbon intensity trajectory and compliance status of baseline vessel (~4k dwt bulk carrier).

6.3.2 Step 2 – Assessment of compliance strategy

In this case we consider use of energy harvesting measures, and more specifically, Flettner rotors. Since the baseline vessel is conventional and has not been prepared for any future conversion of fuel, alternative fuels have not been considered as decarbonization measures (other than use of compatible blend-in fuel). Retrofitting two Flettner rotors is estimated to cost approx. USD 800,000 for this vessel, with an assumed saving of 12% CO_2-eq. The saving potential of the Flettner rotor will in reality depend on factors such as weather conditions and the speed of the vessel.

Each compliance strategy assessed is described in Table 6-8.

Table 6-8 Description of compliance strategies explored in this generic vessel case.

Compliance strategy	Description of compliance strategy
Strategy 1	Future blend-in of carbon-neutral MGO to ensure compliance with target carbon intensity trajectory.
Strategy 2	Retrofit of Flettner rotor in 2022, combined with future blend-in of carbon-neutral MGO to ensure compliance with carbon intensity trajectory.

Figure 6-12 shows the break-down of annual cost for the two compliance strategies. Although, *Strategy 2* has the highest CAPEX costs, due to the retrofit of Flettner rotors in 2022, it has a lower fuel expenditure as the vessel reaches its end of lifetime, due to lower fuel consumption.

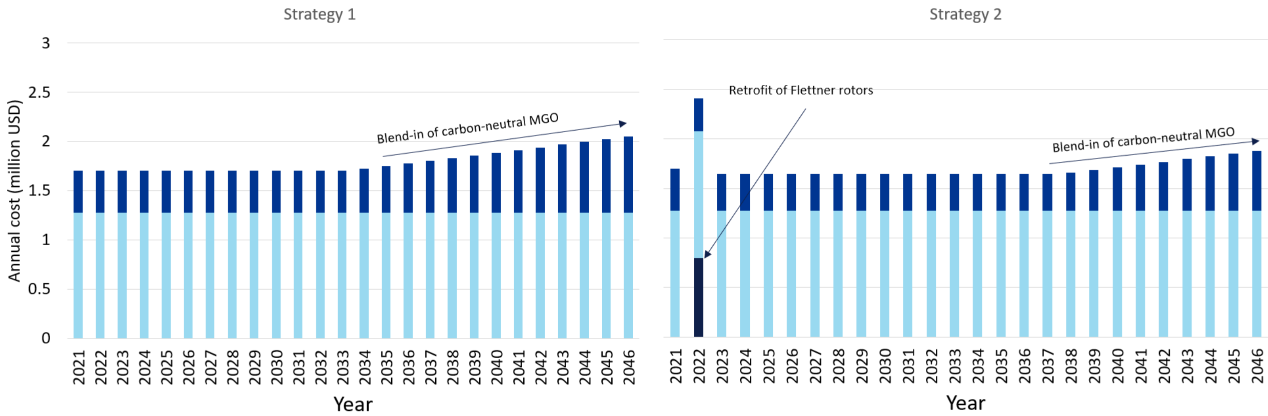

Figure 6-12 Break-down of annual cost for *Strategy 1* (left) and *Strategy 2* (right).

Figure 6-13 shows the total discounted[63] cost associated with each compliance strategy (left), and total lifetime CO_2-eq emissions (right). Under the current economic assumptions, given in Appendix A, *Strategy 2* has a ~1% lower total discounted cost and a 7% lower total lifetime CO_2-eq emissions compared with *Strategy 1*. As a result, selecting *Strategy 2* as the choice of compliance strategy, makes the most sense from an economic and environmental perspective. This conclusion is subject to the given economic assumptions, and sensitivity studies should be performed to make this decision more robust.

[63] Discount rate of 8% applied for all future cash flows.

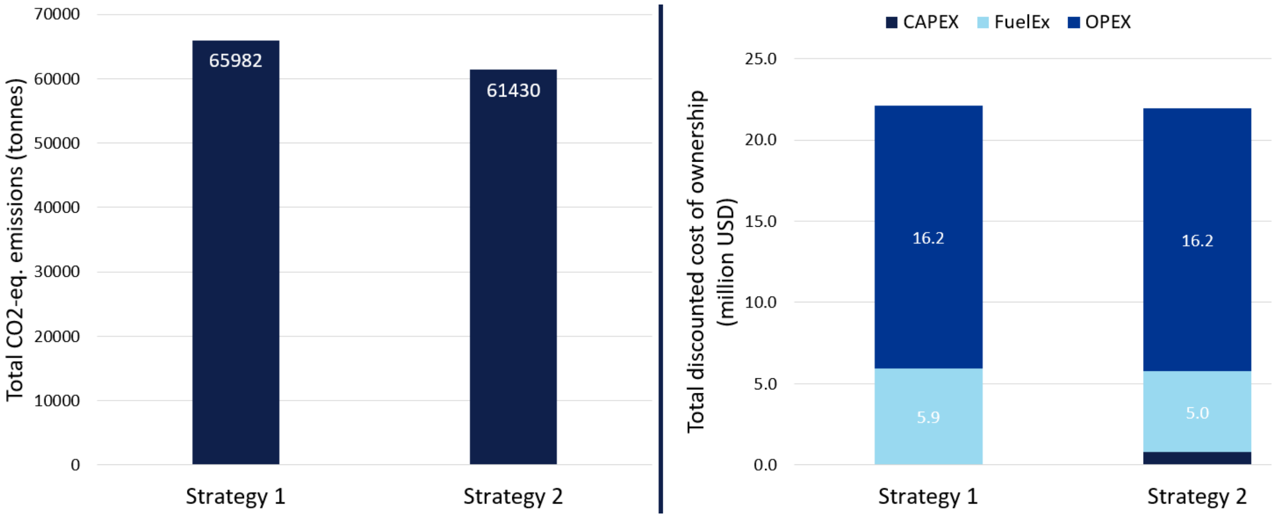

Figure 6-13 Lifetime CO_2-eq emissions (left) and break-down of total discounted lifetime cost (right), by compliance strategy.

6.3.3 Step 3 – ship-specific roadmap for future carbon intensity compliance

Given the results from the previous section (assessment of compliance strategies), *Strategy 2* is the compliance strategy of choice. Figure 6-14 shows the carbon intensity pathway of the selected compliance strategy, until the ship's end of lifetime.

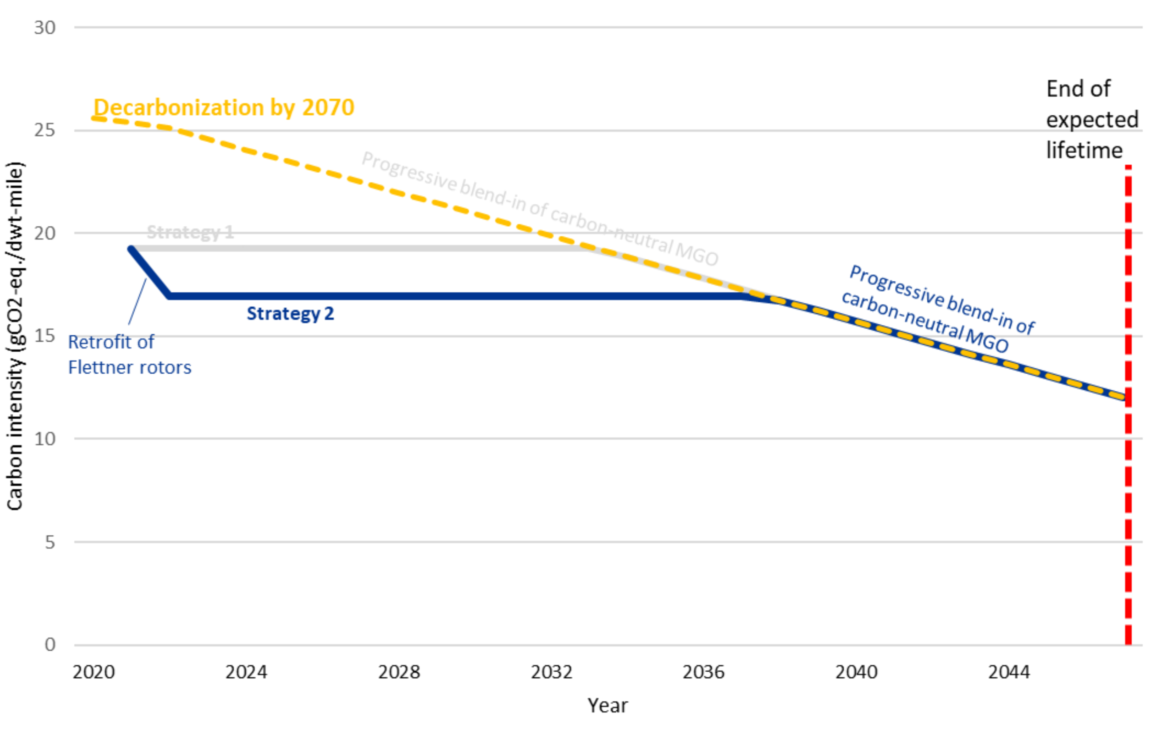

Figure 6-14 Illustration of carbon intensity for the selected compliance strategy (*Strategy 2*).

The shipowner must perform several actions and preparations to implement the selected decarbonization strategy. These are outlined in the decarbonization roadmap presented below, in the form of two items:

- Table 6-9 gives the decarbonization measures and time of implementation necessary to follow the carbon intensity pathway from Figure 6-14. Cost (CAPEX) and CO_2-eq reduction potential of each measure is also given. The volume of carbon-neutral MGO is also provided.
- Figure 6-15 gives a timeline with preparatory actions needed before implementation of decarbonization measures onboard the vessel.

The roadmap looks far ahead into the future, until the vessel's expected end of lifetime. Looking this far ahead in time inherently involves great uncertainty. Therefore, it is recommended that the roadmap is kept up to date with the current drivers for decarbonization and the relevant technology space.

Table 6-9 The different measures and time of implementation needed for selected compliance strategy.

	Measures to be implemented in 2022	**Measures to be implemented in 2037**
Energy harvesting	Retrofit of Flettner rotors	
Fuel		Substitution of fossil VLSFO with carbon-neutral MGO (Up to 200 t carbon-neutral MGO needed annually in 2048)
CO_2-eq reduction potential (%)	**∑~ 12%**	**0%–30%**
Additional CAPEX (million USD)	**∑~ 1 million USD**	

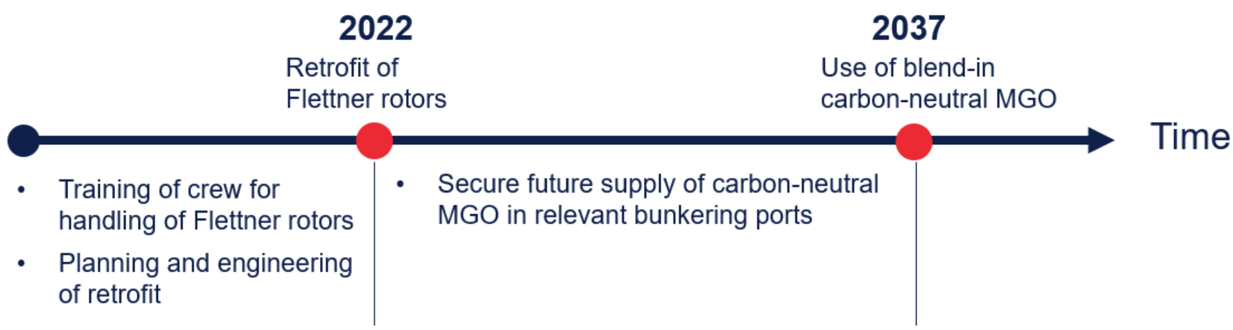

Figure 6-15 Timeline for important preparatory actions needed for implementation of roadmap.

6.4 Handling uncertainties

To make the results from the cases more robust, their sensitivities to uncertainties in key variables should be investigated as part of Step 2. Key input variables for developing the compliance strategy and the roadmaps are projections of fuel prices and CO_2 price, assumed technology costs and reduction potentials of the various measures included, as well as the discounting rate. By varying, for example, the range of fuel and CO_2 prices and technology costs, the results can provide a better picture of the financial robustness of the compliance strategy.

In this section, we exemplify how uncertainty in one key factor can be analysed. In our case results we have assumed that CO_2 prices are zero. In the following we explore the impact of a CO_2 price on the case results.

As noted in Chapter 3, the IMO as part of its medium- and long-term policy measures, could consider a CO_2 pricing scheme in the future to reduce the price-gap between carbon-neutral fuels and fossil fuels. Such a mechanism would likely require a new convention to adopted in the IMO, therefore it is reasonable to assume that it would be hard to implement before the latter half of this decade. Also, the EU, is considering extending its Emissions Trading System to include maritime transport. As such, there is a high likelihood that a significant share of the world fleet will be subject to CO_2 pricing in the not-too-distant future.

To explore the impact of such a pricing scheme on the economic analysis performed for the generic vessel cases earlier in the chapter, we have calculated the total discounted cost of ownership for all cases given two different levels of CO_2 pricing starting in 2030: *100 USD/tCO_2,* and *300 USD/tCO_2*. These are consistent with the range of CO_2 prices stated by some stakeholders as being necessary for achieving decarbonization goals (e.g. Maersk[64], OECD[65], the Norwegian government[66], Trafigura (2020), and DNV GL (2020a), though some stated CO_2 prices are not specifically applicable for shipping. The results from the economic assessment are presented in Figure 6-16, Figure 6-17, and Figure 6-18.

We observe from the Figures that all the cost associated with all the evaluated strategies increases with increasing CO_2 price. Furthermore, the cost of the strategies selected for each generic vessel case remains lower than the alternative compliance strategies. The reason for this is that the compliance strategy with lowest lifetime CO_2-eq emissions was picked and implemented into the roadmaps. There is an increasing difference between the selected and the competing strategies; but since we are assuming that the CO_2 pricing does not come into force before 2030, it has a limited impact on costs. The reason is that no compliance strategy makes a great difference in terms of annual CO_2-eq emissions post-2030.

64 https://shipandbunker.com/news/world/633414-maersk-proposes-450mt-carbon-tax-for-bunker-fuel
65 https://www.oecd.org/tax/tax-policy/effective-carbon-rates-2021-highlights-brochure.pdf
66 https://bellona.org/news/ccs/2021-02-norway-proposes-e200-per-ton-co2-tax-by-2030

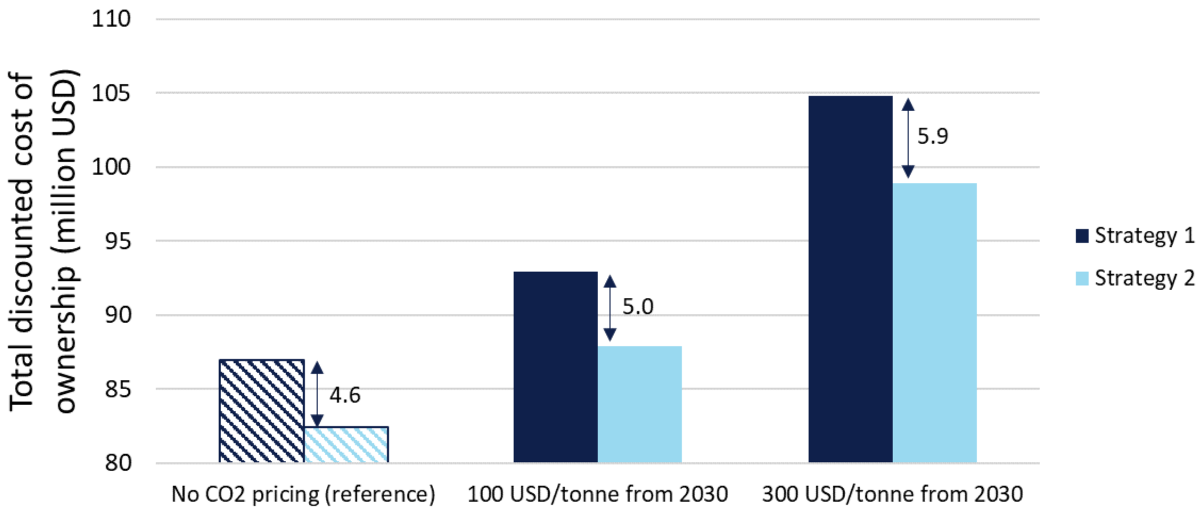

Figure 6-16 Impact of CO_2 pricing on total discounted cost of ownership for the bulk carrier (~60k dwt) generic vessel case.

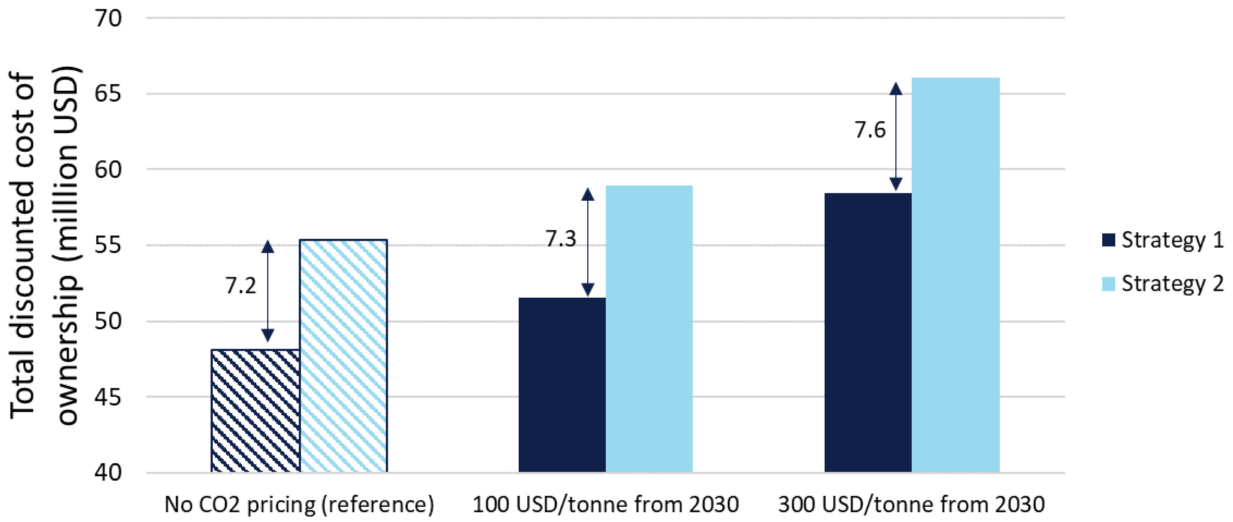

Figure 6-17 Impact of CO_2 pricing on total discounted cost of ownership for the chemical tanker (~10k dwt) generic vessel case.

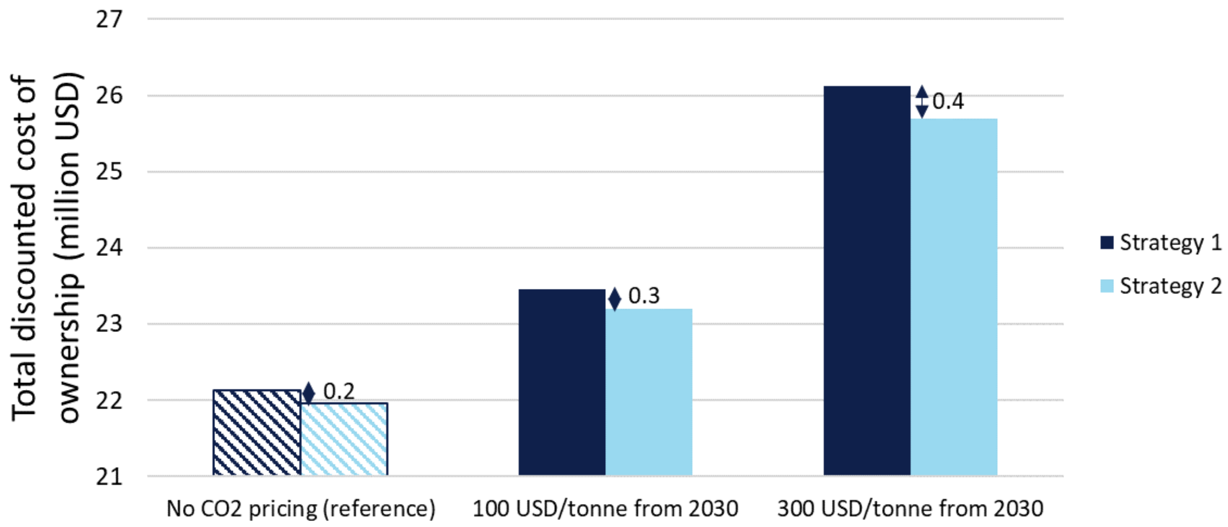

Figure 6-18 Impact of CO_2 pricing on total discounted cost of ownership for the general cargo (~4k dwt) generic vessel case.

BIBLIOGRAPHY

Acciaro et al. (2013), The energy efficiency cap in maritime transport, Journal of Shipping and Ocean Engineering', Vol.3, No. 12, 2013, pp1–10.

Agora (2019), The Future Cost of Electricity-Based Synthetic Fuels, Agora.

Andersson, P. (2017), Green approaches at sea—The benefits of adjusting speed instead of anchoring, Univ, Transportation Research Part D: Transport and Environment, Vol.51, March 2017, pp240–249.

Clarksons (2021), Shipping Intelligence Network, Clarksons Research, retrieved 1 September 2021.

Balcombe et al. (2019), How to decarbonise international shipping: options for fuels, technologies and policies.

Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017), State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. Transportation Research Part D: Transport and Environment, 52, 408–421. https://doi.org/10.1016/j.trd.2017.03.022

Bowen, H (1953), Social responsibilities of the businessman, University of Iowa Press.

Buhaug Ø. et al. (2009), Second IMO GHG study 2009, International Maritime Organization (IMO), London, UK, April 2009.

Bøckmann, E., Yrke, A., Steen, S. (2018), Fuel savings for a general cargo ship employing retractable bow foils, Applied Ocean Research. 76. 1-10. 10.1016/j.apor.2018.03.015.

CE Delft (2012), Regulated Slow Steaming in Maritime Transport - An Assessment of Options, Costs and Benefits, CE Delft, February 2012.

CE Delft (2017a), Regulating speed: a short-term measure to reduce maritime GHG emissions, CE Delft.

CE Delft (2017b), Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships, CE Delft.

CE Delft (2020), Availability and costs of liquefied bio- and synthetic methane – The maritime shipping perspective, CE Delft.

CONCAWE (2020), Role of e-fuels in the European transport system - Literature review, CONCAWE.

Chatzinikolaou, S. et al. (2016), Ship Life Cycle Greenhouse Gas Emissions, Energy, Transportation and Global Warming, Green Energy and Technology, Chapter 65.

Chou, T., Kosmas, V., Acciaro, M., Renken, K. (2021), A Comeback of Wind Power in Shipping: An Economic and Operational Review on the Wind-Assisted Ship Propulsion Technology. Sustainability 2021, 13, 1880. https://doi.org/10.3390/su13041880

DNV (2009), Pathways to Low Carbon Shipping, Abatement potential for existing world fleet, DNV Position paper, 2009.

DNV (2010a), Pathways to low carbon shipping, Abatement potential towards 2030, DNV, February 2010. DNV Position paper.

DNV (2010b), Assessment of measures to reduce future CO_2 emissions from shipping, DNV Position Paper 05.

DNV (2012a), Pathways to Low Carbon Shipping- Abatement Potential Towards 2050, Position paper 14, 2012.

DNV (2012b), Identifying and Overcoming Barriers to Implementation of Emission Reduction Measures in Shipping, DNV.

DNV GL (2016), Teknologier og tiltak for energieffektivisering av skip [in Norwegian], DNV GL report 2016-0511.

DNV GL (2017a), Low carbon shipping towards 2050, DNV GL, June 2017' https://www.dnvgl.com/publications/low-carbon-shipping-towards-2050-93579.

DNV GL (2017b), Sustainable development goals: exploring maritime opportunities, commissioned by the Norwegian Shipowners' association, https://rederi.no/globalassets/dokumenter-en/all/fagomrader/smi/dnv-gl-sdg-maritime-report.pdf

DNV GL (2017c), Navigating a low-carbon future, DNV GL report 2017-0205 for the Norwegian Shipowners' Association, 2017.

DNV GL (2018a), Maritime Forecast to 2050 – Energy Transition Outlook 2018.

DNV GL (2018b), The effect of reducing cruise ship speed in the World Heritage fjords, DNV GL rep. 2018-0260, Rev. 2.

DNV GL (2018c), ASEAN ship emission inventory, DNV GL rep., 2018-0260, Rev. 0.

DNV GL (2019a), Maritime Forecast to 2050 – Energy Transition Outlook 2019.

DNV GL (2019b), Comparison of Alternative Marine Fuels, DNV GL report 2019-0567 for SEA\LNG, 2019.

DNV GL (2020a), Energy Transition Outlook 2020: A global and regional forecast of the energy transition to 2050, DNV GL August 2020, download at eto.dnvgl.com

DNV GL (2020b), Maritime Forecast to 2050 – Energy Transition Outlook 2020, DNV GL, download at eto.dnvgl.com

DNV (2021a), Maritime Forecast to 2050 - Energy Transition Outlook 2021, DNV, download at eto.dnv.com

DNV (2021b), Main Report – Energy Transition Outlook 2021, DNV, download at eto.dnv.com

DNV (2021c), Assessment of the impact on the fleet of short-term GHG measures. Report for the IMO. Report nr. 2021-0262, Rev. 0.

DNV (2021d), Technology Progress Report – Energy Transition Outlook 2021, DNV, download at eto.dnv.com

DNV (2021e), Pathway to Net Zero Emissions – Energy Transition Outlook 2021, DNV, download at eto.dnv.com

DNB (2021), Nordic Bond Market – Green bonds and climate change. *Research report prepared by DNB Markets, a division of DNB Bank ASA.*

Drewry (2020), Ship Operating Costs, Annual Review and Forecast, Annual Report 2019/20, Drewry Maritime Research.

Eide, M S., Endresen, Ø, Skjong, R, Longva, T and Alvik, S. (2009), Cost-effectiveness assessment of CO2 reducing measures in shipping, Maritime Policy & Management, 36: 4, 367-384, 2009.

Eide, M., Longva, T., Hoffmann, P., Endresen, Ø., Dalsøren, S. (2011), Future cost scenarios for reduction of ship CO_2 emissions, Maritime Policy Management Volume 38(1), pp 11-37, 2011.

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.

EUC (2017), Final Report - Building Up the Future - Sub Group on Advanced Biofuels - Sustainable Transport Forum, European Commission.

Faber, J. et al. (2020), Fourth IMO GHG Study, Delft, CE Delft, July 2020.

Frontline (2019), Environmental Social Governance Report 2019, Frontline.

GIE (2021), GIE contribution to Inception Impact Assessment of FuelEU Maritime, https://www.gie.eu/wp-content/uploads/filr/2576/GIE_on%20FuelEU_Maritime_public.pdf

Hoffmann, P., Eide, M.S., Endresen, Ø. Effect of proposed CO_2 emission reduction scenarios on capital expenditure, Maritime policy & Management, DOI:10.1080/03088839.2012.690081, 2012.

ICCT (2011), Reducing Greenhouse Gas Emissions from Ships Cosy effectiveness of available options, White paper no 11, http://www.theicct.org/sites/default/files/publications/ICCT_GHGfromships_jun2011.pdf

ICCT (2019), Rotors and bubbles: Route-based assessment of innovative technologies to reduce ship fuel consumption and emissions, Working paper 2019-11, https://theicct.org/sites/default/files/publications/Rotors_and_bubbles_2019_05_12.pdf

ICCT (2020), The potential of liquid biofuels in reducing ship emissions, International Council on Clean Transportation.

IRENA (2018), Biogas for road vehicles: Technology brief, Abu Dhabi: International Renewable Energy Agency (IRENA).

IMO (2011), Reduction of GHG emissions from ships, Marginal Abatement Cost and Cost Effectiveness of Energy-efficiency measures. MEPC 62/INF.7.

IMO (2015), The Existing Shipping Fleet's CO_2 Efficiency, MEPC 68/INF.24/Rev.1, International Maritime Organization.

IMO (2018), Adoption of the Initial IMO Strategy on Reduction of GHG Emissions From Ships and Existing IMO Activity Related to Reducing GHG Emissions in the Shipping Sector, Note by the International Maritime Organization to the UNFCCC Talanoa Dialogue.

Jalkanen, J-P. et al (2021), Modelling of discharges from Baltic Sea shipping, *Ocean Science 17, 699-728, 2021.*

Jia et al., Energy efficiency with the application of Virtual Arrival policy, Transportation Research Part D: Transport and Environment, Volume 54, 2017, Pages 50-60, ISSN 1361-9209, https://doi.org/10.1016/j.trd.2017.04.037.

Jägerbrand, Annika K., Andreas Brutemark, Jennie Barthel Svedén, Ing-Marie Gren (2019), A review on the environmental impacts of shipping on aquatic and nearshore ecosystems, Science of The Total Environment, Volume 695, 2019, 133637, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2019.133637

KLP, DNB, DNV (2021), Paris aligned shipping and financial uncertainty, A Green Shipping Programme pilot study.

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.

Lindstad, E. et al. (2020), Decarbonizing Maritime Transport: The Importance of Engine Technology and Regulations for LNG to Serve as a Transition Fuel.

Longva, T., Eide, M. S., Skjong, R. A cost–benefit approach for determining a required CO2 index level for future ship design. Maritime Policy and Management, 37(2), 129–143, 2010.

Longva, T. (2011), A New Queuing Policy in Ports, Proceedings of MTEC2011, 13-15 April 2011, Singapore.

LR/UMAS (2019), Fuel production cost estimates and assumptions, Lloyd's Register and UMAS.

Maersk (2020), Sustainability Report 2020, https://www.maersk.com/~/media_sc9/maersk/about/files/sustainability/sustainability-reports/apmm-sustainability-report-2020-a3.pdf

MAN (2019), Managing methane-slip, https://man-es.com/docs/default-source/man-primeserv/sustainability/man_es_methane_slip_technical_paper.pdf?sfvrsn=fde9a343_4

McCarney (2020), Evolution in the Engine Room: A Review of Technologies to Deliver Decarbonised, Sustainable Shipping, Johnson Matthey Technol. Rev., 2020, 64, (3), 374–392.

Mersin, Kadir, Bayirhan, Irsad, Gazioglu, Cem, 2019. Review of CO_2 emission and reducing methods in maritime transportation. Thermal Sci. 23, 2073–2079.

Norwegian Government (2019), The Government's action plan for green shipping, https://www.regjeringen.no/en/historical-archive/solbergs-government/Ministries/kld/news/2019-nyheter/action-plan-for-green-shipping/id2660885

NSA (2020), Guidelines ESG reporting in the shipping and offshore industries, Norwegian Shipowners' Association.

OECD (2009), Greehouse gas emissions reduction potential from International shipping, Paper no 2009,-11, May 2009, http://www.itf-oecd.org/sites/default/files/docs/dp200911.pdf

OECD (2021), Effective Carbon Rates 2021, OECD.

Quang et al (2020), Greenhouse Gas Emissions of a Cargo Ship from a Life Cycle Perspective, International Journal of Environmental Science and Development, Vol. 11, No. 7, July 2020.

Rehmatulla et al. (2015), The diffusion of energy efficiency technologies in shipping, International Conference on Shipping in Changing Climates, Glasgow, UK, 2015

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, pp 44–57.

Sea-Cargo (2021). Reducing fuel consumption and CO_2 emissions. https://sea-cargo.no/2021/01/20/sc-connector-back-service

Schøyen et al. (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

SEA\LNG (2020), LNG as a marine fuel – the investment opportunity, retrieved from SEA\LNG, https://sea-lng.org/wp-content/uploads/2020/04/200224_SEA-LNG_Capesize_study_compressed.pdf

Smith, T. et al. (2014), Third IMO GHG Study 2014; International Maritime Organization (IMO) London, UK, June 2014.

Sphera (2021), 2nd Life Cycle GHG Emission Study on the Use of LNG as Marine Fuel.

Taljegard, M., Brynolf, S., Grahn, M., Andersson, K., and Johnson, H. (2014), Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model, Environmental Science & Technology 2014 48 (21), 12986- 12993. DOI: 10.1021/es5018575

Trafigura (2020), A proposal for an IMO-led global shipping industry decarbonisation programme.

Ushakov, S., Stenersen, D., & Einang, P. M. (2019). Methane slip from gas fueled ships: a comprehensive summary based on measurement data. Journal of Marine Science and Technology, 24(4), 1308-1325. https://doi.org/10.1007/s00773-018-00622-z

WCED (1987), Report of the World Commission on Environment and Development: Our Common Future

Xing et al. (2020), A comprehensive review on countermeasures for CO_2 emissions from ships, Renewable and Sustainable Energy Reviews, Volume 134.

Ytreberg, E., Åstrøm, S., Fridell, E. (2021), Valuating environmental impacts from ship emissions – The marine perspective, Journal of Environmental Management 282 (2021) 111958.

A. APPENDIX – GENERIC CASE VESSEL ASSUMPTIONS

Fuel prices

In principle, the price of a fuel is a function of the cost of raw material, production, and distribution of the fuel, and the relationship between supply and demand in the market. Historically we have seen large variations in prices. Because of this, it is hard to predict future fuel prices for marine fuels, not least because prices will vary between the different bunkering hubs and due to supply and demand. In principle, biomass is the key driver of production cost for biofuels, as is renewable electricity for electrofuels.

There is little consensus in the literature regarding future marine fuel prices. For example, predictions for bunkering prices in 2030 vary in the ranges 500–640 USD/tonne for LNG and 580–850 USD/tonne for VLSFO (CE Delft, 2020; Faber et al., 2020; SEA/LNG, 2020; LR/UMAS, 2019). Current estimates in the literature for the production cost of biofuels also vary widely; 430–1,660 USD/tonne for bio-MGO (i.e. Hydrotreated Vegetable Oil), and 430–1,870 USD/tonne for bio-LNG, excluding cost of liquefaction (ICCT, 2020; IRENA, 2018; EUC, 2017). These large spans reflect the fact that biofuels may be produced from many different sources of raw materials.

Estimated future production costs for electrofuels, produced using renewable electricity, also vary greatly. For example, the predicted cost of producing synthetic diesel (e-MGO) in 2050 is a range of approximately 1,040 USD/tonne up to 3,910 USD/tonne (Agora, 2019; CONCAWE, 2020).

The financial performance of compliance strategies is heavily dependent on fuel price. Since future fuel prices are highly uncertain and depend on various different factors, several fuel price scenarios should be explored to increase the robustness of results. However, to demonstrate our framework for managing decarbonization risk, we use only one fuel-price scenario in this handbook (Table A-1). The given fuel prices are constant and reflect future averages in a scenario where low-cost renewable electricity is available for production of carbon-neutral electrofuels. See DNV (2021a) for a more detailed explanation of the prices.

Table A-1 Fuel prices applied in the generic case studies. The prices are given as future averages and reflect a scenario in which low-cost renewable electricity is available for production of carbon-neutral electrofuels. See DNV (2021a) for more details.

	Fuel	Price (USD per gigajoule)	Price (USD per tonne of oil equivalent)
Fossil	MGO	13.8	578
	VLSFO	12.0	502
	LNG	7.8	327
Carbon-neutral	Ammonia	22.9	959
	MGO	40.0	1675
	LNG	30.7	1285

CAPEX and OPEX assumptions

CAPEX and OPEX assumptions for each generic vessel case are provided in Table A-2 and Table A-3, respectively. The OPEX cost of each generic vessel case is assumed to be constant throughout the entire lifetime of the vessel.

Table A-2 CAPEX assumptions for each generic vessel case. Basic newbuild costs are based on (Clarksons, 2021).

Generic vessel case	Compliance strategy	Baseline vessel	Newbuild cost (million USD)	Retrofit cost
Bulk carrier **(~60k dwt)**	*Strategy 1*	MF conventional	25.2	N/A
	Strategy 2	DF LNG Fuel Ready (ammonia)	32.5	Conversion to ammonia USD 3.3 million
Chemical tanker **(~10k dwt)**	*Strategy 1*	VLSFO (conventional) Fuel Ready (LNG)	N/A	Conversion to LNG USD 3.2 million
	Strategy 2			N/A
General cargo vessel **(~4k dwt)**	*Strategy 1*	MF conventional	N/A	N/A
	Strategy 2			Retrofit Flettner rotors USD 0.8 million

Table A-3 OPEX assumptions for each generic vessel case. The OPEX cost covers all operational expenses related to running the vessel, including manning, repair and maintenance, dry-docking, management, lubricating oils, stores, and spares. The costs are based on (Drewry, 2020).

Generic vessel case	Total annual OPEX
Bulk carrier **(~60k dwt)**	USD 2.1 million
Chemical tanker **(~10k dwt)**	USD 2.0 million
General cargo vessel **(~4k dwt)**	USD 1.3 million*

*Extrapolated cost based on the cost of larger ships of the same type.

B. APPENDIX – CARBON FOOTPRINT OF SHIPPING COMPARED WITH OTHER TRANSPORT MODES

Although the absolute GHG emissions from the sector are significant and must come down, shipping is widely acknowledged as having low carbon intensity[67] relative to other transport modes. Carbon intensity, or energy efficiency, can be compared across different transport modes by using the Energy Efficiency Operating Index (EEOI). The EEOI is calculated by dividing the CO_2 emissions by the product of distance travelled and mass transported. As part of the research for IMO's 3rd GHG Study (Smith, T. et al., 2014), the committee assessed energy efficiency across different transport modes (IMO, 2015), partly through a literature study. While the range of results in the literature study is wide, it tells the same story: sea transport is significantly more energy-efficient than road and air transport, a finding supported by other studies (e.g. Mersin et al., 2019). Using the numbers from the top-down estimate based on global fuel consumption and distances for the transport modes, the EEOI of sea transport is estimated to be 11 gCO_2/tonne-km, compared with 15 gCO_2/tonne-km for rail, 185 gCO_2/tonne-km for road, and 570 gCO_2/tonne-km for air. It must be emphasized that these numbers represent averages across vehicle and vessel sizes, in addition to cargo types, meaning that there will be cases where the modes compare differently. However, to illustrate the differences, Figure B-1 compares how far the different transport modes can transport one ton of cargo to produce 1 kg CO_2 emissions. In other words, a ship could sail almost 17 times further than a truck drives to produce the same amount of CO_2 per ton carried.

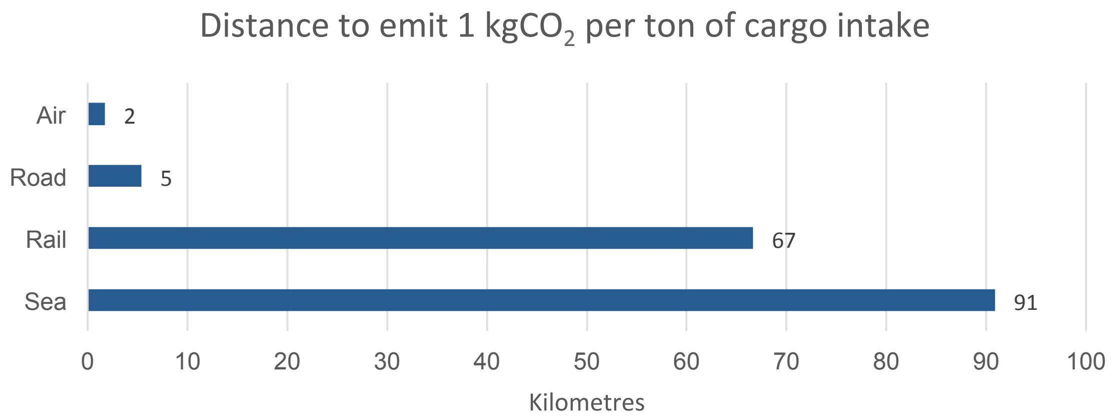

Figure B-1: Distance to emit 1 kg CO_2 per ton of cargo intake.

[67] Carbon intensity indicates emissions per transported quantity.

C. APPENDIX – IMPLICATIONS OF DECARBONIZATION ON COST OF MARINE TRANSPORTATION

Decarbonization of the shipping industry will most definitely be expensive. The capital expenditure to achieve zero-emission shipping have been estimated at USD 3.4 trillion (see Section 3.2). Adding to this, it is widely acknowledged that low- and zero-emission fuels will be substantially more expensive than the conventional alternatives, leading to proposed carbon prices in the range of USD 250 to USD 300 per tonne of CO_2 to levelize the costs (see Section 3.1). To make up for the additional financial and voyage costs, freight rates must be expected to rise. The charterers (who pay the freight bill) will in turn need to raise the prices of their products to cover the increased shipping cost, meaning that the end-users ultimately need to pay for the decarbonization. This chain of events is clearly simplistic, as the transition to low- and zero-emission shipping will entail a period when charterers can opt for cheaper and more polluting ships, and the end-users and consumers can do the same when selecting their products. However, distributing the cost of decarbonization over the value chain can be effective. In its 2020 Sustainability Report, Maersk (Maersk, 2020) presented a calculation showing only a marginal increase in product prices with a doubling of fuel costs (Figure C-1).

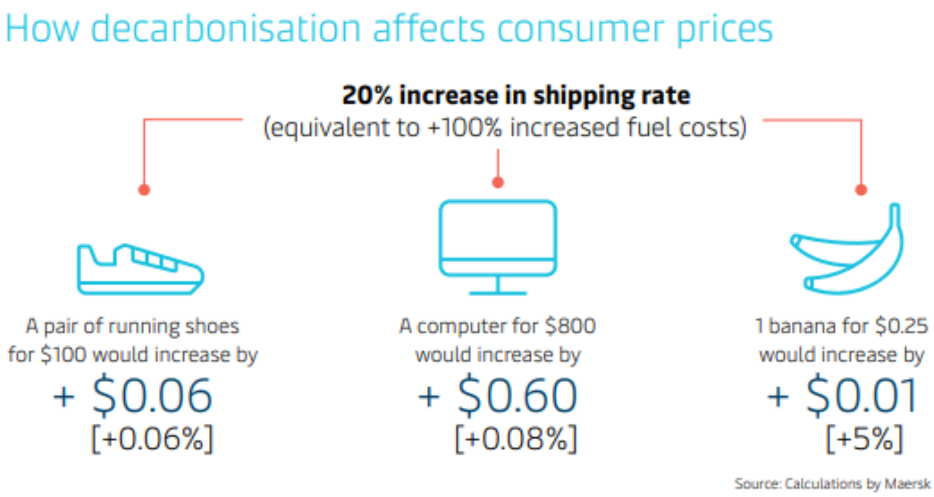

Figure C-1: How decarbonization affects consumer prices (Maersk, 2020)

The calculation is highly dependent on how much transporting the cargo contributes to the product cost, and cheaper products (per weight or volume) will have a higher relative increase in costs with greater shipping rates. While Maersk presumed a doubling of fuel costs in its example, DNV (2021a) estimated the changes in cost intensity under different policy regimes. When compared with currently implemented policies, we estimated cost-intensity increases of 2%, 7%, and 16% for scenarios translating to emission reductions of 10%, 17%, and 27%, respectively. The value chain would have to absorb these costs.

About DNV

DNV is the independent expert in risk management and assurance, operating in more than 100 countries. Through its broad experience and deep expertise DNV advances safety and sustainable performance, sets industry benchmarks, and inspires and invents solutions.

Whether assessing a new ship design, optimizing the performance of a wind farm, analysing sensor data from a gas pipeline or certifying a food company's supply chain, DNV enables its customers and their stakeholders to make critical decisions with confidence.

Driven by its purpose, to safeguard life, property, and the environment, DNV helps tackle the challenges and global transformations facing its customers and the world today and is a trusted voice for many of the world's most successful and forward-thinking companies.

COURSE TO ZERO