SETTING THE COURSE TO

LOW CARBON SHIPPING

VIEW OF THE
VALUE CHAIN

ABS

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ACKNOWLEDGMENTS

This publication was prepared by a group of contributing authors including: Georgios Plevrakis, Sotirios Mamalis, Daniel Barcarolo, Maria Polakis and Russ Barling and in collaboration with the Rocky Mountain Institute and Herbert Engineering.

1 | INTRODUCTION

Welcome to the third in the series of Low Carbon Shipping Outlooks produced by the American Bureau of Shipping (ABS) and industry partners.

As with the previous two editions, the information contained in this report is intended to help provide shipowners and operators with the information they need to manage the transition of their businesses towards low- and zero-carbon futures.

The series is offered solely as a comprehensive set of reference documents and should not in any way be seen as making recommendations, or as an advisory.

The first in the series, *2030 Outlook – 2050 Vision*, examined the International Maritime Organization (IMO)-mandated emissions goals and the varying levels of carbon impact from available marine fuels and other energy sources as shipowners strive to meet those goals.

One of its conclusions in 2019 was that global shipping may be able to meet the IMO's emission-reduction goals for 2030 by using existing technology (including fuels) and adopting operational improvements, but something would need to change for the 2050 targets to be met.

While some emerging technologies have matured in the interim, that assessment continues to ring true today. Shipping is still awaiting the big breakthrough and the emergence of a clear path towards meeting the IMO's most ambitious goals.

In the absence of an obvious single solution that could be applied now, it appears more and more likely that solutions will be found by combining two or more technological options; in that environment, creating a transition strategy that is designed to meet decarbonization targets is an imperative for shipowners.

The second in the series, *Pathways to Sustainable Shipping*, examined the current energy-commodity and consumer trends, and how they could influence the size of the global fleet, its trading patterns and, therefore, its emissions output.

We took a deeper dive into the three main emerging fuels pathways – light gas, heavy gas and bio/synthetic – to anticipate their potential timelines for use at industrial scale and the related trade-offs that may be necessary for prospective ship designs.

We also identified the taxonomies of potential fuel families in order to identify short-term, mid-term and long-term pathways to decarbonization.

In this, the third edition of ABS' Low Carbon Shipping Outlook series, we update the marine sector's progress on reducing emissions, analyze how it is likely to be affected by external decarbonization trends and present a life-cycle – or value-chain – analysis of the greenhouse gas (GHG) footprint of the leading alternative marine fuels.

In addition, we again showcase potential designs for future vessels, including their prospective technical and economic data.

The commercial shipping seascape against which all this is being assessed has recently fallen short of most forecasts offered even five years ago. For the past three years, the boom, for the most part, has left shipping's traditional boom-and-bust cycle. The industry's aggregate average volume growth from 2018 to 2020 fell into negative territory last year after being battered by the COVID-19 pandemic.

Global gross domestic product (GDP), as measured by the World Bank, fell 4.2 percent in 2020. Based on present assumptions about vaccine distribution, concerted health policies and continued government financial support, it expects GDP to grow 4.2 percent this year (2021).

Given the emerging challenges from the markets and climate change, the safe assumption is that, even if the latter rings true, there will be no return to the business as usual of five years ago for shipping. However, the planet's expanding population ensures a return to growth in consumer demand; and accelerating the transition to a zero-carbon future will help mitigate the risk that poses to the industry's emission-reduction goals.

The shipowners' strategic industry partners are encouraging them to intensify their focus on the entire value chain – not just the combustion cycle – when deciding which measures to take to reduce their collective carbon footprint.

Financiers and charterers increasingly appear poised to set the requirements for the environmental performance of vessels in connection with the prospective financing of new ships and new chartering agreements, respectively.

In the following pages, this report will assess the current markets and their prospects, including how those markets are likely to be impacted by the present rate of climate change.

For example, climate change has the potential to disrupt supply-side dynamics and shift the centers of demand in ways that could change global supply chains; it could also increase competition for vital resources (water, energy, food) and cause a reversal of globalization, just like society's recent response to the COVID-19 pandemic.

As reported in *Pathways to Sustainable Shipping*, the growing availability of lower cost renewable energy is spurring investment in research and development and innovation. While deployment remains slow and most new fuels are unlikely to be available at commercial scale anytime soon, their eventual distribution will require significant investment in infrastructure at the many ports that serve the main trade routes.

While the current focus has been on reducing shipping's carbon footprint, pressure is growing for every link in maritime trade's value chain to follow suit, including supporting landside infrastructure.

This report will look at the innovative carbon-reduction practices presently being deployed at ports and the challenges ahead as that sector joins others in transitioning towards a more sustainable business model.

Viewed from any perspective, shipowners and their partners will continue to recognize the emerging opportunity spurred by growing social and commercial concerns to deliver more sustainable business models. There are also significant risks ahead in relation to financing costs, the predictability of demand and industry regulation.

The decarbonization targets set by the IMO will demand changes to the way maritime businesses are conducted, including how the current fleet of vessels are operated and designed.

Reducing the output of carbon emissions will play a key role in shaping the future of the business and how environmental and financial performances are assessed, from individual shipping assets, to fleets and, finally, to the entire value chain that supports them.

Therefore, this report will look at how a climate change view through the lens of different scenarios will impact trade and create decision options related to new designs, technologies and transitions through retrofits and drop-in fuels. Then, it will address the current state of the fleet by establishing the present baseline. As carbon neutral and zero-carbon fuels will be required to assist with the findings in these sections, it attempts to provide an overview of the carbon emissions related to the life-cycle assessment of the fuels explored in ABS Low Carbon Shipping Outlook, *Pathways to Sustainable Shipping*. Finally, it explores the challenges and considerations necessary when identifying possible transitions and retrofits through a series of concept designs.

2 EVOLUTION OF THE GLOBAL SHIPPING INDUSTRY

LOOKING TO THE FUTURE: WHERE WE ARE AND WHERE WE NEED TO BE

The shipping industry is facing increasing pressure from different parts of the global economy to develop a sustainable pathway for future trade. Although there are significant risks for the sector along this transition, such as financing costs, consumer and regulatory risks, the direct consequences of climate change pose much more substantial and disruptive risks that will impact the entire globe. There are no defensive strategies against climate change and no business is expected to continue as usual. The industry should anticipate further increased volatility in an already cyclical environment experiencing downward trends.

Through initiatives such as the International Maritime Organization's (IMO) greenhouse gas (GHG) reduction strategy, the Poseidon Principles and the Sea Cargo Charter, the shipping industry has signaled their start and commitment to decarbonization. In the challenging transition to a 2050 low-carbon global fleet, interim solutions will be crucial for transition. A staged transition, with a focus on retrofitting existing vessels and fuel substitution, can offer valuable time for more aggressive deployment of decarbonization technologies while allowing supply chains to become commercially available. At the same time, this can help to avoid early vessel retirement and asset depreciation, while also avoiding some technology selection risks. This effort accelerates the transition and puts the sector at the center of decarbonization efforts by aligning with end consumer concerns, as well as policy and regulations that could otherwise cause sudden and significant disruptions.

As the marine sector is adjusting to the new conditions for trade, the internal need for transition is reflective of the same pressures and challenges being experienced in many other sectors. The transition to low- and zero-carbon fuels is therefore likely to be both valuable and desirable to consumers, producers and governments striving to mitigate the impact of climate change. The shipping sector can and should be a leader in creating a low-carbon future.

CURRENT STATE OF MARKET AND OUTLOOK

HISTORICAL DISRUPTIONS AND RESILIENCE OF THE INDUSTRY

The shipping industry is critical to the global economy, with over 11 million metric tons of goods shipped in 2019, representing an $18.9 trillion trade value[1]. Marine vessels carry around 80 percent of world trade volume and 70 percent of its value[2], while accounting for 2.9 percent of worldwide carbon dioxide (CO_2) emissions[3]. Although the maritime industry has experienced some decreases in growth rates and market disruptions in the past, the overall historical trend has shown continuous growth. The role of different cargo types has shifted over time; crude oil was the most transported cargo in the 1970s but now represents just 20 percent of the transported goods[4]. Slower growth in specific commodities has been offset by rapid increases in others to maintain the overall growth trend of industry.

Historical events and related disruptions to global shipping volumes are indicative of the type of industry-wide impacts that could be the consequence of climate change impacts and the associated disruption of global industries. Figure 1 shows that even the global recessions had limited impact on shipping. From the major crises highlighted, only the 1979 energy crisis resulted in structural long-term impact on the sector due to the rapid declines in crude oil trade. The shipping industry has experienced a challenging year in 2020 with volumes declining by an estimated 4.1 percent in the wake of the COVID-19 crisis following a slow-growth year of only 0.5 percent in 2019[5]. It is too early to know the recovery rate from COVID-19, but even if the gross domestic product (GDP) declines are more severe than those experienced in 2009 after the financial crisis, the world is likely to rebound from a single recession more resiliently than from a series of shocks or structural trend shifts.

A more troubling aspect of climate change and related weather disruption is that while historic events demonstrate relatively quick recovery after shocks, the expectation is that the sheer frequency of severe events will limit the economy's ability to recover and result in compounding disruptions across the globe. In addition, the economic and political response to what is increasingly acknowledged as a "climate crisis" is likely to have structural impact on seaborne trade across sectors, whether due to challenges related to production, destruction of infrastructure, shifts in trade flows or demand changes.

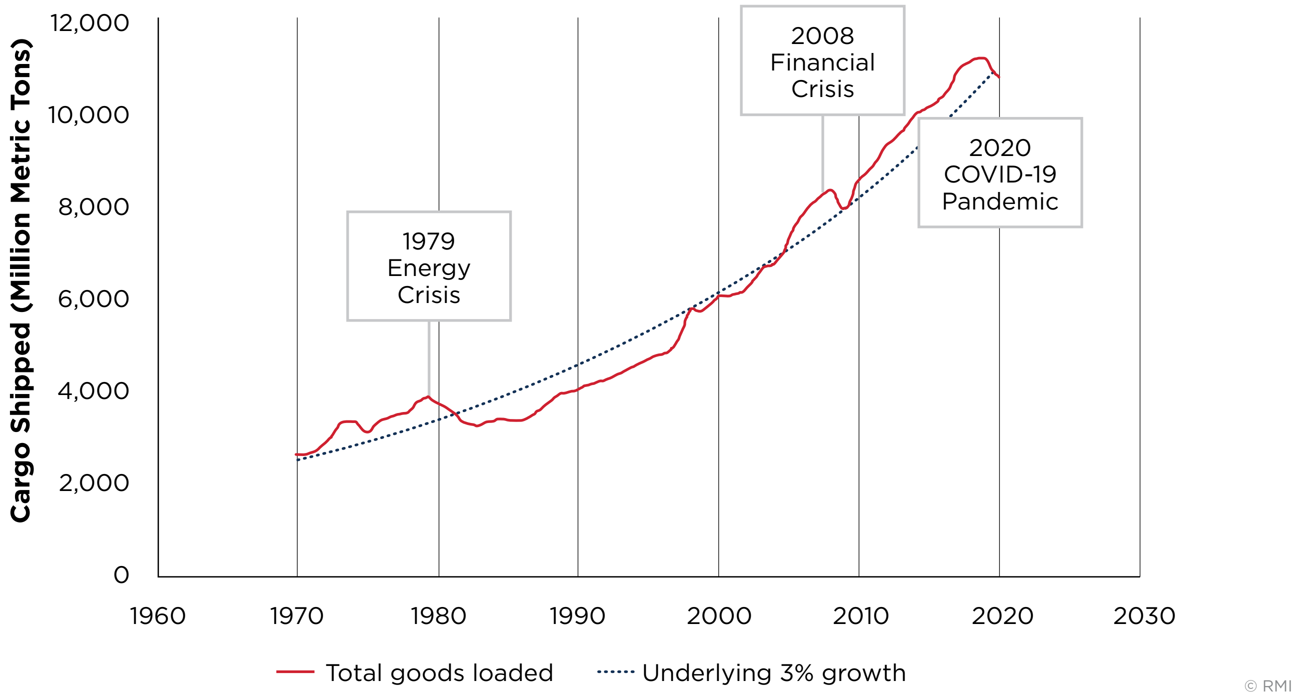

Figure 1: Historical events and disruptions in the shipping industry.

IMPLICATIONS OF CURRENT TRAJECTORY

The pandemic has severely impacted global trade with the World Trade Organization (WTO) estimating a decline of 9.2 percent of merchandise trade in 2020 due to COVID-19[6]. Events like this are expected to increase with climate change. Global shipping is at the center of international trade, therefore the importance of anticipating and planning for similar future events is paramount. The transition to low- and zero-carbon shipping still holds significant uncertainty around timelines for deployment of preferred technologies and fuels. In addition, the transition of the current fleet is a challenging and somewhat unclear process given the long lifetime of vessels. These factors demonstrate the breadth of challenges both directly and indirectly impacting the future development of the marine sector. Aligning with the IMO targets will enable the shipping sector to continue growing its global trade while playing a significant role in driving innovation towards low- and zero-carbon technologies.

Despite the challenges faced by the shipping sector globally due to the pandemic (economic crisis, supply chain disruptions, more inwardly focused national policies), reducing emissions and addressing environmental concerns is still a high priority[7]. Future projections of emissions from shipping are highly dependent on multiple parameters, including overall fleet growth and demand, improvement of vessel efficiencies, and deployment of new technologies. The IMO estimates that emissions from shipping in 2050 will range from 1,200 Mt CO_2/year in a low emission scenario to 1,700 Mt CO_2/year in the high emission scenario[8].

These scenarios reflect alignment with the high end of the Paris Agreement temperature goal while projecting business as usual growth. Despite this high uncertainty in expected emissions, all scenarios significantly exceed the IMO 2050 target of 50 percent reduction in total emissions by 2050 – as shown in Figure 2. The IMO low estimate still exceeds the IMO targets by 67 percent in 2050[9].

The Poseidon Principles demonstrate the first wave of pressure coming from the maritime financiers. The financial sector has recently been subject to increased scrutiny and it is clear that there is a growing expectation for the sector to play a significant role in supporting and promoting climate aligned solutions. The Poseidon Principles 2020 disclosure report shows that financiers are now focused on ensuring that their portfolios are moving consistently towards climate aligned targets and are comfortable with making public reporting part of this effort. This likely indicates a future where non-climate aligned newbuildings face increased scrutiny or perhaps even increased cost of debt compared to low- and zero-carbon vessels.

Similarly, the Sea Cargo Charter shows how major charterers of bulk goods are committed to disclosing emissions attached to these goods on an annual basis and to align this to reporting standards[10]. This also creates the foundational basis for future provision of service requirements centered around the emissions profiles of vessels, thus creating additional expectations around decarbonization for shipowners and operators. This also solidifies public commitments to decarbonize, for example the Gunvor Group's announcement to reduce scope one and two emissions by 40 percent by 2025[11] and reducing its scope one shipping emissions by 35 percent and scope two by 95 percent by 2025[12, 13]. Such efforts also support the emerging demand for future low-carbon shipping.

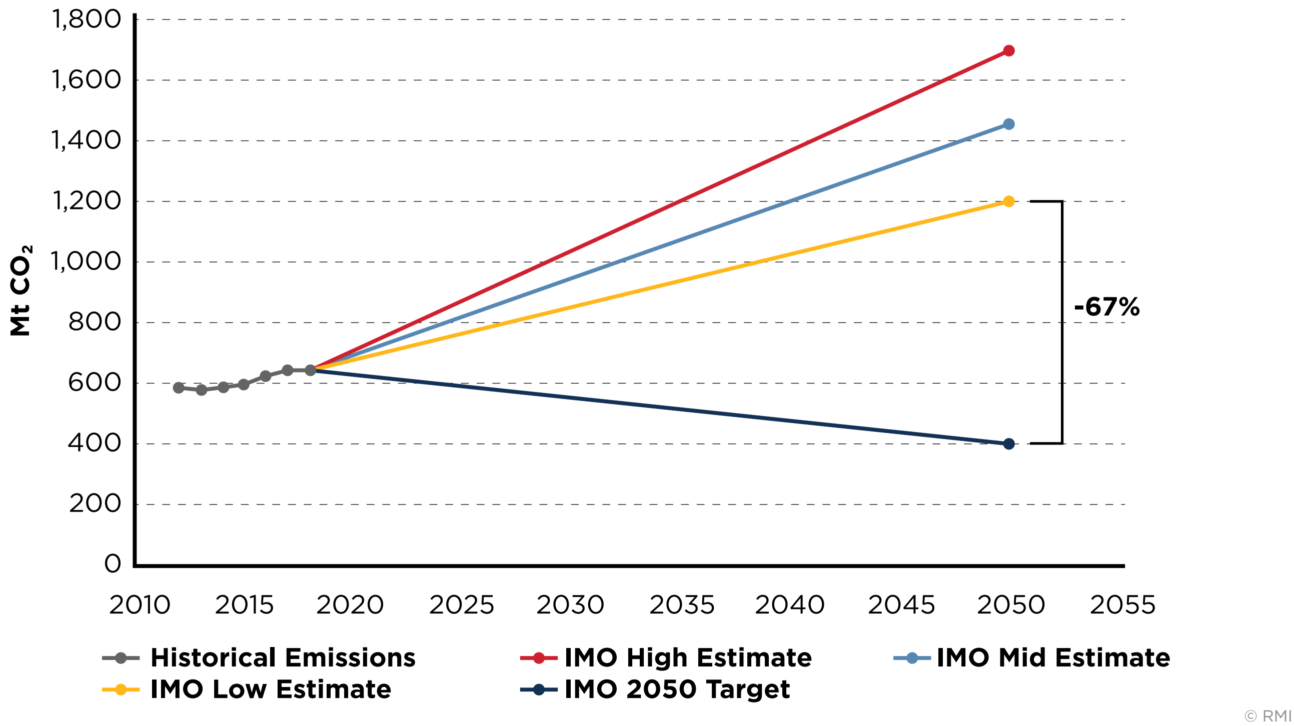

Figure 2: Scenarios of 2050 emissions from shipping.

FUTURE DISRUPTION AND RISK

There is emerging certainty that the combination of climate change, forced technology transitions, government policy, consumer behavior and corporate actions will make the BAU scenario not credible for forecasting. The broad scientific consensus suggests that global warming beyond 1.5° C will have significant negative impacts on the global economy. The inevitable disruption can be illustrated through a scenario matrix considering the characteristics of climate-related change as either organized and managed disruption or disorganized and panicked disruption, as shown in Figure 3. Four quadrant scenarios are shown.

- The "**Current Business as Usual (BAU), 3° C Scenario**" assumes that historic trends in a sector can be applied to predict the future. This historic trend is an approximate three percent continued growth in the global economy and international trade. However, an extrapolation of the current global economy also comes with substantial climate change resulting in an increase in average temperature by 3° C[14].
- The "**Paris Aligned, 2° C Scenario**" suggests a successful, coordinated, global energy transition limiting global warming to 2° C. However, while such an outcome arguably will be achieved with maintained economic growth, even under controlled policies, it requires massive changes in technologies as well as in increased circularity and behavioral patterns.
- In a "**Consumer Revolution, 1.5° C Scenario,**" adherence to an even stricter carbon budget is achieved not through policies but through radical action and pressure from consumers, leading to disruptive demand trend breaks.
- The "**Panicked, 2° C scenario**" is, however, likely the most disruptive of them all. A scenario where global warming continues unmitigated will likely lead to strong political action to secure basic supply chains (food, water and energy) as the negative effects of global warming start to materialize in the 2030s. Learning from the ongoing COVID-19 crisis, this political response will likely prioritize each nation's interest, implying a strongly reversed globalization trend.

The temperature rise indicated in each of the above scenarios is illustrative rather than scientifically calculated. The purpose of this analysis is to explore commonalities across these scenarios and reach conclusions that can be insightful today regardless of the uncertainties embedded in complex topics such as policy forecasting and climate science.

In all these scenarios, disruption in many forms will be a feature of future markets and therefore business as usual is unlikely. The main climate-related risk for the marine sector stems from the way that changes in other sectors cascade to the demand for shipping of goods. Even a complete and successful implementation of the Paris Agreement is expected to have a negative impact to the global GDP, estimated at one to 1.5 percent in the European Union (EU), 0.6 percent in the United States, and 0.06 percent in China[15]. Given the massive economic impacts and consequent recession associated with 3° C global warming, not even the business as usual can be expected to constitute an extrapolation of the past. Assuming business as usual may develop into a missed opportunity for the shipping industry to prepare for transformation, disruption and risk mitigation. More importantly, it would be a missed opportunity for the shipping industry to show leadership in how to transform in an organized manner.

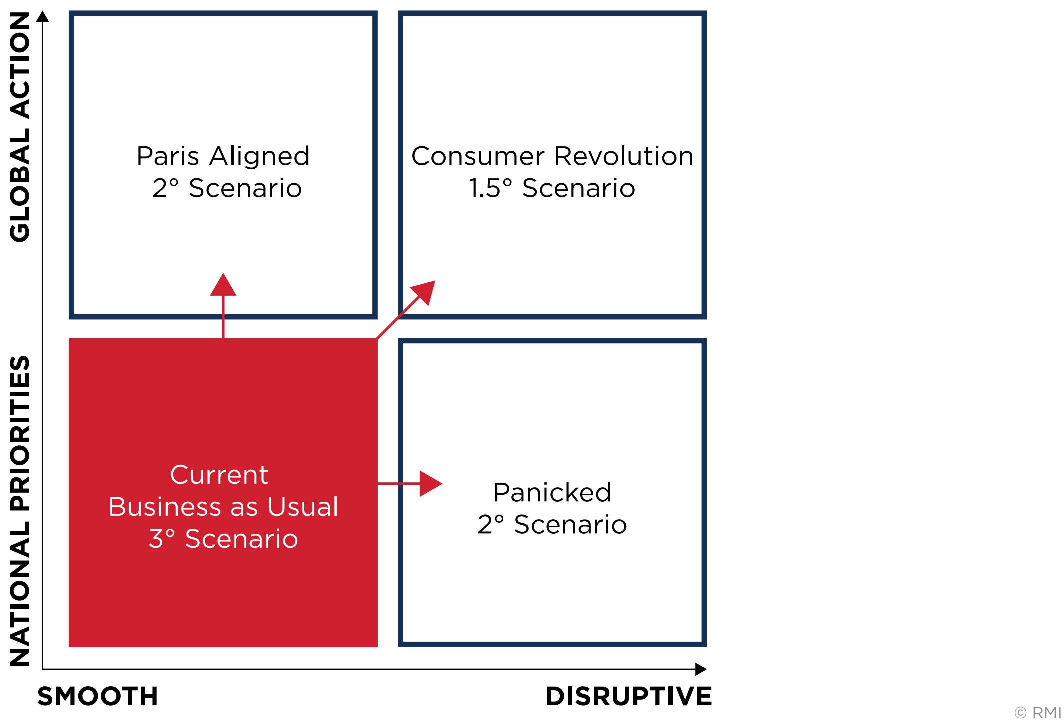

Figure 3: Scenario matrix demonstrating inevitability of disruption.

Forecasts for total trade on a BAU scenario show continuing growth and demand for capacity. This positioning does not account for any factors related to potential immediate disruptions in the relatively near future. Estimated high disruption scenarios forecast significant risk to general economic growth globally as well as disruptions in specific sectors. For example, declines in oil and gas markets associated with vehicle electrification would lead to a declining demand for related shipping capacity. Fundamentally, a zero-carbon economy tends to be more regionalized and anchored in electrification enable by renewable power production, which will impact the international trade of fossil fuel. It is unlikely that other energy carriers will emerge to compensate for the loss in trade volumes, as neither electric energy storage, ammonia/hydrogen, or any other zero-carbon solutions will be cost effective. As presented in the 2020 Low Carbon Shipping Outlook, *Pathways to Sustainable Shipping*, the demand for coal, oil and gas is expected to reach a peak in the following years and decline thereafter. In this landscape, the oil and gas markets are significantly exposed as refineries face varying demand and pricing volatility in outputs[16]. These factors result in significant changes in both refinery product outputs (such as the California renewable diesel) and even closures of large refineries in numerous locations. This trend is likely to continue as pressure on some segments of refinery products increases based on regulations and standards.

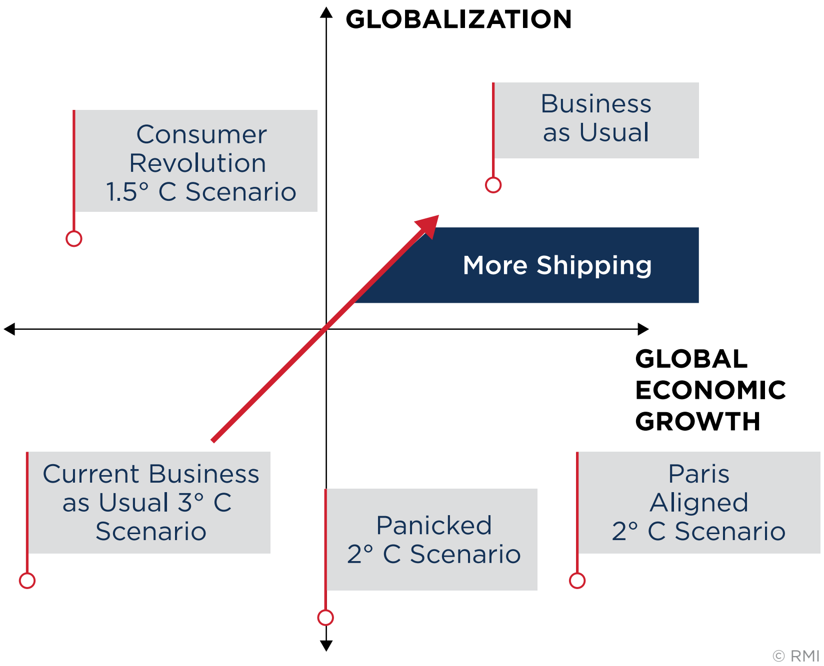

Figure 4: Scenarios implicitly assuming reduction of international trade.

Direct impact of weather events has been quantified from the Food and Agriculture Organization of the United Nations, which found that between 1980 and 1990, there were annually 149 climate-related disasters, resulting in $14 billion of lost economic value per annum. Between 2004 and 2014, these values had increased to 332 incidents and $100 billion in economic losses annually[17]. These increments represent more than twice the number of incidents and a seven-fold increase in total economic losses for the period 2004 to 2014. Additionally, secondary disruption to water resources and non-workable arable land impact trade as local supply can be constrained and markets may be unable to match supply and demand.

Forecasts that predict continuously increasing shipping demand rely on continued growth in both the global economy and globalization. However, as explained above, this BAU scenario with both global economic growth and increased international trade is unlikely. Figure 4 shows four different scenarios considered and all of them imply a downward trend on international trade.

- The forecast of increasing shipping demand relies on a future with continuing growth in both the global economy and globalization. The "**BAU 3° C Scenario**" considers the decline of both international trade and global economic growth as a results of climate change causing global disruptions across major trade sectors. By maintaining current practices, both economic growth and international trade are expected to decline.
- The "**Paris Aligned 2° C Scenario**" may result in sustained global economic growth but the required increased circularity will likely result in less international trade, particularly of fossil fuel commodities.
- The "**Consumer Revolution 1.5° C Scenario,**" is characterized by changes in consumer demand and behavior that decreases energy consumption on a global scale, with associated impact on economic growth, but also regionalizes markets and increases circularity.
- The "**Panicked 2° C Scenario**" assumes that countries which are impacted by climate change will respond disruptively by locking in critical supply chains and nationalizing industries. This will likely result in decreased international trade and stagnant global economy.

Given the emerging challenges in markets resulting from climate change, it is expected that global trade will stagnate compared to historical trends. This expectation is consistent with previous estimates showing regional reductions between zero and two percent under the Paris Agreement Scenario, However, under a 3° C Scenario some estimates suggest the loss of global GDP could be as much as 3.67 percent by 2050[18]. In any of the above scenarios, there are sectors that will face downward trends, of which fossil fuels, iron ore, steel and food commodities are subject to distinct risks.

CHANGING WORLD AND CHANGING MARKETS

The anticipated climate effects on commodity markets and related trade have significant implications for future shipping demand. As decarbonization takes effect across the globe, the use and the associated transport of fossil fuels is expected to decline. The transport volumes of crude oil, coal, natural gas and other chemicals will likely be impacted the most. In addition, other commodity sectors that are adjacent to shipping, such as agriculture, are likely to see major disruptions caused by severe climate events.

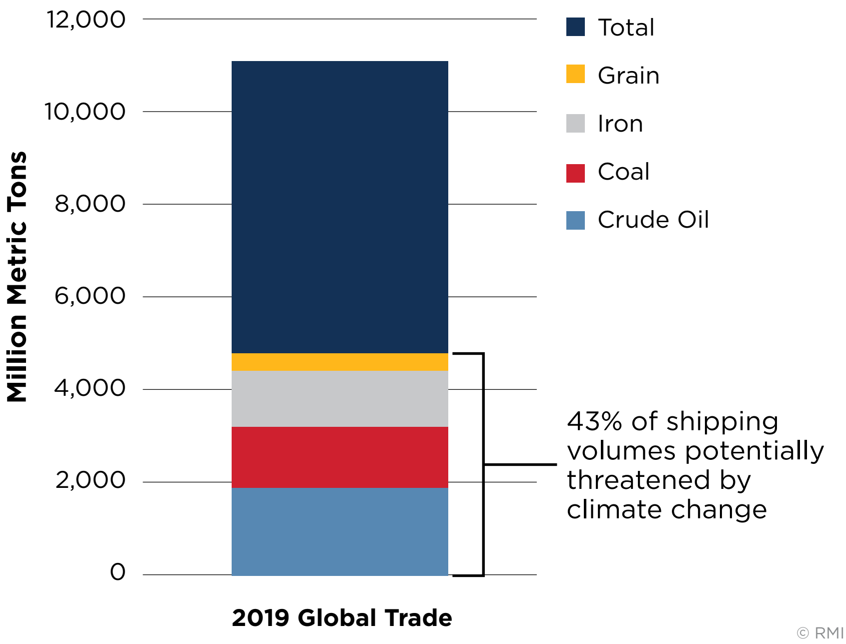

Figure 5: 2019 global trade volumes and share of global trade[19].

The shipping sector has historically experienced single disruption events of individual commodities, such as the decline in crude oil during the energy crisis in the late 1970s. However, the key differentiating factor of future scenarios is the simultaneous decline across multiple key trade commodities. Considering the high probability of concurrent disruptions under climate scenarios coupled with intentional declines in key trade products, makes the continuation of business as usual growth within the industry likely unrealistic.

Figure 5 shows the 2019 global trade volumes, including coal, crude oil, iron and grain, which account for 43 percent of total shipping volumes. These sectors could be impacted by intentional and planned changes to consumption or unexpected disruption caused by extreme events. A single disruption in any sector would have significant impact for shipping; therefore, the potential of combined disruption exposes the shipping sector to high risk.

EXPECTED SECTORAL CHANGES DUE TO DECARBONIZATION EFFORTS

Efforts towards transitioning to sustainable production and operations are underway throughout shipping. These efforts rely heavily on renewable power generation, the ability to produce low-carbon footprint goods, and to reduce emissions associated with the transportation of such goods and commodities. The key drivers behind these efforts are international agreements, global regulations for emissions reduction, domestic policy and consumer preferences. These changes in both the quality of goods purchased and the desire of many industries to shift their efforts towards low-carbon operations are expected to affect the global supply chains and in turn the shipping sector. Changes are expected to occur in the locations of origin and supply as well as the types of goods transported.

The EU has presented a significant body of work on creating standards and carbon price, and proposed the border adjustment mechanism[20] in an effort to penalize imported goods with high carbon footprints. China, who has been a production center of many heavy industrial goods, has committed to reach net zero carbon emissions by 2060[21], as well as to become a leading producer of novel low-carbon footprint goods.

However, major sectoral markets are facing disruption from substitution, circularity or supply constraint. Circularity can reduce the urgency of supply chain upgrades, by reducing the need for physical goods, which is also considered as a "dematerialization" of the economy. In the Mission Possible pathway, the material goods consumption was estimated to be reduced by as much as 40 percent by 2050[22]. More aggressive scenarios suggest greater potential for reduction, as much as 56 percent by 2050[23]. In either of these scenarios, the impacts on global trade flows are distinct and significant for both markets and supply chains.

Coal, Oil and Natural Gas

Figure 6 presents a forecast of global demand for coal, oil and natural gas until 2050. This forecast considers two scenarios: (i) the base case using the stated policies and (ii) the Accelerated Climate Action (ACA) scenario based on the International Energy Agency's (IEA) Sustainable Development goals. The current direction seems to be more aligned with the latter as more countries embrace policies that act to reduce fossil fuel use.

In the base case, the global demand for coil, oil and natural gas is expected to peak in the 2025 to 2030 time frame and decline thereafter. In the ACA case, the global demand for coal, oil and natural gas is assumed to have peaked and to decline in the following years as multiple sectors of the global economy turn to different energy sources.

To a large extent, this forecast follows current conventional thinking that the outlook for natural gas demand will remain significantly more robust than that for other fossil fuels, which is confirmed in each scenario presented by the IEA in the World Energy Outlook in 2020. For example, under the ACA scenario, coal demand falls by five percent between 2019 and 2040, while natural gas declines by just 0.6 percent. Under stated policies natural gas demand is expected to grow until 2040.

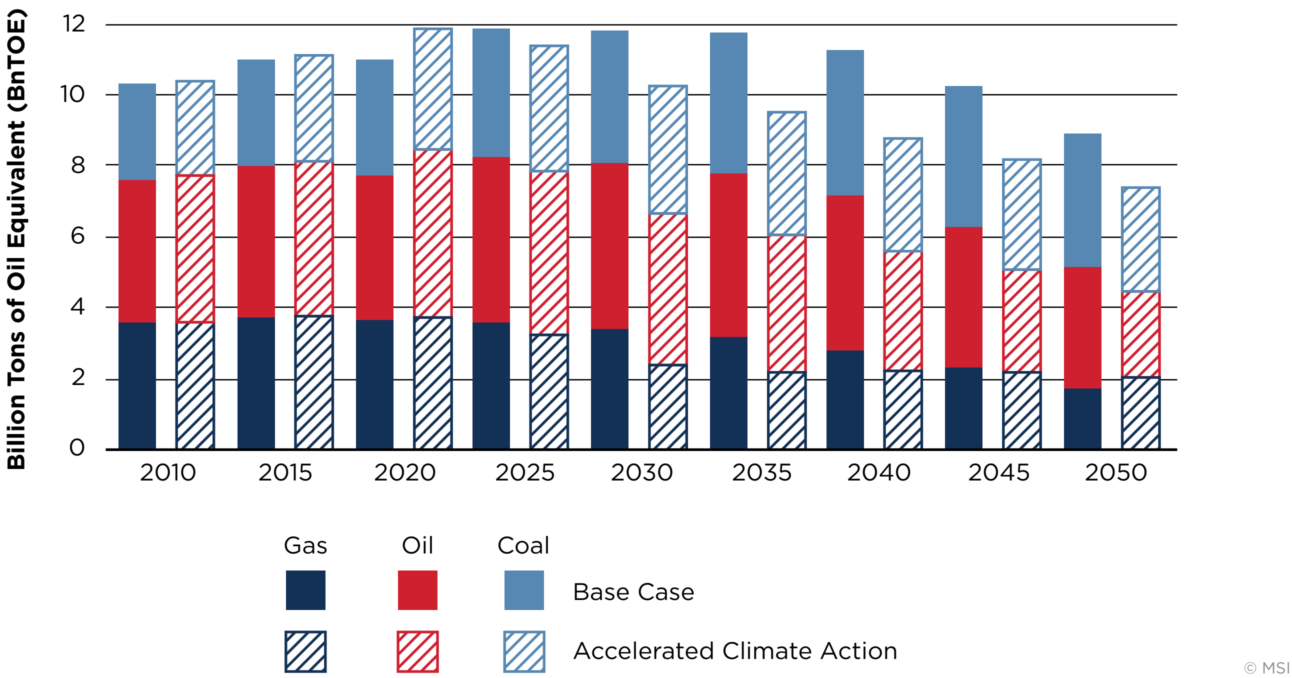

Figure 6: Forecast of global demand for coal, oil and natural gas.

The IEA 2019 report on the coal industry showed that approximately 40 percent of global coal production is used for power generation[24]. This use has decreased by 6.7 percent in 2020, and IEA estimates a reduction of 13 percent by 2025. This reduction corresponds to the share of coal for global power generation declining from 37 percent in 2019 to 28 percent in 2030[25]. In 2019, 92 percent of the coal traded was transported via seaborne trade and coal accounted for 12 percent of the total shipped goods[26, 27]. The expected reduction in global coal consumption will directly reduce the need to transport it, therefore it will affect the shipping demand of the global bulk carrier fleet.

In 2019, crude oil accounted for approximately 17 percent of total shipped goods[28]. The BP world consumption estimate under the rapid scenario, projects a 500,000 barrel per day reduction each year until 2030[29]. This estimate is reflective of a conservative view of the decline rate that accelerates past 2030. The reduction of oil demand is expected to impact the refineries as specific crude supplies become less valuable and the ability of refineries to operate on part product or low value product is constrained. In turn, this sector change can affect the derivative products markets, such as plastics, which may move towards carbon capture and utilization or non-extractive supply streams focused on recovery and recycling than new resource exploitation.

Steel and Iron Ore

The cyclical nature of some trades will determine the rate of decline for iron ore volumes. An example is steel production, in which the trend of increased circularity of use could reduce demand for iron ore by as much as 38 percent by 2050[30]. This reduction stems from increased scrap recycling and use of hydrogen in existing furnaces used for production. This transition would significantly affect the need for metallurgical coal transportation. As a result, the structure of current shipping in the iron ore sector is likely to experience change.

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CLIMATE-INDUCED CHANGE

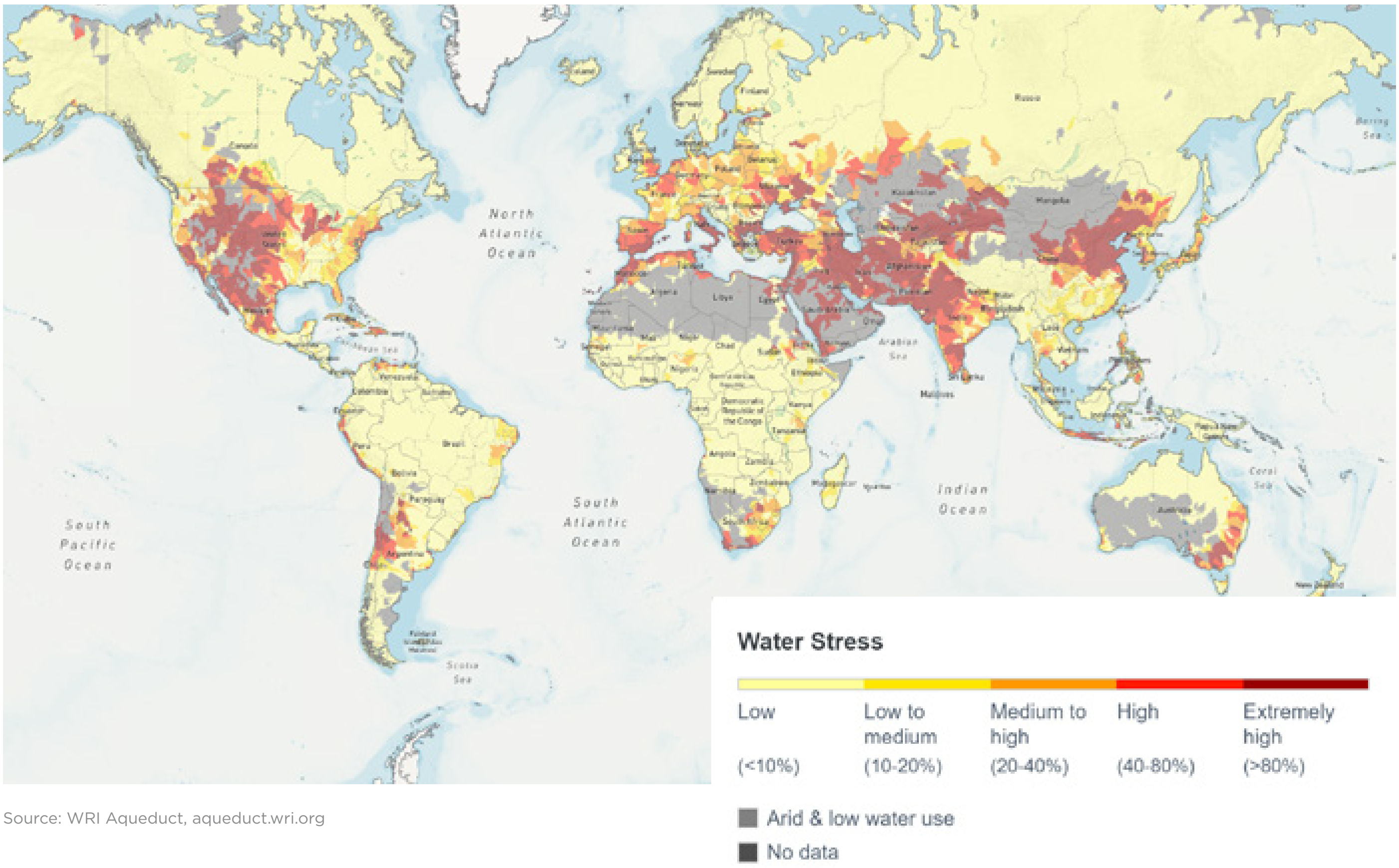
The varying weather conditions and patterns caused by climate change also impact the shipping industry in a direct manner. The increased frequency and severity of ocean storms affect shipping routes and thus makes route optimization increasingly important. Long-term climate impacts, such as coastal erosion and sea level rise can change shipping channels to the extent that new routes need to be planned.

Both short- and long-term impacts also affect port infrastructure. The sea level rise is slow and gradual, thus it can be addressed through infrastructure planning and upgrades. However, short-term effects, such as storm events, occur frequently; therefore, they are challenging to predict and can cause unexpected damage to ports and interruptions to shipping operations.

The gradual melting of Arctic sea ice is opening new shipping routes in the region. In February 2021, a Russian tanker completed a trip through an Arctic route that was previously inaccessible, which marked the already observed impacts of climate change on sea ice in the region[31]. Currently, icebreaker escorts are needed for Arctic vessels but by 2050 it is probable that ships will be able to travel through unescorted[32]. While some benefits of increased Arctic routes can be realized, such as easier access to remote communities and decreased shipping times, the effect of climate change on this area may have significant consequences for the planet, including escalating geopolitical conflicts, complex regulatory issues and other environmental impacts.

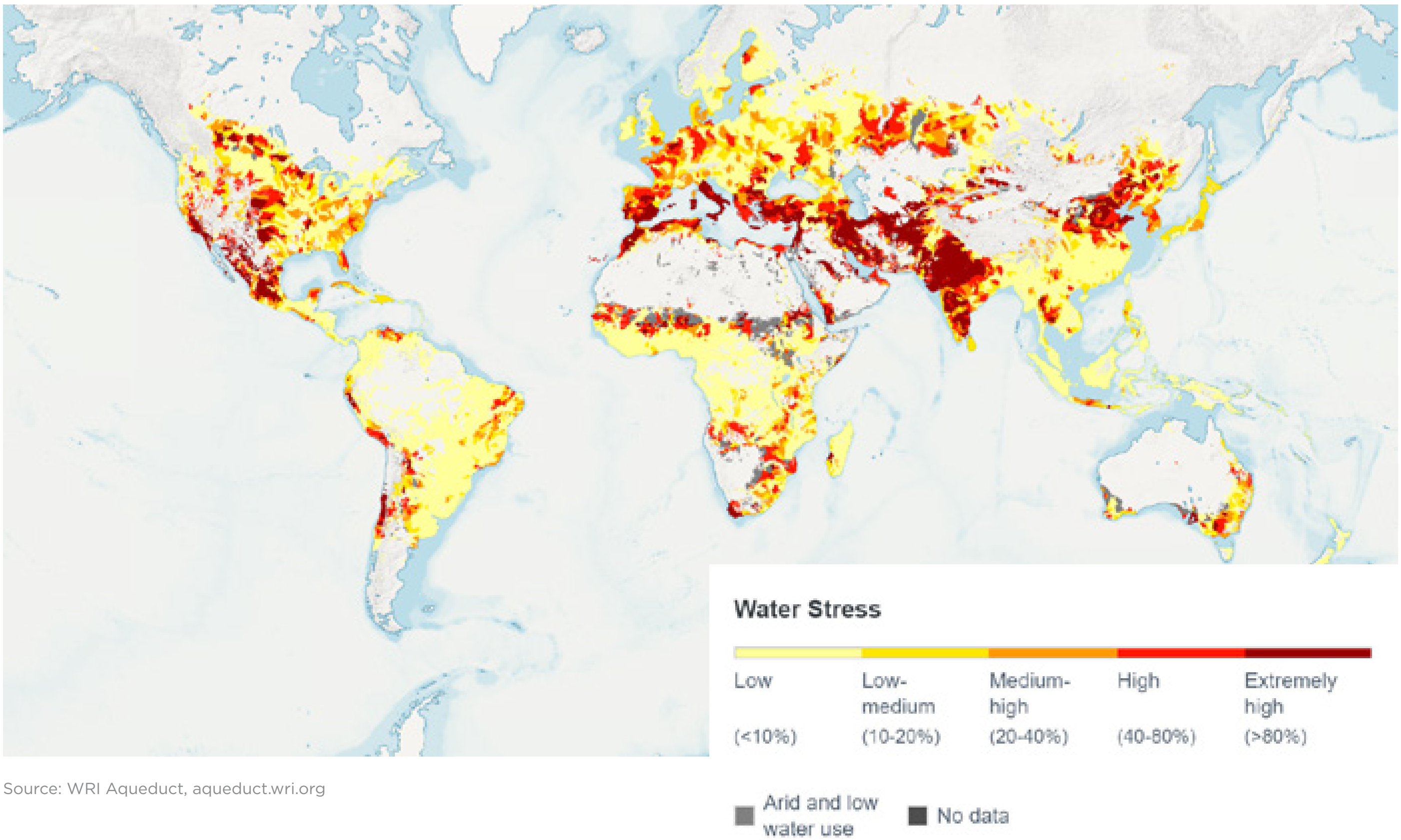
Agricultural disruption and the resulting impact on trade are significant risks from climate change. The potential scale of economic loss resulting from water constraints and the related agricultural shortage has been estimated at three percent of global GDP by 2050[33]. Agriculture faces significant potential for disruption due to the severity of potential shortage of water resources. To illustrate this, Figures 7 and 8 reflect a business as usual scenario based on the UN Intergovernmental Panel on Climate Change SSP2/RCP8.5 case. This scenario projects continued economic growth with the associated CO_2 emissions increase, resulting in global mean temperature increasing by 2.6 to 4.8° C by 2100 compared to 1986 to 2005 levels[34].

As shown in Figures 7 and 8, the severity of water stress by 2030 is expected to be significant across many densely populated and high crop production areas. For the top four maize-exporting countries, which account for 87 percent of global maize exports, the probability that simultaneous production losses is greater than 10 percent is currently negligible, but is expected to increase to seven percent under the 2° C global warming scenario and to 86 percent under the 4° C global warming scenario[35].



Source: WRI Aqueduct, aqueduct.wri.org

Figure 7: Expected 2030 global water stress.



Source: WRI Aqueduct, aqueduct.wri.org

Figure 8: Expected 2030 global crop stress.

Figure 9 displays the potential food stress in 2030 for the U.S., Europe, China and India, and shows that specific commodities in large production regions are likely to experience significant impacts. This food stress is expected to change the type of consumption and the flow of goods between regions. Most critically, regional food stress will create a need for imports to offset any loss in domestic consumption and consequently exacerbate the economic burden on the most impacted areas. This domestic consumption may transition some current exporters away from engaging international markets.

As with any situation where food and general commodity availability is constrained, there is significant pressure on policy makers to find solutions. The results could be policy and regulatory constraints focused on trade of goods and patterns for local consumption.

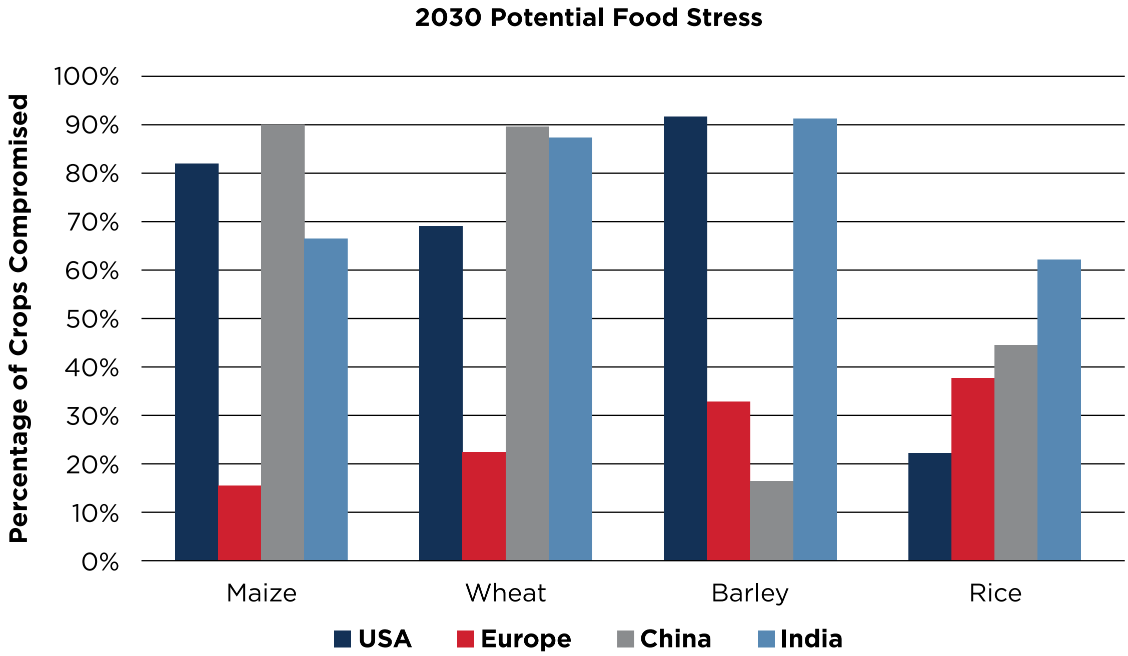


Figure 9: Potential food stress in 2030 for the U.S., Europe, China and India.

TRANSITION TO A LOW-CARBON FLEET

The path of the global fleet towards meeting the long-term IMO GHG reduction targets will require significant changes to the vessel technology and fuels. These changes can be accomplished only through a holistic understanding of the associated challenges and implementation of strategic plans. The adoption of new fuels and technologies will lead to new vessel design and construction, but it will also require significant infrastructure upgrades related to alternative fuel distribution and bunkering at port site facilities.

Ammonia, hydrogen and electrification emerge as long-term solutions that will enable zero-carbon shipping but identifying the appropriate mid-term solutions poses a challenge for shipowners and operators. Such mid-term solutions need to enable the global fleet to comply with the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) regulations, to extend the lifespan of existing vessels through retrofits, and to pave the way for adoption of zero-carbon fuels in the future. Liquefied natural gas (LNG), liquefied petroleum gas (LPG) and methanol are low-carbon fuels that can offer benefits in the mid-term using existing technology and infrastructure.

LNG

Although LNG is a low-carbon fuel that can reduce tank-to-wake emissions by about 20 percent compared to fuel oil, it is important to account for its well-to-wake carbon footprint and the contribution of methane to the GHG effect, through methane slip of fugitive emissions. Both of these factors are important and can lead to up to 80 percent higher GHG emissions that marine gas oil (MGO) on a life-cycle basis, depending on the power generation system used[36]. Methane slip is only a fraction of the methane emitted to the atmosphere across the LNG production, distribution, and bunkering chain. The United States Environmental Protection Agency (EPA) estimates methane emissions from U.S. natural gas production to be approximately 1.4 percent of the gross gas produced; however, recent studies have demonstrated that this value may be underestimated by as much as 60 percent[37]. These factors create the need to account for well-to-wake emissions of all fuels used in shipping, which is expected to make LNG a transition fuel but not a long-term solution[38].

METHANOL

The benefits of reduced emissions from burning methanol could be a significant contributor to reducing GHG emissions from shipping. Existing methanol trade infrastructure can also be an important factor for the cost and availability of methanol over other alternative fueling options. Early adoption of such fuels depends on the demand and the supply landscape. In the case of methanol, even though its trade is evolved, its many uses and demand for manufacturing may not allow surplus for use in marine applications without the appropriate incentives. Due to this widespread use of methanol across the globe, the marine sector can at most claim a fraction of the amount available unless methanol is produced synthetically. However, this option can also incur extra costs[39].

The advent of methanol carriers with the new propulsion systems that can use their cargo for fuel and power generation is driving a new area of demand for vessel construction. If methanol is produced renewably, these tankers could have an even greater potential to reduce life-cycle carbon emissions while concurrently improving the renewable methanol fuel supply chain for other applications.

The advantage of methanol over LNG or other gas fuels is its liquid state and ability to repurpose existing infrastructure to include engines and vessels with efficient retrofits. Methanol is significantly easier and more economical to store on board than LNG. Retrofitting a vessel's tanks from conventional fuel oil, ballast or slop to hold liquid methanol fuel is also easier than installing LNG tanks. However, one of the challenges of methanol as an alternative fuel is the lower energy content when compared to conventional fuel oils. The liquid state of methanol at ambient temperature and pressure, tanks can be converted with minor retrofitting to hold larger volumes of methanol required for an equivalent amount of energy[40]. Further methanol applications in marine fuel may only require a scale-up of existing trade, storage and generation activities. Ongoing research is focused on rapid scale up of methanol availability in terms of infrastructure as well as onboard applications and installations.

AMMONIA

Ammonia is one of the two zero-carbon fuels considered for use in the marine sector and its production pathway is directly related to hydrogen. Therefore, the challenges associated with green hydrogen production and scale up also apply to ammonia production[41]. The key benefits of ammonia stem from its higher density than hydrogen and the fact that it can stored as a liquid at -33° C and ambient pressure on board the vessel and at port site facilities. These factors make ammonia a more volumetrically effective energy carrier than hydrogen, and offer easier distribution, storage and bunkering[42].

As a new bunker fuel, ammonia will require new provisions and guidelines to support wide adoption. It is foreseen that the previous experience from the fertilizer and chemical industry, and the recent developments of LPG/LNG bunkering will help to inform the process. It is necessary to identify any gaps between the established industry and marine bunkering context and propose solutions to align operations using technical and operational measures. Ammonia can be stored at liquid form pressurized, semi-refrigerated or fully refrigerated depending on the needed volume for safe storage, varying from small pressurized 1,000 gallon nurse tanks up to liquefied 30,000 ton storage tanks at distribution terminals.

HYDROGEN

Hydrogen can be extracted from fossil fuels and biomass, or from water, or from a combination of the two. Currently, the total energy used worldwide for the production of hydrogen is about 275 Mtoe, which corresponds to two percent of the world energy demand[43]. Natural gas is currently the primary source of hydrogen production (gray hydrogen, 75 percent) and is used widely in the ammonia and methanol industries. The second source of hydrogen production is coal (brown hydrogen, 23 percent), which is dominant in China. The remaining two percent of global hydrogen production is based on oil and electric power. However, the most interesting option of the future if the production of green hydrogen through electrolysis of water using fully renewable energy.

The availability and low cost of coal and natural gas make the production of hydrogen more economical than using renewable energy, which is reflected in the cost of the finished fuel. The cost of brown and gray hydrogen ranges between $1-4/kg, whereas that of green hydrogen currently ranges between $6-8/kg. However, the cost of producing green hydrogen has fallen by about 50 percent since 2015 and this trend is expected to continue in the following decade as the projects focused on deploying renewable energy for hydrogen production increase. Reducing the cost of green hydrogen to $2/kg can make it competitive for use in the marine sector.

The cost of hydrogen bunkering facilities is expected to be higher than that of LNG facilities, primarily because of the higher cryogenic storage requirement of liquid hydrogen and the material required for tanks, pipes and seals. The main cost components are the storage and bunker vessels, which need to be scaled based on the number of ships serviced. On-site availability of hydrogen would be needed for small ports given the lower flows and high cost of dedicated hydrogen pipelines. However, ship and infrastructure costs are a relatively small fraction of total shipping costs over a 15 to 20 year lifespan, with the fuel cost being the primary factor[39].

BIOFUELS

Biofuels are liquid hydrocarbon fuels that are produced from renewable sources such as vegetable and animal oils or agricultural and forestry waste. Their composition is similar to that of petroleum diesel, thus they do not offer any carbon emissions reduction on a tank-to-wake basis. However, these emissions can be partially or fully offset during their production to create carbon-neutral fuels. Such fuel can offer significant benefits to the marine sector provided that their carbon footprint is calculated on a well-to-wake basis.

The similarity in physical and chemical properties between biofuels and petroleum diesel means that the former can be used a drop-in fuels without any need for equipment modifications or retrofits on the vessels. Currently, many shipowners and operators across the globe embark on biofuel trial exercises to assess their effects on the vessel machinery and emissions. One of the key limitations of biofuels is their low availability and thus high cost, which is expected to change in the following years as more suppliers upscale their production and new suppliers emerge.

FLEET RENEWAL

Historically, shipping demand and fleet capacity has experienced steady growth, shaped by cyclical demand and capacity. This cyclicality is based on the fact that newbuildings are ordered a few years in advance of their expected start of service. The advent of the IMO short-term measures combined with climate related changes may result in low demand for certain vessel types, which can precede the planned retirement rates of such vessels. In this case, certain vessels have the risk of becoming stranded assets.

Historic retirement rates of approximately 1.4 percent have been shaped by efforts to match fleet size with shipping demand in a stable growth environment[44]. However, as shipping trends change, the fleet composition is expected to adjust accordingly. There are two ways that the industry can meet this challenge – either through significantly increasing the rate of retirement of vessels and replacing them with new low-carbon vessels, leading to early vessel retirement, or through retrofitting existing vessels with cost-efficient technologies to reduce GHG emissions. Both options present unique challenges, which will be discussed in more detail in the last chapter of this Outlook by means of specific examples.

Figure 10 shows vessel retirement rates for different scenarios of fleet renewal. Assuming that the observed growth of the past at three percent per annum will continue until 2030, the retirement rates may increase in an effort to align the fleet emissions with the IMO GHG reduction strategy and a potential net zero (NZ) target scenario. Two scenarios are considered for both NZ by 2050 target and the IMO 2050 targets. The 50 percent scenario considers replacing 50 percent of the existing fleet with new vessels and completing equipment retrofits for the remaining 50 percent. The 100 percent scenario is based on replacing the entire global fleet with new vessels in order to accomplish the required emissions reductions. Naturally, the higher the amount of retrofit solutions that can be implemented to reduce emissions, the lower the required retirement rate of vessels.

However, it is important to note that retrofit solutions may be expensive, therefore the economic proposition for each case of retrofit needs to be weighed against extending the lives of assets. The deployment rate of technologies that enable low- and zero-carbon will depend on their commercial availability and are expected to be widely adopted after 2025. Therefore, it is likely that equipment retrofits and operational measures will be critical in the effort to meet the 2030 IMO GHG reduction target.

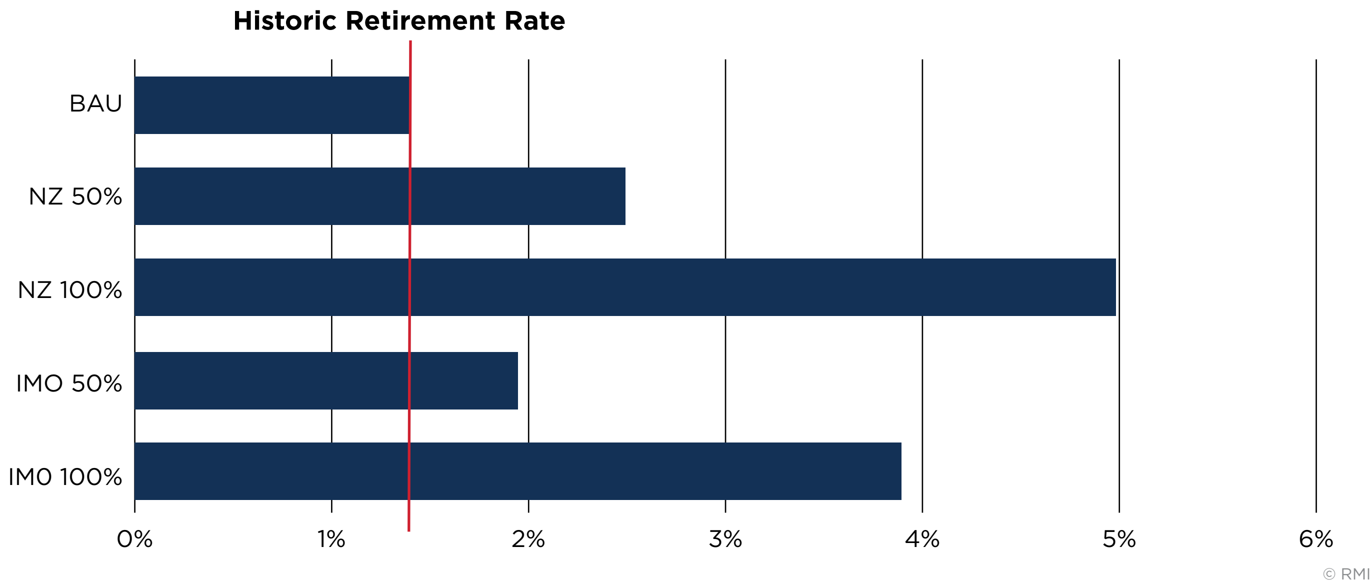


Figure 10: Projected vessel retirement rates for different scenarios to meet the IMO GHG reduction target and a net zero carbon target.

PORT AND INFRASTRUCTURE CHALLENGES

The contribution of port facilities to the reduction of GHG emissions from shipping is essential. Many of the developments required to the infrastructure and bunkering stations are already in progress. As examples, the Port of Los Angeles and the Port of Long Beach have set ambitious targets towards achieving net zero emissions. Proposed actions include employing hydrogen fuel cell cargo trucks for port operations, as well as providing demonstration and testing ground for other low-carbon technologies[45]. These early efforts showcase the feasibility of using the same low- and zero-carbon fuels for vessels and port operations. The Port of Rotterdam recently announced a significant investment in electrolyzer technology that would support the production of green hydrogen from sea water on site[46]. This approach is based on collocated energy resources to generate green hydrogen for use either as fuel or feedstock for further production. The current plan is to install a 100 MW electrolyzer by 2025 with an expansion to 500 MW in the future.

The colocation effort extends well beyond the port operations and into industrial operations that can be significant consumers of hydrogen and ammonia. Such facilities can be merged with transportation hubs to enable the use of shared infrastructure and developed large scale production projects that can generate low cost hydrogen and ammonia at the hub. This approach has the potential to change the manufacturing environment, by moving industrial plants to dockside and changing the size of ports and the infrastructure around them. As a result of this potential shift, the cost of retrofitting existing infrastructure or constructing new facilities could be managed by distributing the cost across multiple different linked sectors, while also reducing the cost related to transportation of new fuels or feedstocks.

The innovation on the vessel side is being matched by enthusiasm on the supply side. Significant deployments for hydrogen and ammonia are now planned at multi-gigawatt scale, such the Pilbara project in Australia which is planned to use nearly 26 GW of renewable energy[47]. A similar project in Saudi Arabia will leverage four GW of solar and wind power to produce 650 tons of green hydrogen per day[48]. These projects are likely to be completed in the next five years, followed by many other in an effort to support an estimated $700 billion global hydrogen market.

Based on the above, it is clear that the shipping industry will experience a decade of significant changes and decisions that will greatly affect its future. The following chapter describes the emerging landscape for shipowners and operates that is formed based on the regulatory framework and market factors.

3 | EMERGING LANDSCAPE

The maritime industry is undergoing a significant transformation that is being driven by: International Maritime Organization (IMO) regulations; the financial institutions supporting the purchase of new ships and retrofits; the charterers; and market-based measures (MBMs) introduced by local and regional authorities. In combination, these developments are creating a unique landscape and new challenges for shipowners and operators.

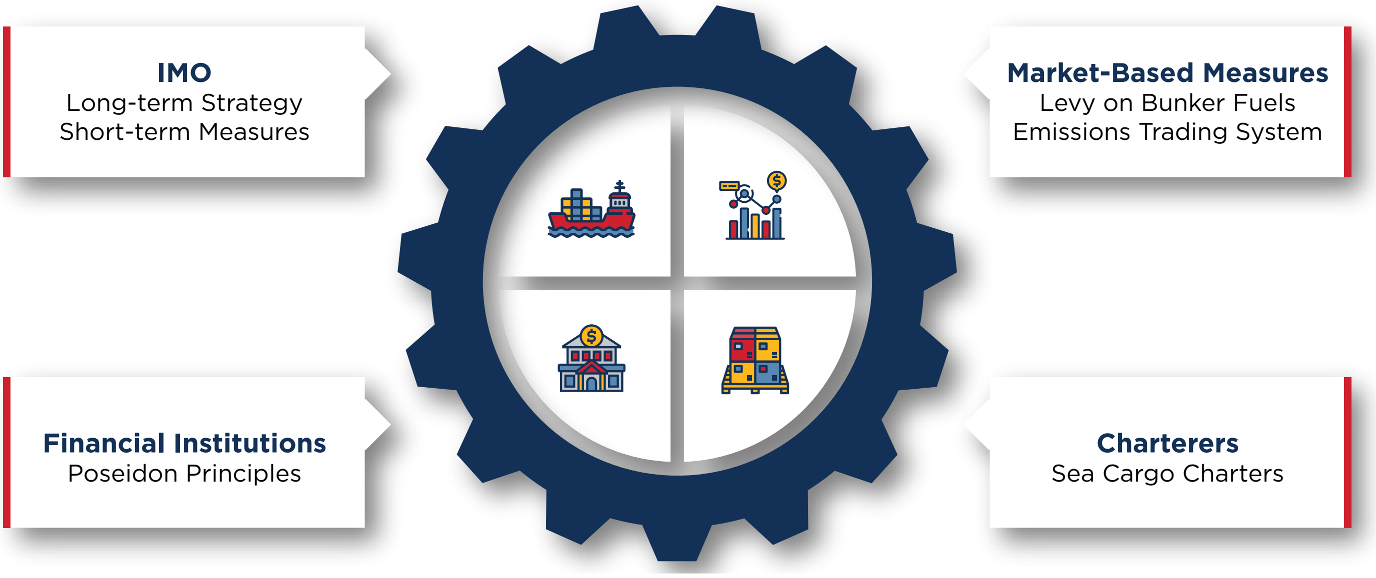


Figure 1: Emerging landscape motivating the transformation of the marine sector.

IMO REGULATIONS

As a result of the IMO's continuous work to contribute to global efforts against climate change, the initial greenhouse gas (GHG) strategy was adopted by the organization in April 2018. Energy regulations and ongoing industry studies on emission reduction options are progressively stimulating innovation and targeting technology readiness. The initial IMO GHG Strategy has established levels of ambition that are subject to ongoing reviews by the organization. The ambition levels have considered potential improvements on vessel design and operational performance as well as the immediate need to introduce low- and zero-carbon fuels.

The initial GHG Strategy introduced a list of candidate short-term, mid-term and long-term measures to support the IMO's ambition levels, as shown in the following table. Short-term measures include the evaluation and improvement of vessel energy efficiency requirement – such as the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) regulations – the application of technical efficiency measures for existing ships – such as the Energy Efficiency Existing Ship Index (EEXI) regulations – and the introduction and regulation of Carbon Intensity Indicator (CII) for ships in operation. Mid-term and long-term measures include developing an implementation program for alternative low- and zero-carbon fuels, adoption of other possible innovative emission reduction mechanism(s) and MBMs to incentivize GHG emissions reduction.

LEVELS OF AMBITION DIRECTING THE IMO INITIAL GHG STRATEGY	MEASURES & APPLICABILITY
Carbon intensity of the ship to decline through further development of EEDI regulations for new ships	Review of EEDI regulations aims to improve the as-designed efficiency of new vessels.
Carbon intensity of international shipping to decline	Measures aim to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008. Development of the EEXI regulatory framework aims to improve the energy efficiency of existing ships by implementation of technical measures. Scope of operational measures is currently under development. Requirements intend to cover individual vessels and/or fleetwide assessment.
GHG emissions from international shipping to peak and decline	Measures aim to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 while pursuing efforts towards phasing them out. Scope is currently under review. Requirements under development intend to cover individual vessels and/or fleetwide assessment.

ENERGY EFFICIENCY EXISTING SHIP INDEX (EEXI)

The seventh session of the Intersessional Meeting of the Working Group on Reduction of GHG Emissions from Ships (ISWG-GHG 7) has considered a number of concrete proposals to improve the energy efficiency of existing ships. The group agreed to introduce the necessary amendments to International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, Chapter 4 by application and enforcement of the EEXI regulations as a goal-based energy efficiency measure, together with CII regulations regarding operational carbon intensity.

The EEXI regulations apply to all vessels falling under the ship type categories subject to compliance with EEDI regulations. EEXI does not apply to category A ships as defined in the Polar Code and ships having non-conventional propulsion except for cruise ships (non-conventional propulsion) and liquefied natural gas (LNG) carriers (conventional and non-conventional propulsion).

ATTAINED EEXI — REGULATION 20A

The attained EEXI will be ship-specific i.e., it will be calculated for each individual vessel and verified by the flag Administration or any organization authorized by it (e.g. classification societies). The calculation will be included in each vessel's EEXI technical file along with any supporting technical data and information used in the calculation process.

For all vessels that have been verified for EEDI and issued an International Energy Efficiency Certificate (IEEC), the attained EEDI will be equal to the attained EEXI, provided that the attained EEDI meets the regulatory limit established by the newly introduced required EEXI regulation 21A.

The EEXI calculation guidelines have been developed but so far remain in draft form. The calculation methodology is aligned with that used for EEDI. However, the determination of specific technical inputs such as the vessel's reference speed (VREF) require further consideration. The supporting data and information that would normally be available during the EEDI verification process, may be difficult to obtain for EEXI. For such cases, an alternative calculation method was introduced based on statistical speed data of existing ships from the IHS Fairplay database also accounting for the correlation with the ship's engine power.

The draft guidelines state that the alternative calculation method for the ship VREF should not overestimate the vessel's energy efficiency. Correction factors that account for specific structural elements and powering needs, such as those used in the EEDI calculation for chemical tankers, ice-strengthened ships, shuttle tankers, roll on/roll off (ro/ro) cargo and roll on/roll off passenger (ro/pax) ships, are pending agreement. The auxiliary power component (PAE) is expected to follow the estimation process by the current EEDI calculation guidelines. However, when engine power limitation is installed, clarifications may be necessary on whether and how the Shaft Power Limitation (SHaPoLi)/Engine Power Limitation (EPL) installation will affect the calculation. It is important to note that the installed EPL will be overridable for safety reasons and operation in adverse weather conditions.

REQUIRED EEXI — REGULATION 21A

Regulation 21A will provide the requirement and guidelines for calculating the required EEXI and verifying that a vessel's attained EEXI is lower than the required EEXI. The required EEXI would be the regulatory limit for EEXI and its calculation will be in line with the EEDI reference line values using reduction factors specific to EEXI, as shown in the following table.

Special consideration was taken by the members of the ISWG-GHG during the determination of the EEXI reduction factors to address the compliance challenges that some older vessels may face while keeping in line with the IMO Strategy's level of ambition for 2030. Furthermore, a review clause was introduced stating that by January 1, 2026, the IMO will assess the effectiveness of Regulation 21A to determine the need for future amendments.

SHIP TYPE	SIZE	REDUCTION FACTOR (%)
Bulk Carrier	200,000 dwt and above	15
	20,000 and above but less than 200,000 dwt	20
	10,000 and above but less than 20,000 dwt	0-20*
Gas Carrier	15,000 dwt and above	30
	10,000 and above but less than 15,000 dwt	20
	2,000 and above but less than 15,000 dwt	0-20*
Tanker	200,000 dwt and above	15
	20,000 and above but less than 200,000 dwt	20
	4,000 and above but less than 20,000 dwt	0-20*
Containership	200,000 dwt and above	50
	120,000 and above but less than 200,000 dwt	45
	80,000 and above but less than 120,000 dwt	35
	40,000 and above but less than 80,000 dwt	30
	15,000 and above but less than 40,000 dwt	20
	10,000 and above but less than 15,000 dwt	0-20*
General Cargo Ship	15,000 dwt and above	30
	3,000 and above but less than 15,000 dwt	0-30*
Refrigerated Cargo Carrier	5,000 dwt and above	15
	3,000 and above but less than 5,000 dwt	0-15*
Combination Carrier	20,000 dwt and above	20
	4,000 and above but less than 20,000 dwt	0-20*
LNG Carrier	10,000 dwt and above	30
Ro/ro Vehicle Carrier	10,000 dwt and above	15
Ro/ro Cargo Ship	2,000 dwt and above	5
	1,000 and above but less than 2,000 dwt	0-5*
Ro/pax Ship	1,000 dwt and above	5
	250 and above but less than 1,000 dwt	0-5*
Cruise Passenger Ship with Non-conventional Propulsion	85,000 GT and above	30
	25,000 gt and above but less than 85,000 gt	0-30*

(*) Reduction factor to be linearly interpolated between the two values dependent upon ship size. The lower value of the reduction factor is to be applied to the smaller ship size.

EEXI SURVEY AND CERTIFICATION

For the verification of a vessel's attained EEXI, an application for a survey would be submitted to the verifier together with an EEXI technical file containing the necessary information for the verification and supporting background documents.

The verification scope is generally expected to align with the one applied for EEDI. However, specific requirements will be introduced on the method to obtain the ship VREF, for situations where SHaPoLi/EPL is installed and for ships having undergone a major conversion. Upon final verification, each vessel's attained EEXI and required EEXI values will be indicated on the vessel's IEEC issued by the flag Administration. For cases where the attained EEDI of the ship satisfies the required EEXI, a confirmation of compliance with EEXI regulations and subsequent update of the IEEC would be sufficient.

TIMELINE TO ENFORCEMENT

The draft amendments to MARPOL Annex VI introducing the EEXI regulations, have been approved by Marine Environmental Protection Committee (MEPC) 75 (Nov 2020). The draft amendments will now be put forward for adoption at the subsequent MEPC 76 session, to be held in June 2021. The MARPOL treaty requires draft amendments to be circulated for a minimum of six months before adoption, and they can enter into force after a minimum of 16 months following adoption. Enforcement of EEXI regulations will begin on January 1, 2023. The verification that the ship's attained EEXI is in accordance with the regulations will take place at the first annual, intermediate or renewal survey for the International Air Pollution Prevention (IAPP) Certificate, whichever is the first, on or after January 1, 2023.

CARBON INTENSITY INDICATOR (CII)

The CII is an operational measure that is intended to track the carbon emissions of each vessel on an annual basis and document the reductions; it will be implemented through an enhanced SEEMP, the operational-measurement mechanism established under MARPOL Annex VI.

The combination of EEXI and CII creates a framework that will challenge shipowners and operators to act quickly and decisively to maintain a low-carbon fleet. As a one-time certification, the EEXI will serve as a filter to block older vessels that cannot be cost effectively retrofitted with new technologies. The vessels that are compliant with the EEXI will then have to follow a trajectory for reducing their carbon intensity on an annual basis, until they reach the 2030 level required by IMO.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The carbon intensity is calculated either through the Average Efficiency Ratio (AER, [gCO_2/dwt-nm]) using the design deadweight of the vessel, or through the Energy Efficiency Operational Index (EEOI, [gCO_2/ton-nm]), which includes the cargo mass. The required information will be sourced from the IMO Data Collection System (DCS), through which the CII will be calculated and reported. However, since the IMO DCS does not contain any data on the actual cargo mass transported, the expectation is that AER will be chosen as main metric and that EEOI will be allowed to be reported on a voluntary and trial basis.

In accordance with the 2030 GHG reduction goal, the IMO will set a trajectory for the reduction of carbon intensity for each vessel segment. A rating system (A-E scale, A and B being below the required level; D and E above; and C close to the required level) will be used to assess the carbon intensity of vessels on an annual basis and each vessel will receive a statement of compliance. Additionally, the IMO will provide guidelines on the possible fuel consumption and voyage exclusions and reduction factors allowed for vessels. The width of each of the rating bands in the scale (A to E) will likely be defined based on the 2019 carbon intensity data, and the amount of vessels in each category will be as follows:

- Category A: 15 percent
- Category B: 20 percent
- Category C: 30 percent
- Category D: 20 percent
- Category E: 15 percent

The annual reduction rates for carbon intensity are based on the findings of the fourth IMO GHG study. In this study, it was seen that depending on the metric used, the level of reduction achieved in the 2008 to 2018 period was different. Based on the EEOI, the reduction achieved was 31.8 percent, but based on the AER the reduction achieved was 22.0 percent compared to 2008. The IMO target for 2030 is to achieve for both AER and EEOI a reduction of 40 percent with respect to 2008. Therefore, current discussions at IMO focus on two reduction rates from 2018 to 2030, one based on the EEOI and another one on the AER, as shown in the following table. The choice between the two options will be based on further discussion at the IMO between member States.

	REDUCTIONS BY 2030 WITH RESPECT TO 2019	
	DEMAND (EEOI)	SUPPLY (AER)
Bulk Carrier	5.5%	22%
Gas Carrier	11.0%	
Tanker	5.5%	
Containership	16.5%	
General Cargo Ship	11.0%	
Refrigerated Cargo Carrier	16.5%	
Combination Carrier	11.0%	
LNG Carrier	11.0%	
Ro/ro Cargo Ship (Vehicle Carrier)	16.5%	
Ro/ro Cargo Ship	5.5%	
Ro/pax Ship	5.5%	
Cruise Passenger Ship having Non-conventional Propulsion	16.5%	

The reference lines and the rating band widths are defined for each ship type. The reduction rates that will progressively be applied are still under discussion together with possible voyage and fuel consumption exclusions and correction factors. Also, an incentive mechanism will be discussed for vessels with ratings A or B, which are performing better than the fleet average.

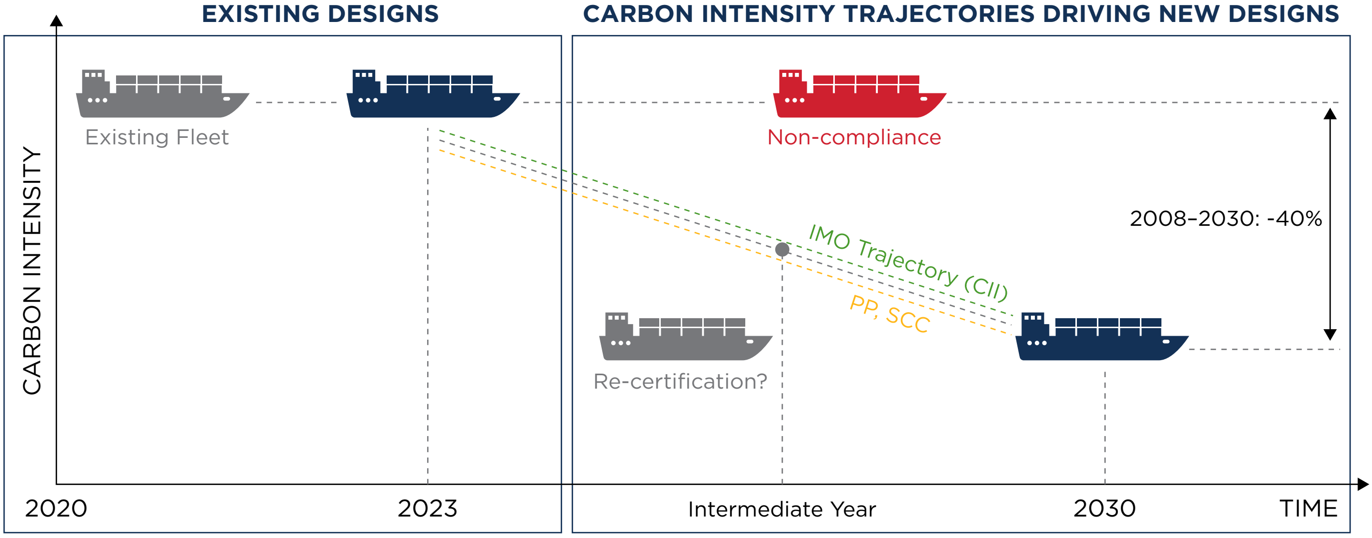


Figure 2. Effects of IMO short-term measures on the evolution of the global fleet.

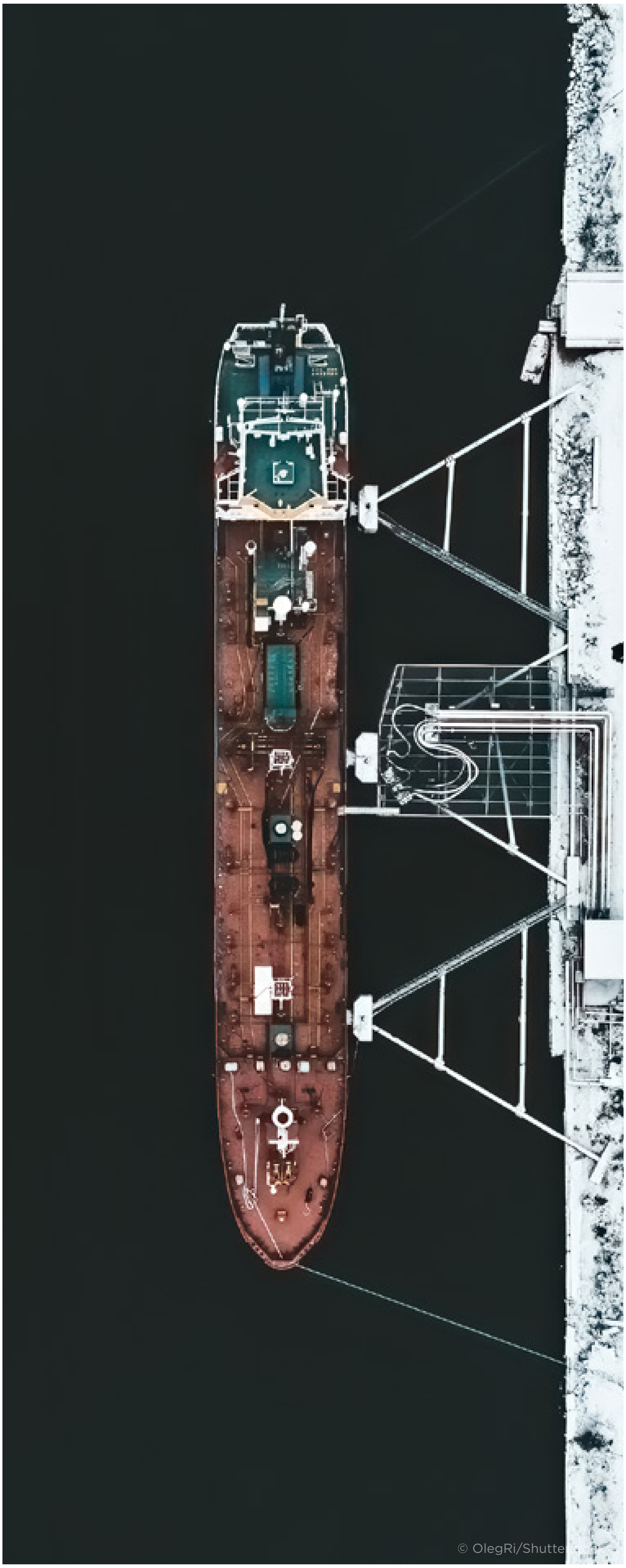
FINANCIAL INSTITUTIONS

Decarbonization has started defining the business decisions to an extent that goes beyond the technical aspects of assets. It has started being reflected on requirements that are being developed in the financing sector. In 2019 the Poseidon Principles created a global framework for assessing and disclosing the environmental performance of the shipping portfolios held by financial institutions. These principles apply to the lenders, the lessors and financial guarantors, including export-credit agencies, and are consistent with the policies and ambitions of the IMO. The signatory institutions commit to implementing the Poseidon Principles to their internal policies, procedures and standards, as well as to work in partnership with their clients and collaborators on a continuous basis.

For the global fleet, the Poseidon Principles adopt a decarbonization trajectory similar to that of the IMO. Therefore, any vessels that have been financed by the signatories need to demonstrate their carbon-intensity reductions on an annual basis. Carbon intensity is measured using the AER (gCO_2/dwt-nm), which is calculated using data from the IMO DCS, ensuring that the Poseidon Principles are consistent with the IMO regulations.

The Poseidon Principles establish a framework for the assessment of environmental performance and disclosure of ship-finance portfolios. However, the framework does not provide solutions for how to improve the environmental performance or achieve the goals. It is the responsibility of each institution to engage with its clients and identify ways to reduce the carbon intensity of the vessels and assets. In this effort, those institutions have the flexibility to rebalance their shipping portfolios over time towards vessels, assets and technologies that are more environmentally friendly, thereby introducing another way to shape the current landscape for shipowners and operators.

Very much linked to the commitment for decarbonization aligned with the Paris Agreement and the agenda for climate change, financing instruments are incorporating decarbonization key performance indicators (KPIs). There is a growing field of environmentally focused bonds structured around how a vessel is designed to minimize carbon intensity and how that asset aligns with decarbonization trajectories for the duration of the bond.



CHARTERERS

Responding to the same decarbonization call as financial institutions, charterers are developing their approach to addressing the carbon intensity of the vessels they Charter. The latest initiative is the Sea Cargo Charter which forms a global framework for assessing and disclosing the environmental performance of chartering activities. The Sea Cargo Charter is applicable to all bulk charterers, those with interest in the cargo on board; those who simply charter out the vessels they charter in, as well as the disponent owners and all charterers in a charter-party chain. It is applied by the charterers to all ship-chartering activities that are:

- "On time" and voyage charters, including contracts of affreightment and parceling, with a mechanism to allocate emissions from backhaul and ballast voyages
- Voyages carried out by dry bulk carriers, chemical tankers, oil (crude and product) tankers and LNG carriers
- Where a vessel or vessels are of at least 5,000 gross tonnage (gt) and engaged in international trade

The current signatories to the Sea Cargo Charter are bulk-cargo owners from segments such as grains and agricultural products, chemicals, energy, metals and mining, as well as commodity traders and shipowners who have an interest in advancing environmental stewardship through their business activities. Their objective is to set a standard for reporting the emissions associated with chartering activities, thus enhancing transparency and creating a global baseline to support the decarbonization of the global economy.

In contrast to the Poseidon Principles, the Sea Cargo Charter uses the EEOI (gCO_2/ton-nm) to measure carbon intensity, which includes the mass of the cargo. However, both the EEOI and AER use the same information about fuel consumption, GHG-emission factors for each fuel and the distances traveled as those reported to and used by the IMO; both align with the climate-related goals of the IMO and the methods used to quantify them.

MARKET-BASED MEASURES (MBMs)

In addition to the regulations set by the IMO and the emissions-reporting schemes set by the financiers and charterers, the reduction of GHG emissions from shipping can also be motivated by MBMs. Various member States and other organizations have proposed MBMs to the IMO that target either in-sector emissions reductions from shipping, or out-of-sector reductions via the collection of funds to be used for mitigation activities in other sectors that contribute to the global reduction of GHG emissions [Psaraftis et al., 2020].

MBMs were included in the initial IMO strategy as a candidate medium-term measure to incentivize the reduction of GHG emissions. Several MBMs have been proposed, but two types seem to have the highest potential for application to shipping: the bunker levy or carbon levy and the global Emissions Trading System (ETS).

The bunker or carbon levy concept is based on a global GHG-reduction target that will be set by either the United Nations Framework Convention on Climate Change (UNFCCC) or the IMO. Any emissions above the target line would be mostly offset by the purchase of emission-reduction credits. The offsetting activities then would be financed by a contribution paid by ships on the purchase of every metric ton of bunker fuel. These contributions can be collected through bunker fuel supplies or through direct payment from shipowners and operators. The contribution rate would be adjusted at regular intervals to ensure sufficient funds are available to purchase project credits to achieve the target line. Any remaining funds would be available for adaptation and mitigation activities via the UNFCCC, as well as for research and development within the IMO framework.

The ETS is a cap-and-trade concept. The cap is set on the total amount of GHG emitted from internal shipping that would be reduced over time. Within this cap, shipowners and operators can receive or buy emissions credits, which they can trade with other companies, as needed. These can include out-of-sector credits, which will enable further growth of the shipping sector beyond the cap. A limited number of credits (ship emission units) would be released into the market each year so that they have a value.

Any company with a low-emissions profile can sell allowances, while any company with a high-emissions profile will have to buy allowances to cover its emissions. This trading scheme aims to introduce some flexibility for shipowners and operators and guide them towards reducing emissions in the most cost-effective manner. In the definition of the responsible entity the text includes the shipowner or any other organization or person such as the manager; the time charterer or the bareboat charterer, which has assumed the responsibility for the commercial operation of the ship from the shipowner and is responsible for paying for fuel consumed by the ship.

The European Union (EU) established its ETS in 2005 and included emissions for stationary power generation and heating, energy-intensive manufacturing and processing plants, and commercial aviation; the marine sector was recently added to this scheme. The inclusion of the marine sector is expected to be approved within 2021 with a view to entry into force in 2022.

The IMO regulations, the trajectories set by the Poseidon Principles and Sea Cargo Charter, and the proposed MBMs create a dynamic and challenging landscape for shipowners and operators. These constraints can motivate the optimization of any fleet based on its mission, trading routes and chartering agreements. They orient participants towards the adoption of low- and zero-carbon fuels, technology upgrades for the vessels and voyage optimizations that maximize efficiency and minimize the emission of GHGs.

4 CURRENT STATE OF THE GLOBAL FLEET

The advent of the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) regulations has created a challenging landscape for shipowners, operators and charterers across different segments of the global fleet. Both of these short-term measures will apply to all vessels in service regardless of age. Therefore, it is important to understand the status of the global fleet in order to analyze the effect of the short-term measures on its evolution. The following sections show the Energy Efficiency Design Index (EEDI) and expected EEXI compliance levels of five key vessel segments: tankers, bulk carriers, gas carriers, LNG carriers and containerships, and analyze how each segment has performed to date.

TANKERS

The global tanker fleet includes 10,309 vessels that are over 4,000 deadweight (dwt) out of which 1,903 have attained EEDI values. Figure 1 shows the EEDI compliance levels for the tankers with attained EEDI values based on the International Maritime Organization (IMO) Global Integrated Shipping Information System (GISIS) database[1]. The tankers with attained EEDI values correspond to 18.5 percent of the global fleet considered. The tankers that are pre-EEDI are 7,974 or 77.3 percent of the global fleet and the remaining 432 vessels are not subject to mandatory submission of EEDI data.

	Vessels #	Total dwt
Total in Service (dwt > 4,000)	10,309	663,045,950
Pre-EEDI	7,974	475,040,987
	77.3%	71.6%

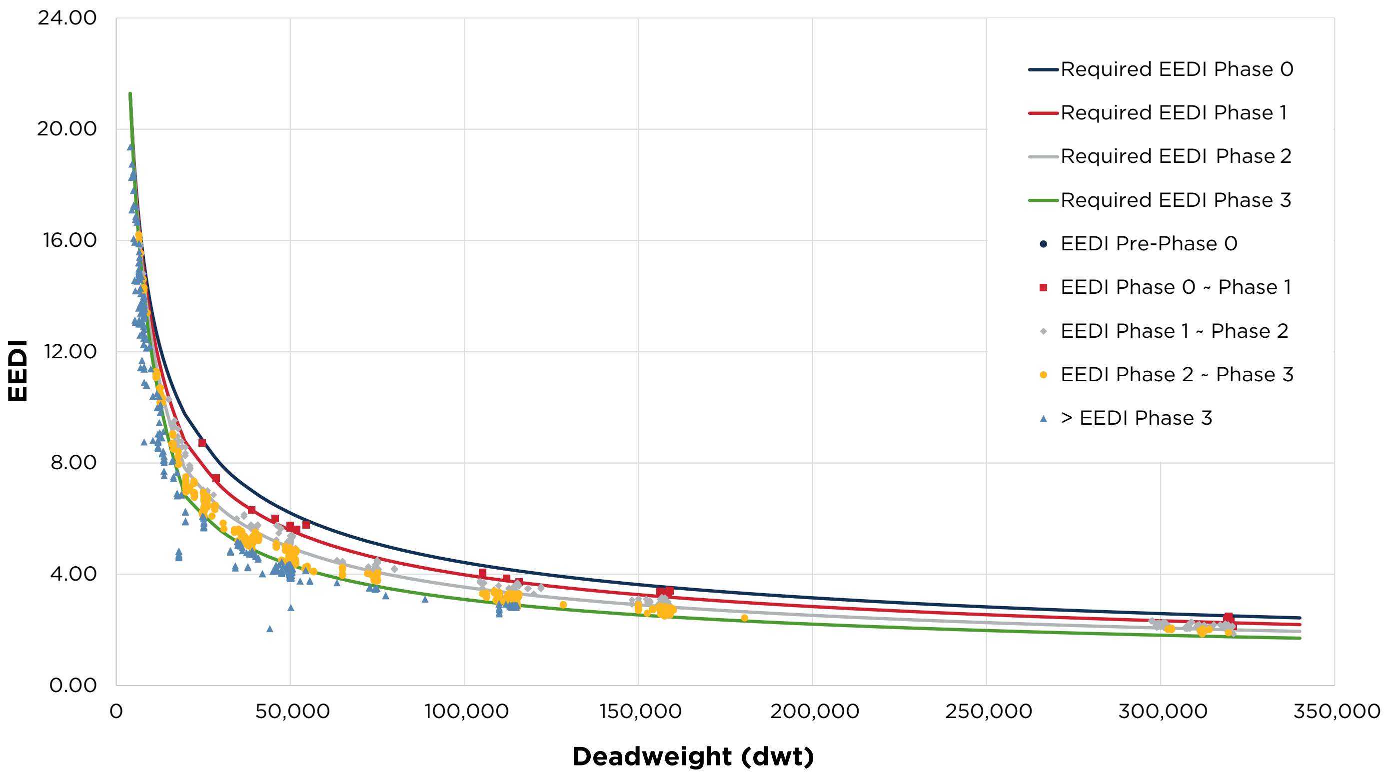


Figure 1: EEDI compliance levels for tankers larger than 4,000 dwt.

ATTAINED EEDI AVAILABLE — 1,903	Vessels #	Total dwt
EEDI Pre-Phase 0	2	637,514
	0.1%	0.3%
EEDI Phase 0 ~ Phase 1	35	4,991,302
	1.8%	2.6%
EEDI Phase 1 ~ Phase 2	494	91,030,738
	26.0%	47.8%
EEDI Phase 2 ~ Phase 3	798	69,880,806
	41.9%	36.7%
> EEDI Phase 3	574	23,837,996
	30.2%	12.5%

Figure 2 shows the expected EEXI compliance of the 1,903 tankers that have attained EEDI values, based on the reduction factors approved by Marine Environmental Protection Committee (MEPC) 75. 1,526 of these vessels are expected to comply, while 377 are not. These 1,526 tankers correspond to 14.8 percent of the global fleet considered and indicate that the remaining 85.2 percent of the global tanker fleet will face challenges with EEXI compliance.

	Vessels #	Total dwt
Non-EEXI Compliant	377	49,340,200
EEXI Compliant	1,526	141,038,156

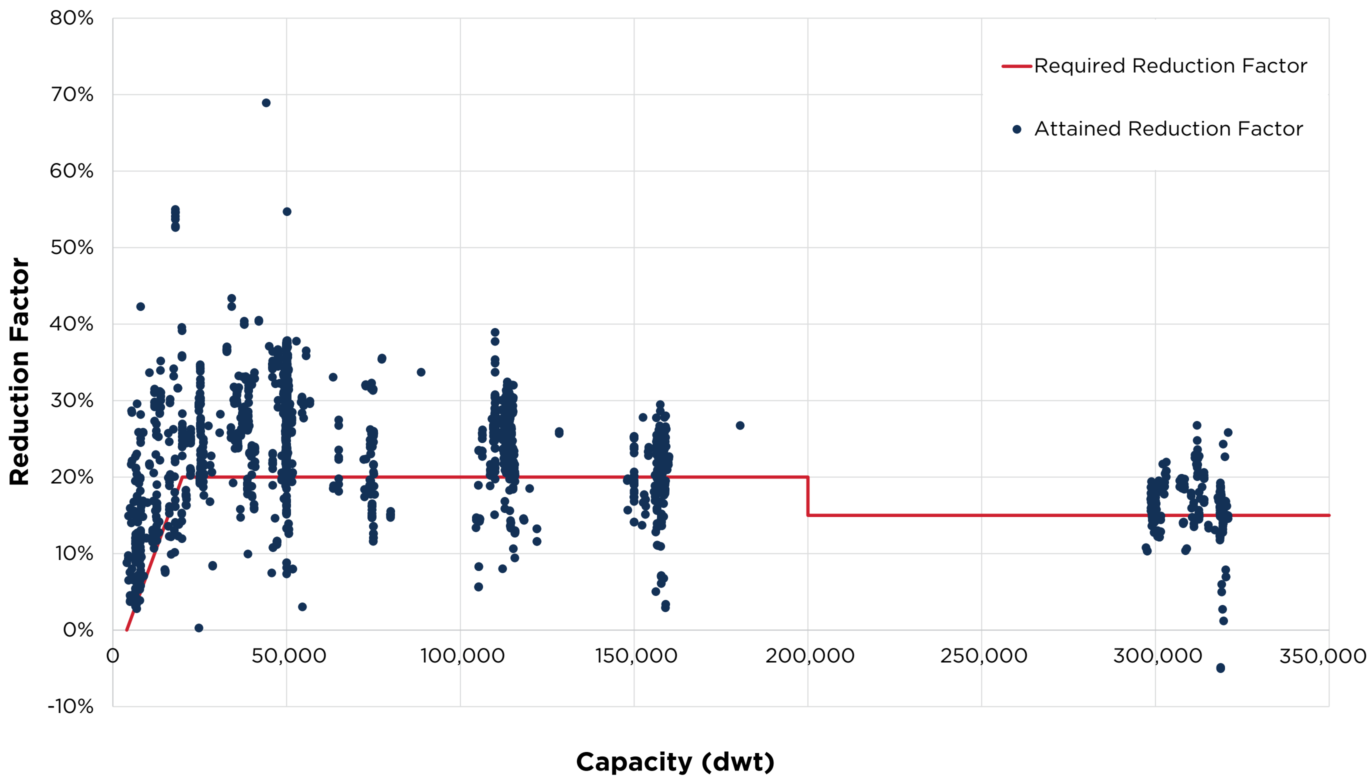


Figure 2: EEXI compliance levels for tankers larger than 4,000 dwt with attained EEDI values.

Based on the EEDI and EEXI results, it seems that design-based efficiency over a range of dwt tanker segments has improved slowly since 2013. Compliance with EEDI Phase III – and in some cases even Phase II – remains a challenge.

Specifically:

- Suezmax tankers (120k–200k dwt) built in the period from 2016 through 2019 show increasing compliance margins with EEDI Phase II. However, no vessel in this category has achieved a 30 percent reduction compared to the baseline yet as needed for EEDI Phase III. The challenge will be greater for older hulls that are now being asked to comply with the IMO EEXI requirements. Pre-EEDI ships have higher installed main engine maximum continuous rating (MCR) and have not necessarily been optimized for fuel efficiency, as is commonly the case for their EEDI-verified counterparts.
- A small number of very large crude carrier (VLCC) tankers (dwt > 300k) have achieved EEDI Phase II criteria, but no vessel in this category has achieved a 30 percent reduction compared to the baseline yet. The key reason for this difficulty is the requirement to meet the minimum propulsion power (MPP) criteria under EEDI Regulation 21.5 of International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI. For older hulls, the MPP requirements would not be assessed under the EEXI framework. A speed reduction will be necessary for the compliance of most vessels, but this can easily be achieved through an overridable limitation on the main engine MCR.
- Smaller dwt segments such as aframax tankers (80k–120k dwt) appear to meet Phase II criteria more comfortably when compared to larger vessels. However, these better performers have marginal compliance with Phase III by only a small number of vessels.

The slow progress made in improving the design-based efficiency of tankers can be attributed to the relative lack of innovative technology adoption. The main technology adopted for tankers and particularly VLCCs was Waste Heat Recovery (WHR) for electric power generation on board.

However, based on experimental case studies reviewed at MEPC 72 and later, the adoption of practical energy saving devices, such as pre/post-swirl devices, contra-rotating propellers, low friction coatings, WHR and solar power, can help increase the design-based efficiency of the global tanker fleet. In addition, the adoption of low- and zero-carbon fuels can offer further significant reductions to EEDI/EEXI as well as the CII by directly reducing the actual tank-to-wake carbon emissions.

BULK CARRIERS

The global bulk carrier fleet includes 11,421 vessels larger than 10,000 dwt, out of which 2,817 vessels have attained EEDI values. Figure 3 shows the EEDI compliance levels for the bulk carriers with attained EEDI values based on the IMO GISIS database. The vessels with attained EEDI values correspond to 24.7 percent of the global fleet of bulk carriers considered. The vessels that are pre-EEDI are 8,523 or 74.6 percent of the global fleet and the remaining 81 vessels are not subject to mandatory submission of EEDI data.

	Vessels #	Total dwt
Total in Service (dwt > 10,000)	11,421	892,678,942
Pre-EEDI	8,523	634,149,782
	74.6%	71.0%

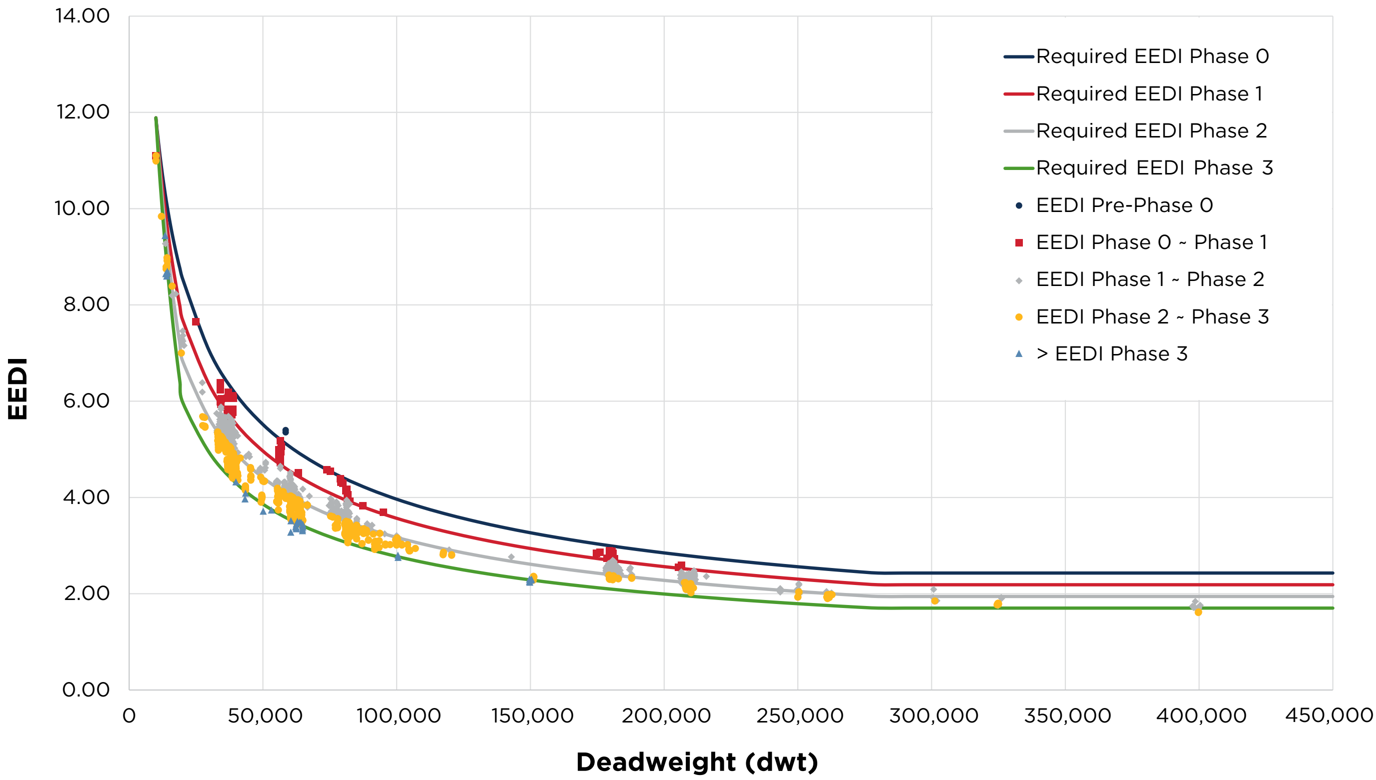


Figure 3: EEDI compliance levels for bulk carriers larger than 10,000 dwt.

Figure 4 shows the expected EEXI compliance of the 2,817 bulk carriers that have attained EEDI values, based on the reduction factors approved by MEPC 75. 1,556 of these vessels are expected to comply, while 1,261 are not. These 1,556 bulk carriers correspond to 13.6 percent of the global fleet considered and indicate that the remaining 86.4 percent of the global bulk carrier fleet will face challenges with EEXI compliance.

ATTAINED EEDI AVAILABLE — 2,817	Vessels #	Total dwt
EEDI Pre-Phase 0	4	234,072
	0.1%	0.1%
EEDI Phase 0 ~ Phase 1	82	6,290,947
	2.9%	2.6%
EEDI Phase 1 ~ Phase 2	1,245	125,299,208
	44.2%	51.0%
EEDI Phase 2 ~ Phase 3	1,440	110,939,120
	51.1%	45.1%
> EEDI Phase 3	46	2,950,060
	1.6%	1.2%

	Vessels #	Total dwt
Non-EEXI Compliant	1,261	115,164,654
EEXI Compliant	1,556	130,548,755

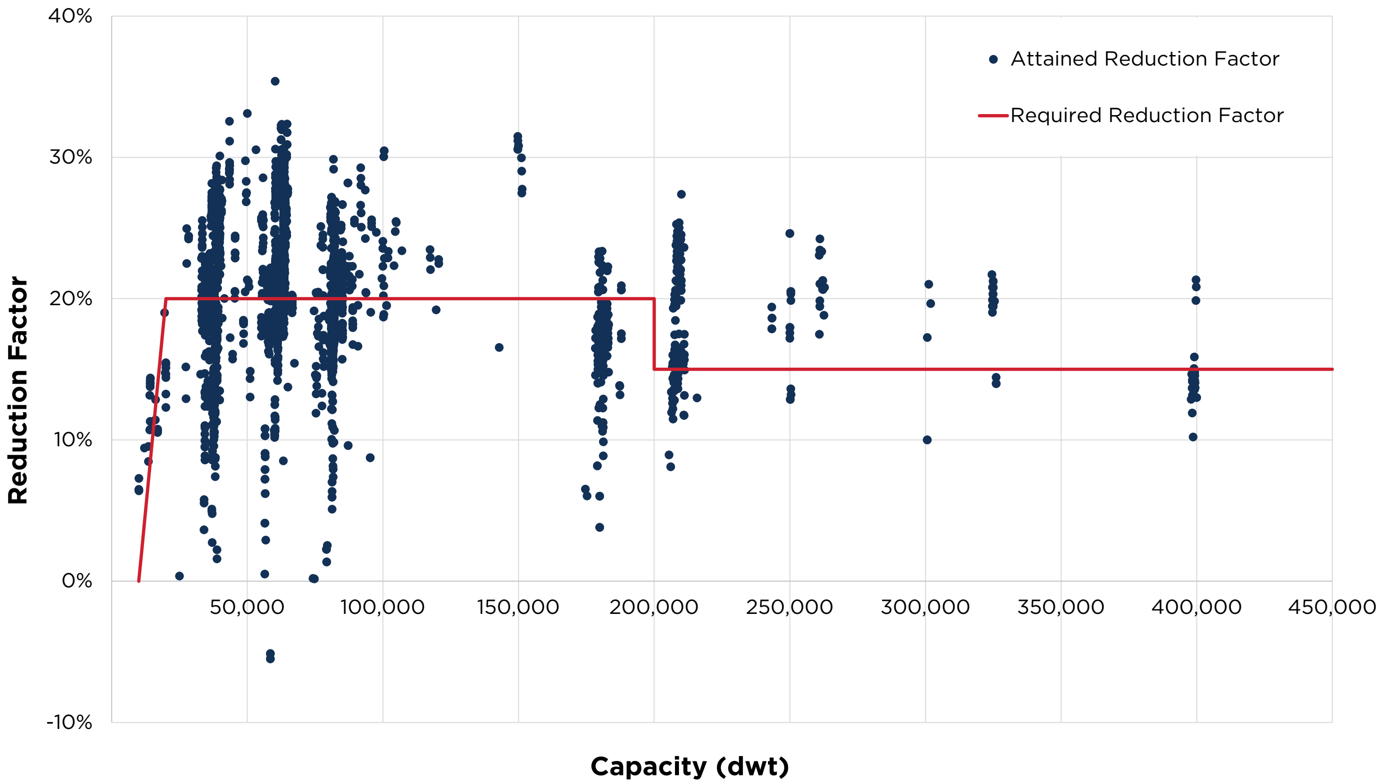


Figure 4: EEXI compliance levels for bulk carriers larger than 10,000 dwt with attained EEDI values.

Based on the EEDI and EEXI results, it seems that design-based efficiency over a range of dwt bulk carrier segments has improved slowly since 2013. Compliance with EEDI Phase III – and in some cases even Phase II – remains a challenge.

Specifically:

- For large capesize bulk carriers (200k–300k dwt), the number of delivered hulls meeting EEDI Phase II appears to be increasing between years 2016 to 2019 with vessels showing improved average achieved efficiency. However, no vessel in this category has achieved 30 percent reduction compared to the baseline yet. In a similar fashion to tankers, the key reason for this difficulty is the requirement to meet the minimum propulsion power (MPP) criteria under EEDI Regulation 21.5 of MARPOL Annex VI. For older hulls, the MPP requirements would not be assessed under the EEXI framework. A speed reduction will be necessary for compliance for most cases, but this can easily be achieved through an overridable limitation of the main engine MCR.
- No very large ore carrier (VLOC) bulk carrier (dwt > 300k) has reported compliance with EEDI Phase II yet.
- Smaller dwt segments such as panamax bulk carriers (60k–80k dwt) appear to meet Phase II criteria more comfortably when compared to larger vessels. However, these better performers have marginal compliance with Phase III by only a few vessels.

In a similar manner to what was observed for tankers, the slow progress made in improving the design-based efficiency of bulk carriers can be attributed to the relative lack of innovative technology adoption. The insights gained from the experimental case studies reviewed at MEPC 72 and later also apply to bulk carriers. The adoption of practical energy saving devices, such as pre/post-swirl devices, contra-rotating propellers, low friction coatings, WHR and solar power, can help the global tanker fleet to increase its design-based efficiency. In addition, the adoption of low- and zero-carbon fuels can offer further significant reductions to EEDI/EEXI as well as the CII by directly reducing the actual tank-to-wake carbon emissions.

GAS CARRIERS

The global gas carrier fleet includes vessels that carry liquefied natural gas (LNG), liquefied petroleum gas (LPG) or ethane as cargo. This fleet includes 1,847 vessels larger than 2,000 dwt, out of which 353 vessels have attained EEDI values. It should be noted that at the early implementation stages of EEDI regulations, gas carriers were grouped together with LNG carriers to evaluate and benchmark their energy efficiency levels. To correct for the high ratio of cargo volumetric capacity to dwt for LNG carriers, the EEDI calculation guidelines allowed for the use of a correction factor. However, in 2014 the IMO effectively split gas carriers from LNG carriers for all ships delivered after September 1, 2019. EEXI Regulations will follow this separation scheme and benchmark all LNG carriers separately using the LNG carrier EEDI baseline. Figure 5 shows the EEDI compliance levels for the gas carriers with attained EEDI values based on the IMO GISIS database. The vessels with attained EEDI values correspond to 19.1 percent of the global fleet of gas carriers considered. The vessels that are pre-EEDI are 1,220 or 66.1 percent of the global fleet and the remaining 274 vessels are not subject to mandatory submission of EEDI data.

	Vessels #	Total dwt
Total in Service (dwt > 2,000)	1,847	74,299,710
Pre-EEDI	1,220	46,567,738
	66.1%	62.7%

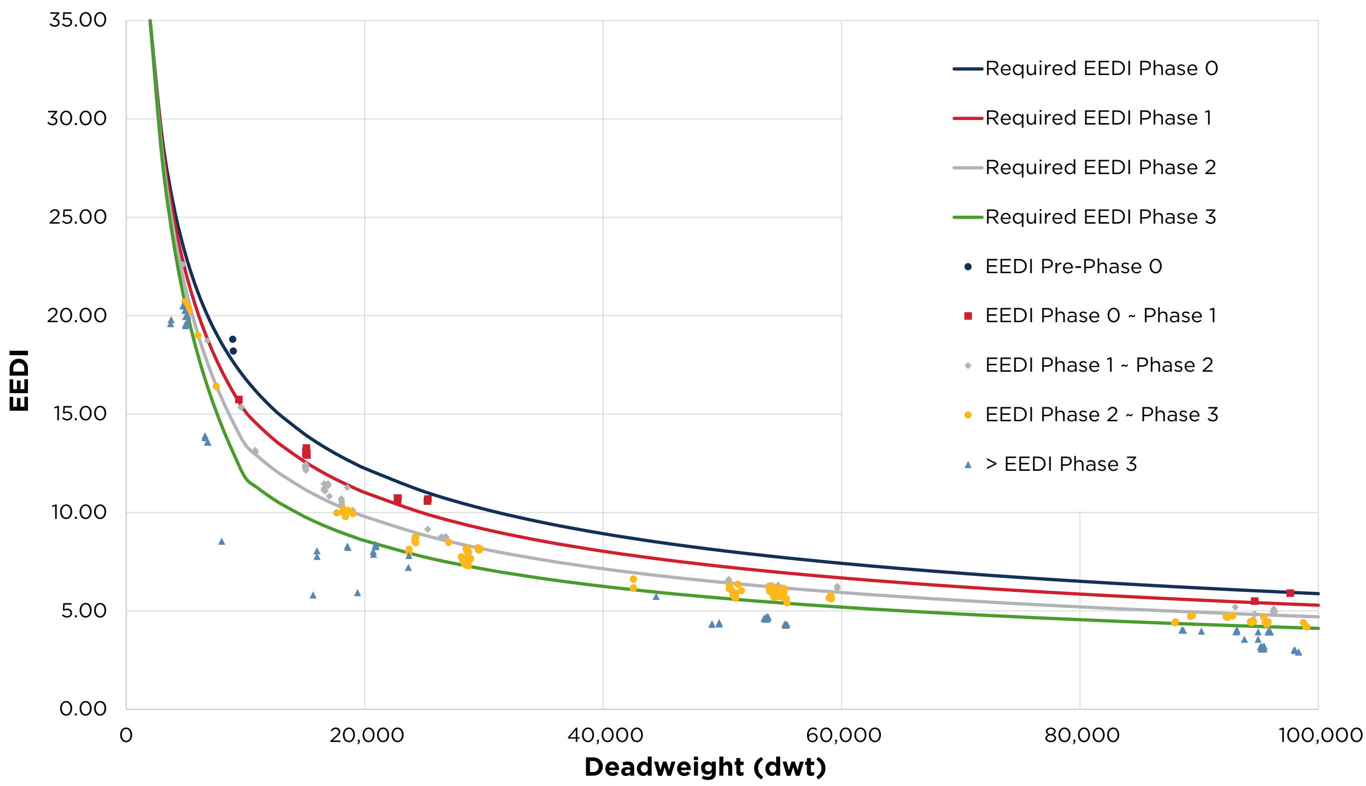


Figure 5: EEDI compliance levels for gas carriers larger than 2,000 dwt.

ATTAINED EEDI AVAILABLE — 353	Vessels #	Total dwt
EEDI Pre-Phase 0	2	17,915
	0.6%	0.1%
EEDI Phase 0 ~ Phase 1	15	434,014
	4.2%	2.6%
EEDI Phase 1 ~ Phase 2	56	1,943,085
	15.9%	11.7%
EEDI Phase 2 ~ Phase 3	203	10,284,242
	57.5%	61.8%
> EEDI Phase 3	77	3,958,814
	21.8%	23.8%

Figure 6 shows the expected EEXI compliance of the 353 gas carriers that have attained EEDI values, based on the reduction factors approved by MEPC 75. 271 of these vessels are expected to comply, while 82 are not. These 271 gas carriers correspond to 14.7 percent of the global fleet considered and indicate that the remaining 85.3 percent of the global gas carrier fleet will face challenges with EEXI compliance.

	Vessels #	Total dwt
Non-EEXI Compliant	271	12,650,330
EEXI Compliant	82	3,987,740

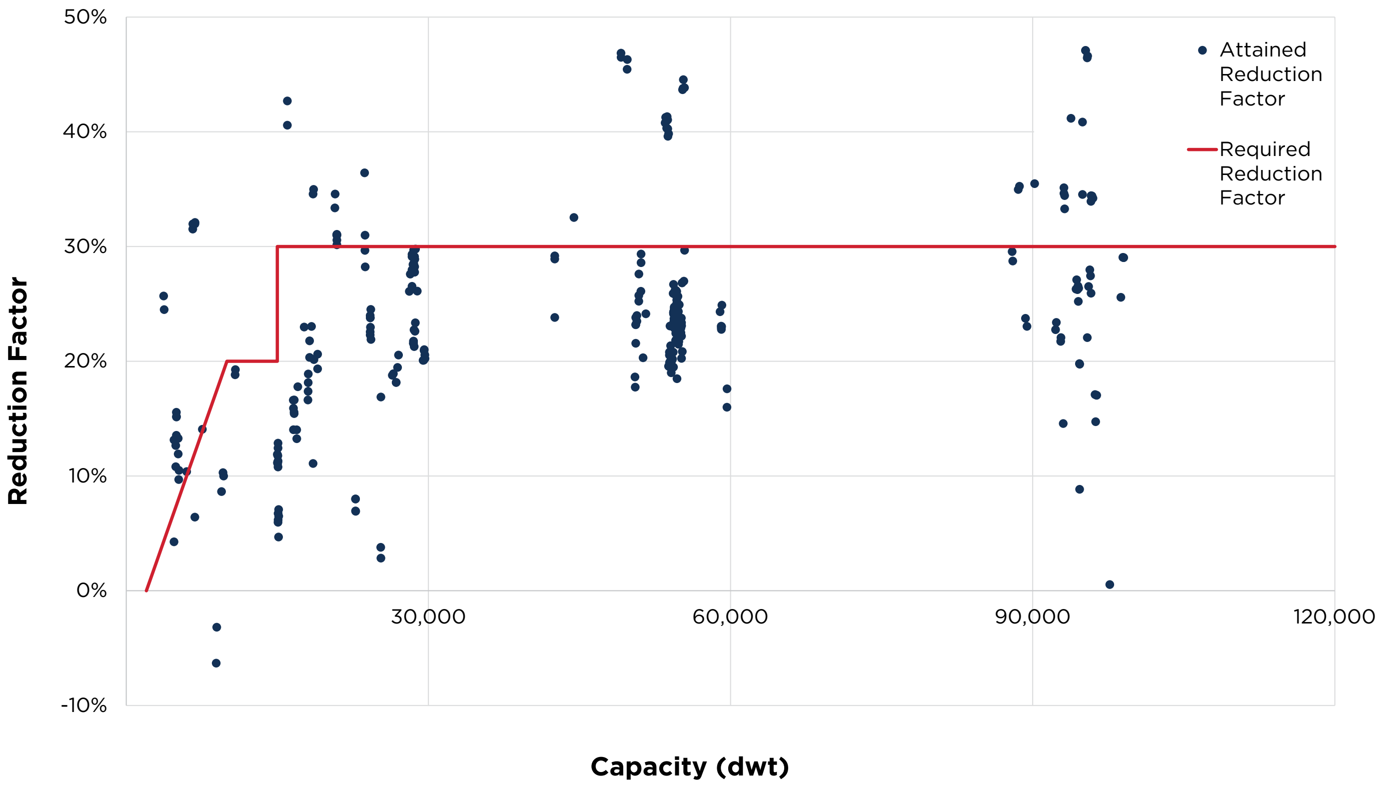


Figure 6: EEXI compliance levels for gas carriers larger than 2,000 dwt with attained EEDI values.

Gas carriers – particularly those of higher dwt capacity – have proven capable to meet the EEXI reduction (30 percent) expected by the IMO GHG Strategy. Even though older hulls were not designed to consume gas cargo as fuel, this trend has recently changed. As gas fuels generally have higher calorific value and lower carbon content compared to liquid fuels, their inclusion to the EEXI calculation provides a significant benefit. For example, a gas-fueled gas carrier may not need to slow down to achieve EEXI compliance and therefore in-service speed obligations would not necessarily be affected.

LNG CARRIERS

The LNG carrier fleet verified for EEDI includes vessels with conventional or non-conventional propulsion that have been contracted on or after September 1, 2015 and/or delivered on or after September 1, 2019. This fleet includes 64 vessels larger than 10,000 dwt, out of which 48 vessels have attained EEDI values. Figure 7 shows the EEDI compliance levels for the LNG carriers with attained EEDI values based on the IMO GISIS database. The vessels with attained EEDI values correspond to 75 percent of the global fleet of LNG carriers considering that any pre-EEDI vessels in this category and those hulls delivered before September 2019, were assessed under the gas carrier reference line. The remaining 16 vessels are not subject to mandatory submission of EEDI data.

	Vessels #	Total dwt
Total in Service (dwt > 10,000)	64	5,829,015
Pre-EEDI	0	0

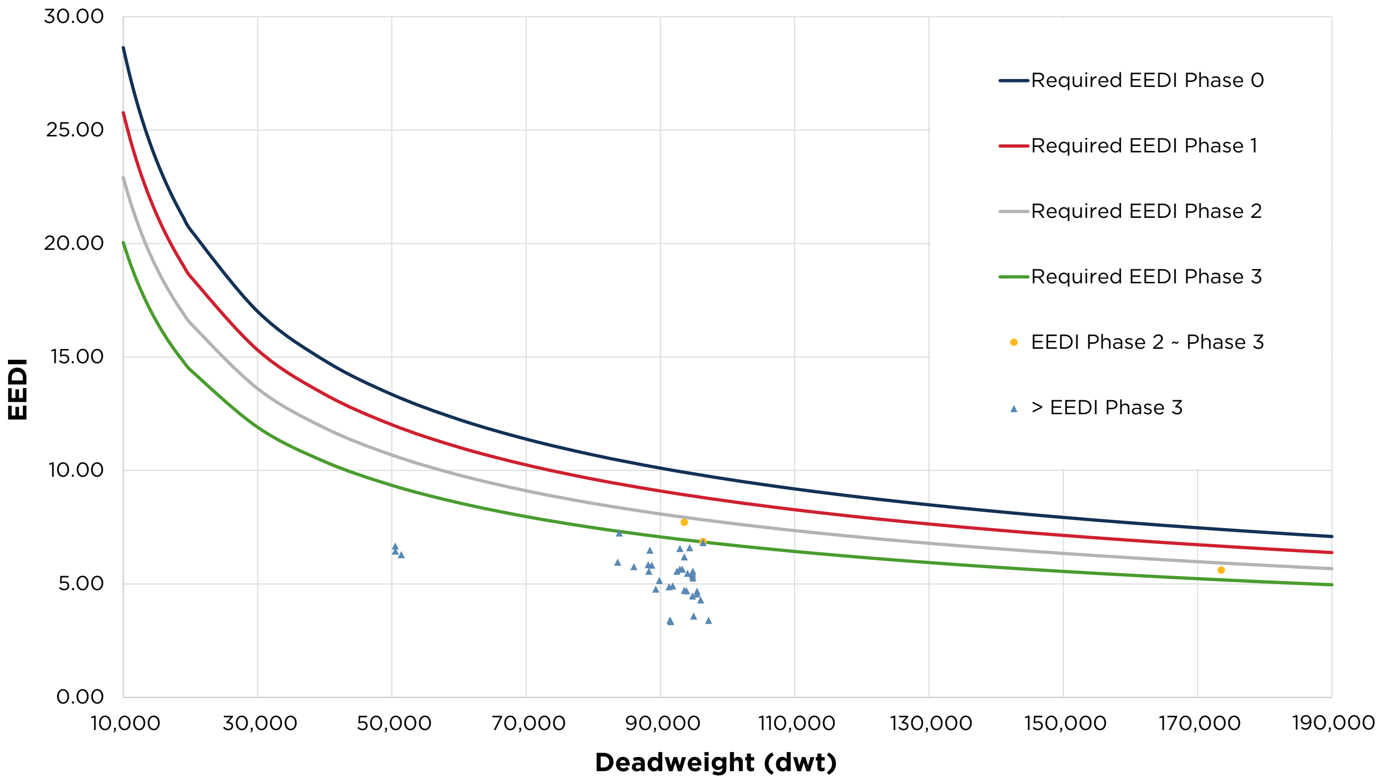


Figure 7: EEDI compliance levels for LNG carriers larger than 10,000 dwt.

ATTAINED EEDI AVAILABLE — 48	Vessels #	Total dwt
EEDI Phase 2 ~ Phase 3	4	536,974
	8.3%	12.0%
> EEDI Phase 3	44	3,936,249
	91.7%	88.0%

Figure 8 shows the expected EEXI compliance of the 48 LNG carriers that have attained EEDI values, based on the reduction factors approved by MEPC 75. 44 of these vessels are expected to comply, while four are not. These 44 LNG carriers correspond to 68.8 percent of the global fleet considered.

	Vessels #	Total dwt
Non-EEXI Compliant	4	536,974
EEXI Compliant	44	3,936,249

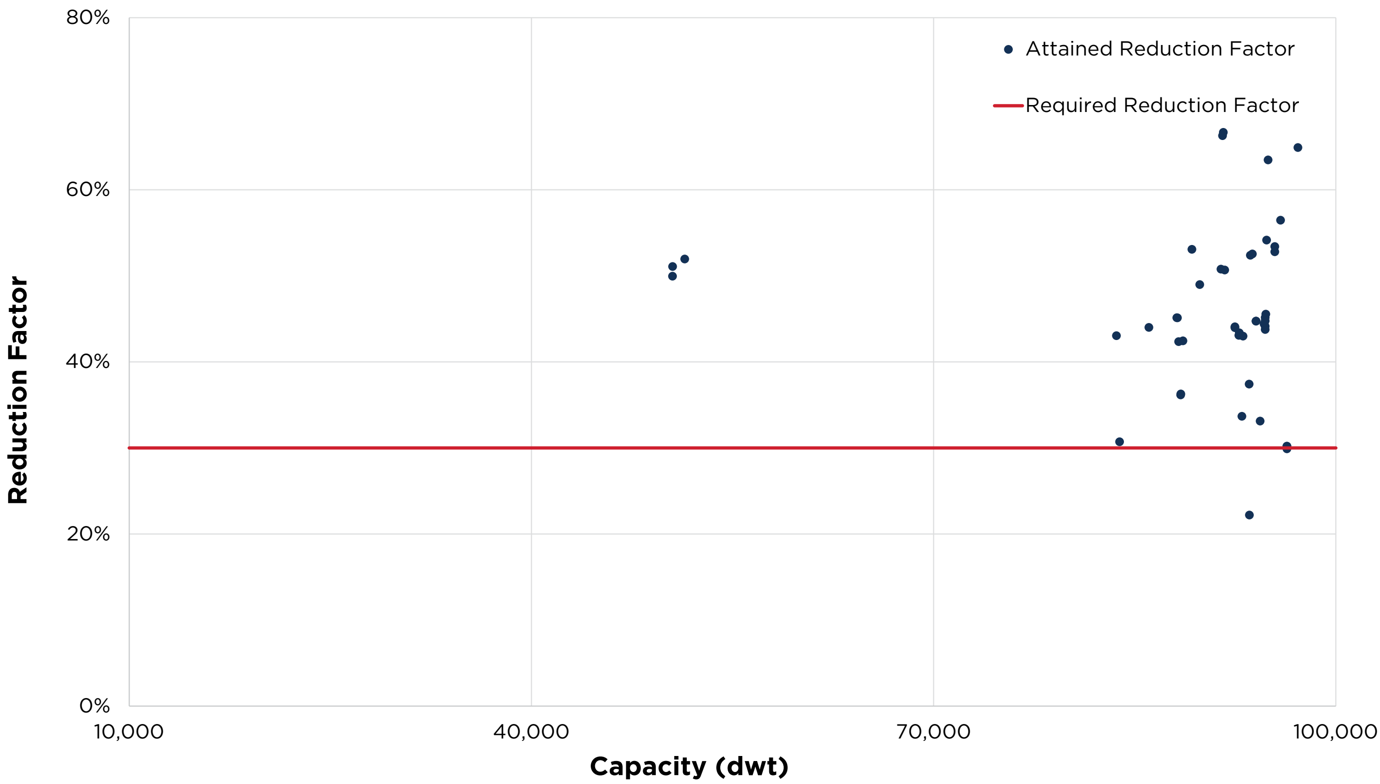


Figure 8: EEXI compliance levels for LNG carriers larger than 10,000 dwt with attained EEDI values.

Following the adoption of the EEXI requirements at MEPC 75, steam turbine LNG carriers will need to comply with a 30 percent reduction rate applicable to the EEDI reference line of this ship category. All of these LNG carriers were built before the enforcement of EEDI regulations and thus demonstrate lower efficiency levels compared to their conventional propelled or diesel-electric counterparts. The Specific Gas Consumption (SGC) of a steam turbine propelled LNG carrier is optimized to the ship's design operation point and directly tied to the nominal boil-off rate (NBOR). It has been observed that in many cases, steam turbine LNG Carriers marginally meet EEDI Phase 0. If a shaft limitation is applied to the output of the steam turbine plant, the resulting SGC increases at a rapid rate at the low load range. This may lead to an approximate 50 to 70 percent shaft power limitation requirement in order for steam turbine LNG carriers to become compliant with EEXI regulations, which has multiple negative implications.

Another group of LNG carriers that will need careful evaluation within the EEXI framework are the conventionally propelled vessels burning liquid fuel. Apart from the high installed main engine power to support service speed needs and the use of high carbon content liquid fuel in the EEXI calculation, these vessels are also fitted with reliquefication units that require high electric power for operation. In this respect, dual-fuel or tri-fuel diesel electric LNG carriers that consume boil-off gas for propulsion do not show any significant issues in meeting EEXI requirements.

Air lubrication system installations have so far shown promising results on improving fuel consumption of LNG carriers. In 2015, a joint development project (JDP) exploring an air lubrication system for an LNG carrier retrofit was set up and conducted in cooperation with BG Group (now Shell), GasLog and ABS. The full-scale performance data suggested that the system can lead to an average power saving of about four percent.

CONTAINERSHIPS

The global containership fleet includes 4,713 vessels larger than 10,000 dwt, out of which 856 vessels have attained EEDI values. Figure 9 shows the EEDI compliance levels for the containerships with attained EEDI values based on the IMO GISIS database. The vessels with attained EEDI values correspond to 18.2 percent of the global fleet of containerships considered. The vessels that are pre-EEDI are 3,777 or 80.1 percent of the global fleet and the remaining 80 vessels are not subject to mandatory submission of EEDI data.

	Vessels #	Total dwt
Total in Service (dwt > 10,000)	4,713	280,437,208
Pre-EEDI	3,777	202,723,912
	80.1%	72.3%

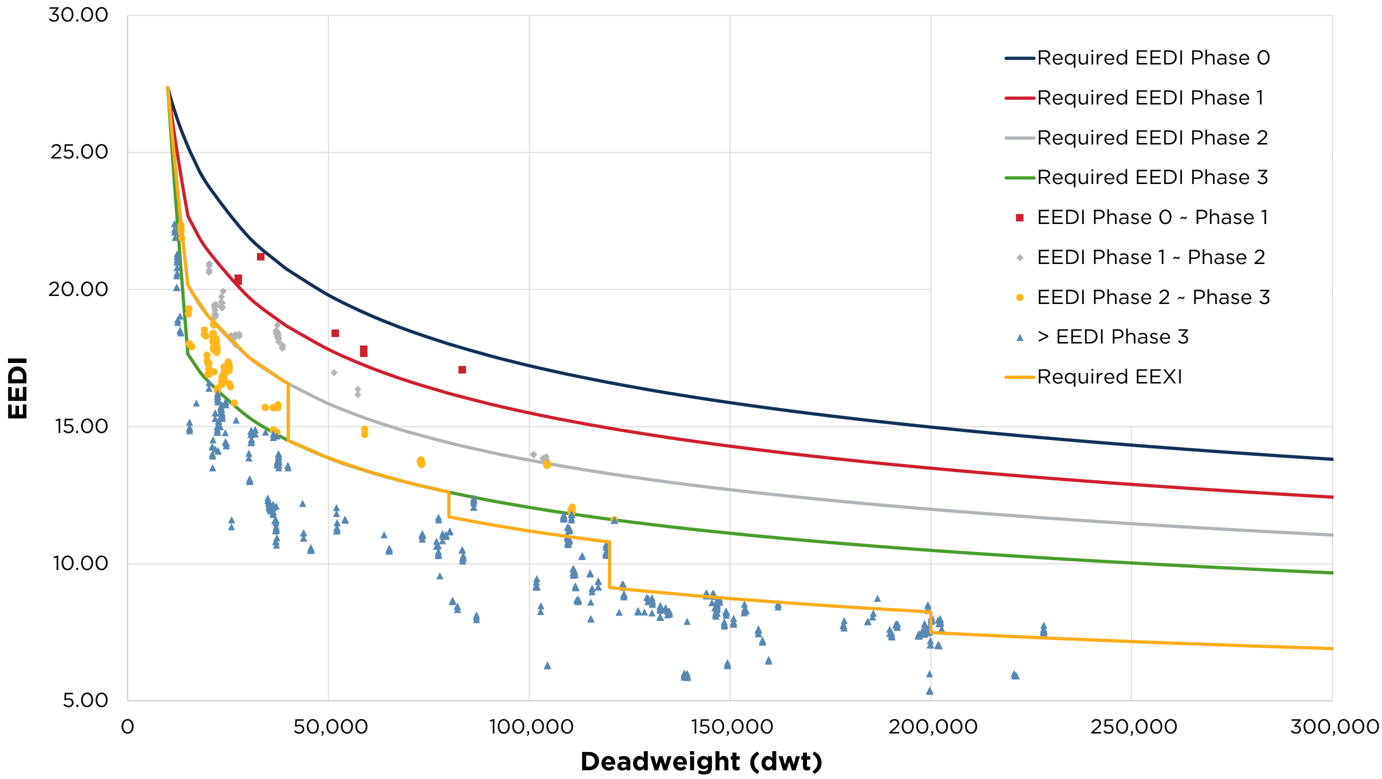


Figure 9: EEDI compliance levels for containerships larger than 10,000 dwt.

ATTAINED EEDI AVAILABLE — 856	Vessels #	Total dwt
EEDI Phase 0 ~ Phase 1	15	747,335
	1.8%	1.0%
EEDI Phase 1 ~ Phase 2	71	2,729,936
	8.3%	3.6%
EEDI Phase 2 ~ Phase 3	130	5,171,430
	15.2%	6.9%
> EEDI Phase 3	640	66,596,871
	74.8%	88.5%

Figure 10 shows the expected EEXI compliance of the 856 containerships that have attained EEDI values, based on the reduction factors approved by MEPC 75. 649 of these vessels are expected to comply, while 207 are not. These 649 containerships correspond to 13.8 percent of the global fleet considered.

	Vessels #	Total dwt
Non-EEXI Compliant	207	19,301,056
EEXI Compliant	649	55,944,516

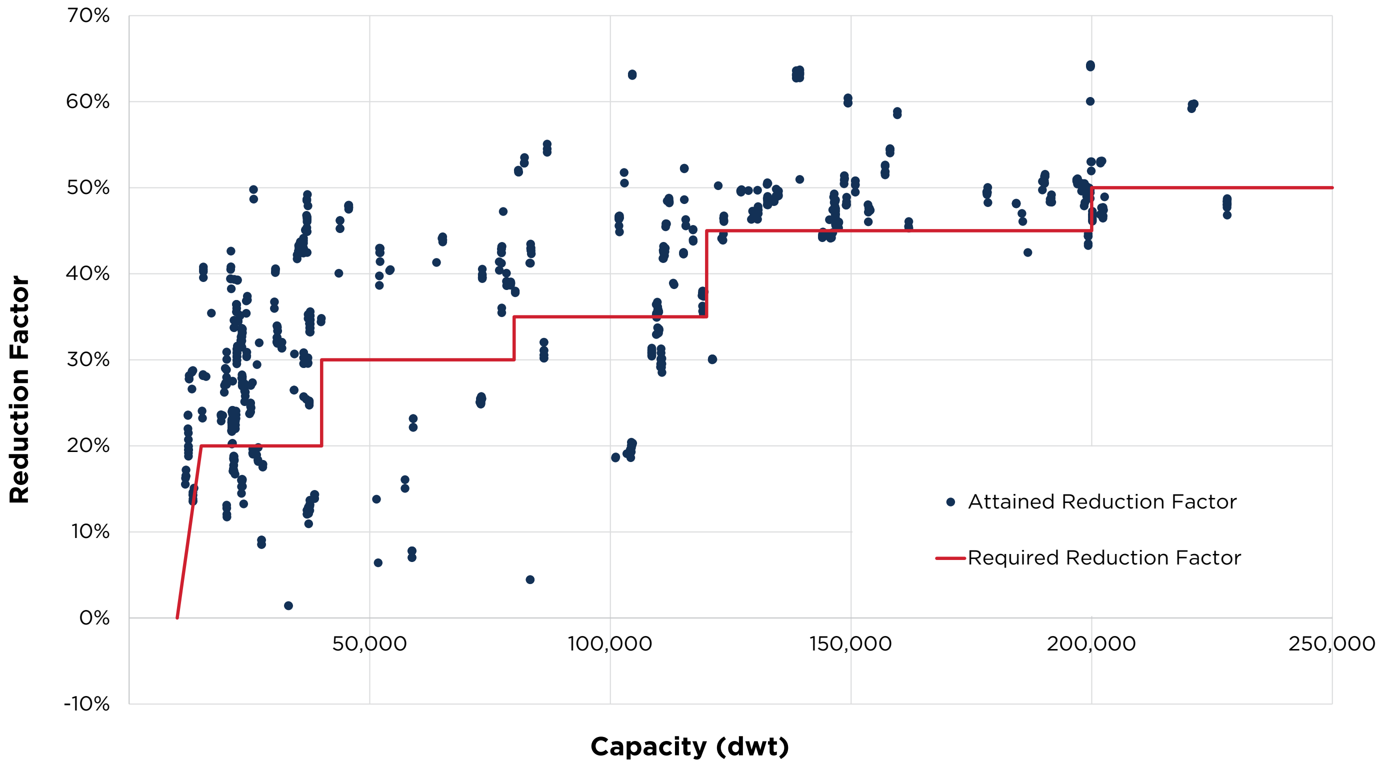


Figure 10: EEXI compliance levels for containerships larger than 10,000 dwt with attained EEDI values.

The global containership fleet has shown good performance and efficiency, with the majority of ships above 80,000 dwt having complied with EEDI Phase III. However, the smaller dwt segments do not perform as well, with less than 100 percent compliance with Phase II and even Phase I. Based on analysis of the global fleet data, the IMO has adjusted the required reduction rates for the lower twenty-foot equivalent unit (TEU) capacities accordingly. It should be noted that common energy saving measures adopted by containerships are waste hear recovery systems and shaft generators. Lately, hybrid options and fully battery-electric propulsion for small scale applications have been explored.

5 | LIFE-CYCLE ANALYSIS OF ALTERNATIVE FUELS

Alternative fuels will play a dominant role in the decarbonization of the marine and offshore sectors and are expected to yield the most benefits for reducing greenhouse gas (GHG) emissions. The current regulatory framework is focused on vessel emissions (tank-to-wake) rather than the overall life-cycle emissions of a given fuel (well-to-wake). However, it is recognized throughout the industry that the life-cycle carbon footprint of fuels provides the most complete description of their environmental impact.

This section presents comparative analyses of some of the alternative marine fuels and their life-cycle emissions, with the objective of offering a holistic view of the challenges associated with adopting low- and zero-carbon fuels.

The fuels include:

- Liquefied natural gas (LNG)
- Liquefied petroleum gas (LPG)
- Methanol (CH_3OH)
- Liquefied hydrogen (LH_2)
- Ammonia (NH_3)

The adoption of alternative fuels will require changes to ship designs in order to accommodate storage tanks, as well as fuel-containment and gas-supply systems. The table below offers some key indicators to compare the fuels and to understand some of the design implications. For comparison purposes, very low sulfur fuel oil (VLSFO) is used as the reference.

Fuel Type	LHV (MJ/kg)	Density (kg/m³)	Storage Volume Ratio	Vessel Specific GHG Emissions (g/kWh)[1]
VLSFO (ref)	41,600	944	1.0	568 (ref)
LNG	50,000	420	1.9	Diesel Cycle: 424 (-25%) Otto Cycle: 492 (-13%)
LH_2	120,000	71	4.6	0 (-100 %)
NH_3	18,800	574	3.6	102 (-82%)
LPG	46,000	448	1.9	500 (-12%)
Methanol	19,900	796	2.5	533 (-6%)

Table 1: Summary of characteristics for fuels produced from hydrocarbons.

Lower Heating Value (LHV, MJ/kg) – Mass-based energy content of the fuel.

Density (kg/m³) – Defined at storage conditions, as it relates to tank-volume requirements.

Storage Volume Ratio – Defined as the product between the density and LHV referenced to VLSFO. For comparison purposes, it is assumed that all other variables to vessel performance, such as engine and propulsion-system efficiency, range, etc., are kept constant.

Vessel Specific GHG Emissions (g/kWh) – Defined as the GHG emissions from the vessel for each unit of energy used for propulsion. The GHG emissions include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and are expressed as equivalent CO_2 accounting for the 100-year Global Warming Potential (GWP) of CH_4 and N_2O. For LNG, GHG emissions are reported for Diesel-cycle and Otto-cycle engines, which generate different amounts of methane slip. The calculations were based on methane-slip values as reported in the fourth International Maritime Organization (IMO) Study: 0.2 g/kWh for Diesel-cycle engines and 2.5 g/kWh for Otto-cycle engines[2].

To assess the impact of fuel changes on storage requirements, it is important to understand the volume that the fuel will occupy on the vessel to satisfy the same energy needs. The storage volume ratio shown on Table 1 is calculated based on the LHV and density of each fuel.

The use of LNG and LPG requires about twice as much tank volume compared to VLSFO, while methanol requires 2.5 times larger tank volume. Ammonia requires 3.6 times higher tank volume than VLSFO, due to its lower energy content, while hydrogen requires 4.6 times higher tank volume due to it very low density.

The bigger tank requirements for the low- and zero-carbon fuels have implications for vessel designs, influencing the available cargo space and the cost of the vessel. Minimizing this impact will require the adoption of operational measures, such as changing some operating routes to gain access to ports where the bunkering fuels are available. The benefit of using low- and zero-carbon fuels is shown in the specific GHG emissions on Table 1.

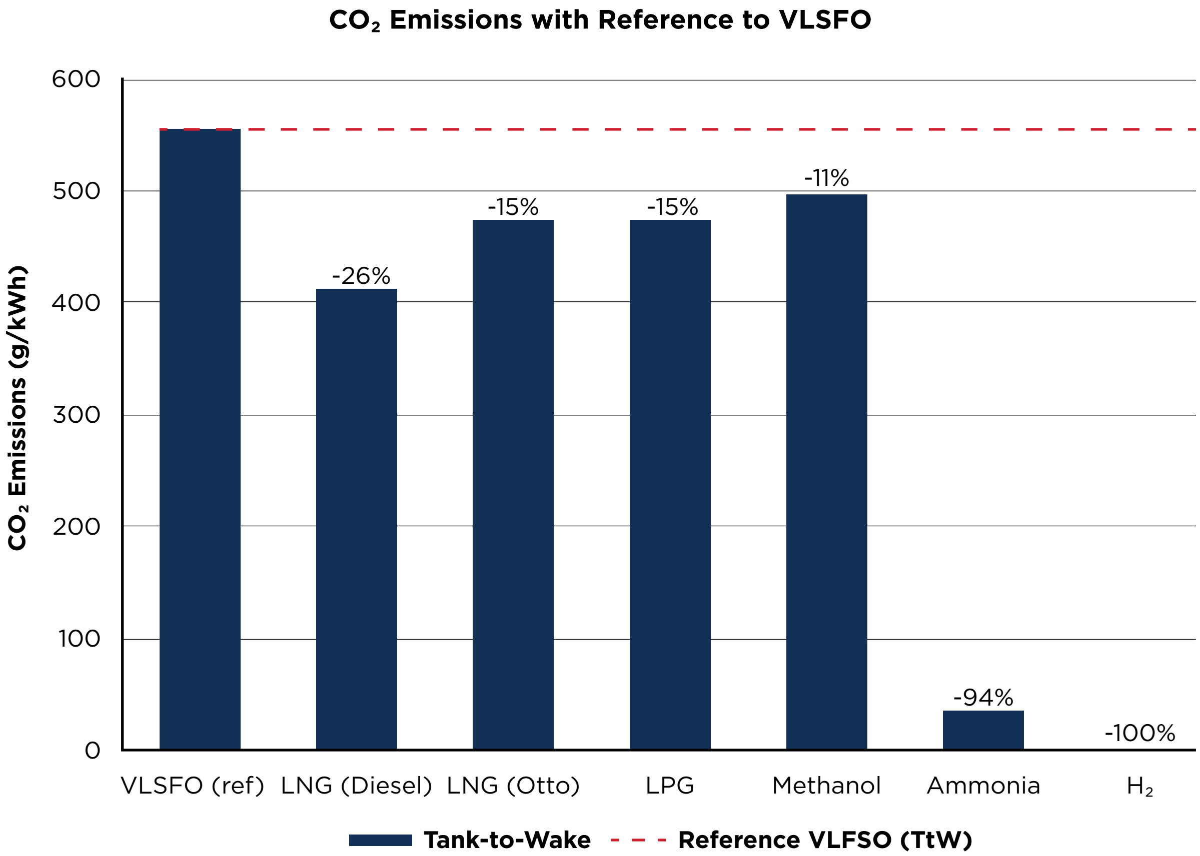


Figure 1: Tank-to-wake emissions of candidate marine fuels.

Using LNG, LPG and methanol can offer reductions of six to 25 percent compared to VLSFO. For LNG, Diesel-cycle engines offer lower GHG emissions than their Otto-cycle counterparts due to lower methane slip, despite the efficiency benefits of the latter. Ammonia can offer as much as an 82 percent reduction in GHG emissions compared to VLSFO, but there is a small contribution to CO_2 emissions from its pilot-oil injection system. Hydrogen can eliminate GHG emissions from the vessel, assuming that it is the only fuel used on board.

The specific GHG emissions shown on Table 1 reflect the tank-to-wake emissions generated from the vessel. However, a considerable amount of GHG emissions can be generated from the processes involved in the production and distribution of each fuel, or well-to-tank (WtT) emissions. The latter are quantified using a life cycle approach and presented in this section.

An accurate calculation of well-to-tank emissions needs to account for the source of each fuel. The majority of the fuels used currently are derived from fossil sources with varying levels of processing and refinement, whereas a small fraction of the fuels are produced from renewable sources with or without the contribution of renewable energy.

Naturally, the level of GHG emissions varies according to the fuel source, the cleaning and refining processes and the transportation methods. Based on these parameters, the industry has introduced a color-coding scheme to describe the different fuels.

- Gray – refers to the fuels produced from fossil sources without the use of renewable energy or emissions-control technologies.
- Green – refers to fuels produced from renewable energy, such as wind or solar.
- Blue – refers to fuels produced from fossil sources using emissions-control technologies, such as carbon capture and sequestration (CCS).
- Orange – refers to a blend of blue, gray or green fuels. Such blends can reduce the overall CO_2 emissions without excessive cost. In the following sections, a constant mix of 50 percent green and 50 percent gray is assumed for comparison purposes.

This color-coding scheme is expounded in Figures 2-4 that show the differences in the production and supply chains used for gray, green and blue fuels.

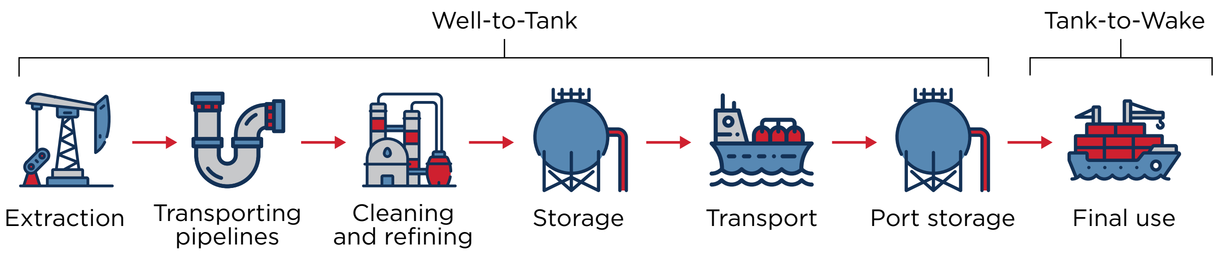


Figure 2: Life cycle of a conventional gray fuel.

Figure 2 illustrates the parts of the value chain accounted for in the well-to-tank and tank-to-wake emissions calculations for gray marine fuels. It represents standard cases of fuel produced from fossil sources using established cleaning, refining and transportation practices.

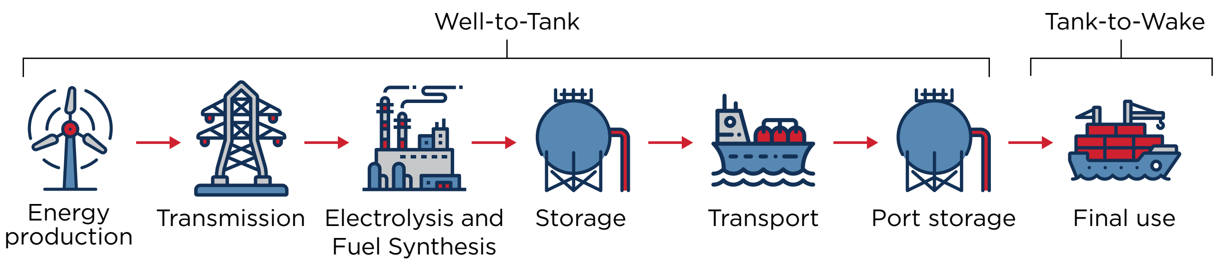


Figure 3: Life cycle of a green fuel.

Figure 3 shows the case of a green fuel and the production process which starts with electrolysis of water to extract hydrogen. The energy used for electrolysis is produced renewably, e.g. from wind power, solar power, hydropower, nuclear or a combination.

Once hydrogen is extracted from the water, it can be used for different purposes, e.g. it can be used as a fuel itself, or used with nitrogen to form ammonia, or utilize CO_2 to produce methane.

Naturally, the fuel that is produced dictates the requirement for storage, transportation and bunkering.

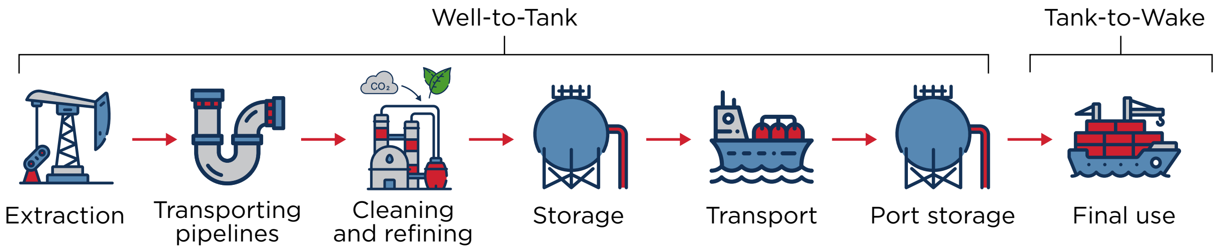
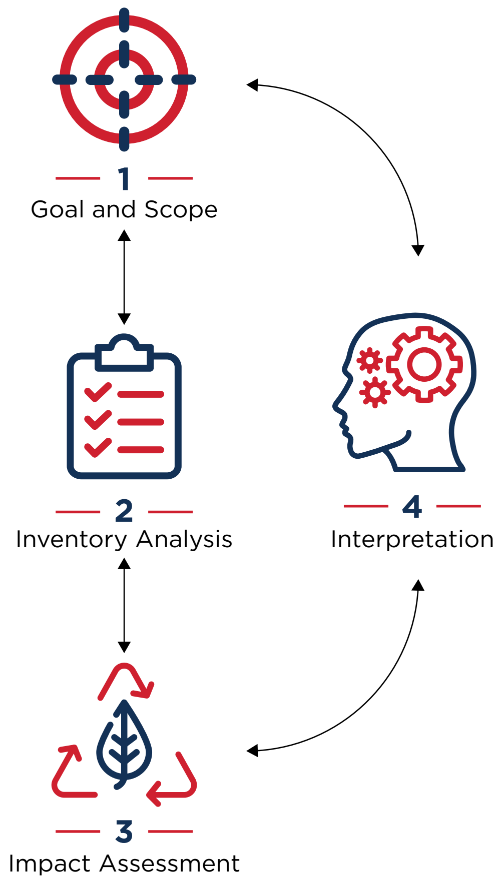


Figure 4: Life cycle of a blue fuel.

Figure 4 shows the case of a blue fuel, which is produced from fossil sources. But the cleaning and refining processes are augmented by emissions-control methods such as CCS to reduce its carbon footprint. The remaining steps in the chain are the same as those used in conventional gray fuels.

METHODOLOGY

The well-to-tank portion of the life cycle includes the emissions from the extraction, production, processing and refining, cleaning and the distribution of the fuel up to bunkering to a vessel. The calculations of the associated emissions were conducted based on the ISO 14040 standard, which is used on a wide range of applications. The ISO defines these four main phases which are used to perform the life cycle analysis:



1. **Goal and Scope Definition.** When performing a life-cycle analysis, the objectives of the analysis and the clear definition of the equipment, product, fuel or process under examination needs to be defined. Defining clear goals and scope ensures that the analysis is performed in a consistent manner, without including unnecessary elements or disregarding important ones.
2. **Inventory Analysis.** During this phase, focus is given to examining the input and outputs of each part of the production chain, or elements of a product.
3. **Impact Assessment.** In the impact assessment, the results of an inventory analysis are translated into values or conclusions. In this case, the impact assessment is done by converting all the emissions resulting from the different production steps into GWP, or grams of equivalent CO_2 for other emissions.
4. **Interpretation.** In this phase, the results obtained are analyzed and verified. The ISO 14040 series defines a set of procedures and checks that can be performed to verify that the conclusions are consistent with the data.

The ISO 14040 is supplemented by three other documents that detail different aspects of the life-cycle assessment. ISO 14041 covers the goals and scope definition, and life-cycle inventory; ISO 14042 covers the life-cycle impact assessment, and the ISO 14043 covers the interpretation methods. The calculation procedure is adaptive, meaning that the outcomes of one phase may require updates to others. For example, while performing the impact assessment, the analysis may show that more data is required hence the inventory analysis would need to be improved.

The methodology described in this section has been used by SINTEF to prepare a proposal for Marine Environmental Protection Committee (MEPC) 77 (late 2021) for calculating life-cycle emissions for marine fuels. This method proposes the use of conversion factors that are based on the life-cycle carbon footprint of each fuel, calculated as:

$$\text{Total WtW Emissions } (t\ CO_2eq) = \sum_{i}^{n\text{-engine}} \sum_{j}^{m\text{-fuel}} (M_{ij} * LCCF\_WtW\_fuel_{ij}) + \sum_{i}^{n} (E_i * LCCF\_electricity_i)$$

LCCF_WtW is the well-to-wake life-cycle carbon factor that accounts for the tank-to-wake (currently accounted for in IMO regulations) and the well-to-tank emissions; M_{ij} is the mass of fuel *j* consumed by engine *i*; E_i is the electric energy delivered to the ship at berth and $LCCF\_electricity_i$ is the life-cycle carbon factor for the electricity supply.

Based on the elements of the fuel life cycle, Figure 5 compares the tank-to-wake and well-to-tank CO_2 emissions of the different gray fuels. Again, VLSFO is used as the baseline for the comparison. The well-to-tank portion includes the emissions from the extraction, production, processing and refining, cleaning and distribution of the fuel, including bunkering to a vessel.

All calculations are done based on the ISO 14040 and 14064 standards for developing a GHG inventory for each process and verifying the results[3]. For the purposes of this comparison, gray hydrogen is assumed have been produced from processing natural gas, and that gray ammonia was subsequently produced by adding nitrogen. However, if hydrogen is intended to be used as the fuel, it is liquefied for storage.

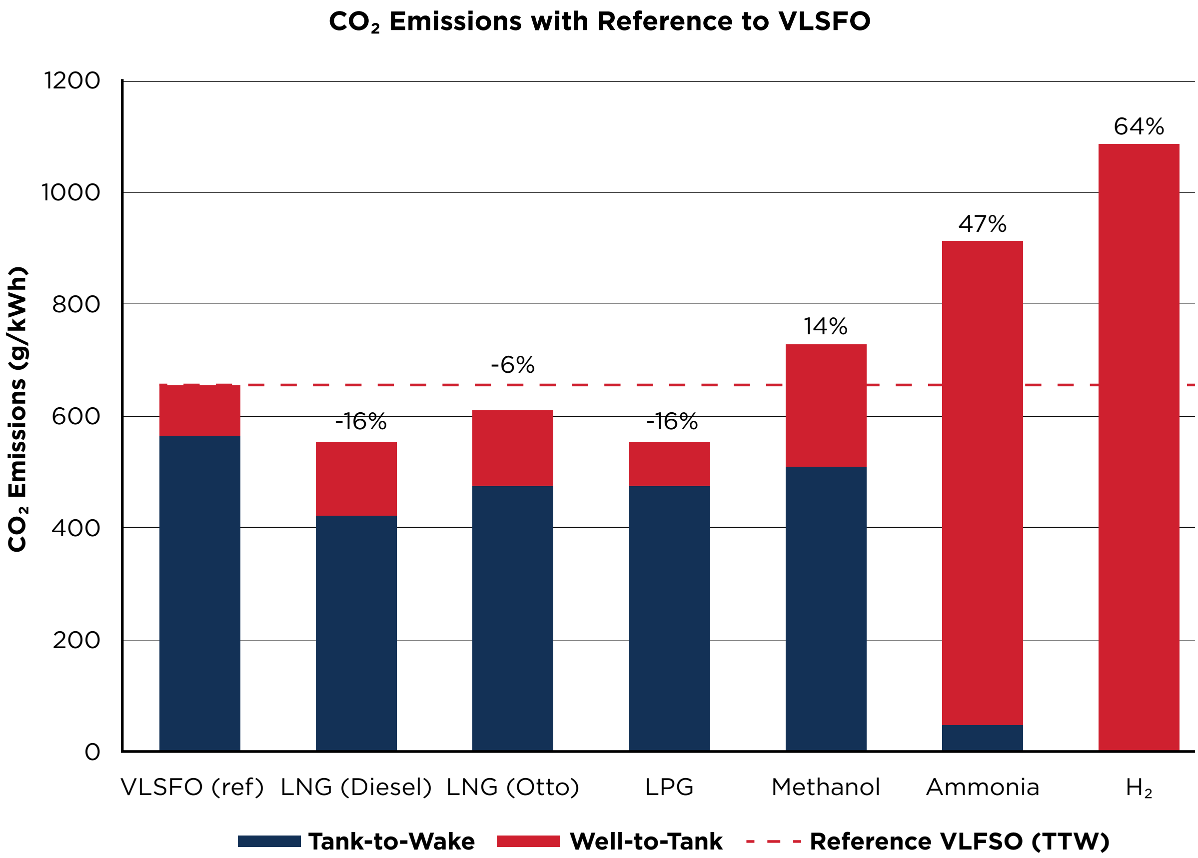


Figure 5: Life-cycle CO_2 emissions comparison between different fuels.

Figure 5 demonstrates the need to produce low- and zero-carbon fuels using renewable sources and energy, as well as the importance of regulating and accounting for the life-cycle emissions of each fuel. The following sections focus on the well-to-wake part of the emissions for each of fuel, and compare the production options.

LNG

LNG can be used as fuel in Diesel- and Otto-cycle engines, which differ in the amount of methane slip. The contribution of the emitted methane is accounted for using its 100-year GWP.

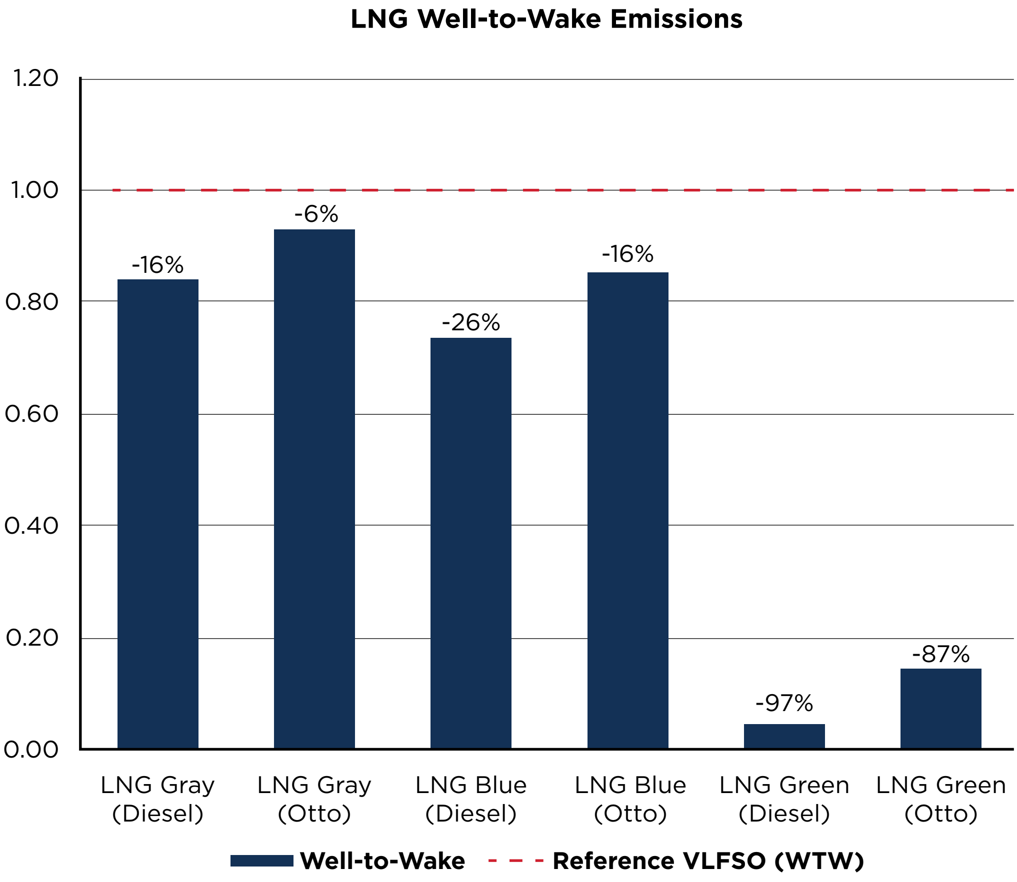


Figure 6: Normalized well-to-wake CO_2 emissions for gray and blue LNG.

Since LNG is directly sourced from fossil reserves, an effective way to reduce its life-cycle carbon footprint is to employ CCS technology to the most energy intensive processes during production, yielding blue LNG. Figure 6 shows a comparison of normalized well-to-wake emissions between gray and blue LNG when used in diesel and Otto-cycle engines. The values are normalized with the well-to-wake emissions of VLSFO for comparison. It is assumed that the application of CCS can offer a 50 percent CO_2 reduction on the LNG production side, which reduces the life-cycle emissions by 26 percent compared to VLSFO in the Diesel-cycle case, and by 16 percent in the Otto-cycle case. These reductions can have a significant impact when assessed over the lifespan of a vessel, but they need to be weighed against the economic proposition of installing and operating CCS systems at fuel-production plants.

CO_2 can be removed either from the exhaust or flue gas of power generation systems or directly from the atmosphere; the latter is often referred to as "direct air capture". Both technologies are based on the same fundamental principles but removing CO_2 from the exhaust or flue gas requires less energy because of its higher CO_2 concentration compared to air. The separation of CO_2 from any stream requires two steps, capture and desorption/regeneration. During capture, the CO_2 is absorbed into a solid or liquid by contacting the CO_2 source with the absorber. In the desorption/regeneration step, CO_2 is selectively desorbed from the absorber, resulting in a flow of pure CO_2 gas, and the original capture absorber is regenerated for further use[4]. Over the last 20 years many research groups have explored CCS technologies in order to increase the efficiency of the capture, as well as to reduce the volume and cost of the systems.

Although this comparison is drawn between gray and blue LNG, it is technically possible to produce green LNG in the form of e-methane or bio-methane, as Figure 6 shows, which has dramatically lower life-cycle carbon footprint. However, the energy required for its production is very high and can only be economically attractive if the cost of renewable electricity used for production is low enough. Based on the global average cost of renewable electricity from wind farms ($0.053/kWh), an electrolysis efficiency of 60 percent, and production cost of $4/kWh, the price of green LNG can be estimated at $1,782/ton, compared to the $240/ton for the gray LNG available at multiple ports worldwide. This price differential is enough to render green LNG less attractive than green ammonia, even without accounting for the tank-to-wake emissions benefit of ammonia. Nevertheless, LNG is seen as an important transition fuel for the marine and offshore sectors, and it has been instrumental in the effort to develop the knowledge, regulations and safety protocols required to handle gaseous and low-flashpoint fuels.

AMMONIA

Ammonia can be produced either by fossil sources such as natural gas or renewably from hydrogen through electrolysis of water. Production from fossil sources is highly energy intensive and thus results in a high carbon footprint, which conceptually defeats the purpose of using a zero-carbon fuel. However, its production from water using renewable energy has the potential to practically eliminate carbon emissions for ammonia on a life-cycle basis.

Figure 7 shows a comparison of normalized well-to-wake emissions for gray, orange and green ammonia normalized against the well-to-wake emissions of VLSFO. Production of gray ammonia is estimated to have 48 percent higher life-cycle carbon emissions than VLSFO. For orange ammonia, assumed to be a 50/50 percent blend of gray and green, the life-cycle carbon emissions are 17 percent lower than those of VLSFO. Blue ammonia has life-cycle carbon emissions 57 percent lower than VLSFO. Finally, green ammonia is estimated to have 83 percent lower life-cycle carbon emissions than VLSFO.

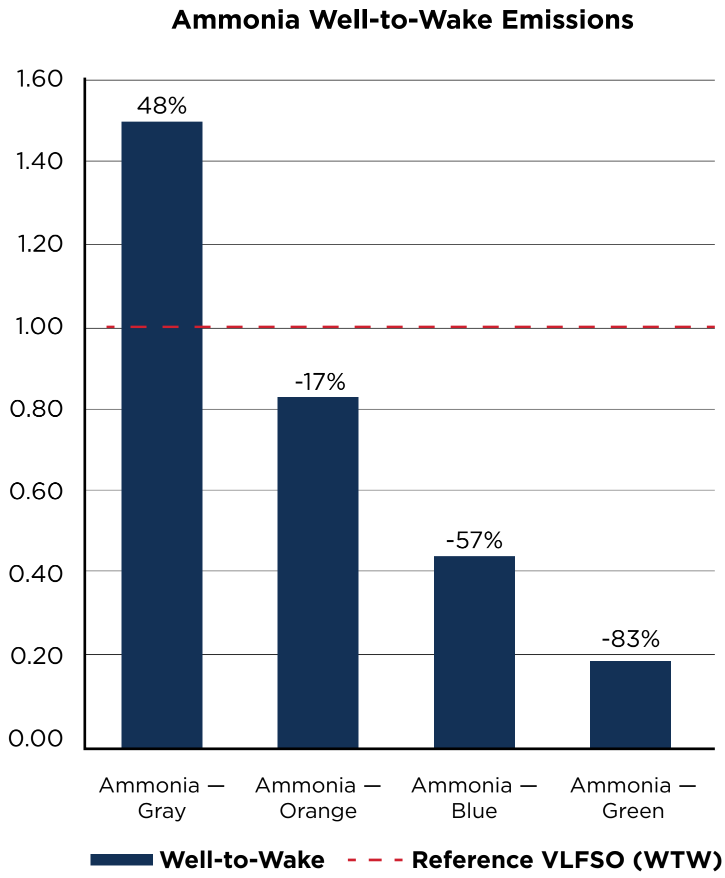


Figure 7: Normalized well-to-wake CO_2 emissions comparison for ammonia.

Any tank-to-wake emissions for ammonia result from the need to use pilot fuel for combustion and the slip of N_2O, which is a potent GHG. The contribution for pilot fuels account for 3.5 percent of the well-to-wake emissions of gray ammonia, while the N_2O is estimated to account for 10 percent. The latter is based on assuming the same amount of N_2O slip as for methane slip in an Otto-cycle engine for simplicity.

The current regulatory framework accounts for only the tank-to-wake emissions, thus the use of gray ammonia would enable an important reduction of the carbon intensity of marine vessels. However, from a life-cycle perspective, it is important to develop technologies that support the production of green ammonia at a larger scale, as it is a promising pathway towards carbon neutrality.

Currently, the price of gray ammonia is estimated to be $230/ton[5]. Using the same assumptions as for green LNG, the price of green ammonia would be $670/ton, or about three times more expensive than gray ammonia. If a blend of 50 percent gray and 50 percent green (orange) is used, the price can be reduced to $460/ton, making ammonia cost competitive against VLSFO, which is offered currently at an average of $450/ton at ports around the world. The orange ammonia blend can also reduce the life-cycle carbon emissions by 28 percent compared to VLSFO, which makes it an attractive option from environmental and economic perspectives.

Recent developments support the adoption of ammonia as a viable marine fuel. In the U.S., Monolith Materials announced a plant to produce up to 275,000 tons of ammonia by using methane pyrolysis powered by green renewable energy. Ørsted and Yara also announced plans to produce 75,000 tons of green ammonia per year using Ørsted's offshore renewable energy production. Additionally, Saudi Aramco announced in 2020 the first shipment of blue ammonia which is produced by re-injecting CO_2 emissions generated during the production process into the wells for enhanced oil recovery.

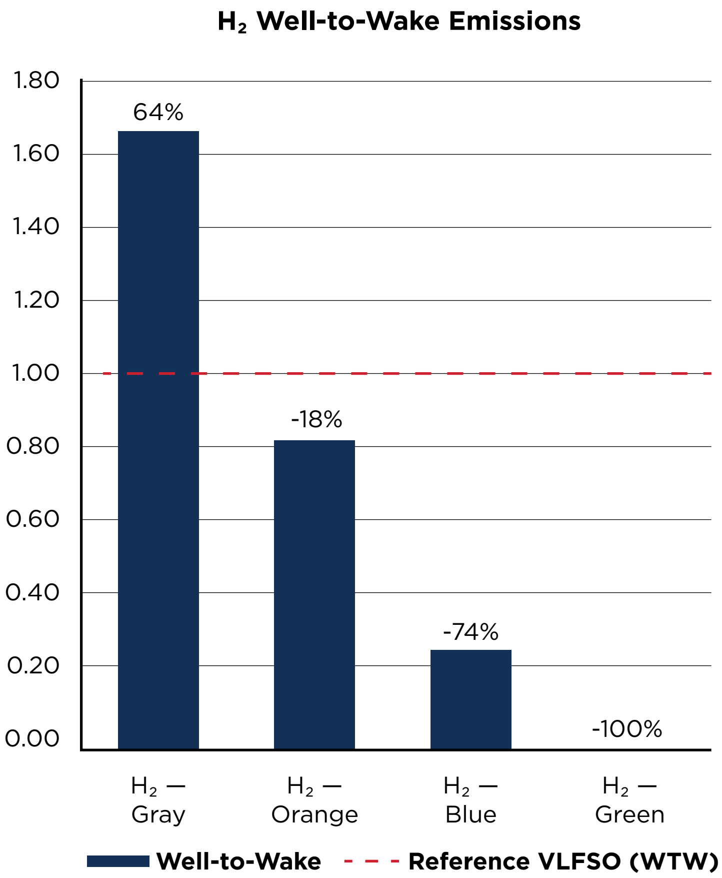


Figure 8: Normalized well-to-wake CO_2 emissions comparison for hydrogen.

HYDROGEN

Similar to ammonia, the vast majority of hydrogen production is currently sourced from natural gas and coal. However, there are multiple initiatives around the world that aim to scale up production of hydrogen from electrolysis using renewable energy.

Figure 8 offers a comparison of normalized well-to-wake emissions for gray, orange, blue and green hydrogen, normalized against the well-to-wake emissions of VLSFO.

Gray hydrogen is estimated to have 64 percent higher well-to-tank carbon emissions than VLSFO, with a large fraction of that resulting from the high amounts of energy required for liquefaction and storage. However, applying CCS during production can result in a dramatic decrease of the well-to-wake emissions, to 74 percent lower than VLSFO.

Green hydrogen can achieve a 100 percent reduction in well-to-wake emissions and essentially offer a zero-carbon life cycle. Nevertheless, orange hydrogen (assuming a 50/50 blend of gray and green) can be used as a transitional fuel until the production of green hydrogen reaches the economies of scale that would make it commercially attractive. Current prices for green hydrogen can range from $2,000 to $6,000/ton, depending on the renewable electricity mix in its production.

METHANOL

Methanol can be produced from hydrogen and CO_2 via the methanol synthesis process. This capability enables the production of green methanol where the hydrogen is sourced from electrolysis of water and the CO_2 is captured from the atmosphere using CCS systems. Therefore, on a life-cycle basis, green methanol has the potential to remove CO_2 from the atmosphere and thus offset part of the emissions generated from its combustion onboard.

The quantity of CO_2 that can be captured and used for methanol production can vary. A pilot plant in Germany produced one ton of methanol using 1.5 tons of CO_2[6]. Other sources provide estimates of over three tons of CO_2 captured per ton of produced methanol[7]. For simplicity, the first one is used to derive the blue methanol values, where the 1.5 tons of CO_2 equivalent are removed from the well-to-tank portion of the gray fuel. For green methanol, which can almost achieve carbon neutrality, as shown in Figure 9, it was assumed that the only emissions remaining are those related to gas slip during the burning process and emissions from the combustion of pilot fuel. Blue methanol can still enable a 27 percent reduction in well-to-wake carbon emissions compared to VLSFO.

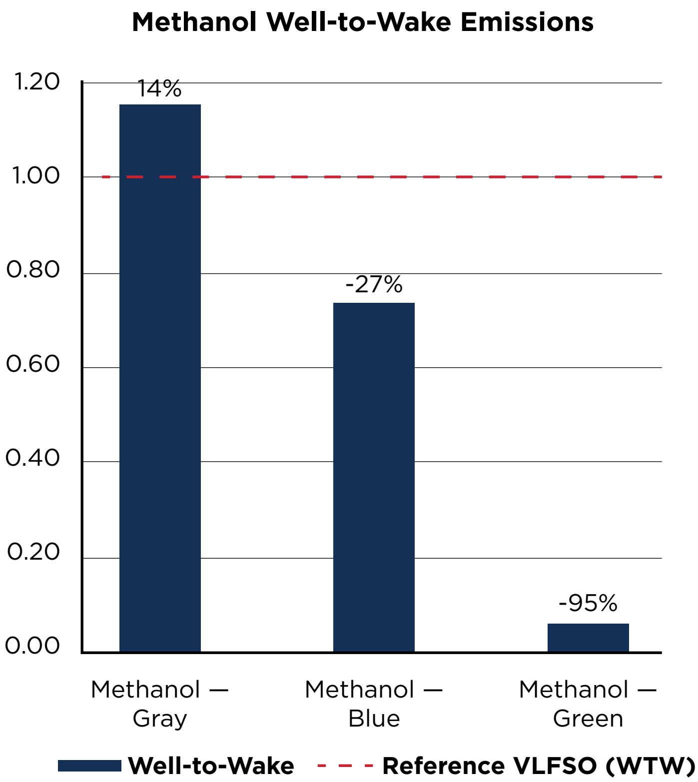


Figure 9: Normalized well-to-wake CO_2 emissions comparisons for methanol.

However, carbon neutrality for methanol is highly dependent on the deployment of technologies that capture a sufficient amount of carbon during its production.

Based on the current market prices, gray methanol is estimated at $460/ton at the Port of Rotterdam[8]. Using the same assumptions as for green LNG, the price of green methanol can be estimated at $709/ton, or less than twice the cost of gray methanol. If a blend of 50 percent gray and 50 percent green is used, the price can be reduced to $585/ton, which brings the price of orange methanol to a competitive level against VLSFO while reducing life-cycle carbon emissions.

BIOFUELS

The biofuels currently available can be produced from a wide range of feedstocks, such as animal fats or waste, forestry or agricultural waste, food crops and vegetable oils (Figure 10). Naturally, the source and processing of each different feedstock will result in different carbon footprint on a life-cycle basis. Therefore, biofuels cannot be strictly described by the color scheme discussed earlier.

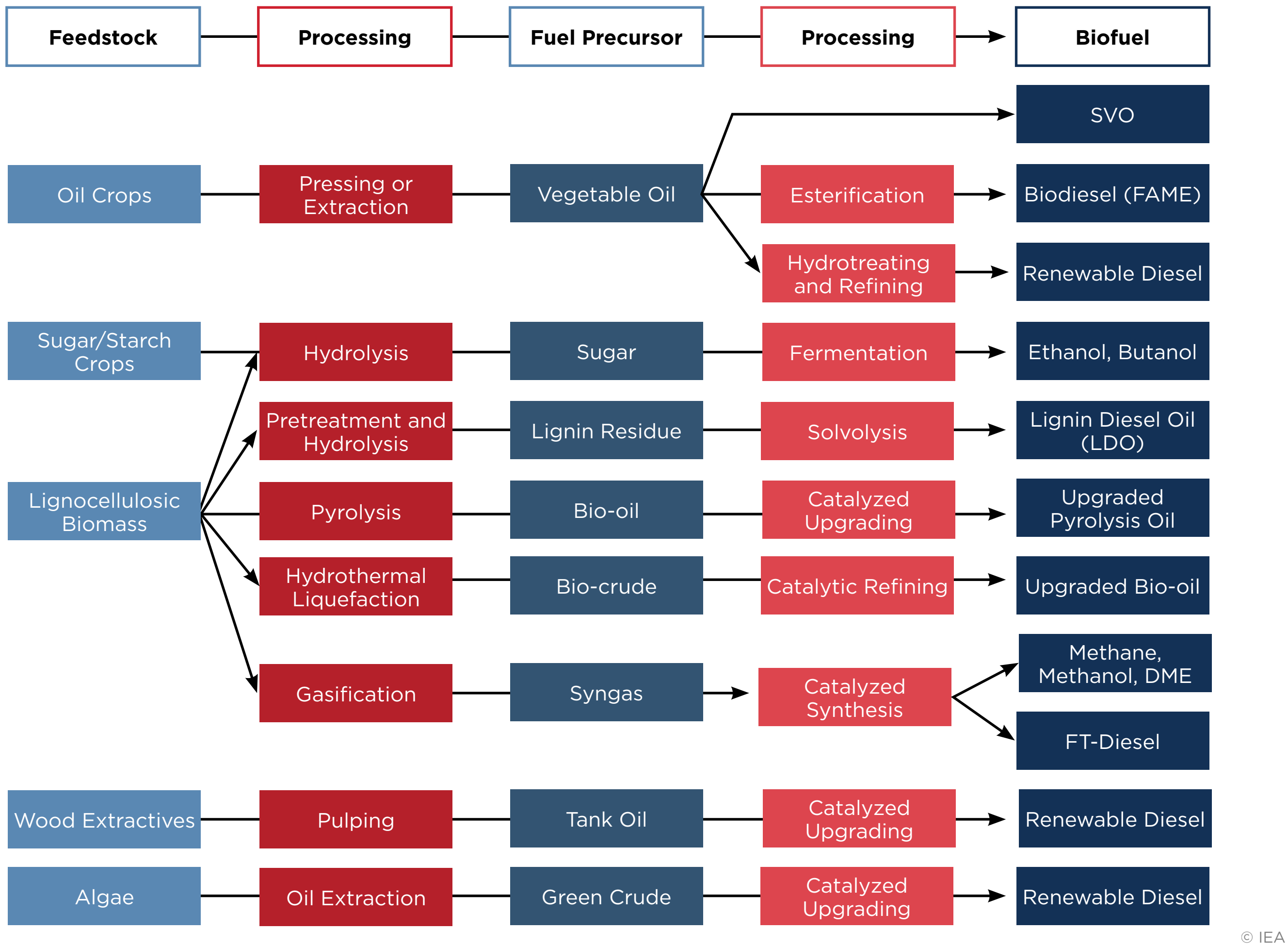


Figure 10: Potential feedstocks and production pathways for biofuels.

Figure 11 shows the well-to-tank carbon emissions of biodiesel produced from different feedstocks. The tank-to-wake emissions of biodiesel or renewable diesel are estimated to be equal to those of VLSFO since the carbon content of these fuels is similar. The amount of well-to-tank emissions generated by biofuel production can vary based on whether the production starts from crops or residues, the location of the biomass, potential deforestation for land use, as well as the efficiency of the production processes which varies from plant to plant. These factors are captured within a range between a low-emissions case (low estimate) and high-emissions case (high estimate).

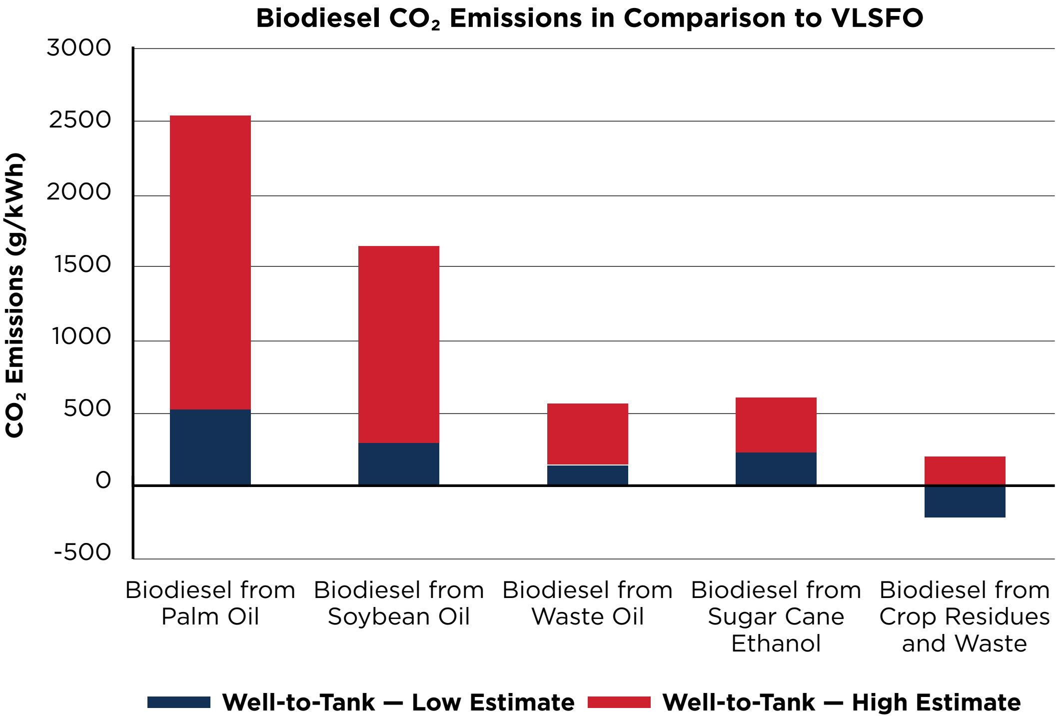


Figure 11: Well-to-tank CO_2 emissions of biodiesel sources from different feedstocks .

The calculation of well-to-tank emissions for different biofuels can vary depending on the production processes included in the calculations and the implicit assumptions. Table 2 shows a summary of well-to-wake CO_2 emissions (in gCO_2eq/MJ) of different biofuels based on different models, as presented by the IEA's recent BioEnergy[9] report.

Also, a recent study by the International Council on Clean Transportation (ICCT) examined the life-cycle carbon footprints of alternative marine fuels[10]. Figure 11 shows life-cycle GHG emissions for alternative marine liquid fuels based on different feedstocks. This comparison showed that second-generation biofuels made from waste and lignocellulosic biomass offer the most well-to-wake GHG reductions, ranging from 70 to 100 percent lower than marine gas oil (MGO). That is due to their small impact on land use, large biogenic carbon uptake, and modest use of fossil fuel energy for feedstock conversion. In contrast, first-generation biofuels produced from soy oil and palm oil generate enough life-cycle carbon emissions to be comparable to MGO.

	BIOGRACE	GHGENIUS	GREET	NEW EC	VSB	Δ GHG EMISSIONS
Soybean FAME	56.94	16.90	34.47	42.27	25.03	40.04
Soybean HVO/HEFA	50.63	48.58	47.57	41.94	25.46	25.17
Palm FAME	65.96	78.21	24.15	57.97	30.78	54.06
Palm FAME	36.94	-	-	42.23	-	5.29
Palm HVO/HEFA	58.90	99.06	37.54	55.99	31.57	67.49
Palm HVO/HEFA	28.97	-	-	39.63	-	10.66
UCO FAME	21.27	2.99	-	17.28	4.86	18.28
UCO HEFA	11.64	-14.85	-	10.71	4.15	26.49

Table 2: Summary of well-to-wake CO_2 emissions (in gCO_2eq/MJ) of different biofuels based on different modeling schemes (IEA Bioenergy, Task 39: December 2018). Acronyms defined on page 76.

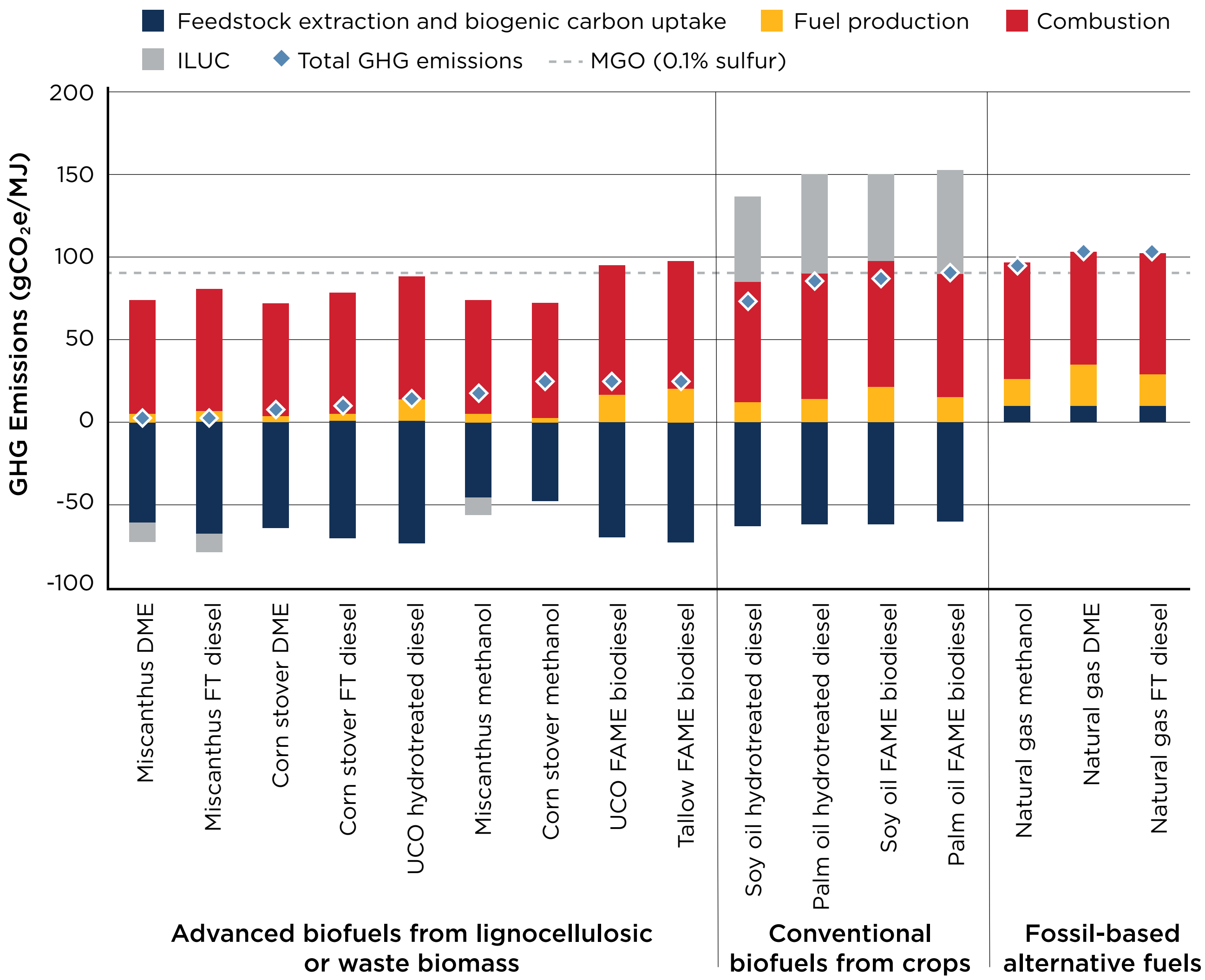


Figure 12: Life-cycle GHG emissions (100-year GWP) of alternative liquid marine fuels and feedstocks analyzed, by life cycle stage (ICCT, 2020).

GREEN FUELS AND GLOBAL ENERGY NEEDS

The previous sections presented a quantitative view of the life cycle carbon emissions of green fuels, which for methanol, ammonia and hydrogen can be very beneficial for reducing shipping's carbon footprint. This section attempts to provide a view of the magnitude of renewable energy required to produce these fuels.

In 2019, the global production of wind power was reported to be 651 GW[11], while solar power production was 586 GW[12]. That same year, the consumption of HFO, MGO and LNG from shipping was 238 Mt of HFO equivalent[13], which corresponds to 2,749 GW of power. In order to replace HFO, MGO and LNG with green fuels industry would need the same amount of energy. Assuming that green fuels can be produced from renewable energy at 60 percent efficiency, the required renewable power production would be 4,582 GW or an amount approximately equal to seven times the wind power produced in 2019, and eight times the solar power produced that year.

For comparison purposes, it is worth considering that the largest wind turbines currently in service produce approximately 15 MW each. Therefore, the power required to produce green fuels for the entire global fleet would take 305,000 of the largest wind turbines, or about 13 times the number of wind turbines (of all sizes, 22,893) that were operating in 2019.

The above numbers indicate the magnitude of the effort required to produce green fuels for the global fleet. However, this task becomes more challenging if those green fuels also have to serve the purposes of other industries as well, such as the stationary power generation, automotive and aviation industries. Addressing this challenge will require an industry-wide coordinated effort but is expected to yield significant benefits for multiple industry sectors.

6 LOW-CARBON TRANSITION DESIGNS

INTRODUCTION

This section examines the potential technical requirements and operational trade-offs that may be necessary in future versions/conversions of existing ship models. The results presented in this study are purely based on technical merit and do not constitute recommendations for new construction or equipment retrofits.

Broadly, this analysis recognizes that modern engine developments enable the adoption of alternative fuels in a much simpler manner than the recent past. It also suggests that the latest electronically-controlled, two-stroke, high-pressure diesel engines are simpler than four-stroke engines to convert to using alternative fuels without loss of power output.

From the safety and commercial points of view, a transition to alternative fuels can be made much more effective and attractive if it is planned at the design stage for new ships; in particular, fuel tanks should be specified based on the original and transition fuel types.

The analysis also suggests that capital expenditures (capex) involved in the transition to alternative fuels appear to be largely independent of the type of fuel selected.

This study takes current fossil-fuel burning tanker, bulker and containerships and conceptualizes their conversion to designs capable of using lower carbon fuels. Three baseline designs are included: an aframax tanker, a chinamax very large ore carrier (VLOC) and a feeder containership.

The base ship designs could be ordered and built today to run on fossil fuels, very low sulfur fuel oil (VLSFO) or liquefied natural gas (LNG), while the lower-carbon designs are likely to be conversions undertaken in the near future.

The general functional requirements for the existing ships in these categories are:

	TANKER	ORE CARRIER	FEEDER CONTAINERSHIP
Size Category	“Aframax”	“Chinamax”	“N. Sea/Baltic Service”
Cargo Payload	100,000 tons at design draft	400,000 tons at scantling draft	≈ 1,800 TEU
Length	250 m	≈ 360 m	≈ 180 m
Beam	≈ 44 m	65 m	≈ 27 m
Endurance	18,000 nautical miles (nm) on heavy fuel oil (HFO)	36,000 nm	12,000 nm
Service Speed at Design Draft	13 knots	14.5 knots	18.5 knots

These performance requirements are generally consistent with typical ships currently being designed and built, but minor speed adjustments have been made to ensure that the base designs meet requirements for Energy Efficiency Design Index (EEDI) Phase II (2020 to 2025). For the low-carbon designs, the service-speed requirements have been relaxed to reflect the anticipated higher capital and fuel costs for low-carbon fueled fleets. To reflect the lower energy density of low-carbon fuels, the endurance has been reduced to about half of the current standard.

For the tanker, the current 18,000 nautical miles (nm) range on VLSFO reflects sufficient fuel and margin for about one and a half round-trip voyages between the Middle East and northern China. The proposed endurance of 9,000 nm for vessels using LNG and LNG/Hydrogen mix reflects about a 50 percent margin over the longest Middle East to China one-way voyage.

For the VLOC, the current 36,000 nm range reflects sufficient fuel and margin for about one and a half round-trip voyages across the longest distance between Brazil and northern China. The proposed endurance of 18,000 nm reflects fuel and margin for a one-way voyage on the Brazil-to-northern-China route.

For the container feeder, the current 12,000 nm range is typical for modern feeders in northern Europe and South Asia, minimizing the need to stop for refueling. The proposed endurance of 4,000 nm for the methanol-fueled conversion reflects a reasonable compromise for a north Europe feeder router between the energy density of methanol and the minimization of the conversion costs.

SCOPE OF STUDY

The intended scope of the study is to examine several options for transitioning the current fossil-fuel burning designs to the lower carbon fuel designs of the future. The base designs either use VLSFO, or LNG, or both, depending on the suitability for conversion.

Chinamax Bulk Carrier – The base ship burns VLSFO, is LNG ready, and has reserved space for a 13,000 cubic meters (m^3) prismatic fuel tank. This represents a pre-2020 configuration designed to meet EEDI Phase I. It would need a small (five percent) de-rating of the main engine to meet EEDI Phase II, thus reducing the design speed to 14.2 knots from 14.5 knots. A second dual-fuel (DF) base design has been added with the LNG tanks and fuel-handling system installed, which meets EEDI Phase II at the 14.5 knot design speed.

Aframax Tanker – Many aframax tanker designs have difficulty meeting EEDI Phase II requirements while burning VLSFO without a significant (≈10 percent) de-rating in main engine power. Most current designs are delivered as dual VLSFO/LNG fueled, or at least "LNG ready". A dual-fueled LNG ship with LNG deck tanks has been selected as the base ship, comfortably meeting EEDI Phase II.

Feeder Containership – The base ship offers a design speed of 18.5 knots burning VLSFO in a two-stroke, direct-connected diesel engine that meets EEDI Phase II.

In addition to the baseline designs, this study also evaluates the following low-carbon transition designs.

Chinamax Bulk Carrier – Transition from base design to LNG and ammonia.

Aframax Tanker – Transition from dual-fuel VLSFO/LNG to LNG with 20 percent liquid hydrogen (LH_2) by weight.

Feeder Containership – Transition from VLSFO to methanol.

The baseline ships are developed based on conventional technology and burn VLSFO and/or LNG. For the transition designs, the current state-of-the-art is extrapolated to 2030 conversions, based on discussions with various equipment vendors.

DESIGN BASIS

FUEL CHARACTERISTICS AND STORAGE

VLSFO – This fuel is currently being used by many vessels of the global fleet and complies with the latest regulations on sulfur oxide (SO_x) emissions (0.50 percent) without using a scrubber. It is stored at ambient temperature and pressure in standard, single-wall tanks that are separated from the ship's hull by cofferdams

VLSFO	
Specific Gravity (-)	0.980
Volumetric Energy Density (MJ/l)	39.4
Lower Heating Value (MJ/kg)	40.2

VLSFO has the second highest CO_2 emission coefficient after marine gas oil (MGO), according to International Convention for the Prevention of Pollution from Ships (MARPOL), with 3.114 million tons (Mt) CO_2/Mt fuel. It is injected as a liquid in the cylinders and often needs preheating to reduce its viscosity.

MGO – Marine gas oil is a common marine fuel that consists exclusively of distillates. It is similar to diesel fuel but has higher density. Unlike heavy fuel oil (HFO), MGO does not have to be heated during storage. MGO has sulfur content below 0.10 percent, suitable for use in an Emissions Control Areas.

LNG	
Specific Gravity (-)	0.450
Volumetric Energy Density (MJ/l)	21.6
Lower Heating Value (MJ/kg)	48.0

LNG (CH_4) – Liquefied natural gas consists primarily of methane and is typically carried in insulated cryogenic tanks as a liquid just below its boiling point at -161° C and atmospheric pressure.

The use of LNG as a fuel is regulated by the International Code of Safety for Ships Using Gases or Other Low Flashpoint Fuels (IGF Code) and it is usually carried in membrane, prismatic or independent Type C tanks.

LNG's CO_2 emission coefficient is 12 percent lower than VLSFO's, according to MARPOL, at 2.750 Mt CO_2/Mt fuel. Reliquefaction plants are normally not needed when LNG is used as fuel, if the boil-off rate (BOR) is lower than the ship's power requirements.

In fact, in most cases, LNG is forced to vaporize in the fuel gas supply system (FGSS) at a significantly higher rate than the natural forced BOR. Notable exceptions are ships that might spend significant periods at anchor or those that are moored with low auxiliary-power requirements. In these cases, a reliquefaction plant might be needed to keep the pressure in the fuel tank at reasonable levels, while containing the boil-off gas (BOG).

Alternatively, vacuum-insulated C-tanks can be used, which can sustain up to 10 bar of pressure and offer very low BOR (0.05 percent/day), without the need for an expensive reliquefaction plant.

An alternative to reliquefaction plants that reduces capex but increases operational expenditures (opex) are gas combustion units (GCU), which can be attained at a lower price and offer lower electric power consumption. However, they do not represent an efficient use of LNG and are net CO_2 producers.

LPG – Liquefied petroleum gas is derived from fossil sources and is composed primarily of a mix of propane (C_3H_8) and butane (C_4H_{10}). It can be stored pressurized at 18 bar at ambient temperatures, or refrigerated at ambient pressure to -26.2° C, or semi-pressurized at five to eight bar and refrigerated to -10 to -20° C. It is typically carried pressurized or semi-pressurized in Type C tanks that do not have strict material requirements. However, as all low flashpoint gases, LPG requires double wall system piping with the outer pipe ventilated at 30 changes per hour, an inert gas (nitrogen) system, and venting provisions. The CO_2 emission coefficient for LPG is between that of LNG and VLSFO according to MARPOL at 3.030 Mt-CO_2/Mt-Fuel.

LPG	
Specific Gravity (-)	0.533
Volumetric Energy Density (MJ/l)	24.5
Lower Heating Value (MJ/kg)	46.0

METHANOL	
Specific Gravity (-)	0.792
Volumetric Energy Density (MJ/l)	15.8
Lower Heating Value (MJ/kg)	19.9

Methanol (CH_3OH) – This fuel is also known as methyl alcohol, or wood alcohol, and is primarily used as a precursor to the production of other chemicals. It can be stored at ambient temperatures and pressures, but it is considered toxic and flammable (flashpoint: 11° C).

Methanol storage requires tanks with cofferdams at widths of 800 mm, inert gas (to less than eight percent oxygen, typically with nitrogen) and gas detection. The material used for fuel tanks is normally stainless steel, or carbon steel with methanol-resistant coatings (either inorganic, zinc-silicate paint or cyclo-silicon epoxy and double-wall fuel system piping with outer pipes ventilated at 30 changes per hour (similar to LNG and LPG).

When produced conventionally, methanol's CO_2 emission coefficient is fairly low at 1.375 Mt CO_2/Mt fuel. If synthesized from recaptured CO_2 (e-methanol), the CO_2 emission coefficient has the potential to become negative. However, no plants produce methanol from recaptured CO_2 and e-methanol is not currently recognized in the EEDI guidelines as a separate, low emissions fuel.

AMMONIA	
Specific Gravity (-)	0.682
Volumetric Energy Density (MJ/l)	12.7
Lower Heating Value (MJ/kg)	18.6

Ammonia (NH_3) – Ammonia can be liquefied by cooling it to temperatures below -34° C. Alternatively, it can be stored in liquid form at ambient temperature, typically compressed to 18 bar. These fuel characteristics imply that NH_3 tanks can be either Type C or prismatic.

Ammonia also has a narrow flammable range (15 percent to 27 percent), so it is not considered to be a fire hazard. However, it is toxic and very reactive. For this reason, the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) has strict requirements for the materials that can be used to contain ammonia, as well as for the design features a plant must have to minimize the risk of exposing personnel.

Burning ammonia in air is very difficult in the absence of a catalyst due to the relatively low heat of combustion, high auto-ignition temperature, high heat of vaporization and narrow flammability range. These characteristics create the requirement for pilot fuel injection to initiate the combustion process in two-stroke diesel-cycle engines.

Based on the contribution of pilot fuel, the CO_2 emission coefficient is estimated at 0.098 Mt CO_2/Mt fuel, assuming the ammonia is produced from "green" hydrogen obtained from the electrolysis of water and using renewable energy
.

LNG/Hydrogen Mix (LNG+20%LH_2) – Methane/hydrogen mixes have been proposed for standard internal combustion engine (ICE) engines to further reduce LNG's CO_2 emission footprint, while keeping the required hydrogen storage volumes reasonably small for specific ship ranges.

For this reason, the energy content of the methane/hydrogen mix used in this study (20 percent hydrogen by weight) was calculated theoretically from the two gases to yield a lower heating value (LHV) of 62.4 MJ/kg. The CO_2 emission coefficient was assumed to be the same as LNG, or 2.750 Mt CO_2/Mt fuel.

However, liquid hydrogen and LNG have significantly different specific gravity values (0.071 and 0.450 respectively), indicating that even a small amount of hydrogen blending would result in much larger storage volume needed than for LNG.

Furthermore, the difference in density is more important for the two gases when stored at the same temperature and pressure, implying that they likely can only be mixed in the cylinders after injection, or immediately prior to injection, to avoid stratification and large fluctuations in the composition of the mixture.

Liquid hydrogen can be transported in cryogenic Type C tanks at -253° C. The materials used need to retain their strength characteristics at this extremely low temperature, but they also need to cope with hydrogen pitting and steel embrittlement. So far, some aluminum alloys and 316-stainless steel have been used. As a result, capex is significant. Hydrogen also presents challenges when in gas form; any leaks from the piping joints would be harder to contain than other gases. Given the extremely high flammability of hydrogen, adequate venting and dilution with inert gas are also required.

SHIPBOARD POWER GENERATION

All designs in this study are based on two-stroke ICEs. The current or base designs are propelled by single-fuel VLSFO or dual-fuel VLSFO/LNG engines; several conversion alternatives were developed for which the engine, fuel supply system, and fuel storage system were modified to suit the new fuel.

Some specific engine models were considered to be more suitable for future fuel conversion because they have available conversion packages. Nevertheless, it is generally assumed that conversion to alternative fuels is technically possible, even if not all alternatives for the specific engine size are currently available.

The current two-stroke, high-pressure, electronically controlled engines offer flexible options for transition to lower carbon fuels. The major engine components remain unchanged in the transition version, with the required upgrades for conversion to each of the alternative fuels expected to be limited to the engine cylinder cover (including the fuel injection and valve control systems), fuel-handling and fuel storage systems.

In comparison, the two-stroke, low-pressure engines have a different cylinder design and height for LNG operation than their standard fuel oil counterparts due to the low-pressure gas supply. This means that they need to be designed with increased displaced volume to offset the reduction of installed power when converted for dual-fuel operation. This will have to be accomplished by design (i.e. installing a larger than required VLSFO engine) if a conversion to LNG is desired later.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All fuel conversions require similar sets and extent of modifications to the vessel, which indicates that the choice of fuel can be made at a lower capital cost if and when an alternative fuel becomes commercially more attractive. For example, transitioning from LNG to methanol could have similar costs to transitioning from LNG to ammonia. Therefore, the choice of methanol versus ammonia can be based of the fuel advantages (cost, availability, greenhouse gas (GHG) emissions, etc.) rather than the conversion costs.

A major component of the scope of work for these conversions is the fuel storage system, this it is essential to design systems for new ships that accommodate a variety of different fuels with little or no modification. This capability can offer significant cost savings related to the fuel conversion and lower installation costs since there will be no need for a tank replacement. Multifuel tanks are generally more expensive than their single-fuel counterparts, but the capex increase is estimated to be significantly smaller than the cost of replacing the tanks with a new one.

As an example, LNG storage tanks can be built to be compatible with ammonia without major changes, as long as the material is austenitic or stainless steel, and the system is designed to withstand the higher sloshing loads of ammonia which has higher density than LNG. Similarly, components such as piping, connections, valves, etc., must have double walls, but to ensure chemical compatibility with ammonia they cannot contain copper, copper alloys or zinc.

Designing tanks for multifuel use has great potential to save capital costs and allows for a wider range of tank technologies to be selected. For example, membrane tanks are generally considered to be unsuitable for conversions, since their typical installation process requires the insulation and internal membrane barrier to be built in place on top of the tank's internal structure, which takes considerable time and skill. In cases where minimizing the time in the repair yard is critical, membrane tanks would not offer a good solution.

Tank manufacturers have developed drop-in concepts for membrane tanks, with the insulation and internal barrier already installed in a tank frame. However, this alternative may be more expensive than a standard Type A independent prismatic tank. The latter can be commercially more attractive for a vessel with space reserved for an LNG tank.

The "LNG ready" term used in this study describes a vessel with a traditional ICE burning VLSFO with space reserved to accommodate LNG fuel tanks. In all cases presented below, it is assumed that the auxiliary power of the base ships would not undergo modifications and would comprise the typical set of two or three diesel generators (DG) burning MGO. The reasons for this design decision are the following:

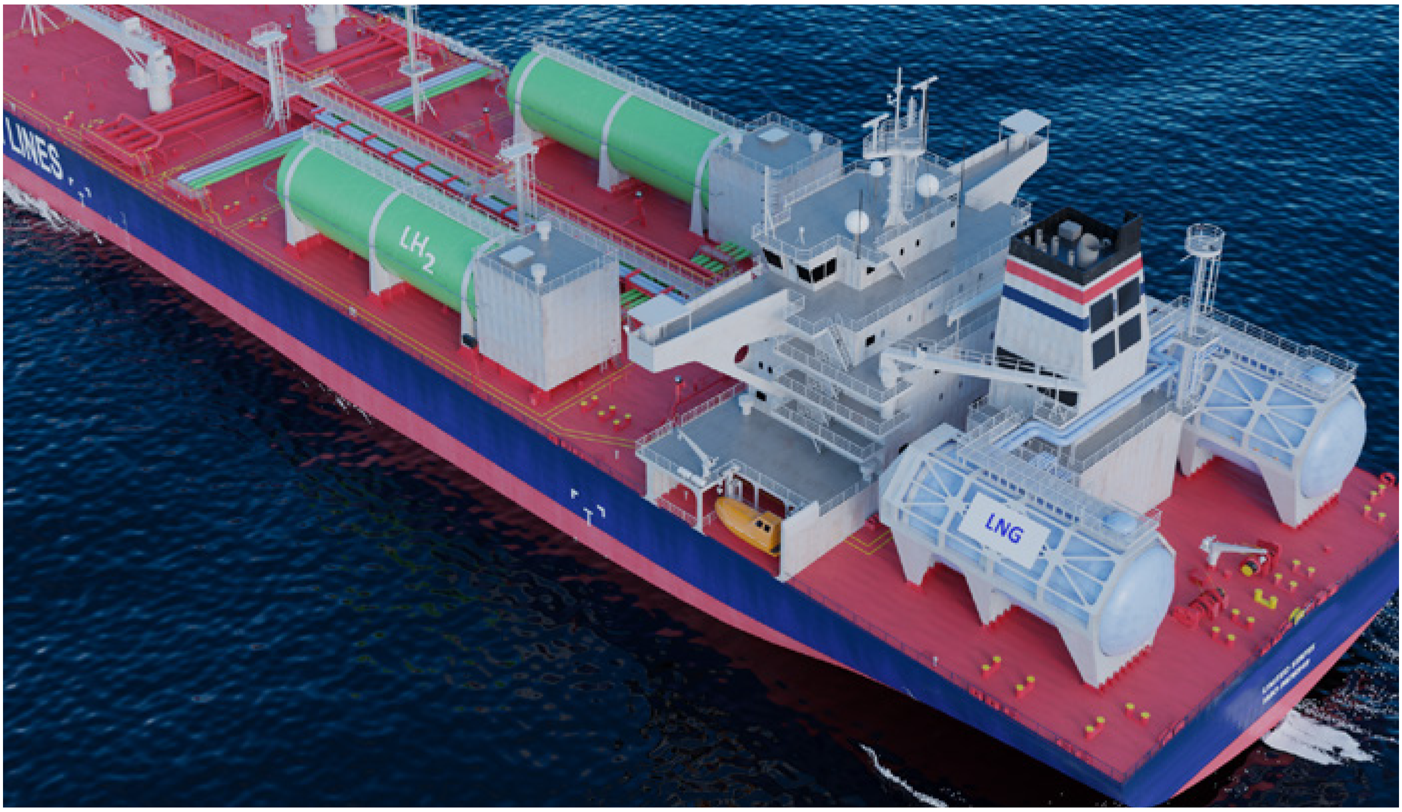
- The auxiliary power capacity is generally small compared to the main engine for all the ship types selected. This is true even for the feeder ships that do not usually have high electrical power needs. For this reason, the impact on EEDI, future Energy Efficiency Existing Ship Index (EEXI)/Carbon Intensity Indicator (CII), and CO_2 emissions of the auxiliaries is relatively small.
- If CO_2 emissions from the auxiliary engines prove critical for future EEXI and CII regulations, the use of lower carbon fuels or cold ironing in port can be considered.
- For certain fuels such as ammonia, it is still unclear when suitable medium-speed engines will be available to drive the generators, so it seems unlikely that vessels would be specified with design features to accommodate them.
- Using MGO for auxiliary power generation will minimize any range loss due to using fuels with lower energy density given the fuel storage capacity of the vessel.

REQUIRED MODIFICATIONS

VLSFO, LNG-ready Bulker – The base ship has a MAN 7G80ME-C9.5-TII engine and approximately 8,500 m^3 of VLSFO capacity. Space is reserved to accommodate a 13,000 m^3 prismatic fuel tank.

Modifications Required for Conversion to LNG

- Conversion of the MAN 7G80ME-C9.5-TII engine to 7G80ME-GI9.5 requires replacing the cylinder cover with one that includes gas injectors, adding gas control blocks and gas chain pipes, adding a sealing-oil system and a ME-GI control system.
- Addition of a fuel-handling system, including FGSS, gas valve train (GVT), and a nitrogen subsystem.
- Installation of a 13,000 m^3 LNG tank of the independent prismatic type with the appropriate insulation and cofferdams.
- Addition of an LNG bunkering station.
- 50 percent of the original VLSFO capacity is retained when converting these tanks to MGO to provide pilot fuel and offer redundancy for a one-way trip, in case FGSS failure.



Modifications Required for Conversion to Ammonia

- Conversion of the MAN 7G80ME-C9.5-TII engine to burn ammonia (likely a modified version of the LPG-burning 7G80ME-LGIP) involves replacing the cylinder cover with one that includes gas injectors, adding gas control blocks and gas chain pipes, adding a sealing oil system and an ammonia control system.
- The addition of a fuel-handling system including liquid fuel supply system (LFSS), fuel valve train (FVT), knock-out drums and an ammonia capture system designed to prevent release.
- Installation of a 13,000 m^3 ammonia tank of austenitic or stainless steel of the independent prismatic type with appropriate insulation and cofferdams.
- Addition of an ammonia bunkering station
- 50 percent of the original VLSFO capacity is retained when converting these tanks to MGO to provide pilot fuel and offer redundancy for a one-way trip in case the ammonia fuel system fails.

Dual VLSFO/LNG Bulker – The base ship has a MAN 7G80ME-GI10.5 engine and approximately 8,500 m^3 of VLSFO capacity. A 13,000 m^3 membrane tank is used for LNG, built from stainless steel and designed to withstand the sloshing loads of fluids with a density up to 0.8 SG. Piping, connections and valves have double walls and do not contain copper, copper alloys, or zinc valves, joints or seals.

Modifications Required for Conversion to Ammonia

- Conversion of the MAN 7G80ME-GI10.5 engine to burn ammonia requires replacing the cylinder cover with one that includes gas injectors, adding gas control blocks and gas chain pipes, adding a sealing oil system and an ammonia control system.
- The fuel-handling system needs to be converted to include LFSS, FVT, knock-out drums and an ammonia capture system.
- The same membrane tank can be used for ammonia.
- The bunkering station also needs to be converted.
- 50 percent of the original VLSFO capacity is retained when converting these tanks to MGO to provide pilot fuel and offer redundancy for a one-way trip in case the ammonia fuel system fails.

Dual VLSFO/LNG Tanker – The base ship has a WinGD 7X62DF engine and approximately 1,500 m^3 of VLSFO capacity. A pair of vacuum-insulated Type C tanks at the sides of the superstructures offer 2,250 m^3 of LNG capacity. The piping, connections and valves have double walls as specified by the IGF Code.

Modifications Required for Conversion to LNG+LH_2

- The WinGD 7X62DF engine needs to be converted to accept a methane/hydrogen mix with 20 percent hydrogen by weight. This conversion may include changes to the fuel-control system, although this is still a subject of ongoing research and development.
- Modified fuel-handling system to include modules for the treatment of hydrogen to bring it to the required pressure and temperature, as well as provisions to mix it with methane and deliver the mix to the engine cylinders.
- Addition of two stainless steel vacuum-insulated Type C tanks mounted on the deck that offer 3,600 m^3 of liquid hydrogen capacity.
- Addition of a liquid hydrogen bunkering station.
- MGO capacity is retained to provide pilot fuel (if needed) and offer redundancy in case the LNG/LH_2 fuel system fails.

VLSFO Containership – The base ship has a MAN 6S60ME-C10.5 T-II engine and approximately 1,140 m^3 of VLSFO capacity in tanks that are designed, built and coated to be compatible with methanol after cleaning. The tanks are built-in carbon steel prismatic tanks with inorganic zinc silicate paint with 800mm cofferdams.

Modifications Required for Conversion to Methanol

- Conversion of the MAN 6S60ME-C10.5 T-II engine to a 6S60ME-LGIM model requires replacing the cylinder cover with one that includes gas injectors, adding gas control blocks and gas chain pipes, adding a sealing oil system and an ME-LGIM control system.
- Addition of a fuel-handling system, including LFSS, FVT, knock-out drums and a nitrogen subsystem.
- Conversion of the 1,140 m^3 VLSFO tank to methanol by adding inert gas (IG) and gas-detection systems to the cofferdams.
- Addition of a methanol-bunkering station.
- Installation of sufficient VLSFO/MGO capacity to provide pilot fuel and offer some redundancy in case the methanol system fails.

CONVERSION COSTS AND TIME FRAMES

The cost of each conversion varies depending on the type of ship, scope of work and the technology chosen. The examples discussed below provide some additional information on the extent and allocation of conversion costs.

The approximate cost of converting the MAN 7G80ME-C used in the base design of the Chinamax VLOC is $5.5 million (M). Its DF LNG version, the 7G80ME-GI, costs approximately $6.5M, plus the cost of the fuel-supply system. The GVT part of the fuel gas supply system for this engine costs about $200,000. In sum, the capex increase associated with installing a dual-fuel engine on a newbuild during construction instead of a standard VLSFO engine is about $1.5M–2M, including the fuel gas supply system and bunkering station, but not the fuel storage tanks.

The cost of two vacuum-insulated 1,000 m^3 Type C tanks for LNG is approximately $5.5M–6M, so the complete LNG DF package would add about $8M to the vessel cost, excluding engineering and installation.

Assuming that the difference based on the engineering and installation costs can be minimized during the ship's construction, the overall cost increase for converting a standard vessel to a DF LNG vessel with 2,000 m^3 of LNG capacity in deck-mounted Type C tanks is about $9M-10M.

Recent media reports indicated that 10 DF LNG very large crude carriers (VLCCs) were ordered in December 2020 for a long-term charter to an energy major. The specification of the DF LNG fuel gas supply system, including the deck-mounted LNG tanks of nonspecified capacity, added $15M to the cost of each vessel, bringing the total reported price to $100M per ship.

The engine retrofit costs to convert a VLSFO-burning 7G80ME-C to an LNG capable 7G80ME-GI were estimated by MAN in a recent webinar at about $4.4M. This did not include engineering, or any modifications to the fuel storage system. Considering all costs and assuming the use of the deck-mounted Type C tanks, MAN estimated that the project costs could reach $18M-20M. Such a retrofit is expected to last approximately 15 months, plus one month in the yard and one month to commission the new system. This cost is about double the estimated cost for installing the DF LNG at the newbuild stage with 2,000 m^3 deck-mounted LNG tanks.

These early cost estimates are likely to be optimistic and include marketing incentives. Also, the costs and complexity of converting the engine and fuel systems could be significantly higher for an existing ship at a repair yard compared to the incremental costs for a newbuild. The cost estimates also suggest that for the same set of engines and LNG capacity, the conversion is a better proposition for a $100M, 300k deadweight (dwt) VLCC than for a $70M, 400k dwt VLOC.

The figures in this section also underline the importance of minimizing fuel storage costs. For example, the capex for the Type C tanks is more than the cost of retrofitting the engine and a few times the cost of the two engine types. Other fuel storage systems can be more expensive than Type C tanks, although some can offer an advantage in terms of space utilization.

In all cases, having a fuel storage system suitable for different fuels can offer significant savings on the overall cost of the conversion.

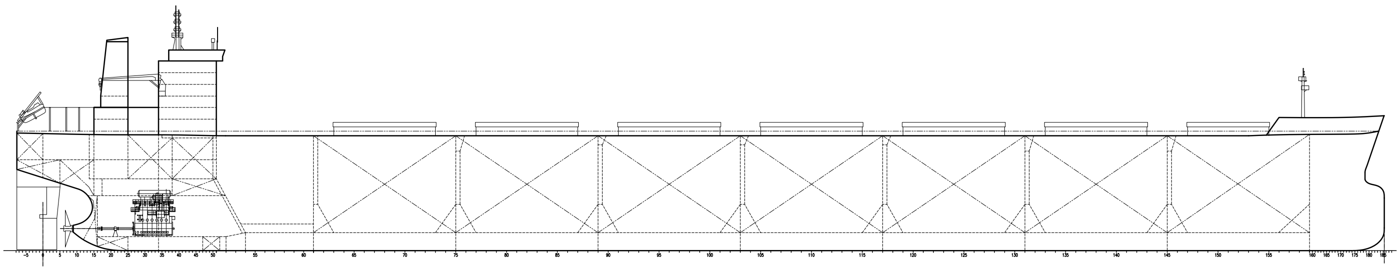
As an example, the cost of a 6,000 m^3 LNG tank would be increased by about $400,000 if it were built to store methanol or ammonia. This additional cost stems from the reinforcement of the containment system but excludes the reinforcement of the hull structure. Designing a fuel tank for future fuels should also consider the energy content of each fuel, which might lead to larger tanks than normally considered for the baseline fuel to preserve sailing ranges.

Based on the above, the scope of work for most of the conversions considered in this study is similar and varies only with ship and engine sizes. Therefore, it is safe to conclude that:

- The choice of alternative fuel is largely capex-independent.
- Conversion costs are similar for different ship sizes, which makes conversions more attractive for larger and more expensive vessels.

THE 2020 BASELINE SHIPS

THE BASELINE CHINAMAX BULK CARRIER, VLSFO, LNG READY



Two versions of this design have been built, the original 2011 Vale version and a newer 2018 version. They are nearly identical, with the main differences being:

- The 2018 version is "LNG ready", including a reserved space forward of the engine room for a 13,000 m^3 prismatic LNG tank under the deck.
- The 2018 version has slightly less power with a nominal speed of 14.5 knots versus 14.8 knots for the 2011 version.

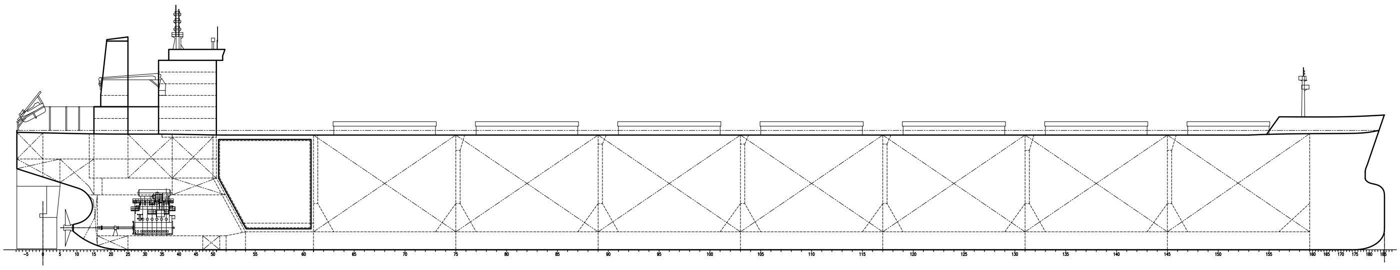
This VLOC is designed with a cubic capacity for heavy iron ore, with a possible backup as a coal carrier. Its volume capacity is not optimized for lighter grains and bulk products.

The 2018 version is used for this study as the first base ship, burning VLSFO, LNG ready, with the reserved space below deck for the 13,000 m^3 fuel tank. The characteristics of its LNG-ready features limit the choice of fuel tank technologies for the transitions to LNG, LPG, methanol and ammonia, as any new tank will have to be compatible with pre-construction of the tank's primary barrier and subsequent drop-in after removal of a portion of the main deck. This makes the use of membrane tanks less attractive. Type C tanks also would not be appropriate due to the requirements for space utilization and deck operations.

The main engine is a MAN 7G80ME-C10.5 TII with 24.2 MW of power, derated by five percent to 23 MW to meet EEDI Phase II requirements at a slightly reduced speed of 14.2 knots. The VLSFO capacity is approximately 8,500 m^3, offering a range in excess of 36,000 nm – or three one-way 12,000 nm legs from Brazil to northern China – with a fuel consumption of 76 Mt/day for the main engine, at 85 percent maximum continuous rating (MCR), equivalent to a specific fuel oil consumption (SFOC) of 162 g/kWh.

Auxiliary power is generated by three 1.35 MW diesel generator (DG) sets, with an MDO capacity of approximately 1,500 m^3. Only one generator is assumed to be running at sea, with a SFOC of 206 g/kWh. The carbon intensity of this base vessel is 1.74 gCO_2/dwt Mt-nm. The required Phase II EEDI is 1.64 and met by its attained EEDI value of 1.63.

THE BASELINE CHINAMAX BULK CARRIER, DUAL-FUEL VLSFO/LNG



For this VLOC design, the second base ship features a dual-fuel VLSFO/LNG engine, with a methanol/ammonia-ready membrane LNG tank installed at vessel construction, and the appropriate reinforcements in the 13,000 m^3 space reserved below deck.

The conversion to methanol or ammonia requires a significantly lower expense if the LNG storage tank and fuel piping are designed to enable this transition. The shape of the tank is an important design parameter as it needs to manage sloshing loads and increased pressure at its bottom. Since sloshing intensity is dictated by the width of the tank, its shape needs to have reduced width and increased chamfer.

The capex differential between a standard LNG-only membrane tank and a reinforced LNG/methanol/ammonia tank is modest compared to fabricating and installing a new independent prismatic tank.

No reliquefaction plant was considered for this DF LNG version. Boil off management depends on the vessel operating profile, and specifically the electrical loads generated while in port and the DF capability of the generators. As an example, very large containerships produce high amounts of power at berth to consume the BOG and maintain the tank pressure. In a few applications it is beneficial to consider a reliquefaction system on board designed to burn LNG, since reliquefaction plants generally require a significant capex.

However, a small reliquefaction plant may be appropriate for this design, as it would avoid the need to use LNG intended for the auxiliary engines, which would lead to a reduction in range and high cost of future conversion to methanol or ammonia.

For this reason, a boiler can be used to manage excessive boil off at berth, or an auxiliary DG that uses LNG. The decision ultimately depends on finding the right balance between opex and capex which, in turn, depends on the date and duration of the conversion and the ship's operational profile. To date, only a few manufacturers of four-stroke engines have LNG-ready designs, but this is expected to change in the future.

The DF LNG version of the MAN 7G80ME-GI10.5 is selected – the original main engine from the 2018 vessel – offering 24.2 MW of power. The use of LNG means that no derating is required to meet the requirements of EEDI Phase II, and the speed remains at the original 14.5 knots.

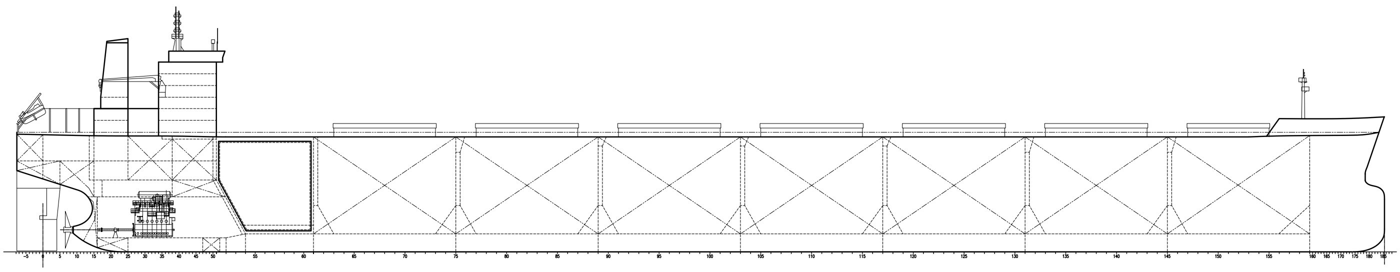
The 13,000 m^3 LNG tank capacity gives a range of approximately 30,000 nm (a reduction of 16 percent compared to the VLSFO base design), equivalent to two one-way 12,000 nm legs between Brazil and northern China with a generous margin. The fuel consumption of the main engine is 67 Mt/day at 85 percent MCR, equivalent specific gas fuel consumption (SGFC) of 136 g/kWh.

The original 8,500 m^3 VLSFO tank was retained to provide pilot fuel and redundancy in the fuel gas supply system fails. However, this capacity is well in excess of what the vessel needs and could be reduced by as much as 70 percent.

Auxiliary power is generated by the same three 1.35 MW DG sets, with an MDO capacity of about 1,500 m^3. Similar to the first baseline ship, only one generator is assumed to be running at sea, with a SFOC of 206 g/kWh.

The carbon intensity of this second base vessel is 1.33 gCO_2/dwt Mt-nm, a 26 percent improvement over the VLSFO base design. The attained EEDI is 1.27, which satisfies the required Phase II EEDI level of 1.64, as well as the required Phase III EEDI value of 1.43.

THE BASELINE CHINAMAX BULK CARRIER, DUAL-FUEL VLSFO/LPG



The third base design for this VLOC design is a dual-fuel VLSFO/LPG configuration, with an ammonia-ready Type B tank. The importance of this design stems from the fact that conversion from LPG to ammonia is likely to be simple and economical since these fuels have similar storage characteristics.

Note that LNG is necessarily carried as a liquid at cryogenic temperature, so it makes sense to use prismatic or membrane tanks to maximize space utilization. Therefore, the conversion of an LNG vessel to ammonia will have to carry ammonia refrigerated to -50° C at close to ambient pressure in order to utilize the same tank. On the other hand, both LPG and ammonia can be carried pressurized at ambient temperature at 8.5 and 17 bar, respectively. These are relatively modest pressure values but still require the use of cylindrical or bi-lobe Type C tanks. Therefore, a vessel designed for LPG with ammonia in mind as a possible future fuel would normally be benefited from using Type C tanks instead of prismatic tanks.

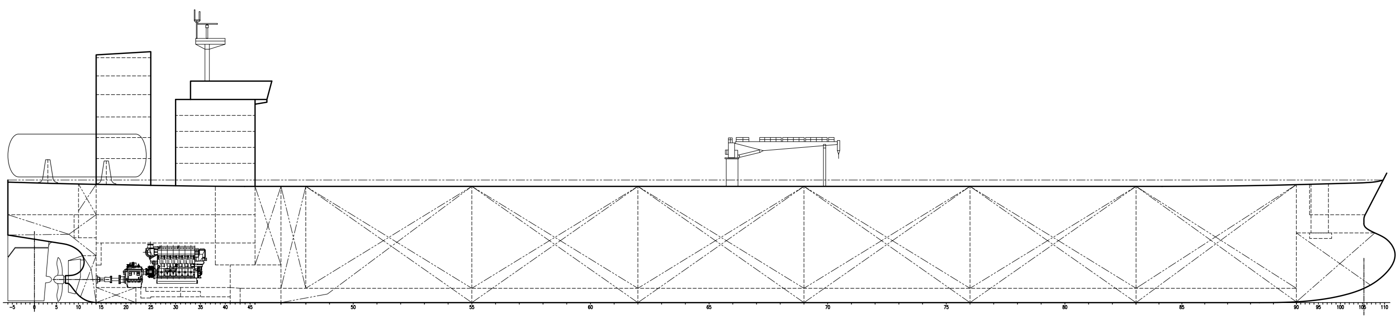
The reason is that handling modest pressures is easier and cheaper that handling refrigerated cargo. Fuel pressurized at low pressure levels is easier to bunker than refrigerated fuel. Also, low-pressure fuel is easier and safer to handle thus only requiring a tank that is strong enough to handle the load. On the other hand, refrigerated fuels need redundant reliquefaction machinery to eliminate venting of fuel. This is particularly important for ammonia due to its toxicity.

However, cylindrical or bi-lobe Type C tanks would have a large mass and a low volume utilization in the case of this chinamax VLOC, since they would have to fit in the under-deck hold forward of the engine room. Furthermore, placing additional fuel storage on the main deck above this hold creates the risk of the tanks being damaged during loading/unloading operations. For these reasons, a Type B tank and a redundant reliquefaction plant were chosen for this design instead of Type C tanks.

The main engine chosen is the DF LPG version of the original 2018 vessel, a MAN 7G80ME-LGIP with 24.2 MW of power. The use of LPG means that no derating is required to meet EEDI Phase II requirements, and the speed remains at the original 14.5 knots. The 13,000 m^3 LPG capacity gives a range of approximately 34,500 nm (a reduction of five percent compared to the VLSFO base design) with main engine fuel consumption of 70 Mt/day at 85 percent MCR, equivalent to a SGFC of 142 g/kWh. In addition to the LPG fuel capacity, the original 8,500 m^3 VLSFO capacity was retained to provide pilot fuel and offer redundancy in case of failure of the fuel gas supply system.

Auxiliary power is generated by the same three 1.35 MW DG sets, with an MDO capacity of approximately 1,500 m^3. Only one generator is assumed to be running at sea, with a SFOC of 206 g/kWh. The carbon intensity of this base vessel is 1.53 gCO_2/dwt Mt-nm, which marks a 15 percent improvement over the VLSFO base design. The attained EEDI is 1.44, which meets the required EEDI Phase II value of 1.64.

THE BASELINE AFRAMAX TANKER, DUAL-FUEL VLSFO/LNG

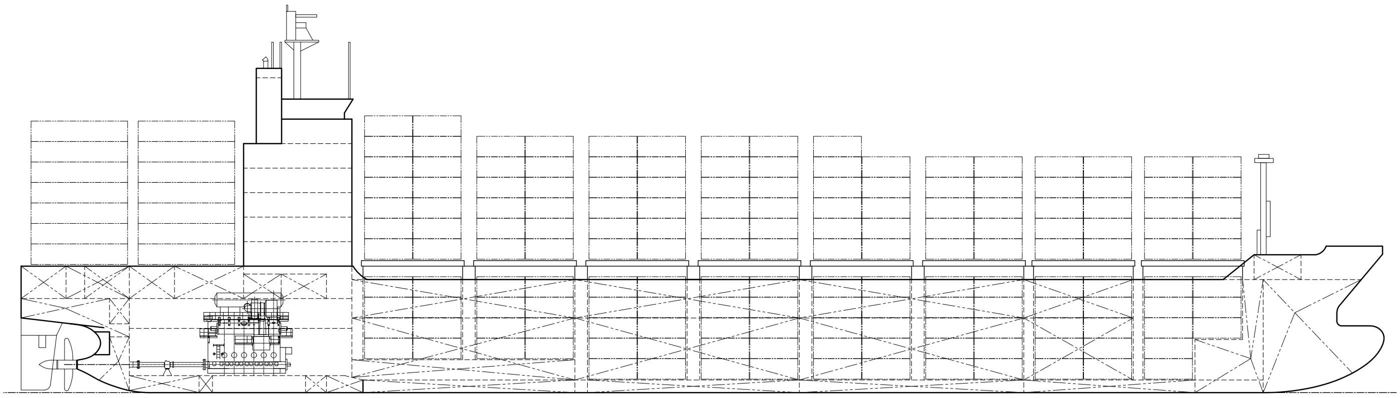


The baseline aframax tanker considered in this study features dual-fuel LNG propulsion and can meet the EEDI Phase II requirement at full power and speed. The base design has 2,250 m^3 of LNG capacity using two Type C tanks installed on the main deck at the sides of the casing. These tanks have double walls and vacuum insulation to minimize boil off, which removes the need for a reliquefaction plant.

The main engine is a WinGD 7X62DF with 13.8 MW of power. The MGO capacity is approximately 1,250 m^3 to provide pilot fuel and offer full redundancy if the fuel gas supply system fails.

The range on LNG is 9,000 nm with a consumption of 35 Mt/day for the main engine, at 76 percent MCR, equivalent to a SGFC of 140 g/kWh. Auxiliary power is generated by three 1.5 MW DG sets, with an MDO capacity of approximately 580 m^3. Only one generator is assumed to be running at sea, with an SFOC of 206 g/kWh. The carbon intensity of this base aframax tanker is 2.74 gCO_2/dwt Mt-nm. The attained EEDI is 2.97, which meets the required EEDI Phase II level of 3.33.

THE BASELINE 1,800 TEU FEEDER CONTAINERSHIP, VLSFO



The baseline containership design was based on a minimum range of 4,000 nm and speed of 18.5 knots. This can be met with approximately 600 m^3 of VLSFO capacity and a diesel-electric propulsion system, which can be readily converted to fully battery electric or fuel cell/battery hybrid electric configurations.

However, the diesel-electric design struggles to meet the EEDI Phase II requirement because of the lower efficiency of the plant compared to an equivalent direct drive ICE design. For this reason, the baseline containership design was chosen to have a conventional propulsion plant burning VLSFO, with a view to converting it to burn methanol.

The base design has 1,140 m^3 of VLSFO capacity in conventional tanks that are also designed for methanol use. These would be built-in tanks with appropriate 800 mm cofferdams and the provision of IG and gas-detection systems.

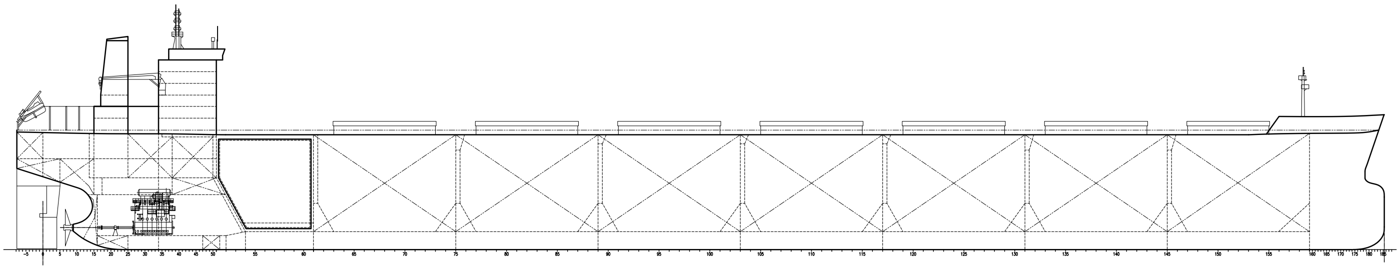
The feeder vessel features a MAN 6S60ME-C10.5 T-II with 12.0 MW of power. The VLSFO capacity extends its range to nearly 12,000 nm with fuel consumption of 42 Mt/day for the main engine, at 90 percent MCR, equivalent to a SFOC of 163 g/kWh.

Auxiliary power is generated by three 1.5 MW DG sets, with an MDO capacity of approximately 150 m^3, sufficient to provide pilot fuel for the future methanol conversion. The MDO capacity can be extended to provide redundancy for the converted ship in case the methanol fuel system fails. Only one generator is assumed to be running at sea, with a SFOC of 206 g/kWh.

The carbon intensity of the baseline feeder is 13.14 gCO_2/dwt Mt-nm. The attained EEDI value is 16.03, which meets the EEDI Phase II level of 18.60 as well as the EEDI Phase III level of 16.28.

THE TRANSITION BULK CARRIERS

THE CHINAMAX BULK CARRIER, LNG READY TO LNG



The general design is very similar to that of the second baseline DF VLSFO/LNG vessel, with similar fuel capacities, range, and CO_2 improvements to the baseline ship. The only major difference is that converting the 13,000 m^3 space below deck to fit a traditional integral membrane LNG tank would not be commercially feasible, due to the high cost and long time required for the installation. A simpler drop-in installation would be the preferred option.

An independent prismatic tank is chosen that can be prefabricated and installed into the reserved space after removing a portion of the main deck. However, even with this simpler installation method, the cost of this conversion, including the engine retrofitting, new fuel-handling and bunkering systems, is about twice as much as the difference in cost between the VLSFO LNG-ready baseline ship, and the dual-fuel VLSFO/LNG baseline ship.

THE CHINAMAX BULK CARRIER, LNG READY TO AMMONIA

The fuel-storage conversion for this design is similar to that for LPG, although the refrigerated ammonia is kept at a slightly lower temperature. However, the corrosion characteristics of ammonia require the exclusive use of stainless or austenitic steels to construct the inner barrier. Similar material constraints apply to all piping. As with the previous conversions, this tank would be prefabricated and installed into the reserved space after removing a portion of the main deck.

The main engine is a future ammonia conversion of the MAN 7G80ME-C10.5 TII, retaining the full 24.2 MW of power and 14.5 knots speed. The ammonia capacity offers a range of about 18,000 nm, which is half of the original 36,000 nm, but still sufficient to cover a 12,000 nm leg from Brazil to northern China, plus margin.

Fuel consumption for the main engine is estimated at 173 Mt/day at 85 percent MCR, equivalent to a SLFC of 350 g/kWh. Auxiliary power is generated by three 1.35 MW DG sets, with the same MDO capacity as the baseline design.

The carbon intensity is estimated to be 0.12 gCO_2/dwt Mt-nm, mostly due to pilot fuel, which marks an improvement of 93 percent over the baseline design assuming that green ammonia is used.

The attained EEDI is 0.20, which comfortably satisfies the required EEDI Phase II level of 1.64 as well as the required EEDI Phase III level of 1.43.

THE CHINAMAX BULK CARRIER, DUAL-FUEL VLSFO/LNG TO AMMONIA

The main difference between this conversion and the previous one is that the changes to the fuel storage system are less significant since the membrane tank of the baseline vessel was designed to be compatible with methanol and ammonia.

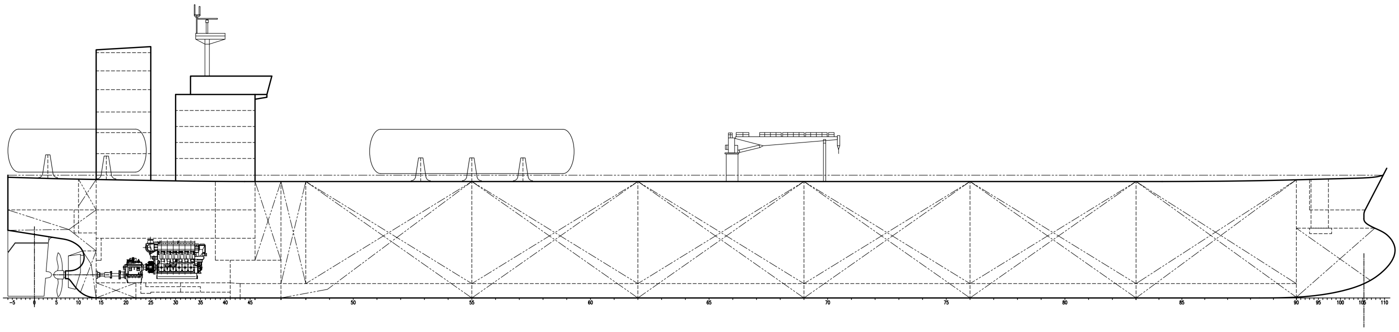
All other design parameters are the same as those described in the previous design, and it is worth noting that the loss in range due to the lower energy content of ammonia is only reasonable if the environmental benefits of green ammonia become available.

THE CHINAMAX BULK CARRIER, DUAL-FUEL VLSFO/LPG TO AMMONIA

This is likely the simplest and more cost effective conversion since the Type B tanks can easily be designed to be used for both LPG and liquid ammonia. This means that there is no need to change piping or fuel storage system, which is already much cheaper than a cryogenic equivalent needed for LNG. All other design parameters are the same as those described in the previous sections.

THE TRANSITION TANKER

THE AFRAMAX TANKER, DUAL-FUEL VLSFO/LNG TO LNG + 20% HYDROGEN



Converting a DF VLSFO/LNG aframax to burn a mix of natural gas and hydrogen is a challenging task. In terms of power generation, it remains unclear what exactly would be needed to adapt a low-pressure engine such as the 7X62DF to use such a mix.

The addition of two high-tech, stainless-steel, vacuum-insulated Type C tanks can provide the 3,600 m^3 capacity of liquid hydrogen required to reach 20 percent hydrogen by weight in the mix but are expensive and still a subject of regulations development.

Nevertheless, it is assumed that sufficient separation would be required between the LH_2 tanks and the LNG tanks, as it would be required between the two bunkering stations and vents. Finally, the requirement for pilot fuel amounts, management of hydrogen boil off and fuel-handling systems are largely unknown.

The conversion design retains the 2,250 m^3 capacity of LNG and the main engine power, which offers a range of 14,600 nm, higher than the 12,000 nm of the original VLSFO ICE design. The main engine would consume 27 Mt/day of the fuel mix (21.6 Mt/day of LNG and 5.4 Mt/day of LH_2) at 76 percent MCR, equivalent to a SGFC of 108 g/kWh.

Auxiliary power is generated by the same three 1.5 MW DG sets, with unchanged MDO capacity. The carbon intensity of this design is estimated at 2.11 gCO_2/dwt Mt-nm, which is only 23 percent lower than the pure DF VLSFO/LNG version. The attained EEDI is 2.35, which satisfies the required EEDI Phase II level of 3.33, but is marginally higher than the required EEDI Phase III of 2.29.

THE TRANSITION FEEDER CONTAINERSHIP

THE 1,800 TEU FEEDER CONTAINERSHIP, VLSFO TO METHANOL

After conversion, the containership would have 1,140 m^3 methanol capacity in the same tanks that previously stored VLSFO. The lower energy content and mass density of methanol compared to VLSFO results in a 63 percent loss in range, to just above 4,000 nm (from 12,000 nm) but no loss of speed. The main engine fuel consumption is 85 Mt/day at 90 percent MCR, equivalent to a SLFC of 329 g/kWh.

Auxiliary power is generated by the same three 1.5 MW DG sets, with unchanged MDO capacity. The carbon intensity of this converted vessel is 12.77 gCO_2/dwt Mt-nm, just three percent lower than the original design, if conventional methanol is used. The attained EEDI is 14.42, which satisfies the required EEDI Phase II level of 18.60 as well as the required EEDI Phase III level of 16.28.

SUMMARY AND CONCLUSIONS

The main conclusions of this study of future transition designs are:

- Modern engine developments have made conversion to most future fuels much easier to achieve than the past.
- The latest electronic-controlled, two-stroke, high-pressure diesel engines are simpler to convert to alternative fuels without loss of power.
- Transition to alternative fuels can be made much more attractive if it is planned at the newbuilding design stage. In particular, fuel tanks should be specified based on the original and future fuels planned to be used.
- The capex of the transition to alternative fuels is largely independent of the fuel.

The following tables offer a summary of all the transitions' main characteristics:

	FUEL	MAIN ENGINE	FUEL TANK
Baseline Chinamax Bulk Carrier, LNG Ready	VLSFO	MAN 7G80ME-C10.5	Single wall integral
Chinamax Bulk Carrier, LNG Ready to LNG	DF LNG	MAN 7G80ME-GI10.5	Type A independent prismatic
Chinamax Bulk Carrier, LNG Ready to Ammonia	DF Ammonia	MAN 7G80ME-LGIA10.5*	Stainless steel independent prismatic
Baseline Chinamax Bulk Carrier, DF VLSFO/LNG	DF LNG	MAN 7G80ME-GI10.5	Membrane
Chinamax Bulk Carrier, DF VLSFO/LNG to Ammonia	DF Ammonia	MAN 7G80ME-LGIA10.5*	Membrane
Baseline Chinamax Bulk Carrier, DF VLSFO/LPG	DF LPG	MAN 7G80ME-LGIP10.5	Independent prismatic refrigerated
Chinamax Bulk Carrier, DF VLSFO/ LPG to Ammonia	DF Ammonia	MAN 7G80ME-LGIA10.5*	Independent prismatic refrigerated
Baseline Aframax Tanker, DF VLSFO/LNG	DF LNG	WinGD W7X62DF	Type C independent, deck-mounted
Aframax Tanker, DF VLSFO/ LNG to LNG + 20% LH_2	DF LNG + 20% LH_2	WinGD W7X62DF+H_2**	Type C independent, deck-mounted
Baseline 1,800 TEU Feeder Containership	VLSFO	MAN 6S60ME-C10.5	Coated carbon steel with cofferdams
1,800 TEU Feeder Containership, VLSFO to Methanol	DF Methanol	MAN 6S60ME-LGIM10.5	Coated carbon steel with cofferdams

	FUEL CAPACITY (m^3)	SPEED (KNOTS)	RANGE (nm)	CAPEX (-)	EEDI COMPLIANCE	CARBON INTENSITY (gCO_2/dwt ton-nm)
Baseline Chinamax Bulk Carrier, LNG Ready	8,490	14.2	37,284	$	Phase 2	1.74
Chinamax Bulk Carrier, LNG Ready to LNG	13,000	14.5	30,406	$$$	Phase 3	1.33
Chinamax Bulk Carrier, LNG Ready to Ammonia	13,000	14.5	17,855	$$$$	Phase 3	0.12
Baseline Chinamax Bulk Carrier, DF VLSFO/LNG	13,000	14.5	30,406	$$	Phase 3	1.33
Chinamax Bulk Carrier, DF VLSFO/LNG to Ammonia	13,000	14.5	17,855	$$$	Phase 3	0.12
Baseline Chinamax Bulk Carrier, DF VLSFO/LPG	13,000	14.5	34,513	$	Phase 2	1.53
Chinamax Bulk Carrier, DF VLSFO/LPG to Ammonia	13,000	14.5	17,855	$$	Phase 3	0.12
Baseline Aframax Tanker, DF VLSFO/LNG	2,250	13	8,967	$$	Phase 2	2.74
Aframax Tanker, DF VLSFO/ LNG to LNG + 20% Hydrogen	2,250 + 3,550	13	14,857	$$$$	Phase 3	2.11
Baseline 1,800 TEU Feeder Containership	1,140	18.5	11,793	$	Phase 3	13.14
1,800 TEU Feeder Containership, VLSFO to Methanol	1,140	18.5	4,330	$$	Phase 3	12.77

7 | CONCLUSIONS

In this, the third in the series of ABS Low Carbon Shipping Outlooks, we have updated the marine sector's progress towards reducing its emissions, analyzed how it will be affected by external decarbonization trends, and presented a life-cycle – or "value chain" – perspective of the leading alternative marine fuels' greenhouse gas (GHG) footprints.

Based on this information, we showcased transitional designs for three future vessel types – a chinamax bulk carrier, an aframax tanker, and an 1,800 twenty-foot equivalent unit (TEU) container feeder – and analyzed the associated technical and economic challenges.

The key conclusions of the report can be summarized as follows:

- The maritime industry is undergoing a significant transformation centered around: decarbonization motivated by the International Maritime Organization (IMO) regulations; the financial institutions that support new vessel construction and retrofits; the multinational charterers of such vessels; and market-based measures (MBMs) emerging from local and regional authorities.
- This transformation will be enhanced by the global industry decarbonization efforts to address the impact of climate change. The latter can impact shipping directly or indirectly by affecting the global production of shipped goods, such as agricultural and industrial products or fuels, and their global supply chains.
- It is critical for shipowners and operators to understand the expected changes in the global supply chains in order to plan their future fleet composition and renewal strategy.
- The short-term IMO measures (Energy Efficiency Existing Ship Index (EEXI) regulations and Carbon Intensity Indicator (CII)) create a very challenging landscape for many vessels of the global fleet. Some vessel segments, such as liquefied natural gas (LNG) carriers with steam turbines, may experience early vessel retirement due to their inability to comply with the EEXI and CII regulations.
- A large fraction of the global bulk carrier and tanker fleet may have difficulty in meeting the EEXI regulation. LNG carriers, liquefied petroleum gas (LPG) carriers and containerships are expected to have less difficulty in meeting the EEXI regulation (with the exception of steam turbine LNG carriers).

Analysis of qualified ships from five key shipping categories – bulk carriers, tankers, gas carriers, LNG carriers and containerships – revealed the following about compliance with the IMO's EEXI regulation:

- A large fraction of the global tanker fleet (60 to 70 percent) is expected to have difficulty meeting the EEXI requirements. Smaller dwt segments, such as aframax tankers, are expected to meet the requirements more comfortably than larger tankers.
- A similarly large fraction of the global bulk carrier fleet (60 to 70 percent) is expected to also have difficulty meeting the EEXI requirements. Again, smaller dwt segments, such as panamax bulker, are expected to meet the requirements more comfortably than larger vessels, such as capesizes or very large ore carriers (VLOCs).
- Gas carriers – particularly those of higher dwt capacity – have proven capable to meet the EEXI requirements.
- LNG carriers with dual-fuel or tri-fuel diesel electric propulsion or two-stroke dual-fuel engines are expected to meet the EEXI regulations. However, those LNG carriers propelled by steam turbines will face significant challenges.
- Containerships above 80,000 dwt are expected to meet the EEXI requirements. However, smaller dwt segments are expected to face some challenges with EEXI compliance.

FUEL LIFE-CYCLE ANALYSIS

- The current regulatory framework focuses on vessel emissions (tank-to-wake) rather than the life-cycle emissions of a fuel (well-to-wake), even though the industry recognizes that the latter provides a more accurate assessment of the carbon footprint of a given fuel across its life cycle.
- The life-cycle analysis clearly identifies the need for green ammonia and hydrogen production in order to have meaningful GHG emissions reduction from these zero-carbon fuels.
- On a life-cycle basis, LNG is not as environmentally friendly as originally considered, due to the contribution of methane slip and fugitive emissions to GHG emissions.
- The required scale up of technology for green fuel production is significant (by an order of magnitude) before they can be widely adopted by the global feet.
- LNG can provide almost 25 percent reduction in carbon emissions on a tank-to-wake basis; however, on a well-to-wake basis – including methane slip and fugitive emissions – the reduction drops to six to 16 percent depending on the engine technology.
- Methanol can be made carbon neutral on a well-to-wake basis.
- Ammonia offers very low well-to-wake emissions, but the use of pilot oil contributes to carbon emissions from the vessel.
- Biofuels do not offer any tank-to-wake emissions reduction, but they can offer benefits on the well-to-tank component. However, the feedstock and production pathway greatly affect the well-to-tank emissions of biofuels. Also, a number of variables involved in biofuel production can shift the estimated well-to-tank emissions.

DESIGNING FOR THE FUTURE

- The advent of modern dual-fuel engine technology makes the transition to low- and zero-carbon fuels easier to achieve than the recent past.
- The transition to alternative fuels can be made much more attractive if it is planned at the newbuilding design stage. In particular, the design of the fuel tank should be specified based on all the fuels planned to be used throughout the life of the vessel.

8 | ABS ACTIVITIES

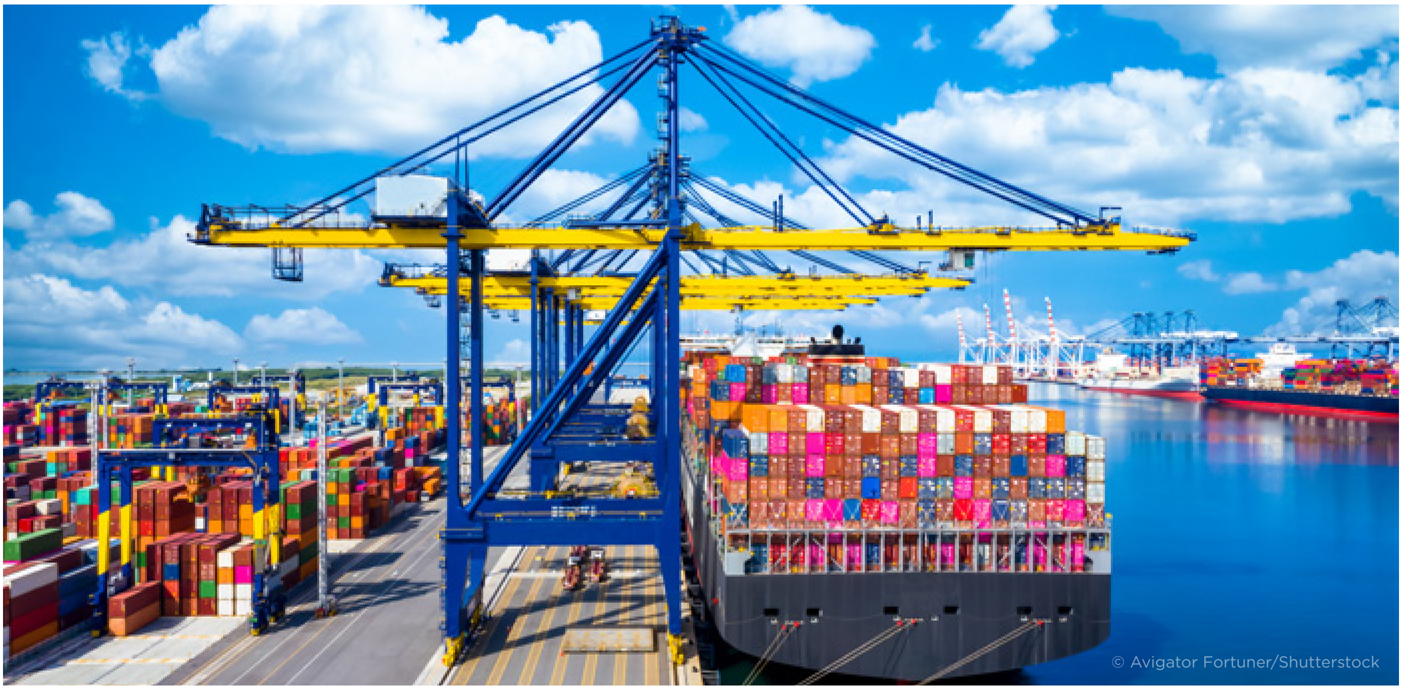
With the International Maritime Organization (IMO) having set ambitious mid-term (2030) targets to reduce shipping's CO_2 and greenhouse gas (GHG) output, owners now face the difficult task of decarbonizing their fleets.

There are so many technology options (including fuels) to consider that selecting a sustainable, fleetwide decarbonization strategy that will align with a company's business goals is increasingly complex.

The carbon footprints of each fleet will be different and each ship will require a bespoke strategy to find the most effective path towards compliance with the new regulations and emissions targets.

Furthermore, the industry is now recognizing how a low-carbon transition is required throughout the value chain, with progress at every link having the potential to positively affect shipping's overall carbon intensity. The value chain perspective is becoming more and more relevant.

So, how do you get started? ABS has devised a clear three-step process towards decarbonization.



GETTING STARTED

Experienced management-systems practitioners will tell you that you cannot manage what you do not measure, so the first step is to build profiles of the fleet's present carbon footprint and intensity.

Benchmarking the current performance of each vessel provides a base against which improvements in fuel efficiency and progress towards decarbonization goals can be measured.

Vessels can be measured against an endless number of options, including their previous performance, sister vessels, against the global fleet, across different trade routes and different ship designs and/or operational conditions.

Subsequent improvements then can be achieved by selecting options such as optimizing power and speed, adopting energy-efficient technologies, or simply by investing in new ships using low-carbon, carbon-neutral and zero-carbon fuels.

The owner will need to decode the data being collected to create a common language to measure the performance of each vessel so comparisons can use common metrics. The data also will help to direct a company's finite resources towards the assets that most need them, or ascertain whether investments are worthwhile.

A critical part of developing each profile is setting clear goals. Establish the desired outcome – a clear picture of what success will look like – and then use the emissions and fuel – performance data to chart the path to progress. Starting at the baseline, there should be clear objectives for near-, mid- and long-term fleet performance.

The details are important, but so is understanding the big picture – which details will be the most supportive in attaining corporate or even industry goals.

In setting the goals, ask what your emissions-compliant fleet will need to look like – including the future ships and the ones presently in operation – rather than just what designs any new ships will need to be compliant. Next, define the goals in the context of the regulatory framework in which they will operate.

Finally, align any internal objectives with external business drivers, such as the demands of regulators, financiers and charterers. Collectively, these will help to shape an effective decarbonization trajectory.

SELECT YOUR OPTIONS

In the next few years, many new technologies – including those that support low- and zero-carbon fuels – will mature and become available. The safety implications of using each one will need to be fully understood and the value of each technology assessed for its ability to deliver the decarbonization goals.

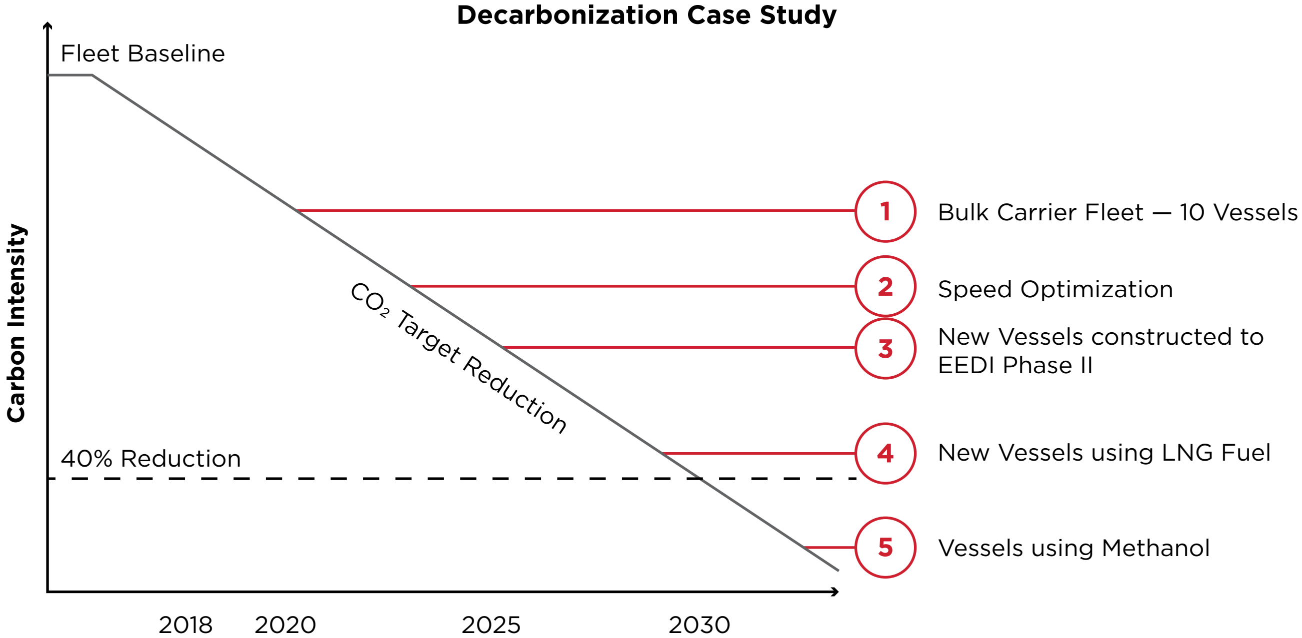
While strategies to improve operational efficiency will be created for each individual ship, it is important to evaluate any potential gains in the context of the fleet. Data and the digital solutions they inform have the potential to optimize everything from fuel consumption and asset reliability to routing, scheduling and port stays.

Many of the new fuels technologies will take time to prove their worth; for example, it remains unclear whether some low-carbon energy sources will deliver the base-load power required for international shipping. Also, there are questions about whether there will be adequate infrastructure and/or supply of some new fuels in time for short-term goals to be realized.

For these reasons, even ambitious shipowners would be well counseled to expect five or more years to pass before decarbonization goals can be fully met. But when these technologies do mature enough for strategies to be put into action, any potential gains will still need to be measured against individual vessels, existing and new.

At that point, it also will be important to take a life-cycle view when predicting the implications and risks of using new technologies/fuels. In most cases, external guidance can be expected to keep pace with developments to support meeting any goals.

Decarbonization Case Study



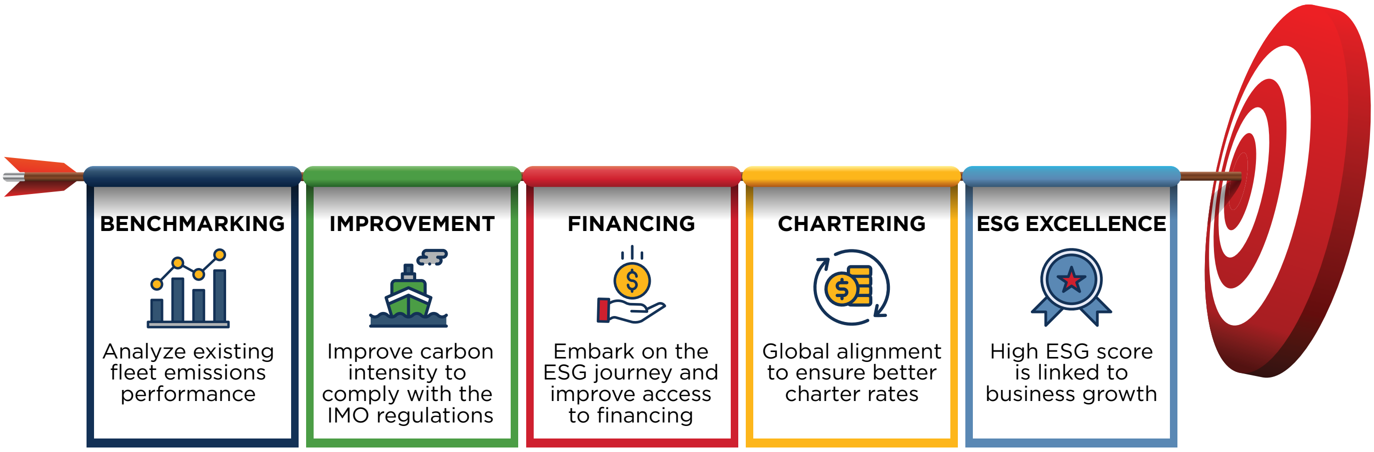
The final step is to implement the strategy. Shifting to low-carbon shipping will require some fundamental changes to how a business is delivered. Goals will need to be clearly communicated to staff on board and ashore; any changes will need to be managed across all departments, operations and procurement activities, including research and development.

In most cases, external guidance and best practices will be available to help the shipowner effectively implement new technologies and operational changes, so it may not be necessary to start from scratch. But transitioning to a low-carbon fleet also will make a return to "business as usual" unlikely.

Measuring progress is critical, so make sure all measurements are derived from quality data. The ABS *Advisory on Data Quality for Marine and Offshore Application* is a helpful reference that provides an overview of the standards and industry best practices, as well as general guidance on assessing, monitoring and controlling data quality for marine and offshore applications.

During implementation, progress towards decarbonization needs to remain aligned with the established decarbonization trajectory; this requirement that can be supported by putting in place an environmental-monitoring system that can quickly identify deviations and provide decision support for corrections. Products such as the ABS Environmental Monitor™ help shipowners to achieve sustainability goals by benchmarking and monitoring fleet or vessel-specific environmental categories, such as emissions, garbage, waste and consumables.

Most environmental-monitoring systems also provide a structured platform for future sustainability reporting.



CONCLUSION

Designing a low-carbon fleet is a process. Shipowners need to be conscious of using the lessons from the transition to decarbonization to build a cycle of continuous process improvement: they can do this by getting to know the impact of decarbonization on all aspects of their business and using that information to power the cycle.

Because the technological solutions that support the decarbonization of international shipping will continue to advance over time, so should safety strategies and a business's ability to adapt to changes with the least possible disruption.

In our two previous outlooks, we established that shipping was an integral part of the value chain, including its carbon footprint. By using carbon-accounting principles to evaluate the contribution of each link, the shipowner gains information that helps to identify areas in need of improvement, and targets for carbon offsets.

However, a harmonized decarbonization strategy is just the first step towards gaining a competitive advantage. ABS is already being asked how these strategies and principles can be used to help meet the requirements of charterers, secure access to Environmental, Social and Governance (ESG) financing and support a company's sustainability strategy.

As the end goal is for the shipowner to use their decarbonization strategy to achieve corporate targets, any plan must be designed to go beyond compliance and form the cornerstone of a company's business strategy.

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CURRENT STATE OF THE GLOBAL FLEET

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10 | ACRONYMS AND ABBREVIATIONS

ABS	American Bureau of Shipping
ACA	Accelerated Climate Action
AER	Average efficiency ratio
BAU	Business as usual
BOG	Boil-off gas
BOR	Boil-off rate
C_3H_8	Propane
C_4H_{10}	Butane
capex	Capital expenditures
CCS	Carbon capture and sequestration
CH_3OH	Methanol
CH_4	Methane
CII	Carbon Intensity Indicator
CO_2	Carbon dioxide
DCS	Data collection system
DF	Dual-fuel
DG	Diesel generators
dwt	Deadweight tonnage
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EEXI	Energy Efficiency Existing Ship Index
EPA	Environmental Protection Agency
EPL	Engine power limitation
ESG	Environmental, social, and governance
ETS	Emissions trading system
EU	European Union
FAME	Fatty Acid Methyl Esters
FGSS	Fuel gas supply system
FVT	Fuel valve train
GCU	Gas combustion units
GDP	Gross domestic product
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
gt	Gross tonnage
GVT	Gas valve train
GWP	Global warming potential
HEFA	Hydroprocessed Esters and Fatty Acids
HFO	Heavy fuel oil
HVO	Hydrotreated Vegetable Oil
IAPP	International Air Pollution Prevention
ICCT	International Council on Clean Transportation
ICE	Internal combustion engine
IEEC	International Energy Efficiency Certificate
IG	Inert gas
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IMO	International Maritime Organization
KPI	Key performance indicator
LFSS	Liquid fuel supply system
LH_2	Liquefied hydrogen
LHV	Lower heating value
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
M	Million
m^3	Cubic meters
MARPOL	International Convention for the Prevention of Pollution from Ships
MBM	Market-based measures
MCR	Maximum continuous rating
MEPC	Marine Environmental Protection Committee
MGO	Marine gas oil
Mt	Million tons
N_2O	Nitrous oxide
New EC	New European Community
NH_3	Ammonia
nm	Nautical miles
NZ	Net zero
opex	Operational expenditures
PAE	Auxiliary power component
SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific fuel oil consumption
SGFC	Specific gas fuel consumption
SHaPoLi	Shaft power limitation
SO_x	Sulfur oxide
TEU	Twenty-foot equivalent unit
TtW	Tank-to-wake
UCO	Used Cooking Oil
UNFCCC	United Nations Framework Convention on Climate Change
VLCC	Very large crude carrier
VLOC	Very large ore carrier
VLSFO	Very low sulfur fuel oil
VREF	Vessel reference speed
VSB	Virtual Sugarcane Biorefinery
WTO	World Trade Organization
WtT	Well-to-tank
WtW	Well-to-wake

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