Smart Maritime | SINTEF OCEAN | NTNU

Sea map to Green Shipping

A summary of our research on green shipping
to inspire and advise shipowners
regulators and maritime stakeholders

December 2023

ABOUT THE REPORT

This reports sums up the research on green shipping from the SFI Smart Maritime programme and associated projects [↗]. The report presents the essence of research at NTNU and SINTEF Ocean to inspire and advise ship owners, policy makers and stakeholders.

This report was written in 2022 based on research made and published in the period 2015-2022. The report has been updated in 2023 with the most recent developments on rules and regulations, political developments and findings from IPCC. The section on alternative fuels has been revised.

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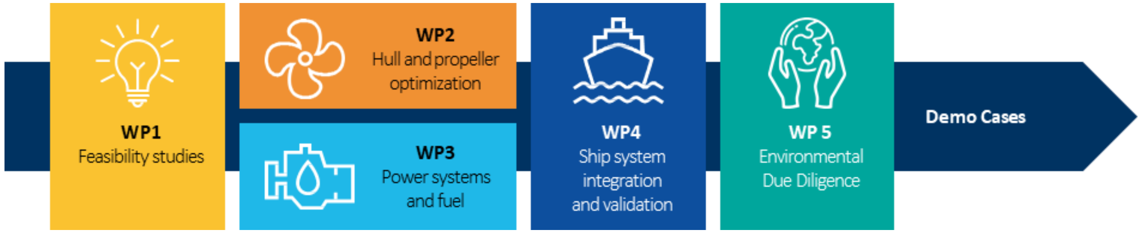
SMART MARITIME

SFI Smart Maritime is a centre for research-based innovation dedicated to improving energy efficiency and reducing harmful emissions from ships. Funded by the Research Council of Norway and Norwegian industry, it was established in 2015 to enhance the sustainability and competitiveness of the Norwegian maritime cluster.

The research is conducted in collaboration between SINTEF Ocean, NTNU and the centre's 21 partners representing the entire maritime value chain, in five interlinked work packages. Eight Norwegian ship owners with a combined fleet of abt. 800 vessels take part in the centre.



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0. EXECUTIVE SUMMARY

Each and every chapter is summarized in a blue box in the left column to present the essence to the busy reader.

Suggested *policy implications* are presented towards the end of each chapter.

Arrows ↗ in the text provide links for further reading.

Key sources are listed at the end of each chapter.

Cargo vessels, passenger ships and fishing boats emitted **1,076 million tonnes (Mt) CO_2-equivalents** in 2018, about 3% of total global CO_2-emissions.

With 1,050 Mt, CO_2 is the most important greenhouse gas from shipping, although increased use of LNG has raised concerns about methane (CH_4) emissions and new research finds that black carbon, although not a greenhouse gas by definition, has very significant contribution due to its effect on ice and snow. In addition to methane and black carbon, the advent of **new fuels will require focus on other greenhouse gases** such as nitrous oxide (N_2O) in and these must be included in regulations as well as reporting schemes and economic incentives.

About 81% of the GHG emissions from ships come from cargo vessels and only 7% from ferries, 4% from fishing vessels and 8% from service vessels such as offshore supply and tugs. Tankers, container vessels and bulk carriers are the biggest sources with 23%, 22% and 18% respectively (63% combined). 76% of shipping GHG comes from vessels with engine power 5 MW or more. To reduce shipping emissions, we must find therefor solutions for large cargo ships with large engines in international trade.

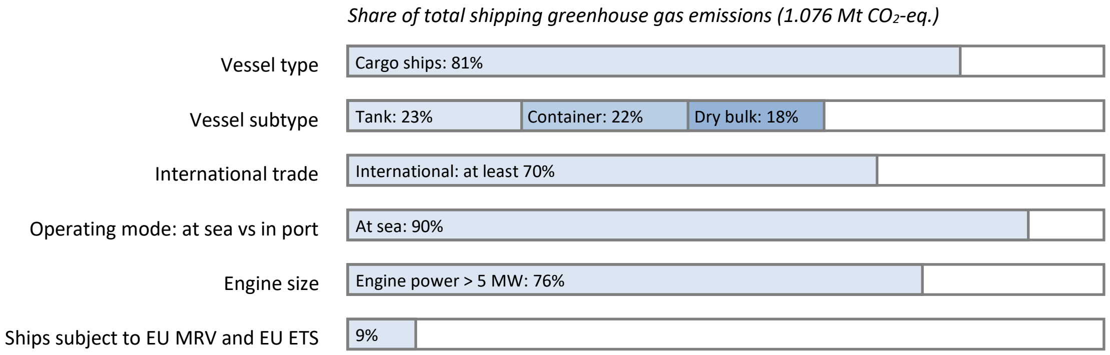


Figure 1: Breakdown of global shipping GHG.

The majority of shipping GHG (70%) is emitted from cargo ships in international trades. Large vessels spend 80-100% of their sailing time in international waters. This explains the **importance of global regulations** and the pivotal role of the International Maritime Organization (IMO), although regional emission standards in e.g., California and EU also play an important role.

Ships sailing between Norwegian ports emit at least 3 and probably 5 million t CO_2 annually, equal to 5% and 10% of the national total. Adding ships in transit and international trade, the annual emissions double to nearly 10 million t CO_2. Worldwide, emissions from ships controlled by Norwegian companies are significant. Therefore, shipping emissions should be a priority for Norway, both at home and globally.

CO_2 emissions were proportional to cargo volumes until 2008 but has since decoupled. In 2018, the carbon intensity (EEOI) was around 30% lower than in 2008, which is the reference year for international maritime emissions and the yardstick for IMO regulations on GHG. However, in absolute numbers, **emissions are climbing** again after a dip around 2010. And global warming is determined by the concentration of GHGs in the atmosphere and absolute emissions, not carbon intensity.

A significant and stable activity growth explains why emissions continue to climb despite a solid improvement in carbon intensity. Historically, maritime trade has grown proportionally to global GDP (gross domestic product) and more or less 3% on average for the last four to five decades. It is therefore very important that the revised IMO GHG strategy adopted in July2023 set goals for reduction of absolute emissions: IMO agreed to reduce GHG by at least 20% by 2030 and strive for a 30% reduction. By 2040, GHG emissions should be reduced by at least 70%, striving for 80%. Also, IMO agreed to "reach net-zero GHG emissions by or around i.e. close to 2050". While the wording is a bit complicated, the ambition and direction is set. The IMO-goals are summarized in figure 2 below. Note that the emissions trajectory between the goalposts is not set, but an indication. The emissions reduction should come gradually and not be postponed until the last minute.

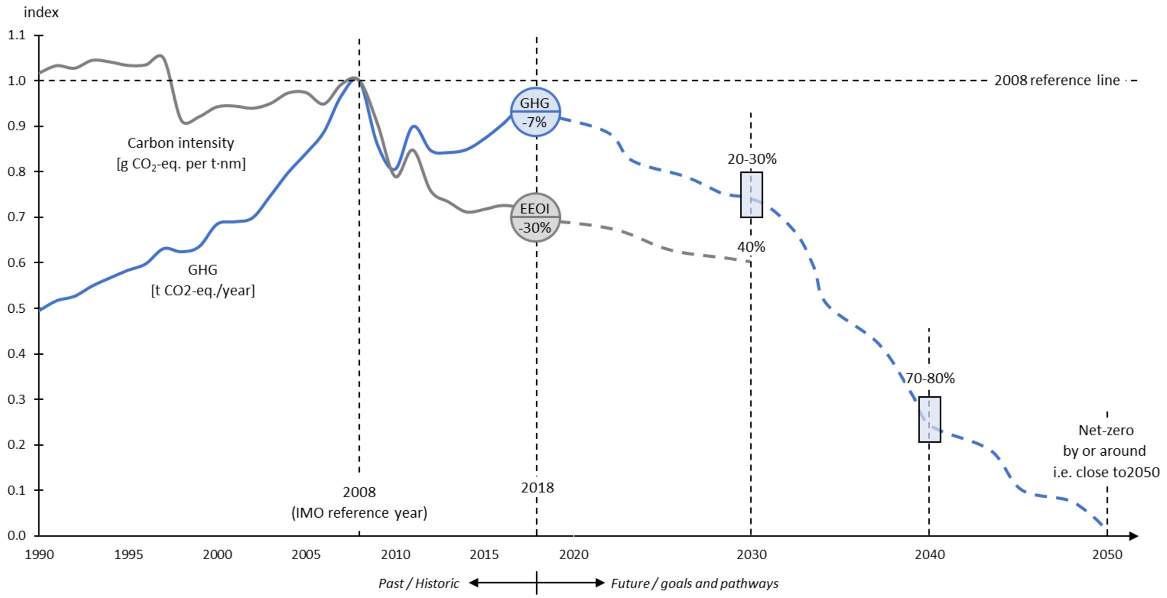


Figure 2: IMO goals for reducing greenhouse gas emissions (GHG) and the carbon intensity of ships in the revised IMO GHG strategy from 2023.

The world faces several environmental challenges at once; mismanagement of waste and intense plastic pollution of the oceans and rivers, loss of biodiversity, polluted air and unacceptable standards at most shipbreaking yards to mention the most pressing ones. We cannot fix one at the expense of another. All possible **measures to curb global warming must meet certain criteria for sustainability, circularity, and societal impact as well**.

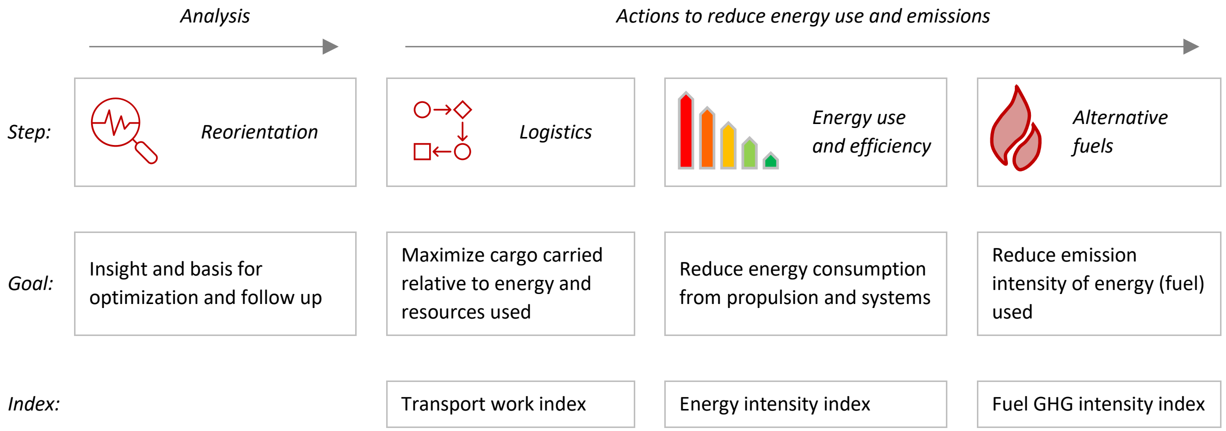
While this report focuses on solutions to limit greenhouse gases and global warming, it is very clear that our efforts here cannot have negative implications on the environment or human health. There is no more room for silo-thinking and suboptimal solutions.

Numerous reports from the Intergovernmental Panel on Climate Change (IPCC) confirm the need for immediate action. Limiting global temperature increase to 1.5°C requires around 45% reduction from 2010-levels by 2030. The very latest assessment report, the sixth since 1990, states that emissions must peak before 2025 (!) and drop by nearly 5-8% annually from 2019 to 2030 depending on activity growth. Such reductions have so far only been observed during the global pandemic.

Based on this, urgent action is needed. Non-committing goals and strategies to become climate neutral by 2050 seems very off the mark unless the path to zero begins with significant steps already today. Moderate steps today may be more valuable than goals to be climate neutral by 2050.

> *Basically, 2030 is the new 2050.*
>
> French president, Emmanuel Macron, April 2021.

Considering the diversity of the fleet and that the effect of a certain emission reduction measure depends on the ship type, size and trade, regulations should be **goal oriented and technology and fuel neutral**. To support this, we suggest a four-step approach to decarbonization to leverage a wide array of measures to reduce energy use and emissions. This approach acknowledges the fact that the world shipping fleet is diverse. The total carbon intensity can be broken down to reflect progress within these three areas; logistics, energy efficiency and alternative fuels to provide more detailed guidance.



Step:	*Reorientation*	*Logistics*	*Energy use and efficiency*	*Alternative fuels*
Goal:	Insight and basis for optimization and follow up	Maximize cargo carried relative to energy and resources used	Reduce energy consumption from propulsion and systems	Reduce emission intensity of energy (fuel) used
Index:		Transport work index	Energy intensity index	Fuel GHG intensity index

Figure 3: The Smart Maritime four step approach.

In chapter 4, we outline the approach step by step and give an overview of several, though not all, measures as inspiration and framework for crafting a decarbonization strategy.

REORIENTATION (step 1)

Every strategy process should start with an analysis of status quo including external and internal factors at the macro and micro level. To help operators and regulators to steer towards significant and meaningful decarbonization, we see a need for a serious **reorientation**; a fundamental change of thinking on eight areas (ref below illustration) is necessary.

1. First of all, we must include all greenhouse gases such as methane and N_2O in addition to CO_2 in emission inventories, regulations, and economic incentive schemes. A lenient view on methane emissions from gas engines have made this the Achilles heel of natural gas. History can repeat itself if we do not address N_2O from ammonia, though the consequence is much worse due to the higher global warming potential: 273 vs 29.8. So far, CO2 has dominated with 98% of shipping's GHG, but the advent of new fuels will change this.

2. All fuels must be evaluated in a life cycle perspective (well to wake, WTW) based on emissions throughout the value chain including production, conversion, distribution and bunkering as well as onboard use. Emissions of hydrogen, ammonia, methanol, synthetic fuels and biofuels are determined by the production method. A narrow focus on emissions onboard (tank to wake, TTW) risks shifting emissions from the vessel to the energy sector.

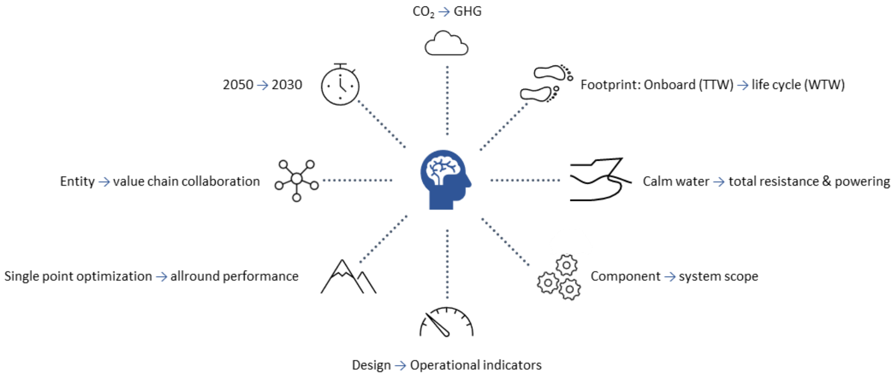


Figure 4: Eight areas where reorientation is necessary.

3. Most of the energy consumed by ships are for propulsion. While hydrodynamic and aerodynamic resistance in calm water and little wind are important, the added resistance from waves and wind can be significant. Optimizing main dimensions and hull shape for the expected wave and wind conditions can pay off. Digital tools as well as model testing are both useful, at different stages of the design process.

4. A wholistic approach is necessary as machinery systems become increasingly complex. Waste heat can be utilized and the cold from LNG-tanks can be useful in reefers or fishing trawlers. Batteries can enhance the fuel consumption of generator sets. The system becomes more important than the individual components.

5. Emissions indicators must reflect reality as much as possible. While design indicators (e.g. the EEDI and EEXI) are useful, they should be considered mere starting points. Only **operational indicators** (in particular EEOI) will paint a complete picture. Operational indicators should be based on the actual rather than calculated fuel consumption and emissions and reflect the actual rather than the theoretical transport work. Such indicators are necessary to ensure good correlation between indicators and real emissions. To be concrete; the EEOI are better than the AER.

The current EEOI (energy efficiency operational index), should be amended to include all relevant greenhouse gases in a well to wake perspective. We can call this a Climate Intensity Operational Indicator (ref chapter 6.3). The index can be broken down into three subindexes to reflect progress in logistics, energy use and fuels to help operators identify strong and weak areas in their operation. While the EEOI makes shipowners responsible for external factors, it also rewards them for all sorts of efforts, including operational measures which are often cheaper and quicker to implement.

Operational indicators reflect reality, awards more ways to reduce emissions, both technical and operational measures which encourages a wholistic view and innovation, recognizes the diversity of the fleet, and supports the most cost-effective measures.

6. We live in changing times and we see merit in flexible ship designs and machinery configurations. Most ships sail at reduced speed and at 40-60% engine load, where the specific fuel consumption and emission factors are typically much higher. Flexibility must be balanced against optimization.

7. Zero emission vessels will likely be more expensive to build and operate and **long charter parties and collaborations will likely be necessary to justify investments** in better ships and fuels. Risks and costs must be shared. Charterers can impact the energy use and emissions by their sailing instructions and ultimately on the carbon intensity indicator. Because new fuels will be available only in select ports, ships sailing on fixed routes will be the first ones to transition to new fuels. Coordination between ship and port will also be advantageous, both to reduce time in port and to secure new fuels. Business models building on standard vessels, asset play and low freight rates as the main competitive argument will be barriers.

8. Finally, operators and regulators alike must focus more on 2030 and less on 2050. We do not know how close we are to releasing irreversible tipping points.

The IPCC calls for deep, rapid and sustained emission reductions. We should therefore evaluate all measures to reduce emissions based on their potential but also based on the realistic implementation schedule; which is determined by the technical maturity (TRL) and availability.

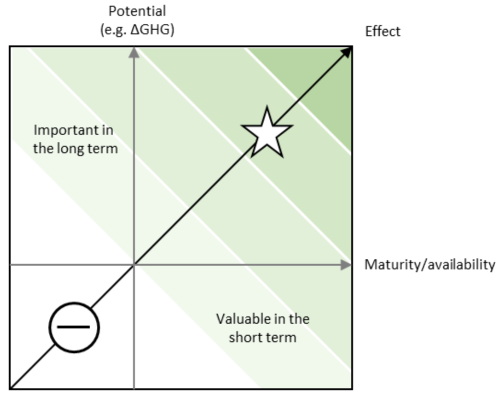


Figure 5: Two factors for evaluation of environmental measures (technology, procedures, fuels etc).

LOGISTICS (step 2)

The hunt for lower emissions begins by setting up an operation that maximizes the transport work while minimizing energy use and emissions. Some vessel types have so far been optimized for cargo intake on the expense of energy efficiency. This must now change.

Ships are means of transportation and the most energy efficient option with the lowest carbon intensity. Even the smaller vessel categories offer **around 70% lower CO_2 per tonne cargo per nautical mile** (ref chapter 7.1). Shifting cargo from road t sea or rail can reduce transport emissions considerably. Road transportation is also a major source of micro plastics and particles from wear and tear of tires and asphalt. Ships move around 1/3 of cargoes within Norway and the EU. Not all cargoes can be shifted to sea, naturally. Despite political intentions, seaborne transportation in Norway grew at only 2.3% per year compared to 4.6% for road.

The average ship has grown in size as the scale effects are significant. At the time of writing, the growth is especially noteworthy for container vessels, but also other ship types continue to grow. The largest vessels must, however, be filled up with cargo. Operational indicators based on cargo carried are especially important to ensure that estimated scale effects are indeed realized; only the EEOI reflects actual cargo hold utilisation.

Speed has direct bearing on energy and emissions and mandatory slow steaming is by many seen to give immediate effects for all vessel types. Our research paints a more nuanced picture and points to some factors that are rarely factored in in the many analyses of the subject. First, **reducing speed from 25 to 20 knots (20%) will give better results than from 20 to 16 knots (also 20%)**. The lower the speed, the smaller effect. This is due to the fact that the speed/power coefficient is less than 3 at lower speed ranges and that the constant energy demand from ship systems at sea and in port is not reduced proportionally. Also, transport work is reduced, and emission factors are generally higher at part loads.

Finally, emissions from building more vessels to compensate for the lower transport work must be added. A fixed speed limit will lead to a construction boom that will set us a few years back in terms of total GHG. This is counterproductive, given that emissions must peak before 2025 and must be reduced urgently to avoid tipping points.

Emissions should be regulated directly and not by means of a proxy parameter such as speed, to encourage innovation and motivate the use of effective operational and technical measures.

The **Northern Sea Route offers a shorter route from Europe to the Far East**. With region specific GWP characterization factors, we find that the stronger impact of black carbon from combustion of fossil fuels in the Arctic more than cancels out the advantage in distance and fuel consumption. Cleaner fuels are necessary if the Northern Sea Route shall be used.

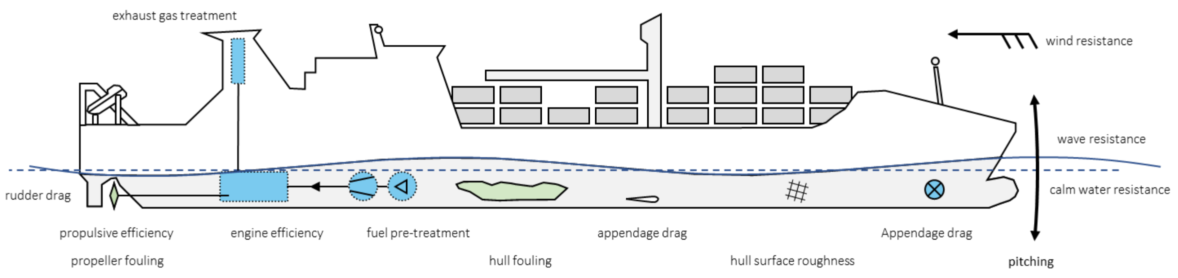
Weather routing is important for avoiding foul weather but depends on accurate modelling of the vessel's response to waves and wind. This can be achieved by profound understanding of the drivers behind resistance and propulsive efficiency or through analysis of operational data.

ENERGY USE AND EFFICIENCY (step 3)

Most alternative fuels are expensive, occupies a lot more space onboard, carry new safety risks and require new systems and partly modified machinery. They are available only in minuscule volumes and many have higher GHG emissions than marine gas oil due to high energy use in production. It is therefore **critical to reduce the use of alternative fuels to a minimum**.

The total carbon intensity (EEOI) of the global shipping fleet has improved by nearly 30% from 2008 to 2018, though there is significant variation between vessel types and sizes. Many of the low hanging fruits have been picked and the next 30% will likely be more difficult. There are, luckily, many measures available but most require more efforts and some sacrifices.

Efforts to reduce energy use should start by mapping main energy consumers and their drivers; the most important ones are shown in the below illustration.



Main resistance components and energy consumers when sailing

Energy consumed by ships' ancillary systems at sea and or in port

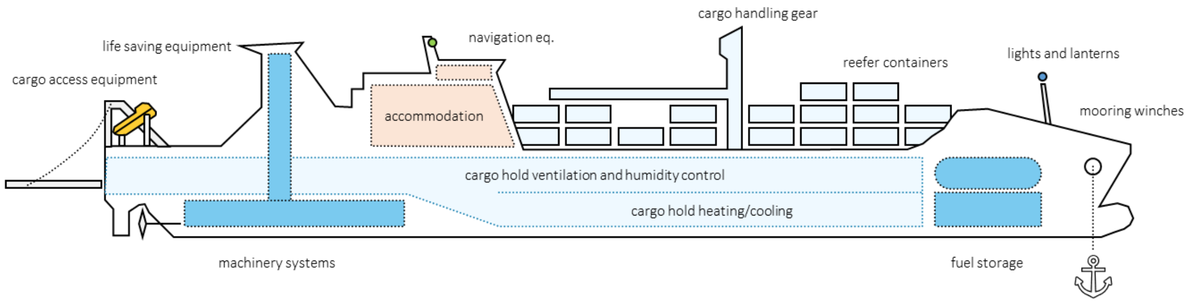


Figure 6: Drivers for energy consumption of ships

Main dimensions are often determined by convention as shipyards, ports and brokers prefer standard sizes. Thinking outside the box– literally – can reduce energy use and thus energy cost and emissions significantly. Some designs have main dimensions and hull form to maximize cargo intake, minimize construction cost at the expense of hydrodynamic performance.

A slender hull, i.e. a finer entrance and smaller prismatic coefficient can reduce propulsion power by more than 20%. The effect is more pronounced for ships sailing at high speeds and for ships currently suffering from very hard main dimension restrictions. Small cargo vessels and fishing vessels are among these.

For existing ships, local changes in the bow or stern can have some impact. The bulbous bow can be modified to suit the current draughts and speeds and replaced in a dry-dock.

SINTEF Ocean and NTNU have developed tools to test run digital twins of hulls with variations in main dimensions and hull shape in realistic waves and wind to quantify the effect for a particular trade. These digital tools complement our model test facilities where we have tested around 8,000 hull forms since 1939. The new Ocean Space centre will enable even better testing and optimization, especially in oblique waves which generally have the most severe impact on speed and power.

Viscous resistance caused by friction between the water and the hull is the most important resistance parameter for most vessels. It can be reduced at the design stage by minimizing wetted surface area, during construction by low surface roughness, in operation by effective anti-fouling and or hull cleaning and in dry dock by blasting. Fouling can add as much as 20% to the calm water resistances between dockings. Air lubrication reduces the viscous resistance. The effect is best for higher speeds and vessels with large flat bottom.

A propeller achieves high propulsive efficiency (η_O and η_R) with **large diameter, few propeller blades, slow turning speed (RPM) and good inflow**. In reality, the propeller design is limited by draught, hull clearance and requirements to pressure pulses. SINTEF Ocean has tested more than 1,600 propeller designs since 1939. Twin screw and contra rotating propellers can improve the propulsive efficiency. Also, there are numerous devices to improve the flow around the propeller. Their effect depends on the hull shape, the propeller load and must always be investigated for the particular case.

Sails are returning to commercial shipping after a more than hundred years break. There are numerous variants to choose from, each with their pros and cons. Through calculations and model tests, we found that **sails can deliver up to half the propulsion power required for a large bulk carrier**, if the hull is designed with sufficient stability and rudder. Sails will give heeling moments but reduce roll and thus increase comfort. Testing of hydrodynamic and aerodynamic properties simultaneously is difficult, so we developed hybrid testing where the wind forces are calculated and applied by wires to a physical hull model. Weather routing is essential when sailing, to find favourable wind.

Sails are more effective at slow speeds. Needless to say, sailing in windy areas is a prerequisite, so is a flexible schedule, ample deck space, good stability and a decent rudder to counter drift. **Sails can be retrofitted** if the original hull has these qualities.

The **thermal efficiency of the combustion engine is mainly determined by the stroke/bore ratio and the speed** (RPM). In recent year, most engines run at close to half load, where the specific fuel consumption and emission factors are quite different, for example, **NO_X-emissions can be 50% higher at part loads**. We have mapped specific fuel consumption and emission factors at part loads to improve the accuracy of emission calculations.

Machinery systems are becoming increasingly complex. Batteries and shaft generators with PTO/PTI-functionality as well as waste heat recovery can help to increase the total system efficiency, especially at part loads. We developed a digital simulation tool; Fuel, Energy and Emissions Prediction for Maritime Energy System **(FEEMS) to calculate the total losses in such complex machinery installations** and thus help to find the best machinery configuration for a given operation. This can help shipowners to quickly ascertain the advantages of a machinery arrangement proposed by a shipyard or to investigate how big a battery should be to avoid idling of generator set no. 2.

ALTERNATIVE FUELS (step 4)

When energy demand has been minimized, a fuel with low, near zero or zero footprint from well to wake is needed to reduce emissions further or eliminate them altogether. Fuels can be categorized as follows although there is no universally accepted definition of *low* and *near zero* emission fuels. Note also that some fuels where the negative emissions in production cancel the positive emissions in use are categorized as *net zero* fuels.

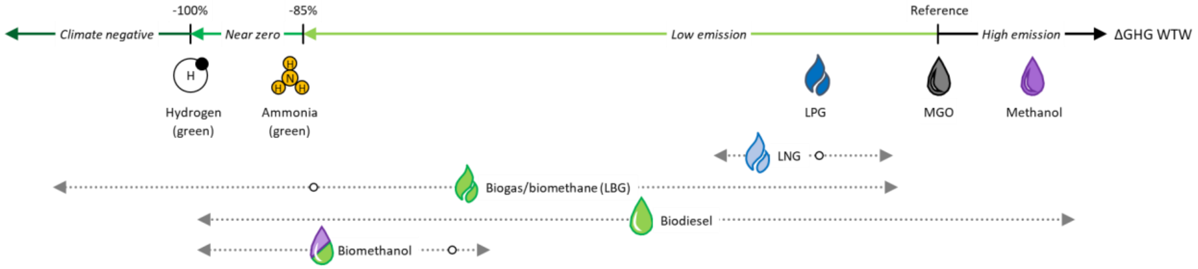


Figure 7: Overview and classification of alternative fuels.

The footprint well to tank depends on the raw material and the production process. There are **multiple variants of methanol, gaseous and liquid biofuels, hydrogen and ammonia**. There is even remarkable variation in the footprint of LNG, depending on the origin, production process and methane leakage in production and distribution. This confirms the importance of evaluating all fuels in a **life cycle perspective (well to wake)** and factor in the specificities of the fuel source, production, and distribution.

Fossil liquid oils currently provide about 96% of the energy consumed by ships. Marine gas oil (MGO) will likely become more important and the de facto standard fuel of the future due to the sulphur limits introduced in 2020, and therefore the basis for comparison in our analysis. In 2018, MDO/MGO covered 32% of the energy and the share grew by 51% from 2012 to 2018. LNG provides 4% of maritime fuels. A very limited number of vessels run on LPG and methanol, mainly only vessels carrying LPG and methanol as a cargo. With the exception of a handful of vessels piloting biofuels and hydrogen, the fuel transition has note really begun for large vessels.

Both environmental, technical, practical, safety, sustainability and economic criteria are relevant when evaluating alternative fuels (these are listed in chapter 9). In addition to the emission reduction potential, practical aspects such as rules and regulations for safe construction and operation, crew competence, maintenance and dry docking, reliability and need for redundancy, safety for crew, passengers and terminal workers must be considered. The motivation for the energy transition is to reduce GHG emissions and, simultaneously, minimize or eliminate pollutants detrimental to people and nature such as NO_X, SO_X and particles.

At the same time, **we must be mindful of the energy losses caused in the production of alternative fuels.** Today, only 14% of the global primary energy is renewable. Nuclear energy adds another 5%. Even Norway, blessed with renewable hydropower, draws only around half its energy from fossil sources, and the renewable share is growing very slowly if at all! So, energy efficiency will likely remain a concern and a priority for decades to come.

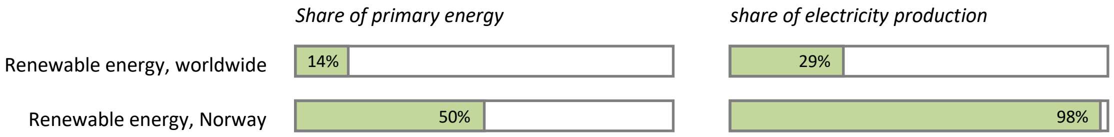


Figure 8: Share of renewables

The following diagram (fig. 9) shows the energy efficiency well to wake (y-axis) and the GHG emissions well to wake (x-axis) relative to MGO. The best fuels are in the upper left corner; combining low GHG emissions with high energy efficiency.

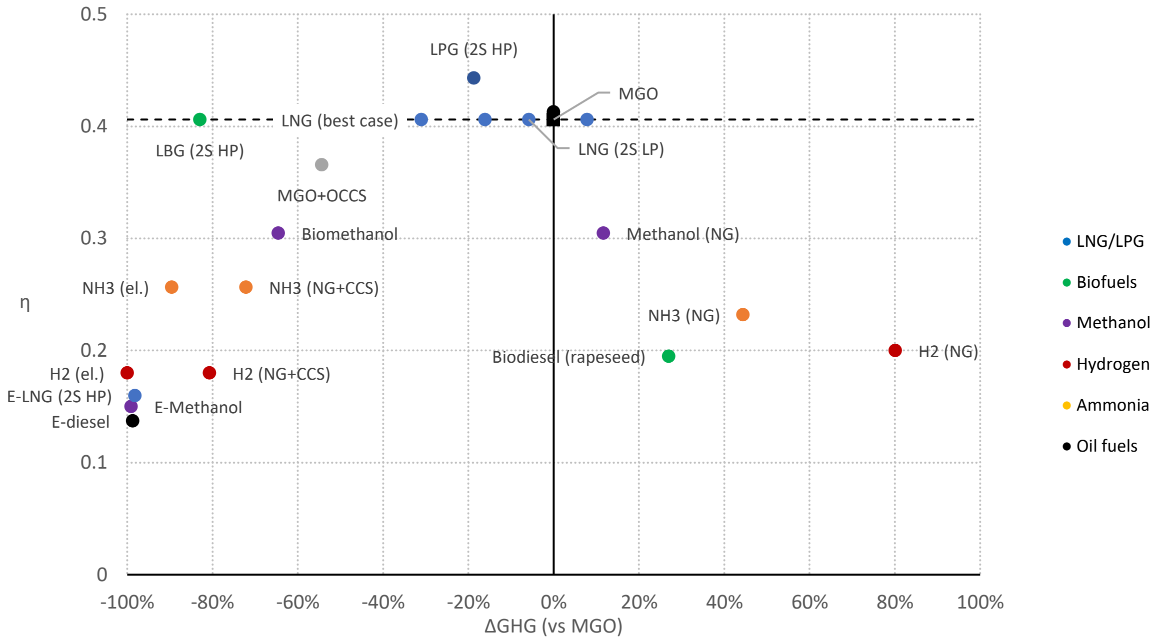


Figure 9: Climate effect relative to MGO and energy efficiency for various alternative fuels

Methanol is a convenient maritime fuel as it stores easily and requires manageable modification of main engine and systems. However, **methanol gives (12%) higher emissions well to wake** than MGO unless the biological variant (biomethanol) or the synthetic variant (e-methanol) is used. Biomethanol combines low emissions with reasonable energy efficiency while synthetic methanol is very energy demanding in production.

LNG is the most popular alternative fuel to date; in use on around 350 vessels plus all LNG carriers and specified for more than 500 new vessels, yet it covers only about 4% of the energy consumed by ships worldwide. LNG was originally appreciated for lack of soot,

SO_X and NO_X (NO_X formation depends on the engine type, though). LNG reduces GHG by 6-16% depending on the engine type used and up to 30% if the production footprint is low and methane slip is avoided throughout the value chain.

The significant **methane slip from low pressure engines can cancel out a lot of the CO_2 advantage**. LNG is by many considered insufficient and a fossil fuel with no place in the future fuel mix. We see a role for LNG as a steppingstone to biomethane or hydrogen. It will take a long time to build up large production capacity for these two fuels and a backup fuel will be required in this period and outside the regions where biomethane and hydrogen becomes available first. LNG can be blended with up to 25% hydrogen and at any ratio with biomethane. Gas engines are a good starting point for hydrogen and onshore infrastructure for natural gas can be converted to carry hydrogen.

Biomethane (LBG) can be produced from a range of organic raw materials, wastes and byproducts. This should allow production almost anywhere in the world and contributes to better waste handling as well. **The climate effect of biomethane depends on the raw material and the process and about be up to 200%**, at best. Biomethane is methane and utilize the same infrastructure and systems as natural gas, on shore and onboard. Sourcing of organic material must adhere to **sustainability standards**; deforestation and reduction of arable land are the major pitfalls. Standards such as the EU Renewable Energy Directive addresses this.

There are very many different biomethane and liquid biofuels and their GHG-effect and sustainability depend on the type and origin of the biological material as well as the production method.

LPG is the most energy efficient fuel of all and offers 17% lower GHG well to wake. It is clean burning, though after treatment of NOX is necessary with high pressure engines. LPG is a maritime cargo and increasingly popular for LPG carriers.

Hydrogen does not contain carbon and thus gives no harmful emissions onboard. The environmental impact is determined by the energy intensive production. Current production is based on reformation of natural gas and gasification of coal which gives hydrogen 60% higher GHG emissions than MGO well to wake. **To be a low carbon fuel, hydrogen requires renewable energy electricity or carbon capture and storage (CCS) with high capture rates.** Bunkering, storage and handling of pure liquid hydrogen is complicated and introduces new safety concerns. Hydrogen storage requires 4-7 times the volume of MGO and a temperature of -253°C.

Ammonia (NH_3) is a way to store hydrogen. The downside of ammonia is the possible formation of N_2O, a very powerful greenhouse gas, and NO_X. Also, ammonia must be cracked if fed to ta fuel cell. While PEM (proton exchange membranes) are more mature, these are less fit for ammonia due to their very low tolerances for impurities. Solid oxide fuel cells (SOFC) are under development, but much less mature than PEM. Ammonia has its safety challenges; it is toxic, colourless and corrosive.

Electricity offers the lowest conversion losses; batteries and an electric drive train utilizes about 80-90% of the energy in the battery compared to 40-50% for conventional combustion engines and 40-60% for fuel cells. This is the key argument for using electricity from batteries where possible. Fully electric operation also avoids any local air pollutants. With no emissions in use, the production footprint determines its well to wake emissions. Norwegian electricity has a footprint of approximately 10 g CO_2-equivalents per kWh, while the global average is 441 g. An electric ferry therefore does not make sense everywhere. **Batteries weigh 30-70 times as much as diesel and occupy 40-65 times as much space** onboard. This makes batteries practical only on ships with very limited energy demand, i.e. low engine power, short sailings and frequent charging opportunities. The emissions coming from production of batteries cannot be ignored, neither can the working conditions in the mines where the necessary metals are extracted.

New fuels require modified or new systems for power conversion. There are already options available for LNG, LPG and methanol.

Most are dual fuel, with MGO as backup. Around 85% of the gas engines in ships are dual fuel; this documents ship **owners' appreciation of a backup fuel**. Nearly all major engine makers have signalled intent to develop internal combustion engines for future use of ammonia (four stroke and two stroke) and hydrogen (four stroke only). Existing gas engines from Wärtsilä can already today take up to 25% hydrogen. A modified combustion engine will likely require less research and development and be ready for production in large sizes and large quantities earlier than fuel cells. It is proven technology well known among engineers.

Fuel cells are currently available up to 1-2 MW with 3 MW expected in the near future. PEM cells are more mature than SOFC, which require quite a lot of further work to be available in large sizes for marine applications. Fuel cells rely on complex systems for load sharing and cooling. Batteries will be necessary to take load variations and assist when starting and stopping. The efficiency of fuel cells is expected to be higher than for engines but remains to be confirmed onboard.

Based on the review of alternative fuels, we highlight some aspects a robust energy transition strategy should consider in chapter 9.15: The transition must begin immediately, energy use must be minimized, and arrangements must be made for using more than one fuel. A **gradual transition with blends or intermittent use of multiple fuels will allow the production side to scale up** production capacity and infrastructure and avoid price shocks for operators and cargo owners alike.

A very critical aspect often forgotten in the discussion on alternative fuels and fuel transition strategies is the time aspect; **when can each of the alternative fuels be phased in?** The near-term feasibility is a product of the fuel availability and the technical maturity level, i.e. availability of machinery, storage tanks and systems, as illustrated by the below diagram (fig. 10). Note that the position of each fuel is approximate/indicative and subject to change.

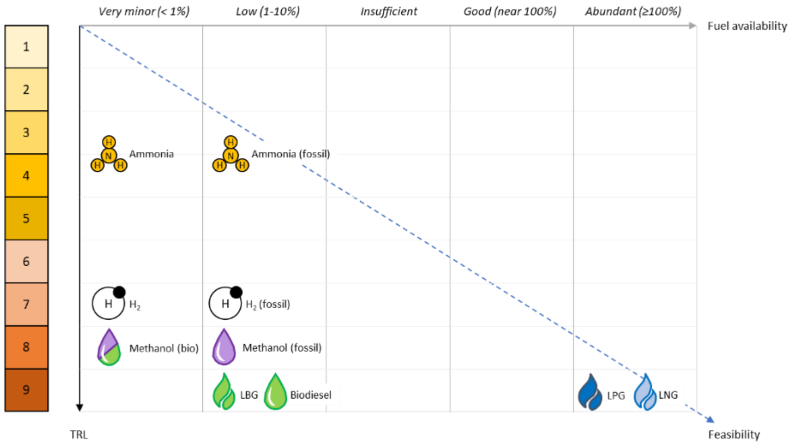


Figure 10: Near-term feasibility of alternative fuels based on technical maturity and fuel availability.

Alternative fuels should be **evaluated by accumulated emissions over a relevant time period** rather than the annual emissions in a given year so that the feasibility and realistic phase in schedule is reflected. Based on maturity of technology and fuel availability we assume that biomethane can be phased in from 2026, biomethanol and synthetic fuels from 2027, hydrogen and ammonia from 2030.

We outline eight fuel transition strategies; the position from left to right indicate the potential GHG emission reduction, the continuous lines indicate the transition, and the dotted lines indicate further combinations that are technically possible. We calculated the accumulated emissions reduction over the 30-year lifetime for each strategy, based on the above feasibility.

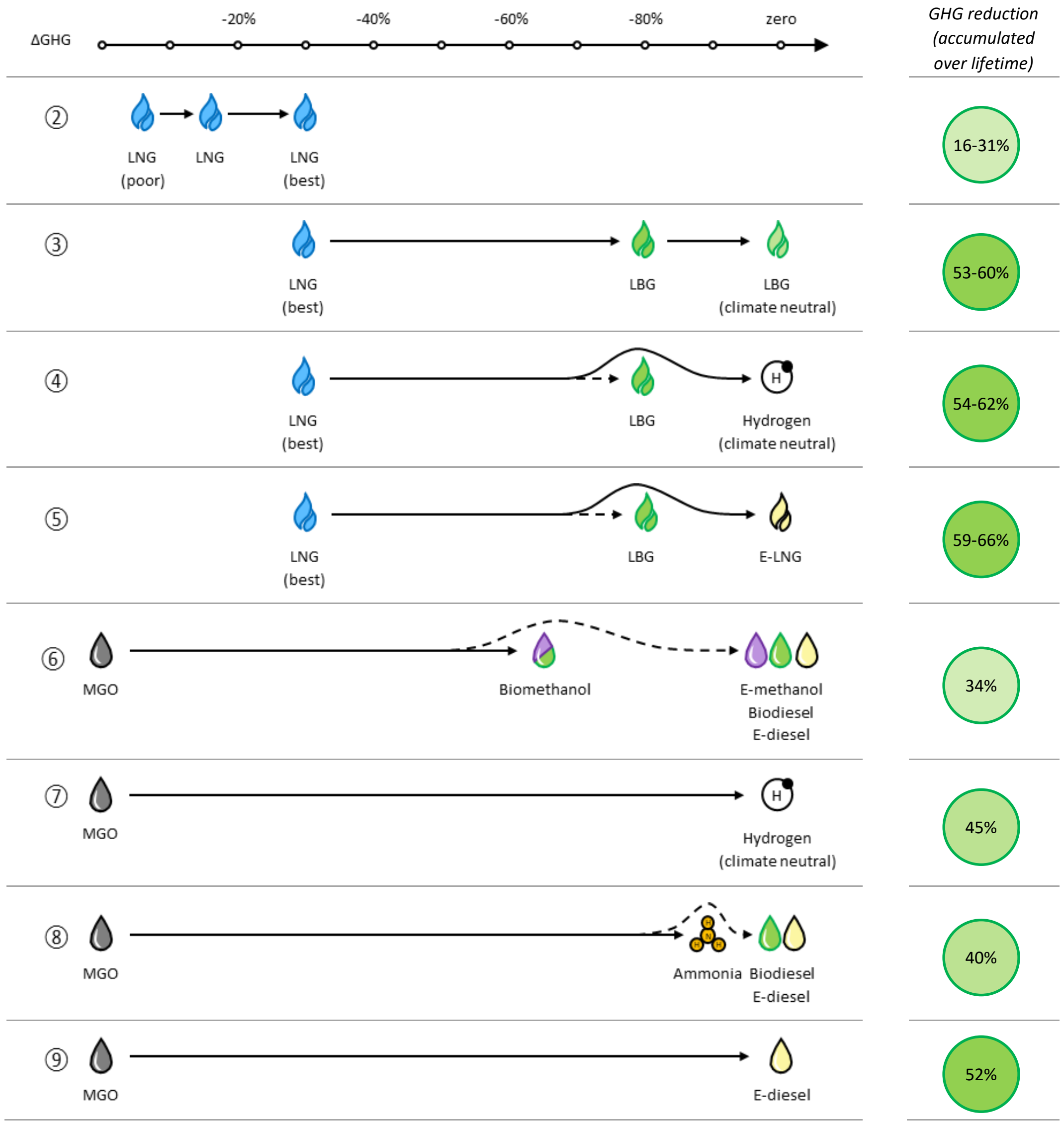


Figure 11: Eight fuel transition pathways.

We find that the paths involving an early uptake of LNG (strategy 2-5) give lower accumulated emissions over a thirty-year period (2025-2054) than the paths that wait for several years for a zero emission fuel to become feasible. We emphasize that support for LNG in strategy 2-5 hinges avoiding methane slip altogether both in production, distribution, and use.

Also, LNG should not be the end station, but an enabler of and steppingstone to greener fuels.

SEA MAPS: COMBINATIONS OF MEASURES

To demonstrate how the pieces of the puzzle can be combined, using the four-step approach, we lay out two example pathways to decarbonization for two very different vessel types at each end of the spectrum; coastal general cargo ships and deepsea dry bulkers. These sea maps or pathways document how many different technical improvements can play together to reduce carbon intensity by 65% by 2030 and 85% by 2050.

Note that the goal *IPCC 2030* on the below scale refers to the emission reduction required per vessel if the shipping industry collectively should reach 45% lower emissions when growth in seaborne trade and maritime activity is factored in.

Regulations and economic incentives should be goal oriented and technology and fuel neutral to encourage innovation and ensure that the most cost-effective solutions are adopted.

Reducing energy use and emissions significantly will likely require many different technical and operation measures. What seems promising and practical for a coastal general cargo vessel may not make sense for a bulker wilt iron ore from Australia to China. Governments and regulators should therefore support many different initiatives and technologies through technology-neutral and goal-based regulations. Each chapter is this report is concluded with a section policy implications explaining how regulators can support shipping's decarbonization efforts.

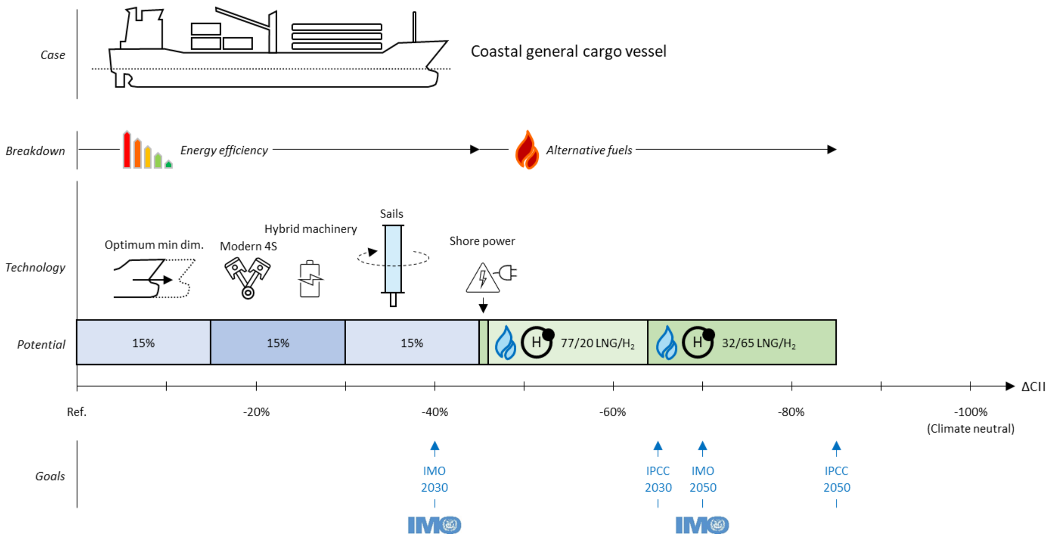


Figure 12: Sea map for a coastal general cargo vessel.

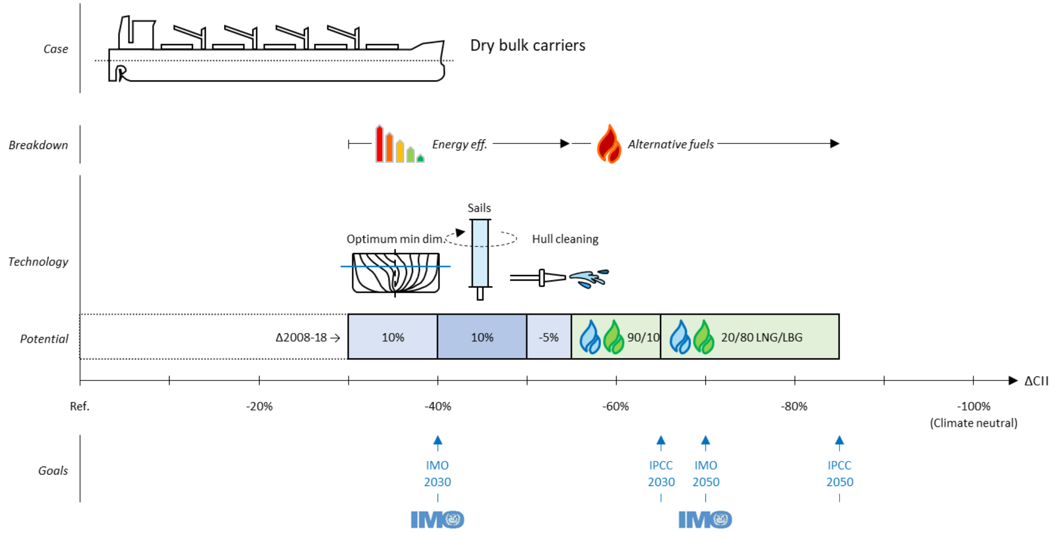


Figure 13: Sea map for a large dry bulk carrier operating worldwide.

Photo: Grieg Star
Vessel Star Lindesnes in port

1. OVERVIEW AND TABLE OF CONTENT

Each and every chapter is summarized in a blue box in the left column to present the essence to the busy reader.

Suggested *policy implications* are presented towards the end of each chapter.

Arrows (↗) in the text provide links for further reading and key sources are listed at the end of each chapter.

① **Summary**

BACKGROUND AND CONTEXT

② **Global warming: Code red**

To put the shipping industry's decarbonization efforts in context, we begin by looking at shipping emissions, development over time, its share of transport emissions and global emissions. We break down emissions into national/international emissions and port emissions and examine the contribution from each ship type, to understand where we must concentrate our efforts. We review relevant GHG-regulations and policies and question if the current IMO GHG-strategy is enough and Paris compliant.

③ **The shipping industry**

Understanding the characteristics and diversity of the industry is essential to find solutions that work, so we look at the role of ships, four distinct operations and some key numbers describing the world fleet.

④ **Four steps to green shipping**

The fleet is too diverse and the challenge too big for a single, silver bullet. A structured four-step approach to greener shipping to leverage all types of emission reducing measures in a cost-effective way. We present an overview of relevant measures, and their potential.

⑤ **Digital tools for green shipping**

While model testing continues to prove important, simulated sailings with a digital twin allows optimization of hull and machinery before the ship model and finally the vessel itself hits the water.

THE FOUR-STEP APPROACH

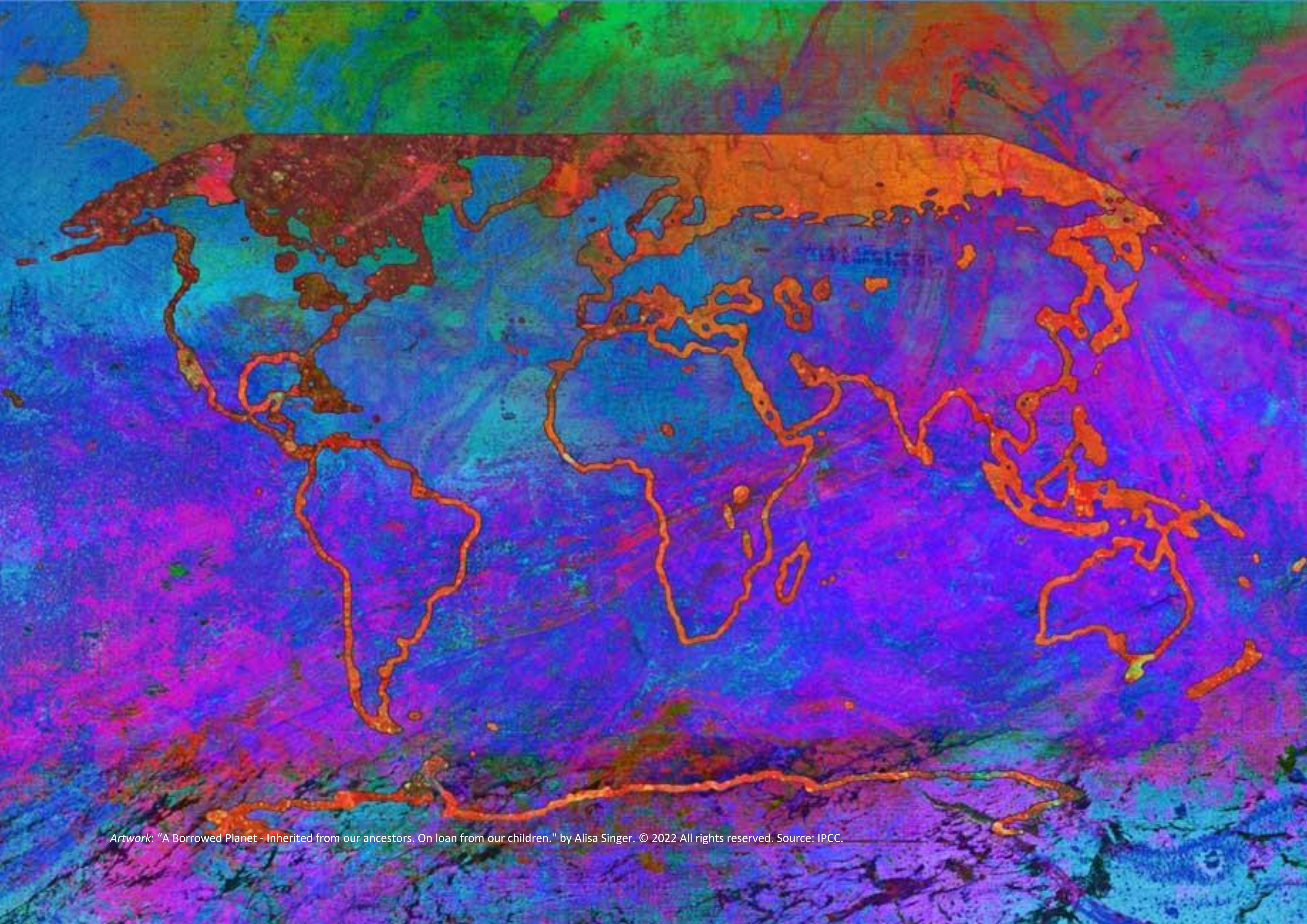
⑥ **Reorientation**

Step 1: A fundamental change of thinking and approach is necessary to transform shipping from 100% fossil fuelled to zero emission in one or two decades. To deliver substantial and actual emissions cuts, our focus must shift in a number of areas: from CO_2 to all GHGs, from tank-to-wake to well-to-wake (WTW) perspective, from calm water to total resistance and powering. Indicators reflecting reality must be used. Collaboration and long termism must replace silo thinking and asset play to align interests.

⑦	Logistics	Step 2: Before looking at the vessel, optimizing the operations can be helpful. We compare ships with road and rail and examine the advantage of larger vessels. High utilization, sailing speed and smart voyage planning improves the carbon intensity.
⑧	Energy use and efficiency	Step 3: As renewable energy is scarce and alternative fuels have their disadvantages, energy efficiency is essential. We examine some ways to reduce energy use; optimization of main dimensions and hull form, minimizing frictional resistance and maximising the propulsive and machinery efficiency
⑨	Alternative fuels	Step 4: With energy use minimized, whatever energy is required should come from climate neutral and sustainable fuels. We evaluate the options based on emissions well to wake, energy use and losses and practical aspects such as space. We look at transition pathways that can be implemented quickly by using blends or multiple fuels. Noting the diversity of the fleet, we point out likely first mover segments

CONCLUSIONS AND RECOMMMENDATIONS

⑩	Sea maps to decarbonization	Using the technologies, operational practices and new fuels discussed in chapter 7-9 as building blocks, we suggest concrete pathways to 2030 and 2050 for two cases on each end of the spectrum, as examples; a small general cargo vessel in coastal trade and a large bulker in global trade.
	Policy implications	At the end of each chapter, based on our research, we suggest policies and regulations, at international, regional and national level that can promote green shipping.
⑪	Dictionary	Abbreviations and nomenclature with definitions and short explanations of key terms.



Artwork: “A Borrowed Planet - Inherited from our ancestors. On loan from our children." by Alisa Singer. © 2022 All rights reserved. Source: IPCC.

2. GLOBAL WARMING: CODE RED

SUMMARY

In this section, we take stock of the situation we are in with regards to global warming, to understand the magnitude and the urgency of the problem.

GHG emissions must drop by 45% from 2010 to 2030 to limit warming to 1.5° and by 25% to stay within 2°. This translates to around 6% reduction per year, every year from now to 2030.

Exceeding 1.5° can trigger tipping points with unknown, irreversible effect. Current policies and national pledges indicate up to 3°C warming or more, though the estimates are highly uncertain.

Climate pledges and policies are uncertain and so is the climate systems response. We simply do not know exactly how nature will respond to warmer climate. The precautionary principle instructs us to err on the safe side.

Shipping emissions have dropped in relative terms (emissions relative to transport work) over the past 20 years but not in absolute figures (tonnes). While CO_2 is the most important greenhouse gas, black carbon is more important than previously thought, methane is still rising and N_2O may be more important if or once ammonia becomes a fuel.

Concentrations of carbon dioxide (CO_2) are driving air and sea temperatures up, with negative effects on weather systems, crops, precipitation, flora and fauna, biodiversity and sea ice. Global warming not only affects nature and the ecosystems, but has indirect effect on people, migration, economy and security. Global warming somehow affects us all. Climate change is also recognized as a major risk for the economy [WEF | ↗] and global security [e.g. BBC, Oct 2021 | ↗], [US Director of National Intelligence, Oct 2021 | ↗].

The average global air temperature has already increased by around one degree [IPCC SR1,5, C1 | ↗], while the temperature increase in the Arctic is twice the global average [IPCC SROCC SPM, A1.4 | ↗]. The Arctic sea ice covers a smaller area than it has in the last 1,450 years [Kinnard et al, 2011 | ↗] and the Arctic will likely be ice-free in the summer in 2050. The Arctic Sea warms more than twice as fast as the global average. The Barents Sea and Kara Sea will be 5°C and 4°C warmer by the end of the century, respectively [Shi et al, 2022 | ↗]. Worryingly, global greenhouse gas (GHG) emissions continue to grow [Our world in data | ↗] and the CO_2-concentration in the atmosphere increases, and at a higher pace than before [NOAA | ↗].

184 countries signed the Paris Agreement in 2015 to limit global warming to limit global warming to 2°C compared to pre-industrial levels and endeavour to keep it below 1.5°C. Yet, few of the submitted national action plans live up the commitments made. Even all the pledges to reach net zero emissions by 2050 are not enough [Climate Action Tracker, 9 Nov 2021 | ↗].

GHG emissions must drop by 45% from 2010 to 2030 to limit warming to 1.5°C and by 25% to stay within 2°, IPCC said in its special report from 2018. The message was reiterated in the 6th assessment report in 2022; GHG must drop by 43% from 2019 to 2030 and by 84% from 2019 to 2050 to limit global warming to 1.5°C [IPCC AR6 WG3 SPM, C.1.1 | ↗]. These percentages can be considered good guidelines for sectoral initiatives and companies who want to contribute their fair share.

> *The next few years are probably the most important in our history. Emission of CO_2 would need to fall by about 45 percent from 2010 levels by 2030, reaching 'net zero' around 2050.*
>
> UN IPCC's Special Report on Global Warming of 1.5°, October 2018
> [IPCC SR1,5, C1 | ↗]

The UNEP's emissions gap report and the Climate Action Tracker suggest we are on track for 2.7°C warming by the end of the century [UN Emissions Gap Report 2021 | ↗], [Climate Action tracker, 9 Nov 2021 | ↗]. Other studies suggests as much as five degrees, but these scenarios are now considered less likely [Peters, 7 Feb 2020 | ↗]. Unsurprisingly, it is difficult to forecast the effect of policies and climate pledges and the difficulty in predicting climate response adds to the uncertainty. A high peak temperature increases the risk of triggering tipping points [Lenton et al., 2019 | ↗].

The conclusion must be that the considerable uncertainty both in policy fulfilment and the climate system's response warrant additional efforts to ensure we meet our target with some safety margin. This is indeed the essence of the precautionary principle, one of a handful of legal principles guiding environmental law. In the absence of scientific certainty, the precautionary principle advocates protective anticipatory action.

A 45% drop in twenty years (2010 to 2030) translates to around 3% pa. However, with little progress since 2010, the 45% cut must be achieved in only a decade or so, which requires 5% annually. Five percent is the sort of reduction observed as a result of the COVID-19 pandemic and very difficult to reach under normal circumstances. The herculean task in front of us is to achieve the same, without the societal and economic sacrifices, and for ten years in a row!

2.1. Shipping GHG: Figures and trends

SUMMARY

Ships carry 80% of international trade at only 13% of transport GHG emissions.

Shipping, including national shipping and fishing vessels, represent about 2.9% of global CO_2. Shipping's share of global GHG is lower (about 2.1%) than its share of global CO_2.

Carbon intensity has improved by 20-30% since 2008. Yet shipping emissions continue to increase. While regulations must set targets for relative emissions, absolute emissions and emissions concentrations determine the global temperature rise.

While CO_2 make up 98% of shipping GHG today, methane and black carbon are increasing. Future GHG inventories should cover all relevant greenhouse gases.

Bulk, container and tankers represent 70% of shipping GHG emissions. The majority of these are big vessels sailing between the continents.

Ships emitted around 1,050 million tonnes CO_2 and 1,076 million tonnes CO_2-equivalents in 2018. International and national shipping together with fishing thus represents around 2.9% of global CO_2 [IMO 4th GHG study, 2021 | ↗].

This is tank to wake emissions. referred to as direct or scope 1 emissions (see chapter 6.1). If we include well to tank emissions from producing maritime fuels, the total CO_2 reaches 1,250 Mt based on the emission factors for fuel oils (ref chapter 9.2).

Emissions from transport globally is around 8 Gt, around 16% of global GHG and 23% of global CO_2. Ships make up around 13% of transport emissions globally and 13% of European transport emissions [Our World in Data | ↗], [EEA, 2021 | ↗].

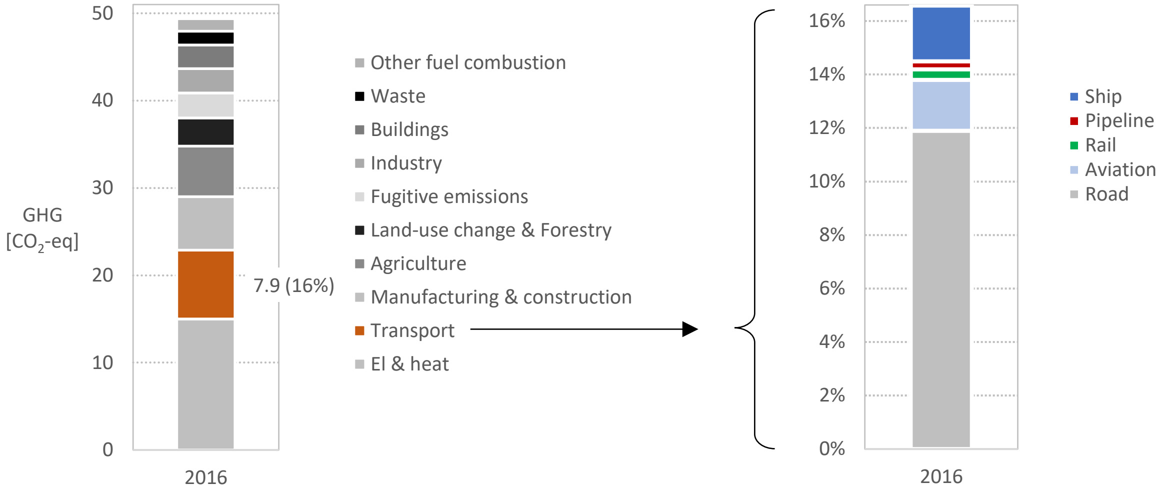


Figure 14: Global GHG (left) and breakdown of transport emissions (right) [Our World in Data, IMO]

Shipping emissions grew by 4% p a from 1990 to 2008, when they peaked. After a few years of reductions in a turbulent market from 2008 to 2013, emissions continued to climb again from 2013 to 2018, but this time at only 2% pa. The growth in emissions is partly explained by continuous and significant growth in transport work; around 3% pa historically over the least five decades [UNCTAD | ↗]. Forecasts indicate that this ±3% growth will continue, with slower growth for tank and faster growth for containerised cargoes [UNCTAD | ↗].

The transportation sector is considered hard to abate, together with steel and cement, inter alia. Regulators such as the EU is therefore targeting the transportation sector specifically. The much lower share of renewable fuels in the transport sector is also a reason to target this sector specifically.

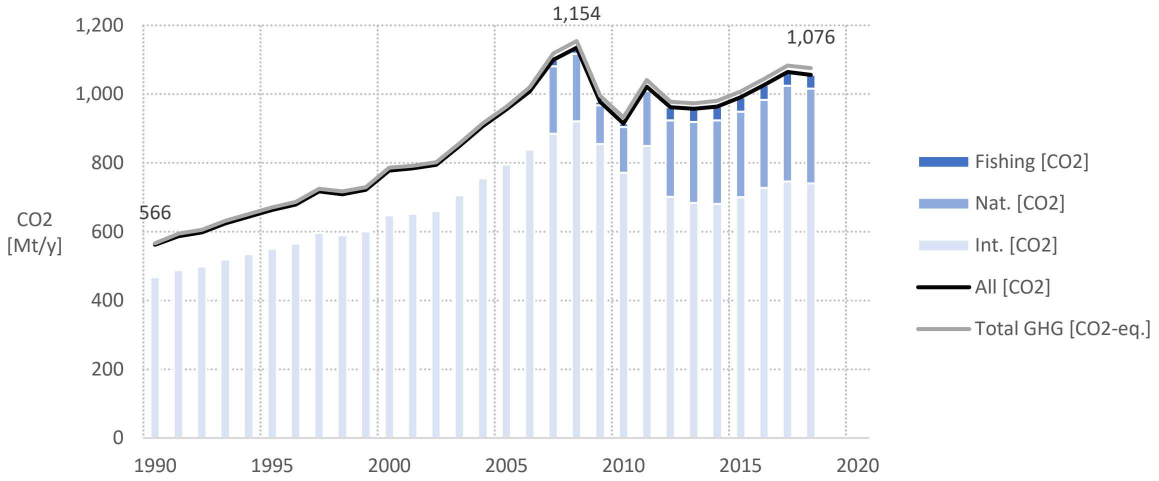


Figure 15: CO_2-emissions from all shipping [IMO 2nd, 3rd and 4th GHG-study]

From the below diagram (fig. 16), we see that shipping emissions followed seaborne trade from 1990 to 2008, and then decoupled. From 2008, trade continued to grow while emissions dropped and climbed again. From 2008 to 2018, trade grew by 35% while emissions dropped by 7%, giving carbon intensities about 30% below 2008-levels. The development in carbon intensity is discussed in detail in chapter 8.1 and the types of metrics used in chapter 6.3. In the below diagram, all figures are indexed against 2008 the IMO reference year.

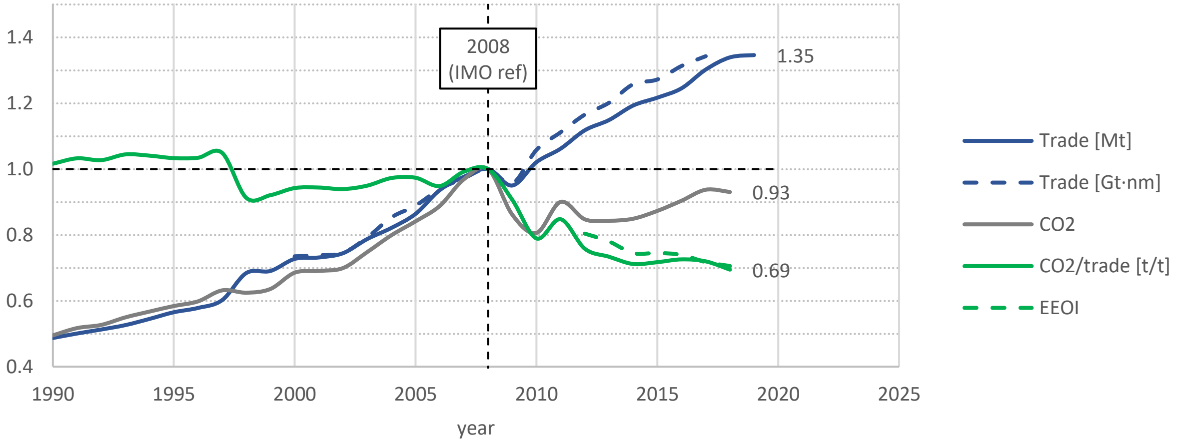


Figure 16: Development in trade, emissions, and carbon intensity (EOOI) [UNCTAD and IMO 4. GHG study]

For a range of plausible long term economic and energy scenarios, the projections for 2050-emissions are between 90 to 130% of 2008-emissions levels [IMO 4th GHG study, 2021 | ↗]. These scenarios assume business continues as usual with current, but no additional policies. However, new policies are under development and the combined effect of these will hopefully address the gap between the BAU-scenarios (-10 to +130%) and the IMO goal (-50%).

Bulk, container and tankers for oil and gas represent 77% of the tonnage and 70% of shipping emissions.

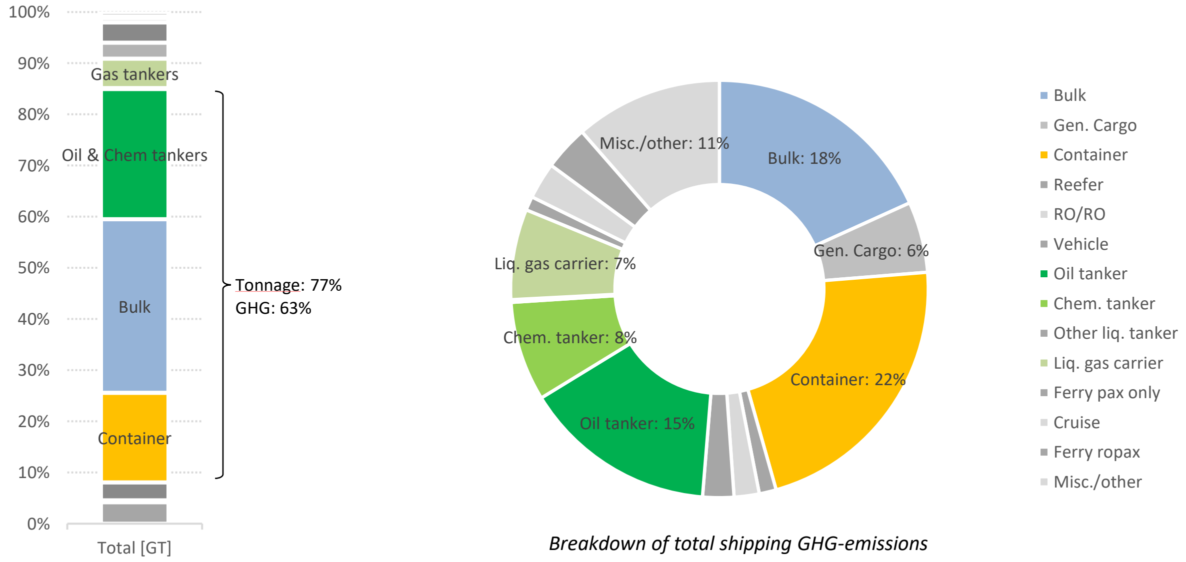


Figure 17: Vessel types by tonnage (left) and emissions (right).

The largest vessels, which represent the bulk of emissions, spend 80-100% of their sailing time in international trades. This explains the importance of getting global regulations through IMO to curb emissions effectively.

The transportation sector is by many considered hard to abate due to large energy demand, space constraints onboard and long sailing distances. Many trades are tramp trades with little predictability. Many segments are under intense global competition where, sadly, price is the single most important factor to secure cargo.

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2.2. CO_2 and the other greenhouse gases

SUMMARY

CO_2 makes up 98% of shipping emissions today and is the most important greenhouse gas, considering its long lifetime.

The advent of new fuels will likely increase emissions of methane and black carbon.

The amount of N_2O from use of ammonia is not yet known. Engines must be designed to emit zero of this very potent greenhouse gas.

Future GHG inventories and policies should cover at least methane, N_2O and black carbon. Similarly, emission indicators and economic incentives should target all relevant GHGs.

The long lifetime of CO_2 makes it the most important greenhouse gas. 15-40% of current atmospheric CO_2 will remain after two thousand years [Strømman et al., 2019 | ↗].

CO_2 makes up around 98% of maritime GHG (tank to wake), both worldwide and in Norway. Other greenhouse gases are more important in other sectors: Globally, across all sectors and countries, the share of CO_2 is around 75% [Our world in data | ↗]. Also, the atmospheric concentration of methane has tripled and thus increased more than the concentration of CO_2 since 1750 [Lindstad et al, 2020 | ↗].

Many emissions inventories and current policies target CO_2 only, including IMO's GHG-strategy and the reporting schemes of the EU (MRV) and IMO (DCS). The introduction of new fuels will change the picture and GHG inventories, policies and regulations should reflect this. IMO is currently discussing both to include the production of the fuels (well to tank) and to consider all GHG emissions, i.e., methane (CH_4) and nitrous oxide (N_2O) as well as black carbon, in future regulations. The EU ETS will target not only CO_2 but also methane and N_2O (see chapter 2.8).

Future regulations, emission indicators and economic incentives should include all relevant GHGs to be effective.

Clearly, while major focus should continue to be on CO_2, emission inventories, policies and economic incentives must include and consider all relevant, future GHGs to be effective. Recommendations for a complete GHG emissions inventory is given in chapter 6.1.

Methane (CH_4)

The main source of methane from ships is uncombusted gas in gas and dual fuel engines. The problem and possible mitigative actions discussed in chapter 9.10. Methane also leaks from production and pipes in some countries and contribute significantly to the well to tank emissions of LNG.

Increased use of LNG as maritime fuel gives higher methane emissions; up around 150% from 2012 to 2018, much more than the use of LNG which grew by abt. 30% in the same period [IMO 4th GHG study, 2021, p.134 | ↗].

Methane emissions from ships increased by 150% from 2012 to 2018, much more than the use of LNG (+30%).

The global warming effect of methane is stronger than previously assumed, and its GWP_{100} has been adjusted several times over the last decades; from 21 in 1996 to 25 in 2001 to 28 in 2014 and 29.8 in 2021. Methane has a stronger effect in the short term than CO_2, with a GWP_{20} of 82.5 (ref chapter 6.1 for more details on GWP).

CO_2 is the main concern, but in a short time perspective, to avoid releasing tipping points, short lived climate forces are also important. For this reason, methane deserves increased attention. Several global political alliances are launched to combat methane emissions, such as the Global Methane Pledge launched at the COP 26 in Glasgow (November 2021).

Nitrous oxide (N_2O)

N_2O is even more powerful than methane, but not a serious concern with today's combustion engines and fuels, and makes up only 1.5% of shipping's GHG [IMO 4th GHG study, 2021, p.135 | ↗]. With ammonia, however, we expect formation of N_2O. The ongoing research at many of the word's engine makers as well as SINTEF Ocean aims to find out exactly how much and how these emissions can be reduced to a minimum.

With a global warming potential of 273, as little as 2-3 grams N_2O per kWh will have the same warming potential as a diesel engine based on a specific fuel consumption of 180 g/kWh.

Black carbon (BC)

Black carbon, emitted for instance from burning HFO, is considered an indirect greenhouse gas as it contributes to global warming by reducing the heat reflection, the so-called Albedo effect. Its effect is bigger in the Arctic and Antarctica where black soot on the white snow and ice is particularly detrimental. Once snow and ice have melted, the darker colour of the earth and sea absorbs more heat which further increases global warming. The global warming potential of black carbon is 1,700 in ice capped landscapes compared to 345 elsewhere in the world [Lindstad et al., 2016 | ↗]. Black carbon emitted far from the Arctic also matter; the majority of BC observed in Abisko in Northern Sweden had travelled 1,000-2,000 km [Winiger et al, 2017 | ↗].

When considering black carbon a greenhouse gas, it accounts for around 7% of shipping GHG-emissions, second only to CO_2 [ICCT, 2017 | ↗], [Bond et al., 2013 | ↗]. Based on this, there is reason to believe that BC from shipping will contribute significantly to Norwegian emissions.

Black carbon accounts for 7% of shipping GHG if included in GHG-inventories.
BC emissions from ships grew by 12% from 2012-18.

With very limited marine traffic in the high north, land-based sources are much more important. However, moving ships spread the black carbon over a much larger area and thus have stronger climate effect relative to the emissions [Berntsen et al., 2006 |↗].

Other greenhouse gases

There are other greenhouse gases; hydrofluorocarbons (HFC), perfluorocarbons (PFK) and sulphur hexafluoride (SF6), but these are negligible. Some are used as cooling medium. Due to their extremely high GWP, their use and accidental release should be monitored and reported.

NO_X and SO_X

NO_X, SO_X and particles are primarily considered air pollutants with effect on human and animal health as well as soil and water. However, these also have indirect effects on the climate system, e.g. SO_2 creates particles and thus increases the heat reflection and reduce global warming.

In the short term, the cooling effect of sulphur and other particles from shipping exceeds the warming effect of CO_2 and methane. In fact, exhaust gases from shipping have for a long period had a cooling effect on the climate.

However, while the effect of NO_X, SO_X and black carbon diminishes after a few decades, the warming effect of CO_2 lasts for hundreds of years, so in the long run reducing CO_2-emissions will be required [Strømman et al., 2019 | ↗].

SO_X will be reduced drastically from 2020 as a result of IMO regulation and regional policies – and the cooling effect will vanish too. This transitionary effect must be compensated by strong reductions in total greenhouse gases.

2.3. National vs international shipping emissions

SUMMARY

70% of shipping emissions come from international trade. This confirms the importance of developing global rules for the shipping activity between countries.

Regional, national or even local regulations should primarily address environmental matters of regional, national or local nature such as NO_X, SO_X, particles including black carbon where the concentrations of such air pollutants are detrimental.

Around 70% of shipping GHG emissions come from ship in international trade and 30% from ships in domestic trades. The split is roughly the same for shipping in Europe; around 60% of emissions come from voyages to and from the EU while voyages inside the EEA represented 32% [EU, 2020 | ↗]. In Norway, the domestic share is higher, although the Norwegian maritime emissions statistics are uncertain (see next chapter, 2.4).

The latest IMO GHG study distinguished domestic shipping from international shipping on basis of individual voyages. Previous studies assumed a vessel would either trade domestically or internationally and the categorization was made based on vessel type and size (so called vessel-based allocation). The new method gave very different results; while previous studies put international shipping at 80-85%, the 4th study concluded with only 70%.

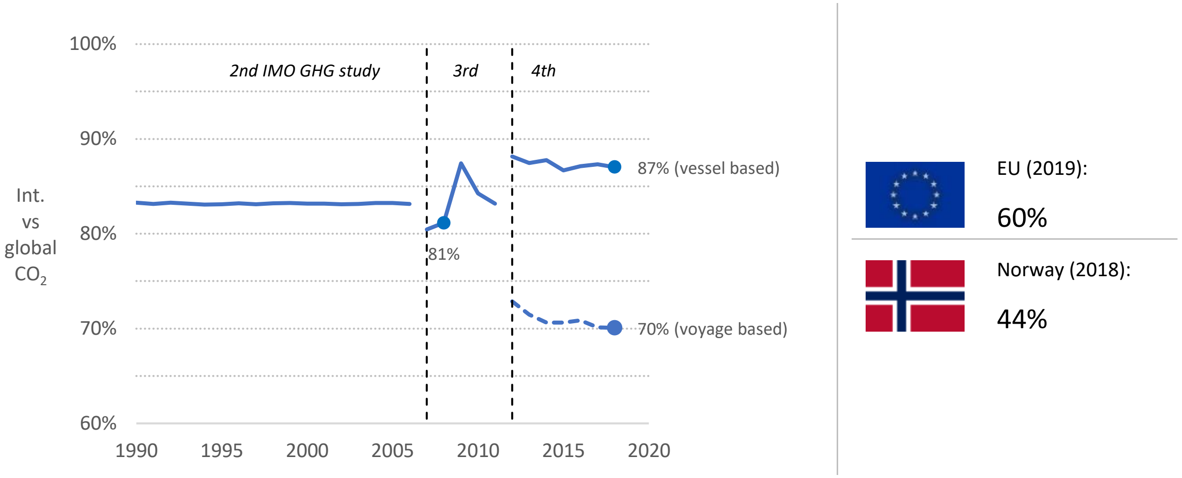


Figure 18: Share of shipping emissions from international shipping worldwide 1990-2018 (left) and in the EU and in Norway (right)

Domestic shipping refers to voyages between ports in the same country, even if these sailing legs are part of an international trade route. For example, vessels calling a number of American ports cannot take cargo between them, but the emissions from these sailing legs are still counted as domestic shipping.

Ships of all flags can serve international routes. This explains the need for international conventions to regulate emissions from ships and other environmental matters.

National governments can only influence the last 30% of maritime emissions through national legislation, mindful of global obligations under UNCLOS (United Nations Convention on the Law of the Sea). The European Green Deal intends to target ships of all flags calling EU ports and the Norwegian government have declared UNESCO world heritage fjords zero emission zones from 2026. Such regional or local measures may have little direct effect but inspire global regulators.

Numerous regulations with small variations and with local applicability may, however, exhaust and impose unreasonable burdens on the industry.

2.4. Shipping emissions in Norway

SUMMARY

Emissions from shipping in Norway amounts to 2.9 million tonnes based on fuel sales and around 4.9 million tonnes if the estimate is based on vessel traffic data from AIS (around 70% more).

Reliable statistics, including breakdown into vessel types and sizes, is essential to follow up the sector's development. The emission inventories should be further developed to include other GHGs such as methane (from gas fuelled vessels), black carbon and N_2O (possibly an issue from future operations on ammonia).

Shipping emissions form a large part of emissions in several municipalities in Norway.

Emission inventories for national transport is based on fuel sales. Official statistics suggest total emissions around 2.8 million t CO_2 in 2017 and 2020 as well [SSB, table 08940 | ↗]. Norwegian shipping emissions grew 1.7% Y/Y from 1990 to 2017.

Many vessels bunker abroad based on convenience or fuel price differences. As a result, we have reasons to believe that the national emission inventory underestimates emissions from national shipping. This was confirmed when the Norwegian government presented very different figures in the Action Plan for Green Shipping in 2019: 4.8 million t CO_2 for 2017, based on AIS [Regjeringen, 20 June 2019 | ↗]. The same publication presented a breakdown of emissions, which is essential to guide efforts (technical, commercial, and regulatory) to curb emissions. The following breakdown of the 4.8 million tonnes estimate conclude that shipping emissions can be split into four roughly equal pieces: Passenger, cargo, offshore and fishing.

GHG [CO_2-eq.] based on fuel sales (SSB):

2.8 Mt (2017)
5% of Norway's GHG

CO_2 based on AIS:

4.8 Mt (2017)
9% of Norway's GHG

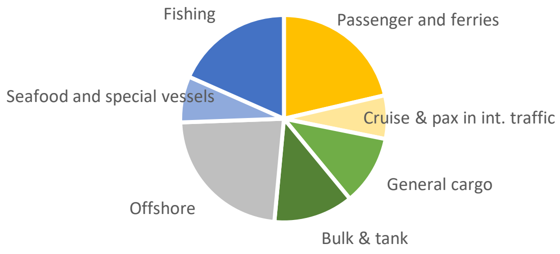


Figure 19:Norwegian shipping CO_2: Total and breakdown

Finally, it is interesting to note that emissions from shipping in Norwegian waters including international voyages and ship in transit total 9.1 Mt CO_2 [Kystverket | ↗]. This equals 18% of Norwegian GHG in 2020. Norway as a flag state has limited possibilities to address these particularly but must do so through IMO primarily.

The principle of basing emission inventories on fuel sales is widely recognized and has its merits. It is nevertheless very important to have solid data including time series for one of Norway's key industries.

Emission inventories based on fuel sales are likely underestimating due to extensive bunkering abroad. Reliable statistics and time series are crucial if Norway shall monitor the effect of regulations and succeed in curbing GHG-emissions.

Noting that black carbon makes up 7% of global shipping GHG, there is reason to believe black carbon will add significantly to the global warming effect from Norwegian shipping. New methods for national emission inventories are needed.

2.5. Emission in ports

SUMMARY

Vessels run generators in port to power ancillary systems, accommodation and support cargo gear for loading and unloading such as cranes, ramps, pumps, conveyor belts etc.

Emissions in port constitute 11% of emissions from international shipping and 6% of shipping in EU.

Analysis from Gothenburg and Oslo port show that emissions in port come primarily from the vessels, not the shoreside operations. Half the emission within the port district occur at berth. These figures vary from port to port depending on the dominating vessel types and the energy intensity of their cargo handling operations.

Reefers, tankers, passenger and cruise vessels as well as ro/ro vessels have the highest share of emissions in port. Cement carriers are a particular niche with energy intensive cargo handling. Shore power should therefore be provided to these vessels first.

Worldwide, around 10% of GHG come from ships in port; this includes ships at anchor waiting to berth [IMO 4th GHG study, 2021 | ↗]. In the EU, the share is 6-7% based on emissions reporting from vessels above 5,000 GT [EU, 2020 |↗]. Other studies indicate 5-15% [Mjelde at al, 2019 | ↗].

Emissions in port depend on the energy use for handling cargo and passengers as well as the energy source and efficiency of machinery used. Of the six ship types most important to the emissions inventories, chemical tankers and oil tankers have on average the largest portion of their total emissions (>20%) associated with phases at or near the port or terminal [IMO 4th GHG study, 2021, p.8 | ↗]. Chemical tankers can spend 40-45% of operation time in port to load and discharge the many different segregations to different terminals [Hammer, 2013 | ↗].

The diagram below (fig. 20) shows the portion of GHG emissions from each operational phase for international shipping [IMO 4th GHG study, 2021, p. 95 | ↗]. On average, for the various segments, emissions in port varies from 5 to 25%.

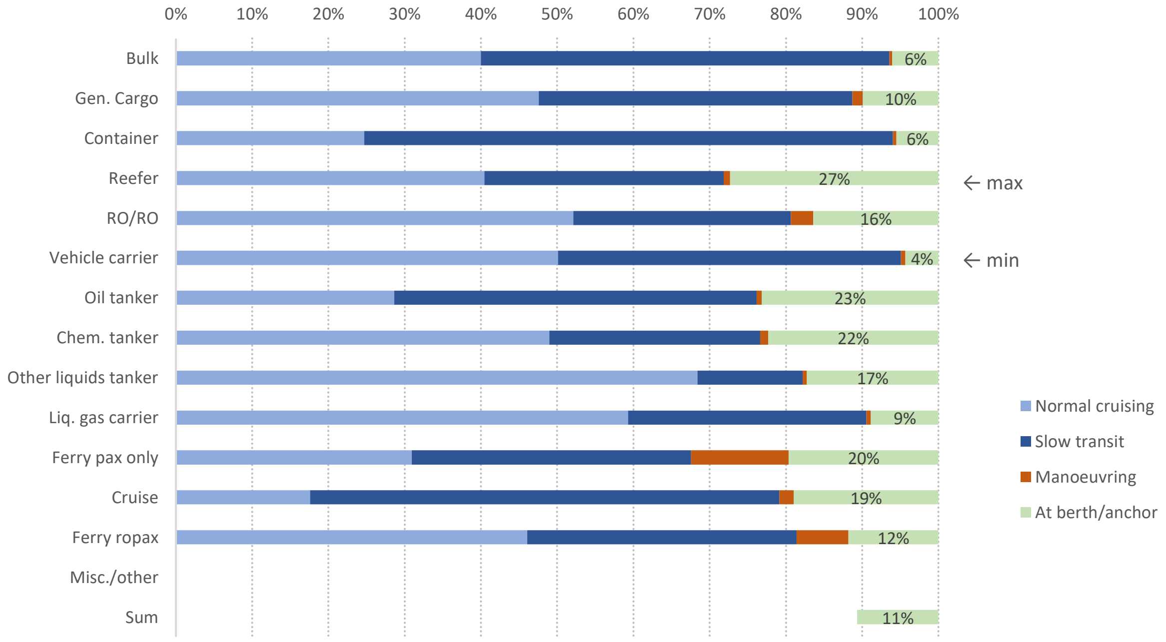


Figure 20: Breakdown of emissions by operational mode [IMO 4th GHG-study]

The majority of emissions in ports come from the vessels and not from the land side operations: The ratio shipside vs shoreside emissions are ten to one in Gothenburg [Winnes et al., 2015 |↗] and six to one in Oslo [Oslo havn, 2018 |↗]. So, reducing emissions in port must focus on the vessels.

How much of port emissions can be eliminated with shore power?

Port emissions include the vessels approach and manoeuvring inside the port district. Emissions from these phases make up about 35%, whereas 50% come from ships while at berth. Analysis from the ports in Oslo and Gothenburg display similar ratio. Shoreside power supply can thus eliminate around half of port emissions if all ships connect immediately after mooring.

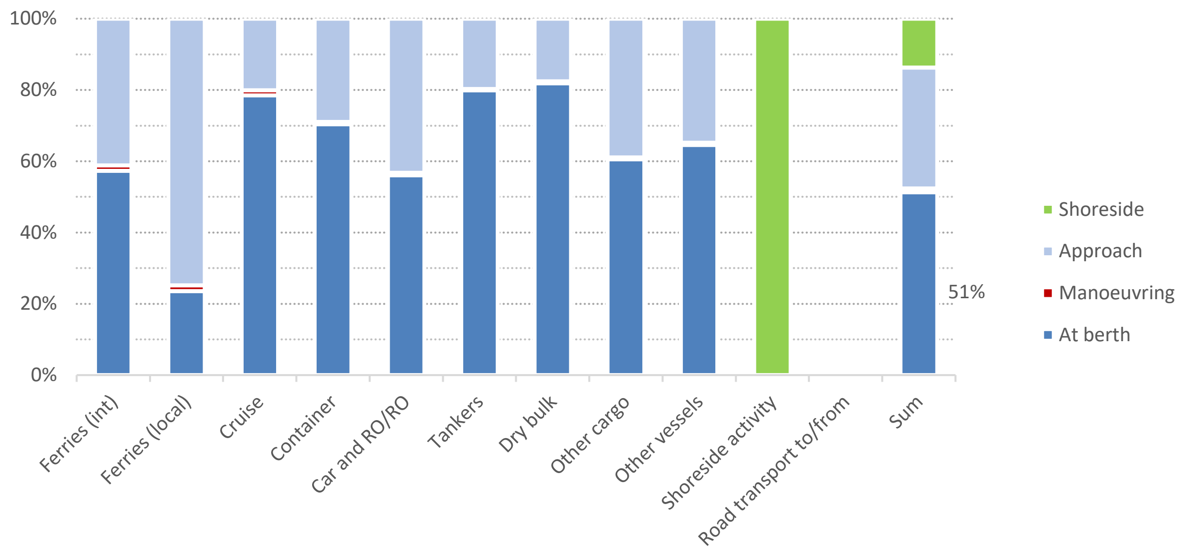


Figure 21: Emissions breakdown in the port of Oslo

In practical terms, emissions from boilers for heating cannot easily be replaced fore existing ships [Oslo havn, 2018 |↗]. Local ferries have low emissions at berth but can likely be fully electrified in the near future.

To conclude, emissions from ships in port make up 11% of global shipping emissions and roughly half of these can be neutralized with shore power. Shore power can thus mean a lot to curb local air pollution but can only make a marginal contribution towards global GHG.

There are around 3,000 ports only in Norway [Kystverket | ↗] and shore power cannot be established in all ports small and large. Shore power can make a difference once available in all or many of the 32 Norwegian key ports, the EU TEN-T core ports and ports for cruise and passenger vessels with high power demand also in port. In October 2021, there were around only 160 ports with electric shore power [Zadeh, Karimi and Sul, 2021].

2.6. GHG regulations

SUMMARY

IMO is the key regulator of maritime emissions and other environmental impacts. The Marine Environment Protection Committee (MEPC) is tasked with developing environmental regulations and most regulations come as amendments to MARPOL, the International Convention for the Prevention of Pollution from Ships.

SINTEF Ocean follows the deliberations at IMO as observer in the Norwegian delegation to MEPC.

IMO's goals for the shipping sector should reflect the global priorities and level of ambitions to ensure that the shipping industry is taking its fair share of responsibility.

Notwithstanding the central and important role of IMO to ensure global applicability of maritime environmental regulations, IMO is often inspired and pushed to adopt stricter regulations by national governments and regional actors.

With its holistic and comprehensive approach, the EU green deal is expected to flavour maritime regulations in the current decade.

As shipping is international of nature and ships literally belong to the spaces between countries, the UN agreed in the Kyoto Protocol (1997) to delegate the responsibility for shipping to the International Maritime Organization (IMO). Work at the IMO must consider and reflect other relevant global instruments to ensure that shipping takes its fair share of the burden, noting the particular challenges and opportunities of the industry.

An overview of relevant regulations is therefore of interest:

1972	🇺🇳	The Stockholm conference, first world conference to make environment a major issue, leading to the creation of the UN Environmental Programme (UNEP).
1973	IMO	MARPOL (International convention for prevention of pollution from ships) adopted by IMO and since then the cornerstone for environmental regulations encompassing oil pollution, noxious and harmful substances, sewage, garbage and emissions air pollution.
1988		IPCC established
1992		UN Framework Convention on Climate Change (UNFCCC) established. The UNFCCC is the parent treaty to the Kyoto Protocol and Paris Agreement. An annual Conference of the Parties (COP) is arranged annually.
1997		Kyoto protocol: 5% cut by industrialized nations and EU by 2012 vs 1990. Shipping/aviation separated.
	IMO	MARPOL Annex VI (air pollution) adopted.
2003	IMO	First IMO resolution to measure and reduce GHG from ships; Resolution A.963(23).
2008	🇳🇴	Norwegian white paper (Klimaforliket) targets 12% cut by 2020 vs 1990.
		UK adopts legally binding climate goals through the Climate Change Act 2008. Denmark follows in 2014, Finland in 2015, Sweden and Norway in 2018 [Lovdata | ↗], EU in 2021.
2011	IMO	EEDI (energy efficiency design index) adopted by MEPC. The EEXI is the basis for the EEXI (adopted 2021) and shall apply the same standards to existing ships.
2012	🇳🇴	Norwegian white paper (Klimaforliket II): 20% cut by 2020 vs 1990.
2015		Paris agreement: Limit global warming to +2°C, endeavour to stay below +1.5 °C.
	🇺🇳	UN defines 17 Sustainable Development Goals (SDG) to promote a holistic approach to multiple societal challenges, recognizing the need to create solutions without repercussive effects.
2018	IMO	The IMO initial GHG strategy is adopted. It targets, inter alia, 40% lower carbon intensity by 2030 and 50% absolute cut by 2050 [↗]
2019	🇫🇮	Finland's government signals intents to become climate neutral by 2035 [↗].
2020	🇳🇴	Norway tightens its goal from 40 to 50-55% cut by 2030 as well as climate neutrality by 2030 [↗].

2021	IMO	MEPC 76 adopts short term measures (EEXI and CII) with effect from 2023 [↗]
	🇺🇸	United States, the second biggest emitter re-joins the Paris Agreement.
	🇪🇺	EU adopts 55% net cut by 2030 and climate neutrality by 2050 and enshrines these in a climate law. The EU Green Deal is followed up by a package of measures to make EU Fit for 55 [↗].
2022	🇪🇺	EU's taxonomy: Sustainability criteria for financing of shipping.
	IMO	MEPC to discuss the possible application of well to wake footprint of alternative fuels.
2023	IMO	EEXI and CII regulates the carbon intensity of existing ships above 5,000 GT.
	IMO	IMO to revise the *initial* GHG strategy at MEPC 80 in July.
	🇪🇺	EU energy taxation directive adds a tax on maritime fuels.

Table 1: GHG regulations of relevance to shipping.

Summing up regulations from 1970 to today, we note that climate ambitions have tightened and that climate laws begin to accompany climate goals from 2008. Yet, emissions continue to grow globally and, in most countries, and sectors. A thought-provoking summary of Norwegian climate politics from 1987-2015 by Cicero is worth reading [Cicero, Berg, 2015 | ↗].

Looking ahead, if the world is serious about limiting global warming to 1.5°C, the current policies and regulations for 2030 and 2050 are not enough; this includes regulations on shipping. Nationally Determined Contributions (NDC) must be reinforced and supported by policy changes. We must also see more focus on regulations and measures with short term effect.

The following regulations have been agreed to enter into force in the coming years or are under development:

2024	🇪🇺	EU ETS: Gradual phase-in during 2024-26 for emissions from ships.
2025	🇪🇺	FuelEU Maritime directive: Increasingly strict GHG intensity limits (WTW) for ships' fuel.
2026	IMO	IMO to revise the CII-code and agree reduction rates for 2027-30, mindful of the 2030 ambitions.
2028	IMO	IMO to revise the GHG strategy again.
2030		

Table 2:Coming (confirmed and expected) GHG regulations of relevance to shipping

2.7. The IMO GHG strategy

SUMMARY

The initial strategy adopted in April 2018 was a landmark for the industry. The strategy was revised in July 2023 and will be revised again in 2028.

The initial strategy was a major achievement when adopted in 2018, but its ambitions fell short of what is needed to curb global warming to 1.5°C.

The revised strategy set goals for reductions in absolute emissions by 2030 and 2040: Emissions from international shipping should be reduced by 20-30% by 2030 and 70-80% by 2040.

The steepest drop in emissions is thus set to come from 2030 to 2040; in this period GHG emissions must drop more than 10% year on year for the whole decade.

The continued high emission levels, the temperature increases observed so far, and the very limited carbon budgets make 2030 and 2040 much more important yardsticks than 2050.

Zero emissions in 2050 are only a meaningful contribution if accompanied by steep emission trajectories. Discussions on net zero goals in 2050 – more than 25 years head in time - can be a distraction and postpone urgent action.

Once or twice a year, government representatives convene to develop environmental regulations in IMO's Marine Environment Protection Committee (MEPC), with intersessional meetings and preparatory deliberations as required.

In 1997, IMO adopted an Annex to MARPOL to address air pollution and began working on greenhouse gases with a resolution (Assembly resolution A.963(23)) in 2003 to, inter alia, establish GHG emissions metrics and baselines and evaluate technical, operational and market-based solutions with a view to *limit or reduce* emissions [IMO | ↗].

These efforts culminated in the Initial IMO strategy on reduction of GHG emissions from ships in April 2018 [IMO resolution MEPC.304(72), 2018 | ↗]. The initial strategy was revised at MEPC90 in July 2023 [IMO resolution MEPC.377(80), 2023 | ↗].

The IMO GHG strategy explicitly refers to both the Paris agreement and its goals as well as relevant research summarized by the IPCC. It also commits to take the development of emissions and technology into consideration. Further, IMO commits to the *precautionary principle*, which means that all policies and efforts should endeavour to play safe and err on the safe side.

The *initial* IMO GHG strategy aimed for 40% reduction in carbon intensity by 2030 and 70% by 2050, from 2008-levels. Absolute GHG emissions should be halved by 2050 but IMO did not set a target for absolute emissions in 2030. Finally, the industry agreed to peak GHG emissions as soon as possible and phase them out within this century. See diagram 22 below.

On the positive side, while the percentages of the carbon intensity goals in the initial strategy were too small and not aligned with the Paris agreement, one must appreciate that the regulations adopted in 2018 were binding upon signatories and apply to vessels of all flags. It is only in recent years that national governments have committed by turning climate goals into climate laws, led by the UK in 2008, followed by Denmark in 2014, Finland in 2015 and Sweden and Norway in 2018 and the EU in 2021. [gov.uk | ↗], [Folketinget | ↗], [EU| ↗].

The *revised* IMO GHG strategy was adopted in July 2023. The most important amendment, perhaps, was the addition of goals to reduce absolute GHG emissions by 2030 and 2040, the so-called indicative checkpoints. IMO agreed to reduce GHG by at least 20% by 2030 and strive for a 30% reduction. By 2040, GHG emissions should be reduced at least 70%, striving for 80%. Also, IMO agreed to "reach net-zero GHG emissions by or around i.e. close to 2050". While the wording is a bit complicated, the ambition and direction is set. See diagram 23 below.

The importance of goals for absolute emissions cannot be underestimated; this means that the industry must take activity growth into account. This is good news because the carbon intensity goals seen in the initial strategy were no guarantee for reducing emissions in absolute terms.

The below diagrams present the historic development of greenhouse gas emissions from shipping 1990-2018. We have indexed GHG emissions (blue) and the carbon intensity (grey) against 2008 which is the IMO's reference year. We note that the carbon intensity has dropped much more than the emissions; the key factor to explain this is the activity growth. This difference also underlines the insufficiency of setting only carbon intensity goals for an industry experiencing significant activity growth.

The below diagrams also present the goals of the IMO GHG strategy, both the initial and revised strategy, and the approximate trajectory required to meet these goals. For sake of good order, we emphasize that *the revised strategy replaces the initial strategy* and the latter is only included to show the progress made at the IMO from 2018 to 2023.

From 2008 to 2018, GHG was reduced by 7% or 0.7% per year. To reach 20-30% lower emissions by 2030, the annual reduction must be 1.8% Y/Y and to reach 70-80% lower emissions by 2040, the annual reduction rate must be 10% /Y every year from 2030 to 2040

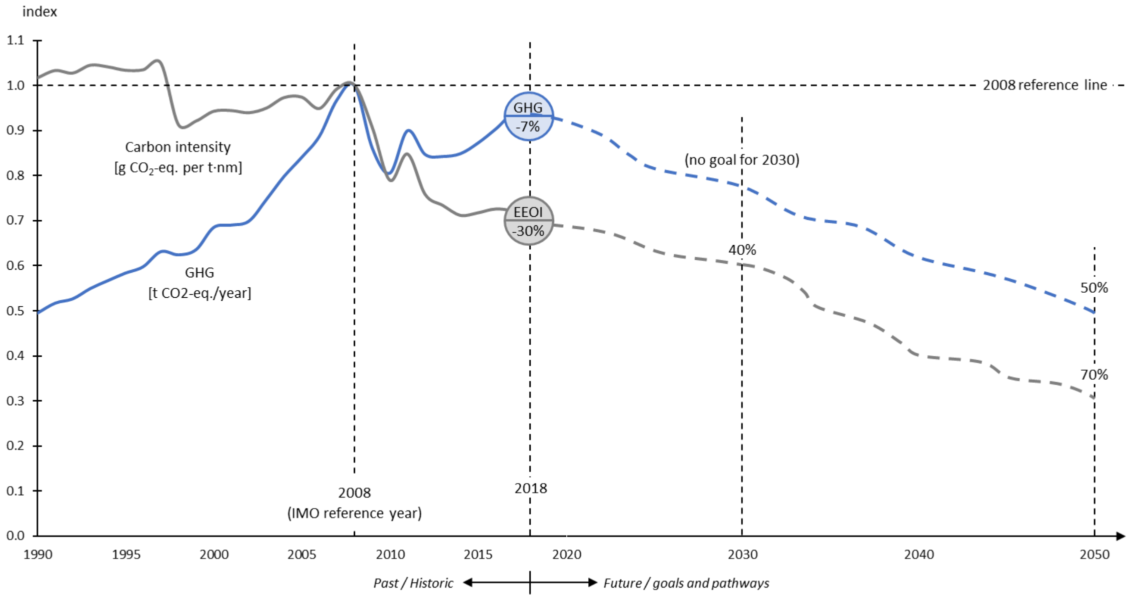


Figure 22: IMO goals for reducing greenhouse gas emissions (GHG) and the carbon intensity of ships in the initial IMO GHG strategy from 2018.

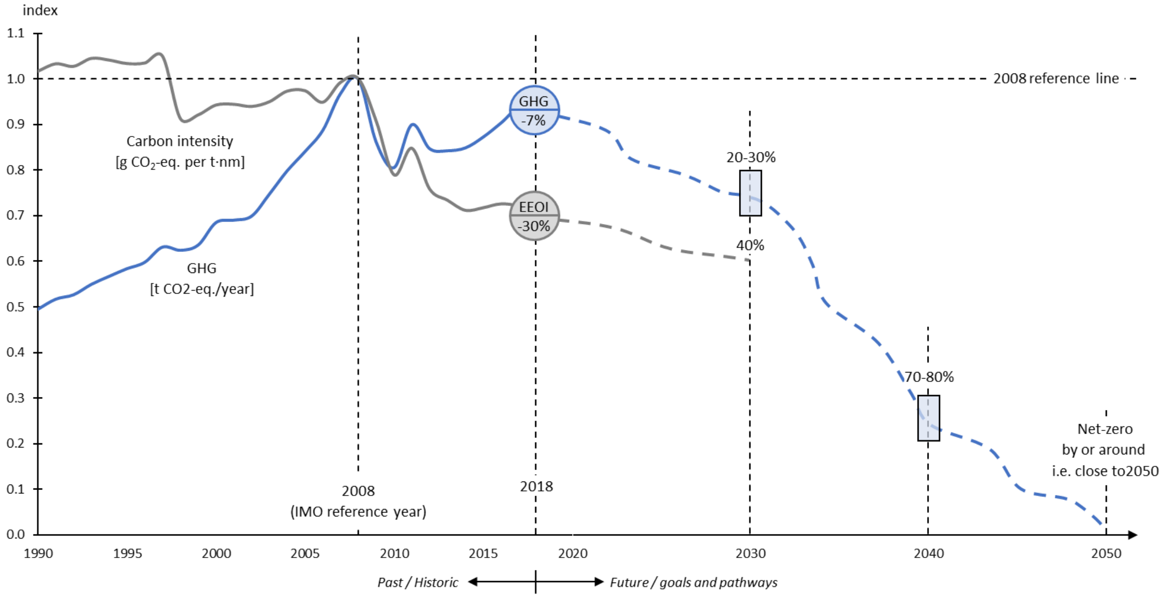


Figure 23: IMO goals for reducing greenhouse gas emissions (GHG) and the carbon intensity of ships in the revised IMO GHG strategy from 2023.

2.8. The European Green Deal

SUMMARY

The European Union is a key driver of environmental policies and works to extend its policies to the maritime sector as well. The US has also stepped up its ambitions in IMO since 2021.

The European Green deal is a comprehensive policy package with particular efforts to curb transport emission including shipping emissions through carbon pricing, fuel tax and requirements to GHG-intensity of maritime fuels.

Introducing a carbon tax on imported goods produced in countries with inferior environmental standards may impact seaborne trade indirectly.

While California and the states along the Baltic Sea have taken turns at driving environmental standards for shipping forward, the major regional driver now is perhaps the European Union. This results in pressure at IMO as well as European policies.

In the last two decades, EU established the largest carbon pricing scheme in the world in 2005, endorsed strict sulphur limits early and is spearheading efforts to improve shipbreaking standards. In 2013, the EU set a strategy to progressively integrate maritime emissions into the EU's policy for reducing GHG emissions [EC, June 2013 | ↗].

The current European Commission (EC) president von der Leyen (2019-2024) made global warming a core issue already at her election campaign. In September 2020, the EC upped the climate goal from 40 to 55% reduction over 1990 by 2030 and backed this by a climate law in June 2021 [EC, | ↗], [Reuters, 24 June 2021 | ↗] . With this, EU aims for climate neutrality in 2050.

While many nations put forward climate goals, the EC drafted a comprehensive set of measures to deliver the 55% GHG reduction adopted ten months earlier: The Fit for 55-package consists of twelve pillars, at least four with impact on the maritime sector [EC, 14 July 2021 | ↗]: The Emission trading scheme (ETS), a maritime strategy for increased uptake of climate friendly fuels (FuelEU Maritime), the renewable energy directive (RED) and the energy taxation directive (ETD). The first two will have significant impact and are discussed below.

The carbon border adjustment mechanism (CBAM) will likely impact seaborne trade indirectly. It is not yet clear if the carbon border adjustment mechanism can and will be used to target fuels onboard a vessel produced with high emissions and without a carbon price. Also, the EU taxonomy, a classification system to identify environmentally friendly economic activities, will also have a bearing on access to and the cost of capital [EU taxonomy | ↗].

Emission trading scheme (ETS)

Note that the following is based on what we know as of December 2022, as we await the final legal text in 2023.

Economic incentives are considered necessary by many to bridge the price gap between green and black shipping and make the most environmentally friendly vessels competitive. The European carbon pricing scheme, ETS, was introduced in 2005 and is, pending China's scheme, still the largest scheme globally. The scheme will be expanded to include shipping from 2024 and road transport and buildings from 2027 [European Parliament, 18 Dec 2022 | ↗].

Different transport alternatives should be subject to the same carbon fees to avoid distortion of the competitive position and to avoid a reversal of efforts to shift transport volumes to the least polluting alternative.

ETS will be phased in for ships above 5,000 GT over a three-year period from 2024 period by taxing emissions on all intra-EU/EEA traffic and half the emissions on voyages to/from the EU/EEA territory. The scheme will thus cover around 95 mill t CO_2-eq. [EC | ↗]; about 70% of European shipping emissions. In the fall of 2022, the EU agreed to include methane (CH_4) and nitrous oxide (N_2O) from 2026. this makes the scheme more relevant for ships running on natural gas and ammonia and thus future proof. Further, the EU agreed to include offshore vessels from 5,000 GT from 2027 and will review the possible inclusion of smaller general cargo ships (400 to 5,000 GT) in 2026. The scheme, although not formally adopted yet, can therefore be summed up as follows:

Geographical scope

Intra EU/EEA voyage: 100% of emissions
To/from EU/EEA: 50%
At berth: 100% of emissions

Phase in

2024: 40% of emissions
2025: 70%
2026: 100%

Emissions:

2024: CO_2 only
2026: Methane (CH_4) + nitrous oxide (N_2O)

Vessel types

2024: Cargo ships + cruise vessels> 5,000 GT
2027: Offshore vessels < 5,000 GT
Inclusion of smaller vessels and passenger vessels to be discussed before 2027.

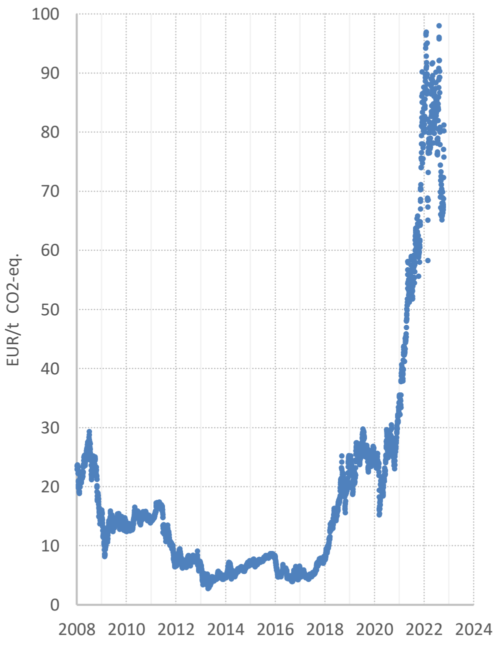


Figure 24: Key elements of EU ETS (NB: Based on what we know as of December 2022)

The carbon price in the EU ETS has fluctuated from near zero to 100 EUR/t CO2 and increased significantly since 2020. Nevertheless, the historic carbon price has been considered, by many, to be too low and many studies indicate that higher carbon prices will be required to make green solutions competitive with the current conventional practices and fuels.

On top of the cost for emission allowances comes the tax on maritime fuels which the EC proposes to increase from 2023. The proposed energy taxation directive will add a tax of around 35-40 EUR per tonne fuel for MGO and HFO and around 30 for LNG and LPG. The Commission considers the current energy tax exemptions outdated and intends to set tax rates reflecting the energy content and environmental impact on nature and health. Yet the EU is cognizant of the risk of creating incentives to bunker outside the union and suggests a gradual introduction with exemptions and reduced tax rates [EC, 14 July 2021 | ↗].

FuelEU Maritime

The directive, as agreed between the European Parliament and the Council 23 March 2023, intends to create demand for alternative renewable and low-carbon fuels (RLF) and work alongside the Renewable Energy Directive (covering supply) and Alternative Fuels infrastructure Directive (covering infrastructure). The proposal contains two key instruments: A maximum limit for the GHG intensity of energy used by all ships above 5,000 GT and an obligation for container vessels and passenger vessels to use shore power from 2030 [EU, 14 July 2021 | ↗]. Note that the GHG intensity includes not only CO_2 but also methane and N_2O and shall include all emissions over the full life cycle (well to wake; WTW).

The below diagram (fig. 25) shows the maximum GHG intensity of energy used by ships. Note that the draft regulation has not yet specified the reference value. We have assumed that MGO will be the reference value and used WTW emissions factors from Lindstad et al. (ref chapter 9.2).

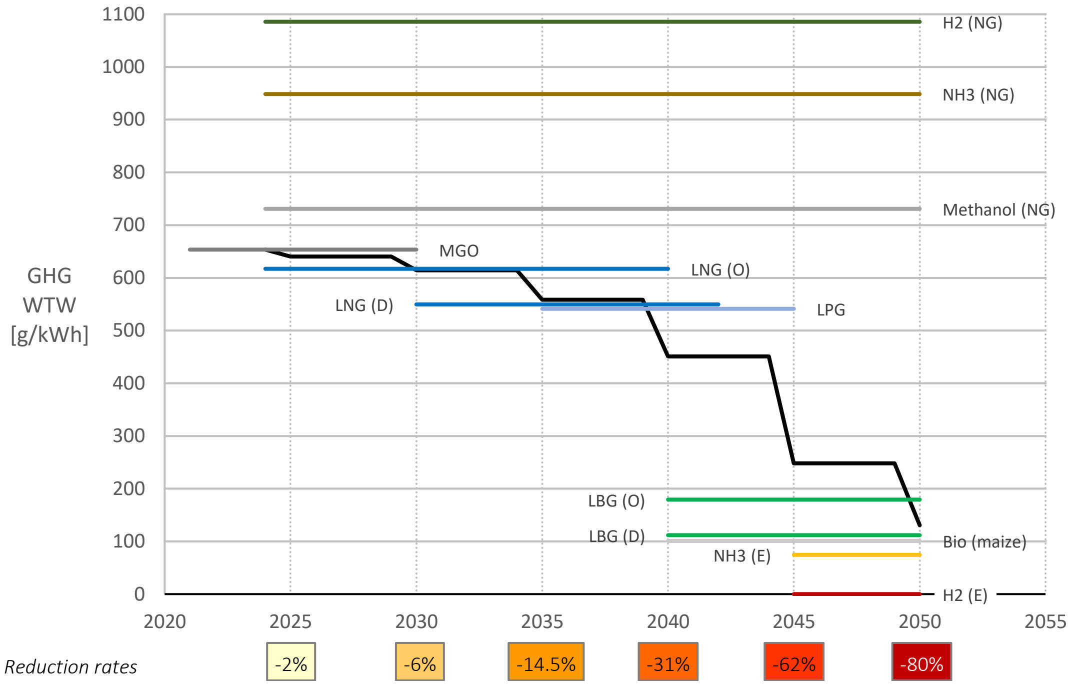


Figure 25: GHG intensity of maritime fuels vs max allowed value set by FuelEU Maritime.

It is interesting to note that gas (LNG and LPG) will be sufficient until 2035 or 2040, provided that the methane slip of LNG can be reduced to a minimum. The gap from LNG and LPG (about 550 g CO_2-eq./kWh) to biomethane, biofuel, ammonia and hydrogen can be met by blends of LNG and biomethane, MGO and biofuel, LNG and hydrogen or dual fuel operations with MGO and ammonia. Such transition strategies are discussed in chapter 9.15.

2.9. Clean air

SUMMARY

NO_X, SO_X and particles cause cardiovascular and diseases and respiratory infections and contribute to acidification of lakes and soil.

Polluted air is the environmental threat with the biggest impact on human health in Norway. Worldwide, 99% of the global population is exposed to poor air quality according to WHO.

Ships are responsible for a large share of these emissions in port cities, straits and along coastlines. About half the NO_X and SO_X in Norway comes from shipping.

Clean air from ships' funnels is a prerequisite to sail close to shore and berth close to population centres. As road transport becomes emission free in the next decade, ships must reduce not only its energy consumption and greenhouse gas emissions, but also NO_X, SO_X and particles.

While global warming and the climate crisis are highest on the agenda, other environmental threats cannot be forgotten or postponed. This includes other exhaust gases such as Nitrous oxides (NO_X), sulphur oxides (SO_X) and particulate matter as well as polluting discharges and wastes.

In addition to operational discharges, there are environmental effects from accidents such as loss of cargo, groundings and collisions. There are environmental burdens associated with both construction and dismantling of ships. These are not discussed in any detail in this report.

Air pollution cause cardiovascular diseases, stroke, chronic obstructive pulmonary disease and lung cancer and increases the risks for acute respiratory infections [WHO, 2016 | ↗]. 99% of the world population live in places where the WHO air quality guidelines levels were exceeded and more than four million deaths are linked to air pollution worldwide [WHO, 2021 | ↗]. In Europe, 96% of the urban population is exposed to $PM_{2.5}$ concentrations above the WHO threshold and 89% exposed to NO_2 concentrations above the WHO limit [EEA, Air quality in Europe 2022, 1 April 2022| ↗].

250-500,000 people die prematurely in Europe and 1,300 in Norway [Miljødirektoratet, M-1669 | ↗]. A recent study from the University of Chicago found that air pollution on average cuts 2.2 years off people's lifetime [Greenstone et al, 2022| ↗], [Guardian, 2021 | ↗].

Polluted air is the environmental threat with the biggest impact on human health in Norway [MDIR, 2020 | ↗] and shortens lives more than any other external cause worldwide [Greenstone et al, 2022| ↗].

There are many sources to air pollution and land-based sources such as road transportation and factories are generally bigger emitters and often closer to population centres. The third IMO study for the period 2007-2012 found that ships emit 15% of global NO_X and 13% of global SO_X. IMO 3rd GHG-study, page 2 | ↗]. In and around busy port cities and in coastal states with intensive shipping (and little heavy industry), the share can be higher. For example; ships are responsible for one third to half of the airborne pollutants in Hong Kong [Wan, 2016 | ↗]. In Norway, about half the NO_X and SO_X comes from ships in Norwegian waters [Kystverket, SSB].

Emissions of NO_X, SO_X and particles are therefore especially important for ferries and other short sea ships operating close to population centres and ships with long ports calls and energy intensive cargo operations in port, e.g. cruise ships, passenger ships, cement carriers and chemical parcel tankers. In the EU, 6% of shipping's greenhouse gas emissions were emitted during port stays [EU | ↗].

Ships passing through busy straits such the Hormuz and Malacca strait will impact the air quality on shore. Intensity maps suggest 36% of marine traffic (by number of observations, not emissions) take place within 25 nautical miles from shore [IMO 2. GHG-study, 2009, p.12 | ↗].

Nitrous oxides (NO_X), sulphur oxides (SO_X) and particles have long been considered a local problem only, where proximity to the emitter was considered critical to reach detrimental concentrations. But air particles travel long distances, so such emissions from ships cannot be considered too distant to affect humanity. Studies find that a large proportion of sulphur emissions on the American west coast comes from emissions in East Asia [Strømman et al., 2019 | ↗] and that the majority of the black carbon observed in Abisko in Northern Sweden had travelled 1,000-2,000 km [Winiger et al, 2017 | ↗].

Ports in close proximity to population centres are considered key to short sea shipping's competitiveness. Minimizing pollution to an absolute minimum is a prerequisite for continued political support to keep ports in city centres and the modal shift policies.

ECA: Emission Control Areas

A vulnerable sea area suffering intense emissions from ships can be declared an emission control area by the IMO and thereafter subject to particularly stringent emissions standards for SO_X and PM and possibly also NO_X. The acronyms SECA (SO_X-ECA) and NECA (NO_X-ECA) are commonly used to indicate areas where SO_X and PM or NO_X are targeted. While SECAS can be imposed for all ships regardless of the construction year, NOX Tier II and Tier III apply to newbuildings only as these emission standards require certain machinery or equipment to be installed.

Large bulk carriers, gas carriers and tankers have the lowest exposure to SECA (SO_X emission control areas); less than 5%. Small oil tankers and reefers are also trading mainly outside SECAs while ropax, ro/ro vessels and ferries are most affected. On average, one of six sailing days occur within ECAs [IMO 4th GHG study, 2021, table 81 | ↗].

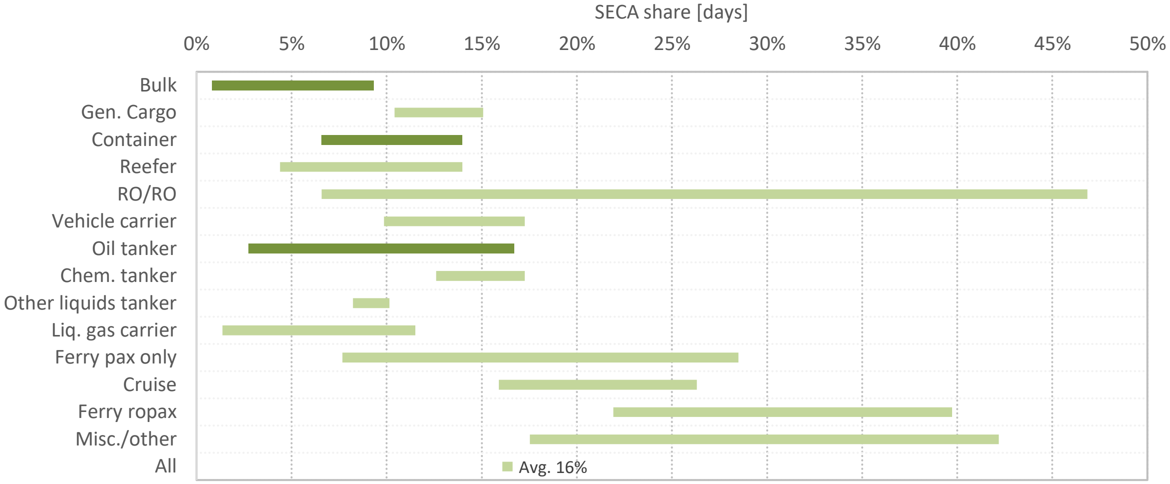


Figure 26: Operating days per year in SECA.

The Baltic Sea became the first SECA in 2006, followed by the North Sea in 2007, North America in 2012 and the Caribbean in 2014. The Mediterranean Sea will be an ECA from January 2023.

Coastal states have traditionally adopted regional or local regulations to ensure clean air. The UN Convention on the Law of the Seas (UNCLOS) allows this as long as innocent passage is permitted and that the same regulations apply to vessels of all flags, the so-called principle of *no more favourable treatment*. Regional sulphur has been limited by, inter alia, California in 2009, the EU in 2010 [EMSA | ↗], Hong Kong in 2015, China in 2017, Taiwan in 2019 and South Korea in 2020.

2.10. Policy implications

The 2030-goals of the 2018 initial IMO GHG strategy are not compatible with the Paris Agreement's 1.5°C target. The 40% lower carbon intensity target adopted by IMO in 2018 will only reduce GHG emissions if the activity growth is much lower than both historical and forecasted growth. 60-70% lower carbon intensity is required if seaborne trade continues to grow at 3% pa.

Noting the urgency of the climate crisis, rapidly rising temperatures and the risk of tipping points, goals and efforts to curb global warming should focus more on near term emissions reduction. Non-committing goals and strategies to become climate neutral by 2050 seems very off the mark unless the path to zero begins with significant steps already today.

Considering the diversity of the global fleet and considering the long list of measures to reduce energy use and emissions, regulations shall be technology neutral and goal based rather than prescriptive, but with clear requirements to environmental standards and procedures for measuring the effect.

Local regulations on GHG should follow and support national and global agreements and policies. While local regulations on air quality, discharge to sea and other environmental matters where the local concentration matters are reasonable, but local regulations on GHG should be avoided.

The polluter pays principle is a key principle in international environmental law, enshrined in the Rio declaration (1992), and a cornerstone in the climate policy in Norway and many other nations.

2.11. Sources and further reading

	Link
Berg, Cicero (17 Feb 201): Norsk klimapolitikk 1987-2015	→
Bond et al. (2013): Bounding the role of black carbon in the climate system: A scientific assessment.	→
Bryan Comer et al., ICCT (2015): Black carbon emissions and fuel use in global shipping.	→
European Commission (May 2020)*:* EU report on CO$_2$ emissions from maritime sector	→
European Commission: Reducing emissions from the shipping sector	→
Faber et al. (2021): IMO 4 GHG study 2020	→
Hannah Ritchie and Max Roser, Our world in data: Greenhouse gas emissions.	→
International Council on Clean Transportation (ICCT)	→
IPCC (October 2018): Special report: Global warming of 1.5°C.	→
IPCC (2018)*:* Glossary from the IPCC 1.5°C report.	→
Kramel et al. (2021): Global Shipping Emissions from a well-to-wake perspective: The MariTEAM Model.	→
Kystverket: Emissions statistics for ships in Norwegian waters (EEZ).	→
*Lenton et a*l (Nov 2019): Climate tipping points — too risky to bet against	→
Lindstad, Bright, Strømman (2016): Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation.	→
Lindstad ands Eskeland (2016): Environmental regulations in shipping: Policies leaning towards globalization of scrubbers deserve scrutiny.	→
Miljødirektoratet (2019): Vi endrer havet.	→
Statistics Norway (SSB): Greenhouse gases, by source, energy product and pollutant 1990 - 2020.	→
Strømman, Muri, Lund, Fuglestvedt (Nov 2019): Skipsfarten bør kutte ut svovel; Veien mot klimamålene inkluderer også store kutt i svovelutslipp	→
Transport & Environment (T&E)	→
UNEP (Dec 2021): Emissions gap report	→

Photo: Agathe Rialland,
Small cargo vessel in the North Sea, February 2020

3. THE SHIPPING INDUSTRY TODAY

SUMMARY

Deep insight into the shipping sector is essential to provide adequate advice to owners, operators and policy makers.

Ships carry 80% of global trade as well as passengers and perform various other work at sea.

No other transport mode can replace cargo vessels. Continued globalisation has increased sea transportation by around 3% pa for the last decades, and this growth is predicted to continue.

There are 33,000 vessels above 5,000 GT, around 50,000 vessels above 1000 GT.

If smaller vessels are included, the world fleet is around 100,000 vessels.

Ships carry cargo we well as passengers across the seas. Specialized ships are used for fishing and by navies and for exploration and production of oil, gas and other marine resources.

Ships are the only meaningful mode of transportation for bulk cargoes and carry 80% of global trade by volume and around 70% by value [UNCTAD | ↗]. 95% of imports to Norway arrive on ships [SSB, 2017 | ↗] and ships move 75% of the EU's external trade [EU | ↗]. Ships move around one third of domestic cargo volumes in Norway and the EU alike [SSB, 2017 | ↗], [EU | ↗].

Seaborne trade	80% of global trade	75% of EU's external trade	95% of imports to Norway

Sea transportation has grown by about 3% pa for the last decades and is predicted to maintain this growth rate [UNCTAD | ↗]. Historically, the growth in sea borne trade has followed growth in GDP. As observed in chapter 2.1, CO_2-emissions from ships have grown along trade volumes, until 2008.

Containerised cargoes have grown more than other segments and forecasted to continue to do so. Transportation of crude and oil products is forecasted to be slower. A transition away from fossil fuels will have great impact on the types and volumes of the various maritime cargoes; currently fossil products such as oil, refined oil products, chemicals and coal make up nearly 40%.

Change in seaborne trade 1970-2012 [Lindstad | ↗]	Cargo	Freight (t·nm)	Value	Fuel consumption
	+3% pa	+3% pa	+6% pa	+2.5% pa

Such high and sustained growth rates make reducing emissions even harder. Even more important Under business-as-usual scenarios, emissions will end up between 10% below and 30% above 2008 levels [IMO 4th GHG].

The energy transition ahead will have profound effects on seaborne trade. The use and therefore the transportation of fossil fuels must be reduced while new energy products such as liquid and gas biofuels, hydrogen and ammonia will be phased in. Hydrogen and ammonia are less energy dense (ref chapter 9.3) and thus will require more tonnage. Carbon captured from factories must be transported to suitable reservoirs for permanent storage.

3.1. Maritime cargoes and the world fleet (vessel types and sizes)

SUMMARY

Dry bulk cargoes make up half the maritime cargo base. 9% is coal. The volumes of coal carried by sea is only a tiny fraction of the global coal consumption.

Oil, petroleum products, chemicals, gas and coal make up 40% of maritime cargoes.

Three vessel types make up 77% of the world tonnage; container, dry bulk and tankers.

Large vessels make up the bulk of the world fleet, especially in terms of tonnage and emissions.

The energy transition will change the types of cargoes carried by sea; fossil energies like oil, refined oil products and coal will gradually drop while new energy types will grow.

Noting the plans to collect CO_2 at various sites in Europe for underground deposition, CO_2 will become a cargo.

Ships carry almost anything and are the only meaningful way of transporting large volumes and heavy cargoes. Dry bulk cargoes make up nearly half of maritime cargo while wet bulk cargoes make up 25%. Containerized cargoes accounts for only 15% measured by tonnes, but is the fastest growing segment.

Energy makes up around 40% of maritime cargo [IMO 4th GHG study, 2021, p. 221, Ch 4.2.3| ↗], [UNCTAD |↗]. Around 1/4 of this is coal while 3/4 remaining is oils, chemicals and gas [Equasis, 2019 | ↗].

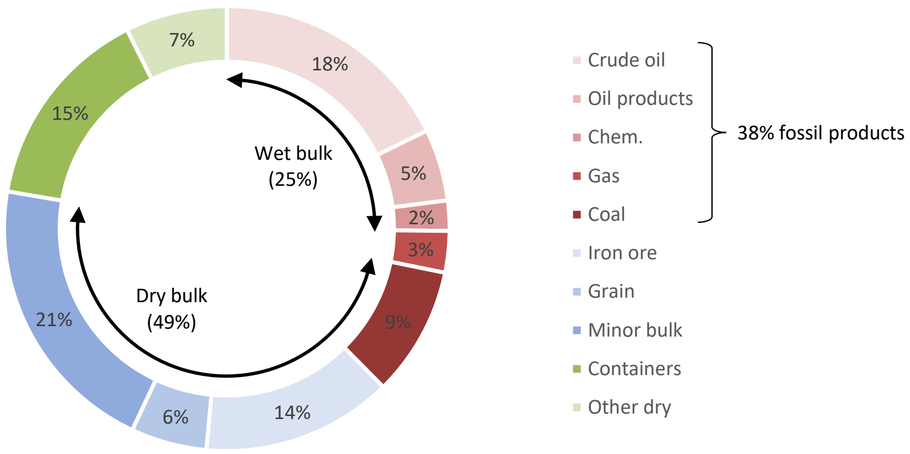


Figure 27: Maritime cargoes by weight based on UNCTAD Review of Maritime Transport [↗].

Almost all energy moved by sea has fossil origins and so the shipping sector is very exposed to changes in the energy landscape. The Norwegian merchant fleet is very exposed to fossil cargoes. On top of this comes the importance service vessels to the offshore oil & gas industry is added. 40% of the revenue of Norwegian maritime sector came from O&G in 2018 [Menon, 2019, p. 22 | ↗].

The decarbonization of society means there will be less fossil energy to transport. However, new types of energy will take over. Hydrogen, ammonia, biomethane and liquid biofuels will also likely need transportation. The impact on volumes and transport work remains to be seen. While fossil energy is a natural resource found in some parts of the world only, raw material for biofuels are more distributed and hydrogen fuels can be made anywhere with electricity. Thus, in the future, energy production may be closer to demand.

Transportation of CO_2 from large industrial plants to suitable reservoirs is another opportunity. The Norwegian Northern Lights project will operate two vessels carrying CO_2 from 2024 [Northern Lights, 3 March 2021 |↗] and more projects on CO2-transportation is under way. Cargo and cruise vessels have grown in size over the decades. Currently, the development is most remarkable for container shipping: The first 10,000 TEU vessel was built in 2015 and the first 20,000 vessel only two years later [McKinsey 2017 | ↗].

Vessels with large main engines are the biggest polluters: If we look at cargo and passenger vessels separately, we find that cargo vessels with main engines above 5 MW emit 85% of the total emissions from cargo ships, while the share is only 75% for passenger vessels, ropax and cruise vessels.

The below diagram (fig. 28) also indicate that a few vessels represent a large portion of the emissions. This is particularly noteworthy for passenger vessels, where 25% of the vessels by number are responsible for 70% of the emissions. 60% of the cargo vessels by number are responsible for 6% of emissions.

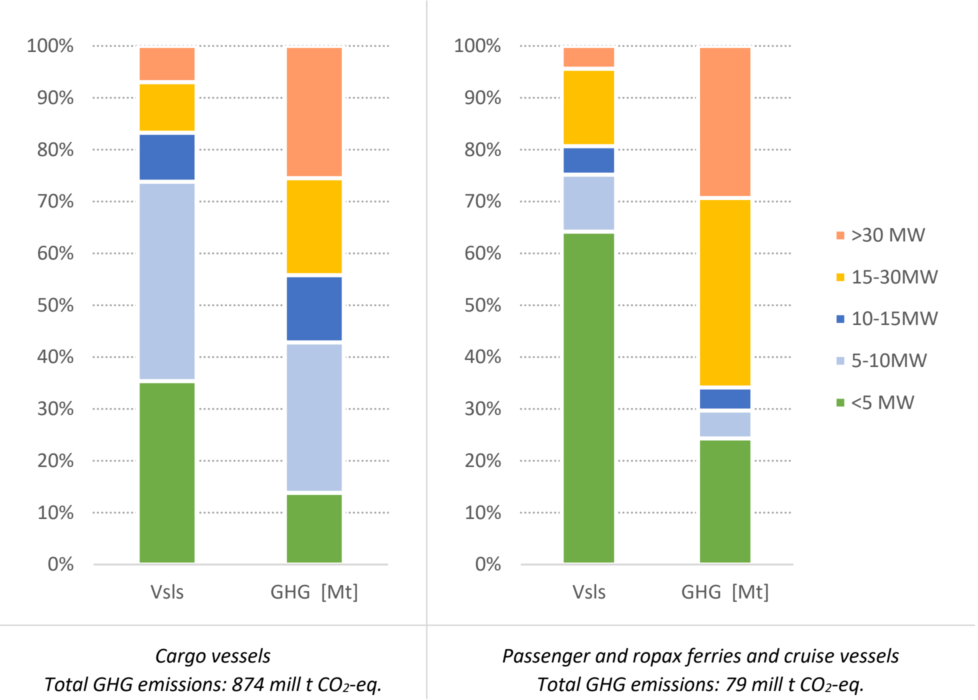


Figure 28: CO_2-breakdown by average installed main engine power.

This confirms the importance of fining solutions for vessels with large machinery and energy consumption.

3.2. Four distinct trades: Deep sea, short sea, passenger and service vessels

SUMMARY

Vessels are built for many different purposes and come in all sizes.

Deep sea refers to large vessels connecting continents. They sail worldwide, in liner or tramp service, and their fuel consumption and emissions are dominated by the energy efficiency of the hull and machinery at sea.

Short sea refers to smaller vessels in coastal or regional trades, connecting neighbouring countries. They will likely be the first to use new fuels as they are generally trade in the same region. They spend more time in port and generally sail close to populated regions.

Service vessels do not provide transport but undertake various services or work such as research, ice breaking, installation work or patrolling. Their operations and machinery installations are often complex with high requirements to operability and redundancy.

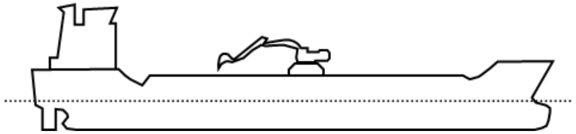
Small ferries cross fjords and sounds, large vessels connect continents. Not only the size, but also the operation and technology are very different, and so are the possibilities and potential for new technology and fuels. Recognizing the inherent characteristics and differences is critical to understand the opportunities and barriers and helps to find the most effective decarbonization pathway.

While ships in coastal or regional service dominate in terms of number, ships in deep sea trades dominate by size, engine power, fuel consumption and emissions.

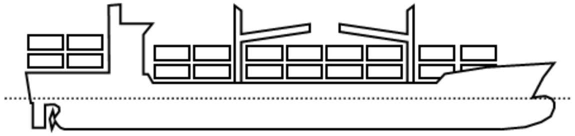
The Smart Maritime programme was established in 2015 with eight Norwegian deep sea operators with a combined fleet of 800 vessels, to find solutions for large vessels in global trades.

Short sea

Short sea shipping refers to coastal and regional shipping. The ships are typically smaller, run on a fixed route or within a limited geographical area, e.g. the North Sea. Ships carry around one third of domestic cargo volumes in Norway and the EU alike [SSB, 2017 | ↗], [EU | ↗]. For high value manufactured goods or perishable goods, transit times are often critical to compete with the truck. Keeping the schedule to ensure timely delivery of raw materials or semi-processed goods is essential. Fuel costs are generally a smaller share of the total costs than in deep sea shipping. With short sailing distances, the energy consumption in port is also important.

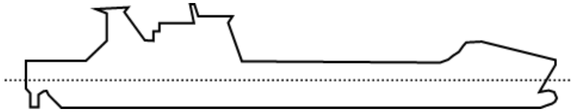


Coastal dry bulk carriers



Container (feeder) vessels

General cargo vessels

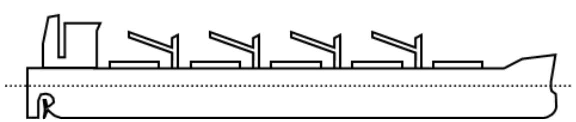


RO/RO (roll-on/roll-off carrier)

Alternative fuels, occupying more space and increasing the fuel cost, are more likely to debut in short sea shipping due to the smaller energy demand and shorter sailing distances. With significant sailing time in national waters, short sea shipping is a more likely target for national regulations and economic incentive schemes, as those under investigation in Norway and the EU.

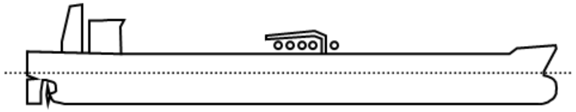
Deep sea shipping

Deep sea shipping is characterized by large vessels sailing longer distance, generally between continents and operating worldwide. These ships must be prepared to take cargo between any of the major shipping ports worldwide and carry enough fuel for trans-Atlantic or trans-Pacific crossings. They cannot commit to a new fuel until it is available in major ports across the globe. On the positive side, operational measures often have a bigger impact on large ships spending more time at sea. Dry bulk and tank carry commodities on spot or short term contracts and are rarely tailored or optimized for a specific trade. The competition is fierce with very fluctuating charter rates, especially for bulk and tank.

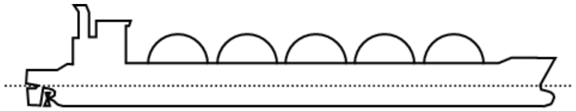


Dry bulk carriers

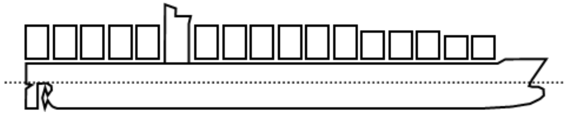
Open hatch vessels (for timber, forestry products, steel, paper).



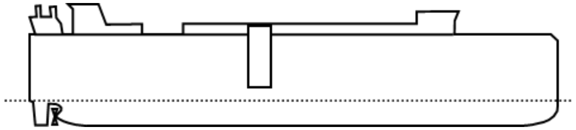
Tankers (for crude oil, oil products and chemicals)



Gas carriers (for LNG, LPG, ethylene, CO_2)



Container vessels

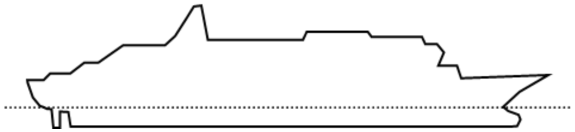


Vehicle carriers: PCC and PCTC

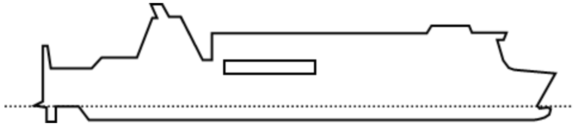
Bulk carriers, tankers and container vessels represent more than half of total shipping emissions (about 18, 15 and 22% respectively), so finding a solution for these is essential to succeed [IMO 4th GHG study, 2021 | ↗]. National and regional policies and regulations have limited impact, only those adopted by the IMO can change the game.

Ships with passengers

Vessels carrying passengers have private individuals as their customers and are part of peoples' daily life, travels or vacations. The key success criteria are therefore shifted to comfort and convenience, both onboard and when it comes to departure and arrival time, transit time and embarkation and disembarkation. The environmental concern of individuals may be different and decision making is influenced by feelings and consciousness as well as facts.



Cruise and passenger vessels

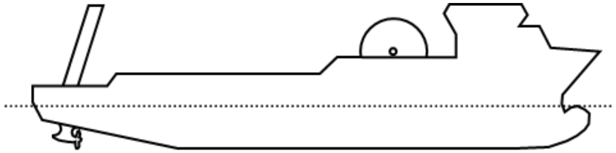


Ropax

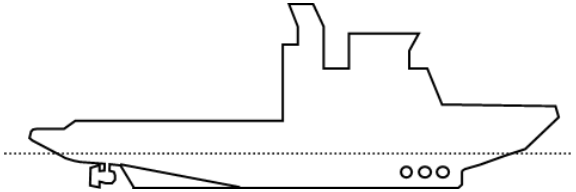
Globally, passenger and cruise vessels emit around 7.5% of shipping's GHG [IIMO 4 GHG study |↗] while the share is above 20-30% in Norway [Kystverket, 2019| ↗], [Regjeringens handlingsplan for grønn skipsfart, 2019 | ↗]. The carbon intensity of ropax vessels vary significantly and depend on size and trade as well as the onboard service and machinery and fuel. Some struggle to compete with the carbon intensity of airlines and must reduce energy use and emissions considerably.

Service vessels

Service vessels differ fundamentally from cargo vessels. They perform installation or maintenance work or other services. The fuel consumption and emissions are determined by the work performed rather than the distance sailed. This makes it harder to estimate emissions by using AIS and these ship types should be measured by other metrics than cargo ships. Also, most importantly, they require different technology and abatement measures. They often work in harsh conditions with high requirements to reliability and operability.



Offshore supply and service vessels



Icebreakers

Many are employed by the oil and gas (energy) sector which give other possibilities to influence the choice of fuel. Other ships are on governmental contracts which allows governments to introduce environmental performance requirements in public procurement. In Norway, service vessels to the oil and gas industry emit 15% of shipping emissions [Kystverket, 2019| ↗].

3.3. Current fuels

SUMMARY

Fossil, liquid oil fuels power almost all vessels. Use of MGO grow and now make up 32% of maritime fuels. LNG powers nearly 400 vessels plus most LNG-carriers.

Methanol is used by 20-30 vessels also carrying methanol.

LPG powers less than hundred vessels, but orders for more than hundred LPG-engines suggest growing interest.

The use of both methanol and LPG is – so far – limited to vessels carrying methanol and LPG. Despite the limited application, such pioneering use will build up experience with these fuels and can also motivate infrastructure that other ships can benefit from, eventually.

Liquid biofuels are tested on short sea and deep sea vessels alike, primarily as a drop in fuel, but also as the main fuel for some voyages.

A high share of new vessels under construction will have alternative fuels, analysts reported in 2021. LNG dominates and the majority will have duel fuel engines.

We discuss the future for alternative fuels in chapter 9.

Fossil fuels such as heavy fuel oil (HFO) and marine gas oil (MGO) fuel almost all vessels today [IMO 4th GHG study, 2021, p.7 and p. 97 | ↗].Among the alternative fuels discussed in chapter 9, only LNG, LPG, methanol and biofuels are in use today. The use of LPG and methanol is near negligible.

LNG carriers have generally been powered by boil off gas from the cargo since the beginning. For other vessels, LNG was first used as a fuel onboard the car ferry Glutra in 2000. By the end of 2022, LNG fuels around 350 vessels and 500 more are on order [DNV AFI | ↗]. Almost all LNG carriers have historically run on LNG. Gas carriers sailing within and to/from the EU draw 72% of their energy from LNG and consume 86% of the LNG consumed by ships [EU, 2022, p. 23 | ↗]. LNG makes up 4% of marine fuels worldwide and 6% of fuels within and to/from the EU [EU, 2022, p. 23 | ↗]. Less than a hundred ships sail on LPG.

Biofuels are used occasionally or as drop-in fuel by a few ships, but no reliable statistics are available. The volumes are likely minuscule, yet the interest and piloting of biofuels is positive. Biofuels encompass a range of different types, both liquid and gaseous fuels produced from wastes and purpose-grown biological materials.

Around 20-30 vessels sail on methanol. All but one are on charter to the methanol industry [DNV AFI | ↗]. The volumes are minuscule and makes up only 0.02% of marine fuels. The order from Mærsk for a series of container carriers using methanol as fuel signals a breakthrough for methanol as a maritime fuel [Mærsk, 1 July 2021 | ↗].

There are seven nuclear civil vessels, mainly icebreakers and a single cargo ship for the Russian Arctic [Stopford, May 2020].

The below diagram (fig. 29 and 30) presents the fuel split for all shipping and international shipping for 2018. Extensive use of MDO/MGO in the coastal fleet and fishing makes the share of MDO/MGO higher for all shipping than for international shipping.

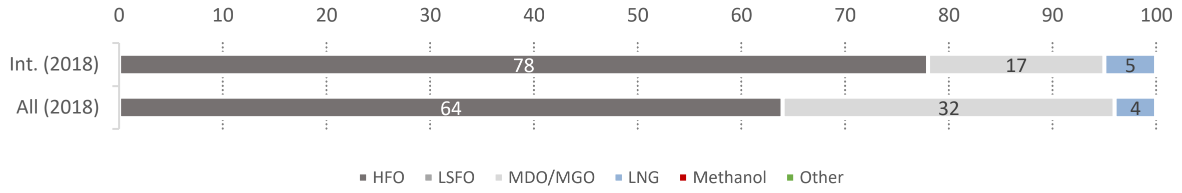


Figure 29: Breakdown of fuels for international and all shipping in 2018.

Data from EU MRV for 2018, 2019 and 2020 confirms that HFO is increasingly replaced by fuels with low sulphur.

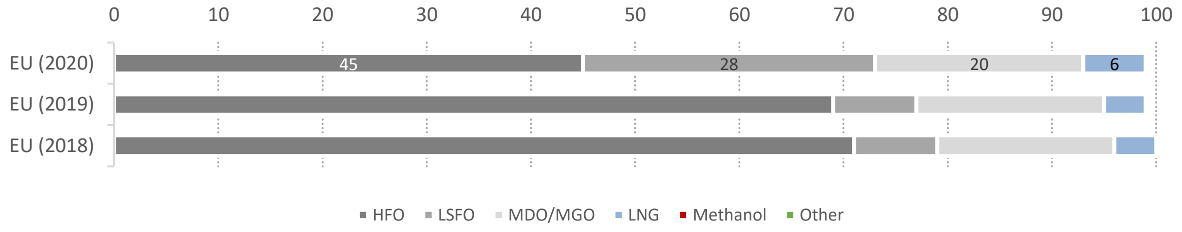


Figure 30: Breakdown of fuels for shipping covered by EU MRV in 2018-2020.

Note that residual and distilled oils can be blended to meet the sulphur limit and residual oils will therefore continue to be used in ships. Vessels reporting to the EU MRV-scheme reduced the HFO share from 69% to 45% while the share of light fuel oil increased from 8% to 28%, thus the total of HFO + light fuel oil dropped only marginally, from 77% to 73% [EU, 2022, p. 23 | ↗].

Signs of an emerging fuel transition?

Engines for heavy fuel and diesel, LNG, LPG and methanol are available from the major engine makers. A few engines and turbines can take blends of gas and hydrogen. The development of machinery for new fuels continues and is discussed in detail in chapter 9.4.

Reports from brokers and class societies suggest that new ships are increasingly built for dual fuel operation: For 2020, Clarkson report 27% of newbuildings (measured by gross tonnage), while DNV says 12% [DNV ETO 2021 | ↗]. Around 17% of new vessels built in China have DF-machinery [BRS Annual review 2021, page 28 | ↗].

Looking closer at Clarkson's numbers, 11.5% are LNG carriers and 13% are LNG fuelled and likely dual fuelled. 1.3% will run on LPG, 0.3% on methanol and 0.5% on ethane while 0.7% will have batteries fitted [Clarkson cited in Splash 24/7, 30 Nov 2020 | ↗]. The conclusion is that fossil gas fuels dominate. Note that batteries are generally a supplement rather than a replacement (as we discuss in chapter 8.7).

The majority of the dual fuelled vessels on order are designed to run on LNG. Only a few vessels are designed for LPG, methanol and ethane. And as only 0.2% of the current methanol production is green, the transition away from fossil fuels have really not started.

Note also that alternative fuels do not necessarily mean climate-neutral fuels – yet. IRENA estimates that 0.2% of the current methanol production is green [IRENA, 2021 | ↗] and less than one percent of the current hydrogen and ammonia volumes are produced without GHG emissions [IEA, Global hydrogen review 2022 | ↗], [International Fertilizer Association, 2021 | ↗].

3.4. Current machinery

SUMMARY

98% of the world fleet is powered by diesel engines.

Two stroke engines power the largest vessels. These engines power 78% of the ships above 5,000 GT and the share is higher measured by kW.

While four stroke powers 20% of ships above 5,000 GT, they are smaller and thus four stroke engines power only 3% of the world fleet measured by dwt.

Counting all marine machinery, there are 40% two stroke engines, 34% medium speed engines and 26% high speed engines. Medium and especially high speed engines are smaller and have a much lower share measured in kW.

The average main engine size is 6,500 kW but much larger for bulk carriers and container vessels and many other important vessel types. F

Future marine machinery must be available in MW-sizes to be relevant for large vessels.

More than 98% of the world fleet is powered by diesel engines [IMO 4th GHG study, 2021, p.59 | ↗]. Two stroke engines dominate.

Counting the number of engines in the global fleet, IMO finds nearly 40% slow speed two stroke engines, 34% medium speed four stroke engines and 26% high speed diesel engines [IMO 4th GHG study, 2021, p. 48 | ↗]. Because high speed and medium speed engines are smaller, they have a much lower share measured in kW. Data from Martin Stopford for vessels above 5,000 GT is perhaps more relevant; measured by dwt he finds that 92% of the fleet is powered by two strokes and only 5% by four stroke engines. The discrepancy between IMO and Stopford is likely due to the 5,000 GT threshold; there are about 55,000 ships below 500 GT [Equasis, 2020 | ↗] so including these will increase the number of four strokes significantly.

Diesel electric (DE) is common in offshore supply and construction vessels, cruise ships and LNG carriers. Steam turbine vessels and non-propelled barges represent around 1-2% combined. Note that the sums in the following table do not add up to 100% because steam turbines and non-propelled barges are excluded and because vessels with figures for diesel electric propulsion overlap with four stroke engines.

Market share of marine machinery (vessels > 5,000 GT)	Two stroke:	Four stroke:	Diesel electric:
	78% by number	21% by number	4% by number
	92% by DWT	5% by DWT	2% by dwt

Fuel cells with a combined output of 520 MW were installed in marine applications by 2018 [Shakeri, Zadeh and Nielsen, 2020 | ↗]. These are generally small and provide auxiliary power.

The average main engine power of tankers is 5,000 kW, the average for bulk carriers is 9,500 kW while container vessels have on average 29,000 kW on the main engine [IMO 4 GHG study, 2021, table 81 | ↗].

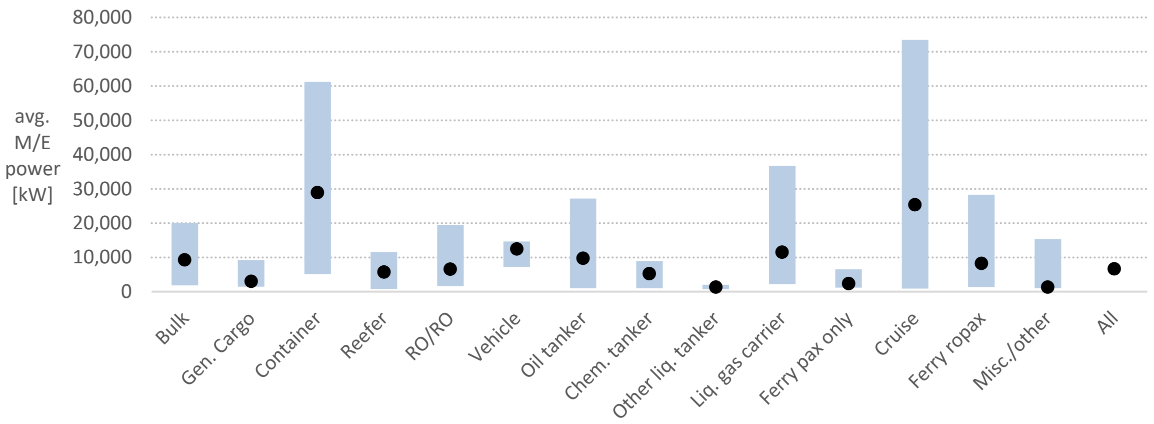


Figure 31: Typical range and average main engine power for various vessel types.

3.5. Speed

SUMMARY

Speed is an important parameter for energy use and emissions, but the positive effect of slow steaming is not without limits and less advantageous for vessels already operating well below their boundary speed.

Halving the speed can reduce energy for propulsion by 85-90%. However, the energy required for ancillary systems at sea and in port makes the total effect much smaller. At slow speed, vessels spend more time at sea. Also, energy use in port remains the same.

Finally, additional tonnage must be constructed and operated.

Speed is an important parameter for energy use and emissions. Average sailing speeds have indeed been reduced over the last decade, partly for environmental reasons and partly to adjust supply to demand.

The average speed range for different vessel types are shown below (fig. 32, left diagram) together with the average speed relative to the design speed (fig. 32, right diagram). The dots represent the average speed in 2018 while the bare indicates the range for the size categories. Outliers exist well outside the indicated range [IMO 4GHG-study, table 81, page 446 | ↗].

The diagrams indicate that most vessels in 2018 sailed at speeds around 20% below their design speed [IMO 4GHG-study, table 81, page 446 | ↗]. Bulkers, tankers and container vessels have reduced speed by 16, 18 and 24% respectively from 2008 [Clarksons Research, October 2019].

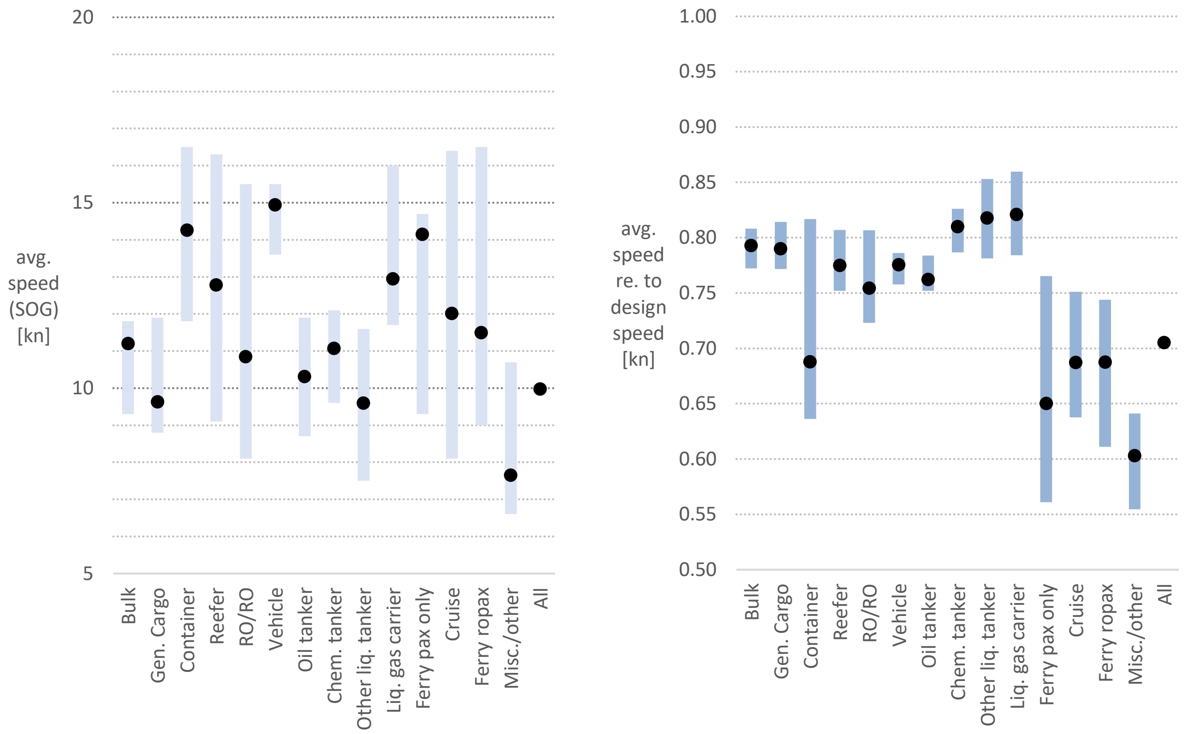


Figure 32: Typical speed range and average speed for various vessel types (2018); in knots (left) and relative to design speed (right)

Noting that the current speed of most vessels has been reduced, we must ask if the potential for further emissions reductions by even slower speed been exhausted. We discuss this in chapter 7.3.

3.6. Sources and further reading

	Link
Barry Rogliano Salles (2021: Shipping and shipbuilding markets.	→
DNV: Alternative fuels insight (AFI)	→
Equasis: The 2020 World Merchant Fleet Statistics from Equasis	→
Faber et al. (2021): IMO 4 GHG study 2020.	→
IRENA (2021): Renewable methanol	→
Lindstad (2013): Strategies and measures for reducing maritime CO_2 emissions.	→
Martin Stopford (April 2020): Coronavirus, Climate Change & Smart Shipping: Three maritime sceniaros 2020-2050.	→
McKinsey (2017) : Container shipping: The next 50 years	→
UNCTAD: Review of maritime transport	→


Photo: Tersan shipyard / Havila Kystruten
Havila Capella and Havila Castor under construction in 2020.

4. FOUR STEPS TO GREEN SHIPPING

SUMMARY

The very high emission cuts required, the scarcity of renewable energy and the diversity of the fleet warrant a multi-faceted approach to ensure that all possible measures are used.

SINTEF Ocean and NTNU suggest a four-stepped approach to find the most effective emission reduction measures for each segment, company and vessel.

Generally, many different measures, operational practices and technologies can delivery some emission cuts, but very few can eliminate them altogether. A stepwise and combined approach seems necessary to reduce emissions with minimum cost and disadvantages.

Some technologies and operational practices can have great effect on some vessels, but very limited effect on others. The resistance of slow, full-bodied vessels is mainly from friction while wave making is more pronounced in fast, slender hulls. Thus, there is no panacea, and understanding the challenge of each particular vessel is key to reducing emissions.

SINTEF Ocean and NTNU consider the following four steps, in the prescribed order, essential to cut emissions cost effectively:

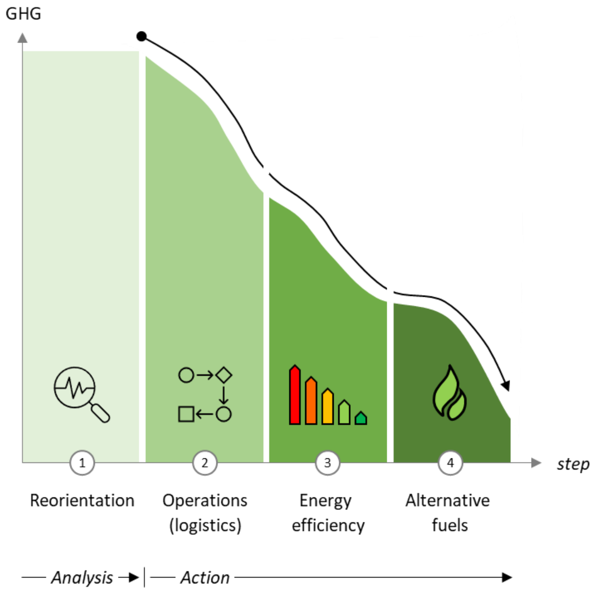


Figure 33: The Smart Maritime four step approach.

Our sea map to greener shipping builds on these four steps. We will outline our research in the four areas in the following four sections (section 6 to 9). The following table presents the goal and essence of each area and can be considered a blueprint or recipe for making pathways to greener shipping:

Reorientation	Logistics	Energy use and efficiency	Alternative fuels

GOAL

Insight/basis for optimization and follow up.	Maximize cargo carried relative to energy use	Reduce energy consumption.	Use energy with less emissions and footprint.

RATIONALE & ESSENCE

To move forward, we must analyse external and internal factors to establish a starting point and baseline as well as gaps and goals. Intimate knowledge of current operations including the operational profile, energy use and emissions is necessary to find the drivers behind. Noting the lack of progress, a fresh approach seems necessary. We must rethink scope as well as system borders. Reorientation refers to a change of mind and increased insight into key factors that must be considered to deliver significant and lasting emission cuts that does not violate other sustainability criteria.	Using the existing fleet in a more efficient manner gives results in a short time frame compared to develop and build new vessels. Logistics optimization includes finding the most energy efficient and least polluting transport from A to B, including transport mode, route and speed. On the cargo side, economy and ecology of scale should be utilized when possible and high utilization and return cargo and circular trading patters can reduce carbon intensity.	Renewable energy is and will be scarce for the foreseeable future (ref chapter 9.1) and many if not all industries will compete for clean energy. Also, new fuels occupy more space onboard, cost more and carry significant risks. Reducing the need for new fuels is therefore advantageous in all respects.	Whatever energy is required should come from low and zero-carbon carriers to push the final carbon foot print towards zero.

INDICATORS (ref chapter 6.3)

-	Transport work index (TWI)	Energy Intensity index (EEI)	Fuel GHG Intensity index (GII)

GENEREIC STEP BY STEP GUIDE

Reorientation

Include all GHG and other emissions in emission inventories and reporting.

Estimate emissions with engine specific and load specific emission factors.

Estimate climate impact with region specific GWP characterization factors.

Establish relevant emissions and sustainability indexes based on operational figures and cargo carried.

Focus on total resistance rather than calm water resistance in hull optimization, model testing, contract guarantee clauses and charterparty terms.

Run digital twins in realistic weather conditions to help optimize hull and machinery for real life conditions.

Establish long term collaborations with downside/upside sharing to reduce risk.

Take a lifecycle approach to energy and fuel and other environmental burdens.

Logistics

Optimization of maritime logistics and total supply chain.

Find the right vessel type and cargo handling gear for the cargo/trade.

Utilize economy of scale to reduce energy per transport work.

Set up a sailing route to ensure good access to cargo to maximize utilization. Consider a schedule with some slack for inducement calls (for liner trades).

Specify cargo handling gear to optimize cargo operations and minimize port turnaround time.

Optimize vessel speed to minimize emission, cost and idling time prior to berthing.

Maximize vessel utilization including ballasting/repositioning voyages.

Weather routing: Plan and adjust sailing route, considering wind and vessel's characteristics.

Energy use and efficiency

Optimize main dimensions.

Minimize displacement; by construction, materials and avoiding water ballast.

Minimize resistance and propulsion power in calm water as well as waves and wind, taking vessel's added resistance into account.

Consider energy loss from pitch and roll.

Minimize power consumption for onboard systems.

Utilize wind for propulsion.

Utilize energy saving devices and optimize the combination of hull and propulsor.

Reduce friction resistance by minimizing hull roughness, at newbuilding stage and by blasting in dry dock. Monitor hull fouling and clean the hull between dockings. Study the savings of air lubrication systems.

Optimize the machinery configuration including transmission losses.

Evaluate hybrid machinery; the advantages of combining conventional main engine(s) and generator sets with batteries.

Utilize waste heat for heating and cooling.

Recover kinetic energy from cranes and elevators.

Alternative fuels

Change to fuels with lower footprint well to wake.

Investigate the fuel's energy in a life cycle perspective, considering production, compression/liquefaction, storage, distribution, conversions etc.

Consider other sustainability criteria and environmental impacts, mindful of the indirect effect of biofuels.

Endeavour to switch fuel as soon as possible, mindful of availability of sustainable, low carbon fuels and necessary machinery and systems. Calculate the accumulated emissions from today to discover the effect of waiting.

Noting the urgency to curb global warming, evaluate the relevance of GWP_{20} in addition to GWP_{100}.

4.1. An overview of green measures

SUMMARY

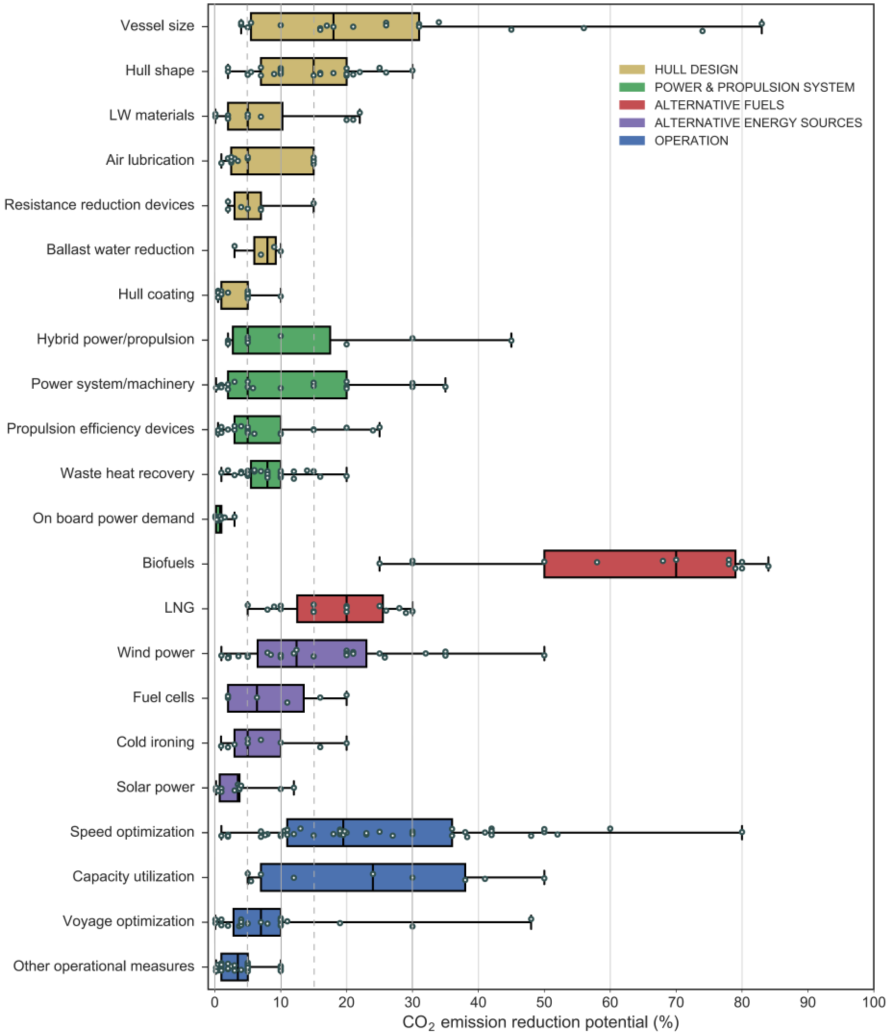
There are many ways to reduce emissions. The potential, applicability, compatibility varies between the measures and vessel types.

The four-step approach is inspired by the long list of possible emission reducing measures and the fact that these have very different effect on different ship types. Only by using any and all of these technologies and procedures can we achieve cost effective emission cuts.

Some technologies can be combined while others are mutually exclusive.

Percentages are rarely cumulative. The effect depends on a number of factors and must always be ascertained on a case by case basis.

Researchers from NTNU and SINTEF Ocean, led by Evert Bouman, reviewed nearly 150 studies and produced the following non-exhaustive overview of 22 types of measures to reduce energy and emissions [Bouman et al., 2017 |↗]. We would like to stress two key points: First, there are many different ways to reduce energy use and emissions: Secondly, the effect of each measure vary significantly and depends on specifics of the vessel and intended trade. The effect on a particular vessel case must be analysed carefully (ref Ch 6.5).



Point: individual analysis

Line: whole spread

Bar: typical (1st to 3rd quartile)

Figure 34: Overview of emission reducing measures.

Note also that percentages cannot always be added; if a better hull form and a better engine both cuts 15%, the total is 28% (0.85 x 0.85 = 0.72). This is discussed in a paper from 2012 by Balland, Erikstad and Fagerholt [↗].

4.2. Success criteria for emission reduction technologies

SUMMARY

The true potential of mitigating measures is measured in the accumulated metric tonnes GHG saved from today.

This chapter gives an overview some of the key evaluation criteria for new technologies and fuels.

From the previous chapters, we note that emissions must be reduced significantly and rapidly. We learned that the largest vessels in intercontinental traffic emit the most and that this activity is under fierce international competition and price pressure.

Based on this insight, the following four factors must be considered when we evaluate new technologies, amended operational practices and alternative fuels:

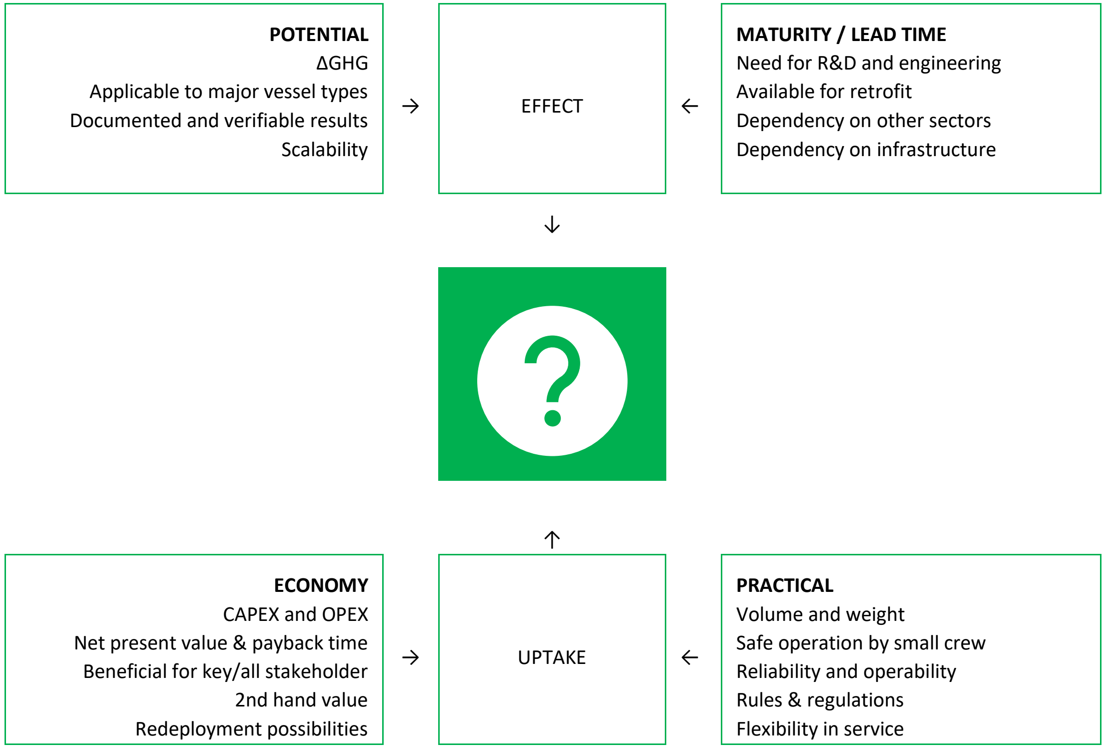


Figure 35: Success criteria for effective and environmental technology, procedures and fuels.

The potential for reducing emissions is determined by the effect for each vessel and how quickly the measure can be implemented. A good solution today may be better than a perfect solution available in 2030. Measures suitable for the major vessel types contribute more. Technologies must be scalable to be relevant for the largest polluters.

The uptake of each emission reducing measures is eventually also determined by the economics.

4.3. Sources and further reading

🗎	*Link*
Bouman, Lindstad, Rialland and Strømman (2017): State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review.	→
Getting to zero coallition (17 March 2021): Mapping of Zero Emission Pilots and Demonstration Projects.	→
Lindstad, Bø and Eskeland in the texboook Marine Design XIII (ISBN: 978-1-138-54187-0): Reducing GHG emissions in shipping – Measures and options.	→
Rialland and Lindstad (2021): Shipping decarbonization scenarios.	→

Illustration: The Open simulation platform

5. DIGITAL TOOLS FOR GREEN SHIPPING

SUMMARY

Added resistance from waves and wind have significant impact on energy consumption. Similarly, specific fuel consumption and emission factors are generally quite different at part loads. Subsequently, these factors must be considered when estimating energy use and emissions.

Including these factors in the ship design phase can give vessels optimized for real rather than ideal conditions.

Two tools for estimating energy use and emissions have been developed: GYMIR is intended for optimization of individual vessels while MariTEAM is relevant for fleets where the combined effect of technology, operational practices and policies can be investigated

Hear Vegar Johansen explain the role of Ocean Space Centre in future maritime R&D in a SINTEF podcast 22 September 2021 [↗]

For the last decades, vessels have been designed for only a few types of cargoes and a few loading conditions. Hull and machinery have commonly been optimized for the sea trial and guarantee condition. Verifications of machinery by shop trials and the complete vessel by sea trials are conducted only for a very limited number of operating conditions. All in all, vessels have generally performed better on paper than in real life. There are many reasons for this practice:

1. The practices of building series of standard vessels prevents a single ships to be fine-tuned for its expected service. Series production is advantageous when building is expensive, and operation is cheap. With high fuel prices and concern for emissions, the priority should be questioned – and possibly turned around.

2. The importance of the guaranteed speed at near calm water conditions would also encourage the designer and shipyard to focus on calm water performance. Similarly, the main engine's consumption is commonly tested at a four engine loads but guaranteed at only a single point, typically in the range from 75% to 90% of MCR.

To break away from this practice and to ensure that the best design is identified and built, SINTEF Ocean and NTNU developed GYMIR, a simulation tool to evaluate a digital twin of an unbuilt vessel at its early concept phase.

GYMIR handles the hydrodynamic aspects such as resistance and propulsive efficiency while machinery and transmission is analysed by a module called FEEMS; Fuel, Energy and Emissions Prediction for Maritime Energy System.

GYMIR and FEEMS utilizes the many building blocks developed in the Smart Maritime programme, such as methods for added resistance in waves, emission factors at part load and interplay between generators and batteries, summarized in the below illustration:

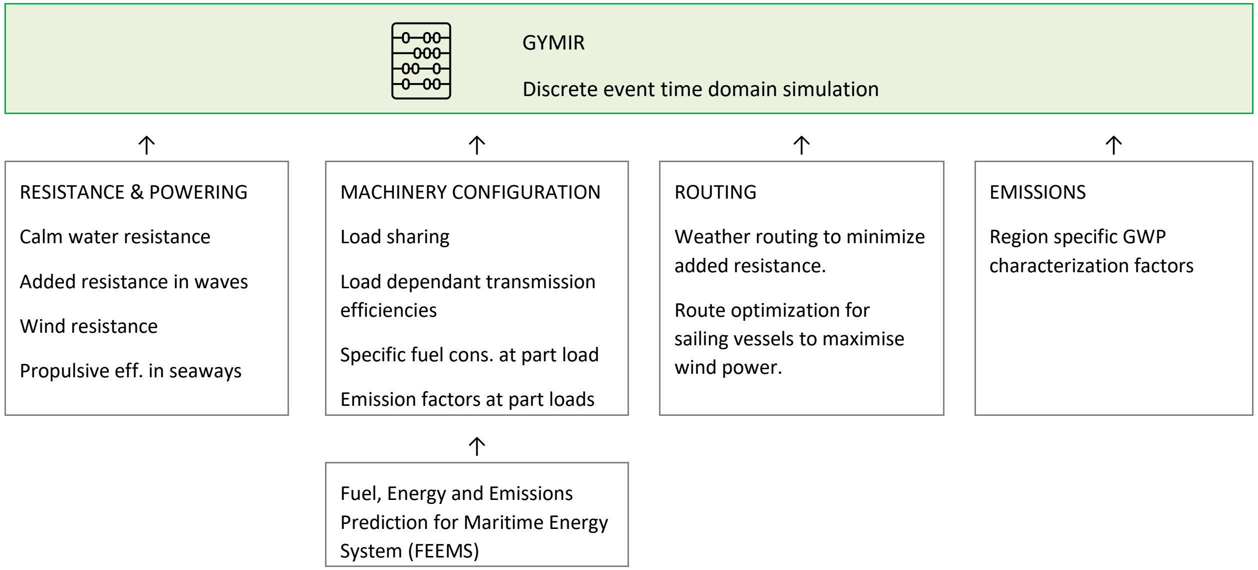


Figure 36: Components in the GYMIR simulation tool.

5.1. GYMIR: A simulation based tool for ship design optimization

SUMMARY

To achieve real emissions reductions, vessels must be designed and optimized for a range of realistic loading conditions and weather conditions.

GYMIR was developed to this end, based on methods to estimate added resistance, wind resistance and propulsive efficiencies.

Also, a logic for route optimization including weather routing and sailing control has been developed to take these operational practices into account to ensure good match between simulations and real operations.

The simulator is based on discrete event simulation; this is a compromise between high accuracy and low computational power.

GYMIR can be used at concept design stage to identify the best designs.

GYMIR is useful to estimate the energy use and emissions for a design on the intended trade. It takes variations in cargo, draught and loading condition and weather en route into consideration so that the calculations are based on realistic operating conditions. GYMIR can simulate a year or more of operations to ensure that the variations in weather and loading conditions are reflected.

> *SINTEF Ocean and NTNU developed GYMIR to find designs that performs best in reality, not on paper. The tool is useful to evaluate main dimensions, hull forms, machinery configurations, power transmission alternatives, batteries and sails.*

GYMIR is a compromise between accuracy and computational power to facilitate analysis of multiple variants at a very early stage where the potential for emissions reductions is higher. Simulations does not replace the need for CFD, nor model testing, which can refine the most promising concepts further. As the design process progresses, data from CFD and model tests can be fed back to the GYMIR model, allowing for more accurate predictions, and possibly refining and optimizing the operational profile.

Proposed procedure: ① *Approximate formulae* → ② *GYMIR* → ③ *CFD* → ④ *Model testing*

Simulations has proved to be an indispensable tool for many of the case studies presented in this sea map, including the short sea case and the Supramax case (see chapter 8.2), the evaluation of powering options for Aframax tankers (discussed in chapter 8.6) and for evaluation of machinery configurations (chapter 8.6 and 8.7).

The work process and use of simulations is illustrated on the next page for a typical ship design optimization case with a number of possible main dimension and hull form alternatives. Multiple virtual prototypes are built and test run on the intended trade where they meet weather according to hindcast for each day of the year. A long simulation period, e.g. a full year, means that the vessel will meet weather considered typical for the trade. Based on the project specifics, energy use and emissions are calculated for a time period for possible combinations of the design alternatives

Energy and emissions are calculated using specific consumption and emission factors. This captures both the positive and negative effects of slow steaming and ensures realistic estimation of fuel consumption, methane slip, NO_X and black carbon which are higher at low engine loads.

Not only main dimensions and hull forms can be tested, simulation of possible machinery configurations can also be tested to find the effect of hybrid machinery where generators and batteries work alongside the main engine to reduce energy use and emissions.

Finally, the results from the simulation of the design alternatives are compared to guide the investment decision. Simulations can be helpful to determine the minimum required engine power to keep the schedule with the desired probability, useful for ropax and LNG-carriers on fixed routes, inter alia.

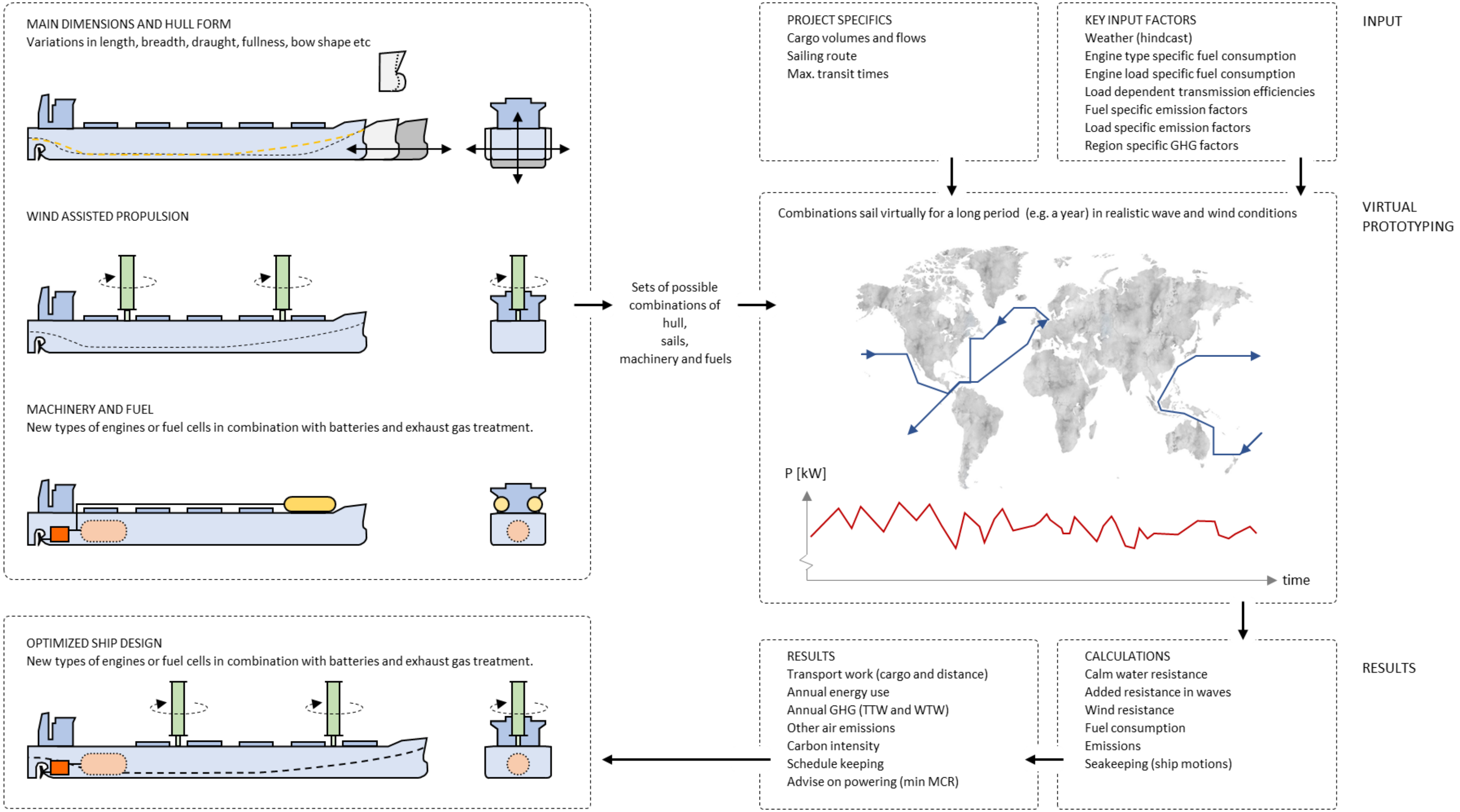


Figure 37: Example of design optimization of a bulk carrier design where energy and emissions for combinations of multiple hull form alternatives (A to G), wind assisted propulsion (H) and two machinery and fuel options (I-K) can be estimated by simulation of operations over a full year, on the intended route, taking realistic waves and wind into account.

5.2. Fuel, Energy and Emissions Prediction for Maritime Energy System

SUMMARY

Machinery systems are becoming increasingly complex. Batteries and shaft generators with PTO/PTI-functionality as well as waste heat recovery can help to increase the total system efficiency, especially at part loads.

FEEMS was developed to calculate the total losses in such complex machinery installations and thus help to find the best machinery configuration for a given operation.

The machinery installation is modelled using components from a library.

With the current emphasis on increasing efficiency, decarbonization and flexibility, the machinery systems on ships are becoming increasingly complex.

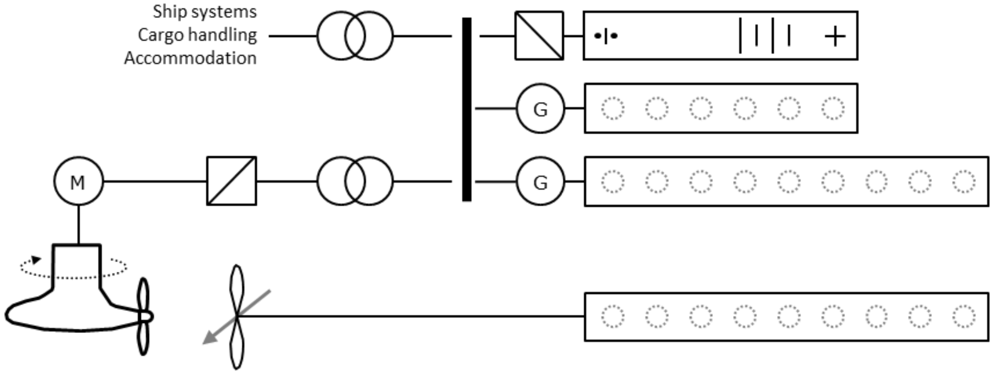


Figure 38: Novel machinery arrangement with contra rotating propellers, electric podded propulsor and fixed shaft

Examples include a vessel equipped with several engines and generator sets in combination with a battery. The battery can facilitate optimal running of the main engine and generators and provide short periods of silent and emission free sailing (see chapter 9.7).

The introduction of fuel cell for maritime application also involves using different power source such as batteries or internal combustion engines to mitigate the limitation in providing the necessary power or turning them off when they are not in need.

As the complexity and interdependency increases, it is challenging for a ship designer to choose a right configuration of the system, optimal sizes of each machinery and proper way of controlling them because they are coupled problems. In this regard, a new way of modeling and analyzing the complex system in a simple and flexible way is needed.

SINTEF Ocean and NTNU have developed a new modeling framework to analyze the fuel consumption, efficiency, and emissions of such complex machinery system for an actual operational scenario, called Fuel, Energy and Emissions Prediction for Maritime Energy System (FEEMS).

In this framework, the machinery configuration can be modelled based on propulsion and machinery configuration and single line diagram using components from a library.

The framework allows the user to model most of known power systems and propulsion systems such as hybrid or conventional diesel electric propulsion system, a hybrid propulsion system with PTI/PTO and mechanical propulsion system with a separate electric power system. FEEMS framework provides a bottom-up approach for building up a system model with simple parameters based on an object-oriented approach. The system is built from components and a larger system is built from smaller systems. The created components or systems can be reused for other cases.

5.3. MariTEAM: Maritime Transport Environmental Assessment Model

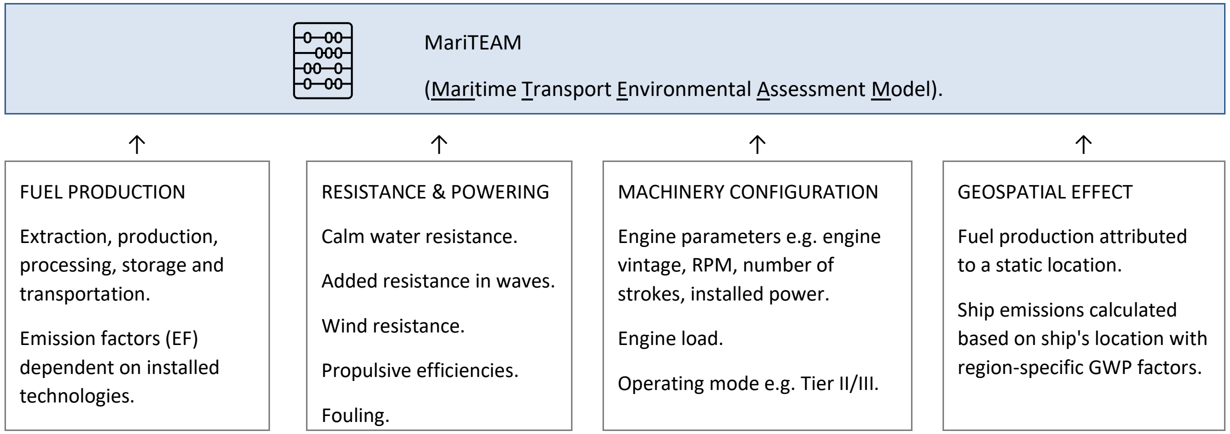
SUMMARY

MariTEAM was developed to investigate the combined effect of technology, operational practices and policies. It combines expertise in naval architecture and marine machinery with climate modelling.

Emission inventories have traditionally been based on fuel sales statistics. The 3rd IMO GHG study in 2014 was the first major maritime emission inventory to utilize the activity logs of ships. It builds on the assumption that the engine power is a function of speed, primarily, and that the energy use of other onboard consumers can be calculated based on the operational mode. Specific consumption and emission factors is based on data for the onboard machinery.

The IMO's DCS (data collection system) and EU's MRV (monitoring, reporting and verification) schemes are based on reports from ship owner.

NTNU and SINTEF Ocean have developed a state-of-the-art emission inventory calculator for the maritime sector based on expertise in climate modelling, naval architecture and marine machinery. It was developed to investigate the effects of novel technologies, fuels and policies on national, regional or global fleets and described in a paper published in 2021 [Kramel et al., 2021 | ↗].



MariTEAM

(Maritime Transport Environmental Assessment Model).

↑ ↑ ↑ ↑

FUEL PRODUCTION

Extraction, production, processing, storage and transportation.

Emission factors (EF) dependent on installed technologies.

RESISTANCE & POWERING

Calm water resistance.

Added resistance in waves.

Wind resistance.

Propulsive efficiencies.

Fouling.

MACHINERY CONFIGURATION

Engine parameters e.g. engine vintage, RPM, number of strokes, installed power.

Engine load.

Operating mode e.g. Tier II/III.

GEOSPATIAL EFFECT

Fuel production attributed to a static location.

Ship emissions calculated based on ship's location with region-specific GWP factors.

Figure 39: Components in MariTEAM.

The calculation builds on activity and location data from AIS as well as weather statistics (hindcast). It uses state of the art empirical resistance prediction methods rather than simple admiralty coefficients to estimate the required propulsion power for a given speed and draught. It also uses prediction methods for added resistance in waves and wind.

Specific fuel consumption and specific emission factors are estimated based on the engine type and engine load. The global warming effect is calculated based on the geolocation of the vessel, using region specific GWP-factors (ref chapter 6.1).

Critical aspects that have been addressed include, inter alia, added resistance in waves, specific fuel consumption and emission factors at engine part load and the geospatial impact of the various exhaust gases and particles.

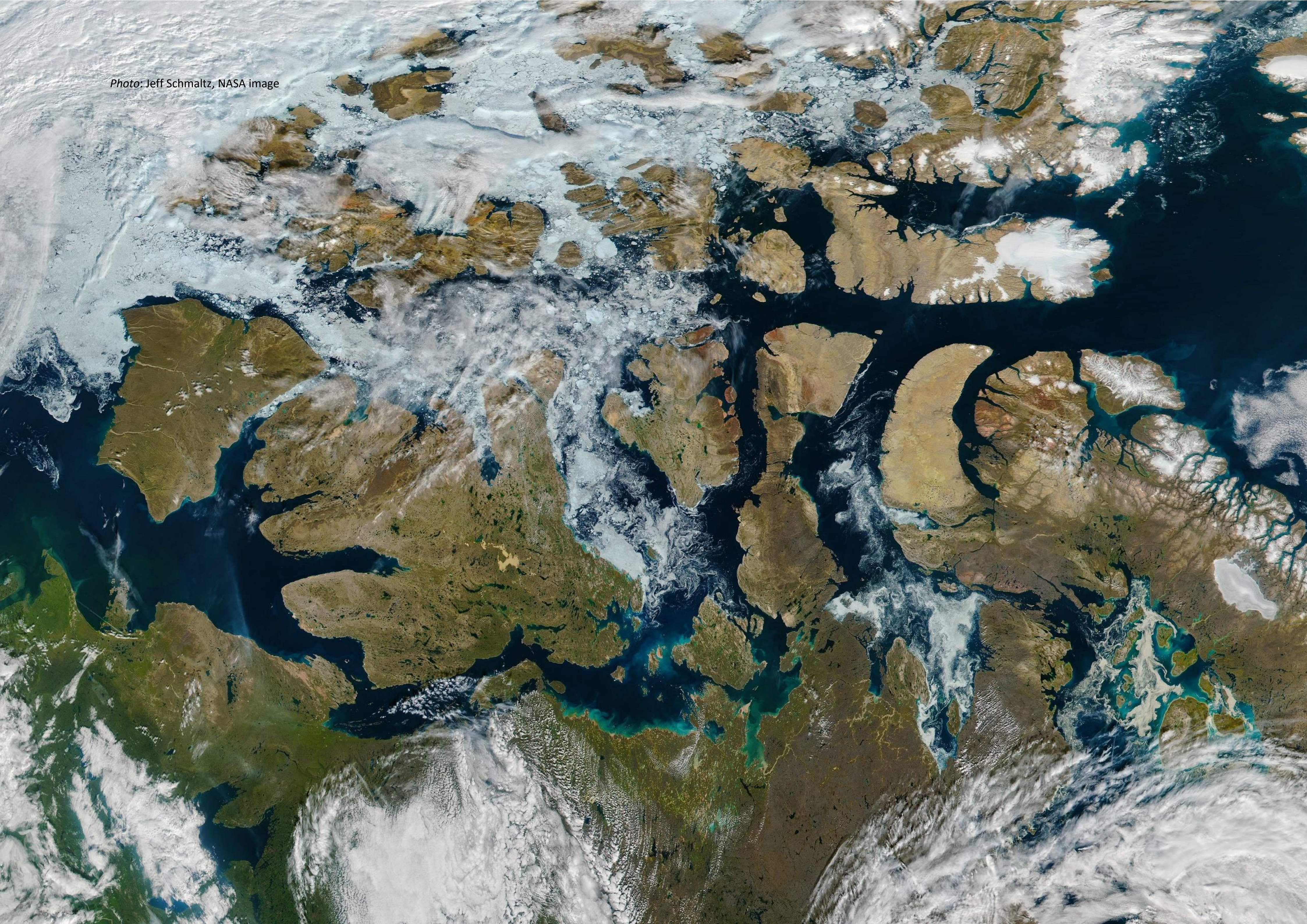


Photo: Jeff Schmaltz, NASA image

6. REORIENTATION

SUMMARY

To speed up decarbonization, we need to ensure the right scope, system boundaries and focus.

The transition to new fuels is full of pitfalls such as carbon leakage and other greenhouse gases than CO_2. The scope of emissions included in optimization work as well as sustainability reporting must cover all relevant GHGs and examine both production (well to tank) and use (tank to wake)

Good indicators give insight while poor indicators confuse and lead astray. Operational indicators are more comprehensive and correct than design indicators. We suggest breaking down the operational indicator into three factors to reflect vessel utilization, energy use and fuel's carbon content.

A complete emissions inventory and comprehensive indicators will support the right focus on resistance, alternative fuels and system optimization.

Finally, collaboration is necessary, and time is of the essence.

Despite strong political attention and high ambitions, global emissions, Norwegian emissions and the shipping industry's emissions are too high and not on a path consistent with the 1.5°C target. (ref chapter 2.1, 2.6 and 2.7).

Therefore, a fundamental change of thinking and approach seems necessary on many fundamental areas, from simple calculation practices to business models. We suggest a fundamental shift on the following eight areas summarized in the below table.

		Shift	*Chapter*
1	Emissions	From CO_2 to all greenhouse gases including those emitted from new fuels (methane from LNG and N_2O from ammonia) to ensure a more accurate and granular approach with emission factors and GWPs reflecting reality.	6.1 6.2
2	Carbon intensity indicators	From design indicators (EEDI and EEXI) to operational indicators (CII) based on cargo carried to reflect all factors impacting energy use, emissions and vessel utilization.	6.3
3	Ship resistance and powering prediction	From calm water to total resistance and powering to optimize vessels for realistic operating conditions and take account of the *actual* performance of energy saving devices.	6.4 8.2
4	Alternative fuels	From tank to wake (TTW) to well to wake (WTW) to avoid carbon leakage when switching to new fuels.	9.2
5	System scope	From component to system thinking and optimization to correctly evaluate the compatibility, interaction and side effects, e.g. the positive effect of batteries on engine load and specific fuel consumption.	8.5 8.6 8.7
6	Flexibility	Noting that vessels' sailing speed and engine load vary and that future ships will use multiple fuels, hull forms, machinery and systems must be more flexible and perform well on many From single point optimization to flexibility and adaptability. This applies to machinery, systems, vessels and logistics.	
7	Collaboration	We must move from entity to value chain perspective to reduce risks through long term partnerships and collaborations with charterers and energy suppliers inter alia. The need for tailor making vessels and making long term fuel supply agreements can also challenge the business model built on asset play.	6.6
8	Time scale	Considering the urgency of the climate crisis, we must find solutions with effect tomorrow rather than in a very distant future.	2.7

6.1. Emissions inventories: Scope and global warming potential (GWP)

SUMMARY

To reduce emissions, we must measure and analyse emissions.

New fuels will give other exhaust gases than CO_2, so the scope of emission inventories must be expanded to include all relevant GHGs, particularly methane (when using LNG and LBG) and N_2O (when using ammonia).

Region specific GWP characterization factors are particularly important in Arctic, Antarctic and snow capped landscapes and should be used to measure the real global warming effect of shipping. As an Arctic nation, Norway has a particular responsibility for this.

The expertise in naval architecture and climate modelling is combined in the MariTEAM emission inventory calculation tool (ref chapter 5.3). This can be used to estimate all relevant GHG-emissions on fleet-basis, useful when evaluating new technologies, practices, policies and fuels.

Most governments and many companies have set emission reduction goals, but many emission inventories are not complete and does not reflect the true climate impact. To evaluate progress – or lack of progress – relevant emission inventories are required from each funnel, each company, each sector and every nation.

The EU introduced the first mandatory reporting scheme for shipping, with reporting of CO_2-emissions from all ships to, from and between union territory from 2018. IMO followed in 2019. Both schemes apply to vessels above 5,000 GT. EU estimates that whilst only 55% of the vessels are above this size threshold, the scheme still covers 85% of emissions as the largest vessels use the most fuel [EU, 2020, Ch 2.2 | ↗]. Other states for example China and stakeholders such as the banks and financial institutions now demand similar reporting.

Charterers and cargo owners show increasing interest in climate neutral transport and are thus interested in emissions per cargo unit.

Monitoring, analysing and reporting is not a paper exercise but an opportunity to gain insight into operations. Current emission inventories should be improved in three ways: Exhaust gas scope, engine load specific emission factors and region specific GWP-factors, which we discuss below:

Emissions scope

On basis of tank to wake emissions, CO_2 makes up around 98% of maritime GHG, both worldwide and in Norway (ref chapter 2.2). The advent of alternative fuels and a larger variety of engine types will like change this and give more methane (CH_4) and nitrous oxide (N_2O). The range of greenhouse gases produced will vary between the various fuels.

Global warming potential factors (GWP) are used to add up the effect of different greenhouse gases and understand their relative importance. The effect can be measured over any period of time, with hundred years being the most common. However, considering the urgency of the climate crisis and the risk of reaching irreversible tipping points, it may be appropriate to consider the more imminent effect of all greenhouse gases. Methane and black carbon have a much stronger impact in a twenty-year perspective. With a longer time horizon, CO_2 dominates.

Noting the urgency of the climate crisis and the risk of reaching irreversible tipping points, it may be appropriate to consider greenhouse gases in a 20-year perspective (using GWP_{20}*).*

The high GWP for methane and the very high GWPs for N_2O and black carbon explain the importance of including these exhaust gases. Methane slip is still a problem with LNG and ammonia will likely give N_2O when combusted in an engine. With the very high GWP, only 2-3 g/kWh of N_2O from combustion of ammonia can give the same warming effect as diesel.

Region specific GWP characterization factors

A global GWP_{100}-factor of 910 was proposed by Bond et al with ±30% variations between emitting regions [Bond et al, 2013 | ↗].

Black carbon reduces the albedo of white surfaces and melts show and ice, which in turns reduces the albedo further. The GWP of black carbon is therefore much higher in the Arctic and Antarctica and other snow-covered areas such as glaciers than in the rest of the world. Research at NTNU and SINTEF Ocean gives insight into the pronounced effect of black carbon in the Arctic and suggests region-specific GWP-factors for black carbon.

Such differentiated GWP-factors are clearly important when we evaluate shipping activities in the Arctic and Antarctic. In a study of the environmental effects of taking the shorter Northern Sea Route from Europe to the Far East, Lindstad, Bright and Strømman found that the conclusion would be very different and even opposite if the analysis is based on CO_2 only rather than all GHGs with region specific global warming characterization factors. Sailing the Northern Sea Route gives less CO_2 but when the effect of all greenhouse gases are included, a vessel sailing the Northern Sea Route will cause more global warming than a vessel sailing the longer route via Suez [Lindstad, Bright, Strømman, 2016 | ↗]. This is further explained in chapter 7.4.

A complete GHG emissions inventory should cover the following exhaust gases and consider the following aspects:

	Global warming potential			*Emission factors*	
Exhaust gas	*GWP_{100}*	*GWP_{20}*	*Factors determining the emissions*	*Load-specific*	*Region-specific*
CO_2	1	1	Proportional to the fuel consumption and the fuel's carbon content.	N/A	N/A
Methane CH_4	29.8	82.5	Determined by the combustion process, higher slip from low pressure Otto-engines. Higher at low loads (2-4 times higher at low loads for both high and low pressure engines).	Yes	N/A
Nitrous oxide N_2O	273	273	Insignificant from oil and gas fuels. Use of ammonia will likely give some N_2O.	Likely	N/A
BC	Global: 345 Arctic: 1,700	Global: 1,200 Arctic: 6,200	Formed by incomplete combustion of fossil fuels. Higher emissions at low loads (up to 10 times higher).	Yes	Yes
OC	-69	-240		Yes	Yes
NO_x	-11.6 (cooling)	-15.9 (cooling)	Determined by the combustion process; valve timings, air to fuel ratio and combustion temperatures.	Yes	Yes
SO_x	-38	-141	Proportional to the fuel's sulphur content. Can be reduced by exhaust gas after treatment.	Yes	Yes

Table 3 Greenhouse gases from ships and the need for load specific and region-specific emission factors.

Source: GWP factors taken from IPCC 6th assessment report, 2021, chapter 7 [IPCC AR6WG1, Chapter 7, page 1017 | ↗] and Lindstad, Bright, Strømman, 2016 [↗]. Negative GWPs indicate a cooling effect.

Note that load-specific emission factors apply to nearly all exhaust gases. Note also that the effect of black carbon is up to five times higher at Arctic/Antarctic latitudes and snow-capped landscapes.

While NO_X and SO_X (mainly SO_2) have a cooling effect, these exhaust gases must be reduced for health and environmental reasons. Also, as the cooling effect will diminish and cease within decades while the warming effect of CO_2 will remain for hundreds of years.

6.2. Engine specific and load-dependant factors for fuel consumption and emissions

SUMMARY

Exhaust gas emissions vary with the engine load. For some engine types and exhaust gases, the variation may be significant.

Most vessels run their main engines on reduced load and the load varies between trades, vessels and years depending on, inter alia, market conditions. The average load factor for the three dominating vessel types (bulk, tank and container) is 0.45 to 0.55.

SINTEF Ocean has mapped the specific exhaust gas emission factors for a range of engines and loads to contribute to increased accuracy in emission inventories. These are used in the simulation tool GYMIR and fleet emission inventory model MariTEAM.

Such factors are also important to properly assess the effect of slow steaming for existing vessels.

The 4th GHG-study found the average engine load of bulkers, tankers and containers, the three dominating vessel types, to be lower than 60% [IMO 4th GHG study, 2021, p.105 | ↗]. The diagram (fig. 40) shows the range and average values for 2018. The range indicates the variation between vessels of different sizes.

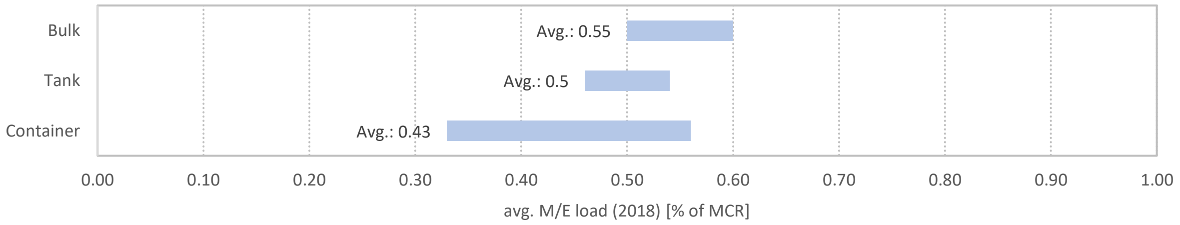


Figure 40: Average M/E load relative to installed power for the three most important vessel types in 2018.

This confirms the need for load specific emission factors to accurately report emissions for conventional merchant vessels, yet the latest IMO GHG-study employed low load emission factors only for engine loads below 20% [IMO 4th GHG study, 2021, p.74 | ↗]. Load specific emission factors are also necessary to assess the effect of slow steaming for existing vessels, as slower speed will reduce the load of the main engine further. We discuss this in chapter 7.3.

Mapping of emission factors from a large range of engines by SINTEF Ocean finds that that the emissions factors vary significantly with engine load. NO_X measurements for a two-stroke engine, below, illustrate the case: Compared to the weighted test cycle value (E3 for propulsion engines), the specific emission factors are lower at 75-100% load but higher at 25-50% load. Noting that many vessels operate at low loads around 35-60% load, the importance of load specific emission factors become evident. At 50% load, the emission factors are more than 50% higher!

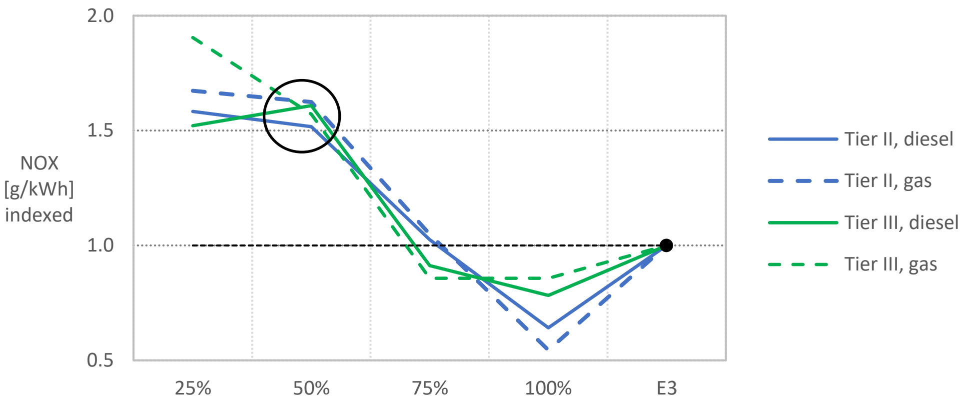


Figure 41: Specific NO_X emission factors for a modern two stroke, slow speed, high pressure dual fuel diesel engine (5G70ME-C9.5-GI)

SINTEF Ocean has mapped emission factors for a range of engines and loads. We find that the emission factors vary significantly with the engine load, also for loads above 20%. These granular emission factors are used in our analysis of individual vessels and design cases in GYMIR as well as for large fleets of vessels in MariTEAM.

Engine load specific emission factors are necessary to produce accurate emission inventories, find the positive effect of batteries in hybrid propulsion machinery configurations and evaluate the effect of slow steaming.

A similar discrepancy between emissions measured in real driving to those measured in laboratories were observed for road transport vehicles. In response, to ensure the emission regulations have full effect, the EU introduced Real-Driving Emissions test procedures (RDE) in 2017 [EU | ↗].

To conclude, engine load has significant impact on the emission factors for methane slip, black carbon, NO_X and SO_X and likely also for N_2O. Methane slip can be 2-4 times at low loads while black carbon can be 10 times higher at low loads. NO_X formation is determined by the combustion process; valve timings, air to fuel ratio and combustion temperatures.

6.3. Energy indicators and emission indicators

SUMMARY

First of all; climate intensity and GHG intensity should be used rather than carbon intensity, though all three could be considered synonyms.

Operational indicators are calculated based on actual emissions and actual transport work and is quite simply a more realistic measure of carbon intensity.

Operational indicators carry more risk, but also more rewards for the operator, which becomes liable for the charterers' dispositions, weather, port congestion and other externa factors.

On the positive side, operational indicators give operators a wider array of tools to reduce emissions who, importantly, includes operational measures which can be implemented rather quickly at low cost.

While absolute emissions determine the concentration of CO_2 and other greenhouse gases, many economic activities are also evaluated by their emissions relative to the value created. The concept of Greenhouse gas emissions per value added (GEVA) was described by Jørgen Randers in 2021 [↗]. For transportation, it makes sense to use transport work as proxy for value creation.

There are two types of indicators: Design indicators and operational indicators. The parameters involved in the calculation are presented on a following page.

In line with our multi-step approach, we suggest breaking down the total emission indicator into three factors to reflect the utilization, the energy use and the GHG intensity of the fuel.

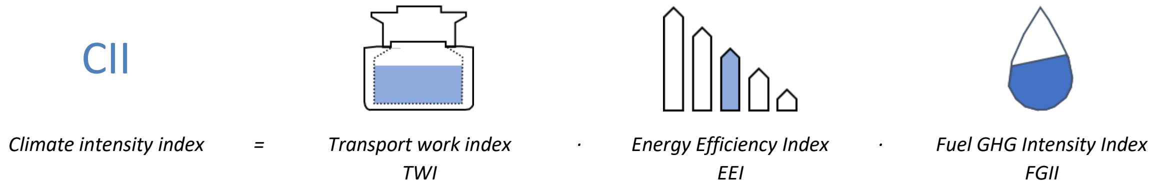


Figure 42: Breakdown of total CII into three subindexes.

This will provide better insight into the operations and pinpoint where each vessel or operator performs well and where there is further potential. A breakdown of the overall CII seems necessary as the EU introduces requirements to the GHG intensity of the fuel through FuelEU maritime (ref ch. 2.8).

While the term «carbon intensity» is often used, we should rather use «climate intensity» to include all greenhouse gases. In daily use, however, carbon is synonymous or a proxy for climate.

Design indicators (e.g. EEDI and EEXI)

Although called energy efficiency indicators, the EEDI and EEXI are really emissions indicators thanks to a carbon factor. However, when they were devised, almost all vessels ran on the same fuel, so the energy efficiency and emission intensity were proportional.

Design indicators calculate emissions based on factors informed by the designer, yard and engine maker for a given operating condition. Such indicators can be estimated already at the design stage. Ships can thus be approved before built or converted. This gives more certainty to the owner and operators.

However, the actual carbon intensity achieved in operation is not limited, nor guaranteed and can be higher or lower owning to circumstances onboard or outside the operators' control. Some designs will perform better on paper than in reality and vice versa.

Lindstad and Bø investigated the effect of three possible emission reduction strategies for an Aframax tanker; a slender and optimized hull, hybrid power system and LNG. They found that all three reduced the EEDI more than they reduced actual emissions. The study concludes that design indexes are helpful, but not enough [Lindstad and Bø, 2018 | ↗].

While design indexes certainly will contribute to lower emissions, the actual emissions may be higher than indicated by the vessels' EEDI or EEXI. Operational indexes are necessary to avoid disappointments.

The explanation might be according to Lindstad et al. (2019) that current sea-trial procedures for EEDI adjust to ‘calm water conditions’ only, as a comparative basis, despite calm sea being the exception – rather than the rule – at sea. We find that this adjustment procedure excessively rewards full bodied ‘bulky’ hulls which perform well in calm water conditions. In contrast, hull forms optimized with respect to performance in realistic sea-conditions are not rewarded with the current EEDI procedures. Their results indicate that without adjusting the testing cycle requirements to also include a threshold for performance in waves (real sea), the desired reductions will be short on targets and GHG emissions could potentially increase.

Operational indicators (CII, carbon intensity indicators)

Operational indicators are based on actual emissions and thus include the effects of absolutely everything (provided that onboard instruments work and calculations are done properly); hydrodynamics, loading of the vessel and draught and trim, hull fouling, strong winds, routing, idling upon arrival in port engine condition etc etc.

AER (annual efficiency ratio) was proposed by member states to the IMO and is based on the nominal cargo capacity and the total distance sailed, utilizing info provided in the DCS (data collection system). No commercially sensitive information is thus required and is not influenced by market fluctuations.

EEOI (energy efficiency operational index) was introduced by the IMO in 2009 for voluntary use [IMO MEPC.1/Circ. 684, 2009 1 ↗]. It is calculated based on actual cargo onboard and the actual distance this cargo is moved. EEOI gives a more accurate picture of relative emissions as it captures almost all technical and operational influencing factors and is based on the actual cargo onboard. EEOI is also flexible with regards to the cargo metrics and suggest using dwt as well as TEU, GT, passengers, lane metres etc [IMO 4th GHG study, 2021, p.167 | ↗]. Therefore, the EU and the banks in their Poseidon principles, argue that EEOI reflects actual carbon intensity better. The need to know cargo carried causes concern among ship owners and the IMO therefore failed to include this in their data collection system (DCS).

The difference between the two operational factors is not trivial; indeed, while the AER improved by 21% from 2008 to 2018, EEOI improved by 29% (ref chapter 8.1). The discrepancy between the two indicators has been challenged by some studies.

EEOI is quite simply a better measure of ships carbon or climate intensity as it reflects reality better. EEOI also rewards ship owners and operators for more emission reduction measures including operational measures – and thus more freedom to choose the most cost-effective ways to decarbonize.

Over the last decades, cargo vessel designs have been optimized for particular cargo types. These highly specialized vessels are indeed very effective but less versatile than the general cargo vessels dominating worldwide trade until the 1950-60's. As a result, they are more effective when loaded but sail empty as much as half of the time due to trade imbalances.

Also, vessel sizes have increased due to increased trade volumes and centralization of demand around big cities. Large and specialized vessels are very effective, but only when filled up with cargo.

Only operational indicators and the EEOI in particular can ascertain coherence between the indicator and real carbon intensity.

Proposal for an improved EEOI; the Climate Intensity Operational Index (CIOI)

The EEOI can be improved in three areas:

1. The EEOI should include all greenhouse gas emissions and at least methane, black carbon and N_2O. Methane is the Achilles heel of natural gas and must be included for a wholistic evaluation of LNG and biomethane. Black carbon has impact in certain areas, and accounts for 7% of total shipping GHG according to one paper [ICCT, 2017 | ↗]. N_2O can be an issue with future use of ammonia. This change turns the carbon intensity factor into a climate intensity index.

2. To be relevant and useful when benchmarking vessels running on very diverse fuels with very diverse production pathways, the climate intensity indicator should factor in emissions from well to wake. Only then can the indicator distinguish between vessels running on grey, blue and green hydrogen.

3. The EEOI should apply to vessels smaller than 5,000 GT.

Smart Maritime proposal
↓

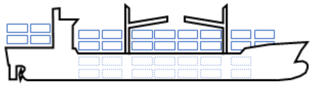
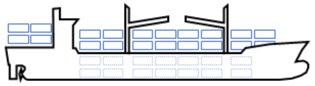
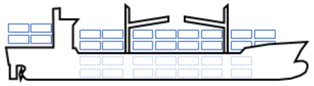
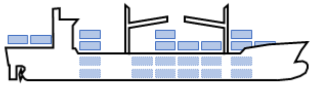
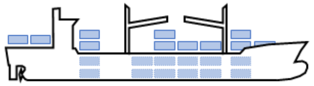
	DESIGN INDICATORS		OPERATIONAL INDICATORS		
	CARBON INTENSITY				CLIMATE INTENSITY
	EEDI Energy Efficiency Design index	EEXI Energy Efficiency Existing Ship index	AER Annual Efficiency Ratio	EEOI Energy Efficiency Operational index	CIOI Climate Intensity Operational index
Emissions	CO_2	←	←	←	GHG: CO_2 + at least CH_4, N_2O, BC
Emissions estimate	Based on installed/available power	←	Calculated/measured in actual service	←	←
Emission scope	Tank to wake (scope 1)	←	←	←	Well to wake (scope 1+2+3)
Cargo capacity	Nominal, based on capacity plan (▭)	←	←	Cargo carried (payload) (▬)	←
					
Cargo metrics	DWT, GT for pax/cruise ships	←	DWT, GT for pax/cruise/ropax/PCTC	Dwt, TEU, pax, GT, lane metre etc	←
Sailing distance	Total distance at reference speed	←	Distance with cargo + ballast voyages	Distance with cargo	←
Applicability	New vessels	Existing ships without EEDI.	Ships in operation	Ship in operation on voluntary basis	←
Size threshold	≥ 400 GT	←	≥ 5,000 GT	←	≥ 400 GT (calculation/reporting only)
Required improvement	Yes, in steps: Phase 1, 2, 3	Yes, for vessels above a certain dwt/GT	Yes.	←	Yes, for vessels ≥ 5,000 GT
Reflects	Hull, machinery and outfitting	←	← + Weather, maintenance, operation	← + Cargo capacity utilization	←
Influencers	Designer and shipyard	← + Owner, vessel manager, dockyard	← + Crew, charterer	←	←
Approval	Before construction	Before operation	After operation	←	←
In force	From 2013	From November 2022	From November 2022	From 2009	

Figure 43: The key characteristics of design indicators (EEDI and EEXI) and operational indicators (AER and EEOI), also known as carbon intensity indicators (CII).

6.4. From calm water to total resistance

SUMMARY

Calm water resistance has so far been the key or even single focus in ship design, shipbuilding contracts and sea trials. Vessels have been optimised and evaluated based on performance in sea conditions that rarely occur.

Simple, yet reliable, methods to estimate added power in sea passage is necessary for ship design, ship operations and emission indicators. Novel methods have been developed for various use with different levels of accuracy and requirements to computational power.

Estimating the added resistance from environmental factors (wind, wave, current, sea water temperature etc) is also important to isolate the effect of biofouling.

The ocean is rarely calm. In real life, added resistance is a lot more important to the vessels performance than it may look like on the drawing table and can add 30% to the calm water resistance [Anna Karina Magnussen, 2017 |↗]. The case studies on optimal main dimensions in chapter 8.2 illustrate the importance of including added resistance in the concept design phase.

The diagram below (fig. 44) breaks down total ship resistance. The magnitude of each resistance component will vary between vessel types and depend upon size, hull shape, superstructure, outfitting and hull surface roughness as well as external environmental factors. The possible methods to determine each component is indicated by a circled letter. Work on new or improved methods made by SINTEF Ocean and NTNU are indicated by yellow colour.

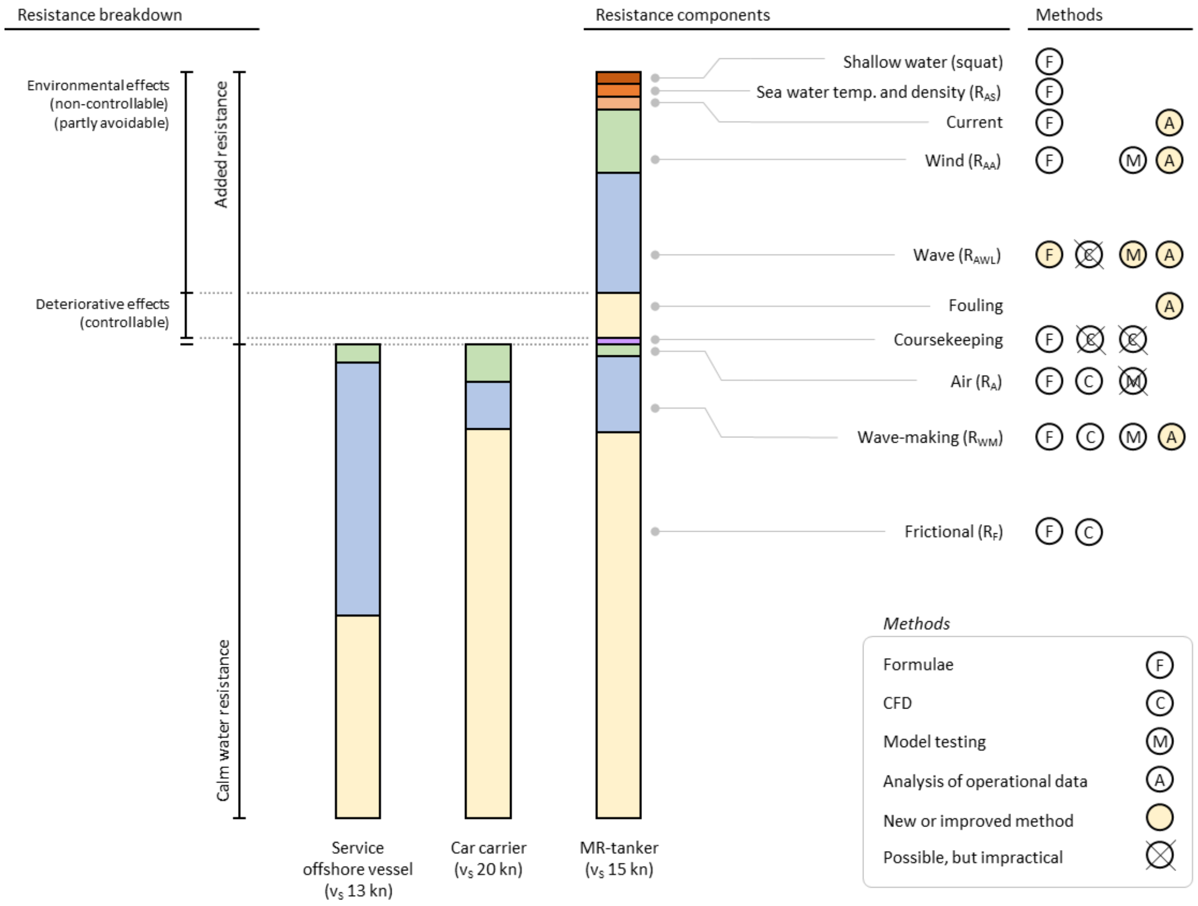


Figure 44: Ship resistance components and methods for determining them.

Methods and tools at different levels of fidelity and complexity are needed for different purposes. Simple empirical methods/formulae are needed for early-stage parametric studies and to analyse operational data in the cases where only basic hull parameters are available. Fast medium-fidelity methods such as those based on linear potential theory are needed to practically optimize designs/hullforms for a broad range of operating conditions in terms of draughts, speeds, headings and sea states. High-fidelity methods such as nonlinear panel methods and CFD are useful to study specific effects and design details for a limited set of conditions, and finally model tests are needed both to develop and validate all of the aforementioned methods. Model tests as part of a vessel newbuild program is as well fed back refine and tune the digital twin used for operational and routing optimization.

Total resistance in the prevailing weather conditions deserve more attention than calm water resistance. This should apply to ship design, hull optimization, model testing, shipbuilding contracts, sea trials and charterparty agreements.

Simple formulae using main dimension and hull form parameters are practical at early stages of conceptual ship design work. These must reflect the impact of L, B, T, C_B, C_P, slenderness, entrance angle and other principal particulars. While absolute accuracy is beneficial, these formulae are often used to determine the relative performance of hull main dimensions. These formulae are used to predict added power for parametric variations and thus to find optimum main dimensions and economy of scale (see chapter 7.2).

Operational data can be analysed by a combination of cleaning, filtering and regression analysis to find the impact of various environmental parameters such as wave height and direction, wind speed and direction, current. The fouling margin can also be analysed by comparing data from year 2 to 5 with data from the first year of operation, where fouling is assumed negligible.

Operational data are first cleaned to improve the data quality. Large datasets allow more aggressive cleaning, while many outliers must be kept for small datasets. Calm water performance is determined by analysing data for calm water sailing days. We can assume that no fouling is present, say, the first year of operation. Once calm water performance has been established, regression analysis can be used to determine the relationship between the environmental parameters and the environmental resistance factors. Gjølme (2019) found that models developed based on regression analysis of operational data could predict the speed loss with an accuracy of 2-5% [Gjølme, 2017 |↗]

6.5. Perspective and scope: From onboard to full life cycle

SUMMARY

A meaningful decarbonization of maritime transport must consider emissions in a well to wake perspective to avoid carbon leakage.

While combustion accounts for 90% of current life cycle emission, this will change with the advent of new fuels.

A lasting and meaningful transition requires a shift from silo to holistic thinking.

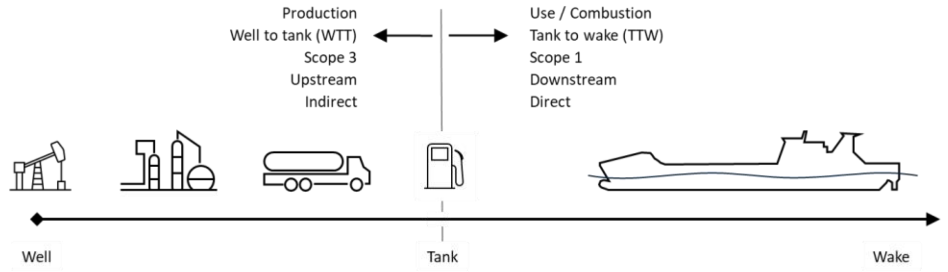
It may be tempting to address the environmental and societal challenges piece by piece. Noting that many things in nature is connected and the butterfly effect – that even minor happenings or choices we make have repercussions – we believe that a true, green transition must address and balance many if not all environmental challenges.

While this may seem overwhelming, there are several tools and approaches at hand to guide us. Taking a life cycle perspective on fuels and other elements is one.

Life cycle analysis of fuels

Direct ship emissions are the largest source of GHGs (greenhouse gases) in maritime transport, estimated to account for nearly 90% of fuel-related life cycle emissions [Kramel et al., 2021 | ↗], [Winebrake et al., 2007 | ↗]. These estimates correspond well with the life cycle assessments of alternative fuels by Lindstad et al. we have used in our review of alternative fuels in chapter 9.

The advent of new fuels with more energy intensive production will change this and we must shift from a tank to wake (TTW) perspective to a well to wake (WTW) perspective to avoid carbon leakage.



Responsible	Energy company Bunker supplier	Shipowner Ship manager and crew Charterer Port
Key factors	Raw material Production process Footprint of energy (e.g. electricity) used Supply chain Form of delivery (pressurized, liquefied)	Storage Pre-treatment Machinery's thermal efficiency and total system efficiency Waste heat recovery (WHR) Exhaust gas cleaning: carbon capture and scrubber

Figure 45: Life cycle perspective on fuels.

This shift from tank to wake to well to wake does complicate the picture, as international frameworks and legislation are territory-based. Breaking away from the current convention can also increase the risk of double counting. While national and sector emission inventories may continue to report tank to wake emissions, the well to wake perspective is essential in decision making and policy formulation.

Life cycle analysis of the ship

The environmental impact from building, maintaining, upgrading and finally breaking and recycling of ships is not insignificant and should be considered when making plans and policies.

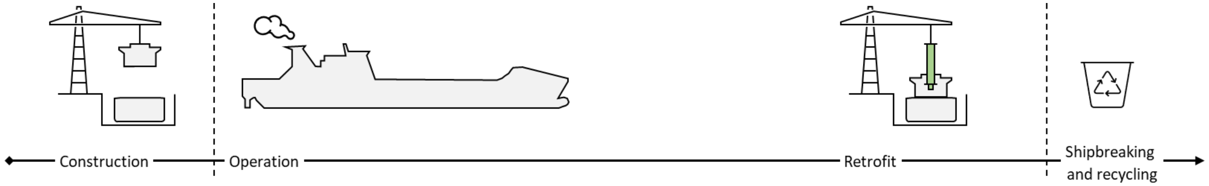


Figure 46:Phases in the life cycle of a ship.

A life cycle perspective is especially important when we evaluate options where emission cuts in the operation phase will give higher emissions or other environmental burdens in another phase. Examples include slow steaming where more ships must be built to offer the same cargo capacity, installation of batteries leading to increased mining, and blasting of a hull and application of an effective anti-fouling in dry dock which can release toxic chemicals.

> *Environmental burdens can shift between life cycle phases, between sectors, between locations, and between types of environmental impacts.*
>
> Professor Anders Arvesen, NTNU (2019)

In addition to global warming, a complete analysis of the environmental effect from building, operating and breaking up ships for recycling will typically analyse resource depletion, ecotoxicity, human toxicity, eutrophication, ionising radiation, particulate matter and photochemical oxidant formation, terrestrial acidification and land occupation and transformation, as well as total emissions of nitrogen oxide, particulate matter and sulphur oxide [Galaaen, 2020 | ↗].

While some consider global warming and greenhouse gases to be the most pressing issue, others see resource depletion, persistent toxic substances and liquids or loss of biodiversity as equally detrimental and important. These very different parameters cannot be combined into one measure or index, nor is it obvious how to weigh them against each other.

The same life cycle perspective should indeed be applied to other products than the fuel. A full environmental evaluation of maritime transport should include the impacts from building and breaking up ships.

6.6. Collaboration is key

SUMMARY

New technology will likely be more expensive and more risky, at least initially. Alternative fuels will be available in few places and, likely, cost more.

To achieve progress and uptake of new technology and fuels, collaboration in the design and operation phase is required.

Ship owners and charterers must align their interests and have shared incentives to reduce energy consumption and emissions. Longer contracts are likely required to ensure predictability for all parties.

The transition ahead may encourage a shift from asset play to life-long ownership.

Vessels in fixed liner service with long term industrial perspective can invest and arrange for supply of new fuels in a handful of key ports along the trade lanes they serve while vessels in tramp service must wait until the new fuels are widely available.

The transition ahead will require novel, proprietary technology and new fuels not used today. At least initially, there will be few reputable suppliers of machinery, fuel and services. The risk of off-hire may be higher and there may be new safety and operational concerns. Costs and risks will be higher. Alternative fuels will be available only in a few locations and thus limit the operational reach of vessels, unless a dual or multi fuel strategy is pursued.

A single industry cannot change without support from its stakeholders. Similarly, change must take place in the ecosystem surrounding the industry. The following stakeholders can influence – speed up or delay – the development:

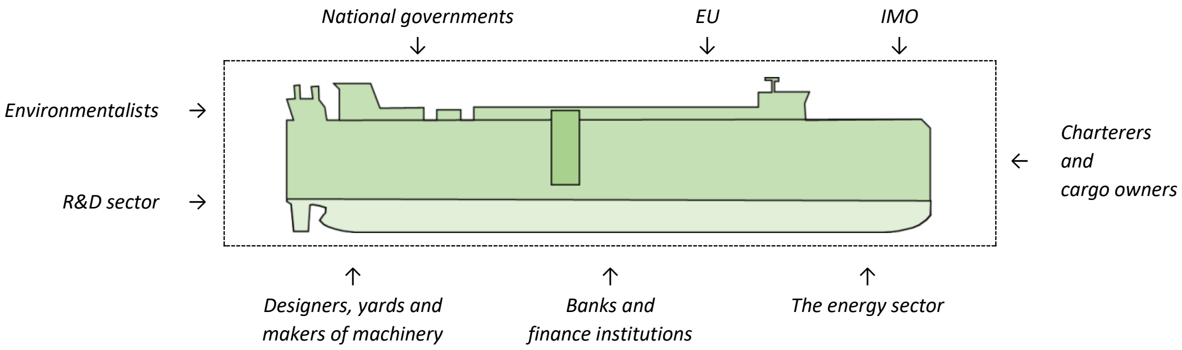


Figure 47: Stakeholders and contributors to the decarbonization of shipping.

Increased collaboration is required to decarbonize shipping. In the first instance, ship owners, designers, suppliers and ship yards must cooperate to fine-tune new vessels for the intended operation. In the operation phase, increased collaboration between ship owners, charterers and ports are required. Charterers can contribute by awarding longer contracts which give certainty for the ship owner. Today's split incentive where ship owners make investments in energy efficiency while charterers pay for fuel must be overcome. It is telling that we see many new green concept vessels developed by cargo owners themselves. Similarly, reliable fuel supplies at predictable prices in key locations must be negotiated before a vessel is built to run on alternative fuel.

> *Collaboration is absolutely necessary to reach 1.5 degrees.*
>
> *Dr Fatih Birol,* International Energy Agency (IEA),
> 24 June 2021 [Forskningsrådet | ↗]

Long term thinking is also necessary. Optimized main dimensions and hull forms can give significant advantages, if vessels can be tailor made for the intended trade. Such optimization will make it harder to swap vessels between trades and limit second hand use and values. The current business model of asset play where low newbuilding cost, standard main dimensions and full operational flexibility may be challenged.

6.7. Policy implications

Noting the diversity of ships, the effectiveness of each measure must be evaluated for the specific case considering the vessel type, trade, speed, weather and operational profile.

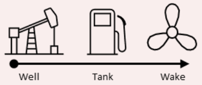
Technologies that can be scaled up and give sizeable emission cuts should be given priority. In practice, this means solutions that can be applied to vessel types with high fuel consumption and emissions.

Emission inventories should cover all relevant exhaust gases and be calculated with engine load specific emission factors to reflect the actual emissions at part loads and region specific GWP factors to determine the true impact of the various exhaust gases. This is important to avoid discrepancy between estimated and actual emissions reductions.

Design indicators are a good start but have very clear limitations both for regulators and operators and should be complemented by operational indicators. CIIs such as the AER and EEOI reflect nearly all technical and operational measures and factors better than EEDI and EEXI.

Operational indicators (EEOI and AER) should be broken down into three sub-indicators to reflect the development in cargo utilization, energy efficiency and the fuel's climate footprint to give insight into where further development is needed.

Energy efficiency and carbon intensity indicators should be based on actual cargo carried and sailing distance with cargo (e.g. EEOI) to reflect vessel utilization and ballast/repositioning legs. IMO's DCS should be amended to use cargo carried and thus support use of EEOI.



Alternative fuels as well as other green measures should be evaluated in a life cycle perspective to avoid carbon leakage. The need to address the totality when making decisions and policies must be reconciled with current conventions on territory-based national emission reporting.

6.8. Sources and further reading

	Link
Bond et al. (2013): Bounding the role of black carbon in the climate system: A scientific assessment	→
Cariou, Lindstad and Jia (2021): The impact of an EU maritime emissions trading system on oil trades.	→
Ejdfors, Kristian Olof MSc (2019): Use of in-service data to determine the added power of a ship due to fouling.	→
Faber et al. (2021): IMO 4 GHG study 2020.	→
Kramel et al. (2021): Global Shipping Emissions from a well-to-wake perspective: The MariTEAM Model.	→
Lindstad, Bright and Strømman (2016): Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation.	→
Lindstad, Borgen, Eskeland, Paalson, Psaraftis. Turan (2019): The need to amend IMO's EEDI to include a threshold for performance in waves (realistic sea conditions) to achieve the desired GHG reductions.	→
Lindstad, Verbeek, Blok, Syl, Hübscher, Kramer, Purwanto, Ivanova (2015): GHG emission reduction potential of EU-related maritime transport and on its impacts.	
Poseidon Principles (2019)	→

Photo: Torvald Klaveness.
MV Baru at Bunbury port, Australia.

7. LOGISTICS

SUMMARY

Getting the logistics right should be the first step to reduce energy consumption and emissions. This entails picking the best mode of transport, optimizing the entire multimodal transportation chain and finally optimizing the sea transportation leg.

The key logistics variables with impact on emissions and environment is ship size, frequency, trade, trade balance or imbalance and speed.

Ship size has generally a positive effect on carbon intensity, but only if the cargo base supports larger vessels.

Frequency and routing are ways to fill up the cargo hold but must be balance against transit time, convenience, and cargo related costs.

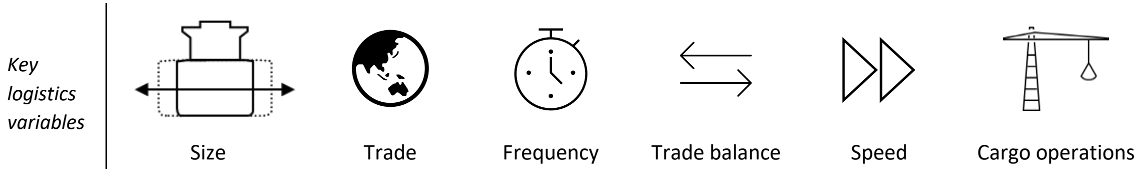
Speed reduction *can* have a positive effect on energy use and emissions, but not always. As many vessels have already reduced speed, a second or third round of speed reductions will not be as rewarding as the first one.

While some vessels perform services or undertake work in the marine environment, most vessels carry goods from A to B. Cargo vessels must offer the right cargo carrying capacity, frequency, transit time, time of departure and arrival, cost, reliability, and safety. For other types of vessels, the quality criteria may be different.

The operations can be set up to maximise the transport work or by finding a balance between cargo carried and energy and emissions.

In chapter 8.2, we learn that some vessel types have been designed for maximum cargo at the expense of energy efficiency. Recently, and increasingly, low emissions have been added to the long list of charterers' requirements s. A small but growing group of charterers now include environmental criteria in their screening and award criteria and promise to report emissions from ships they charter [Sea Cargo Charter, Oct, 2020 | ↗].

Getting the logistics right is the first step to reduce energy consumption and emissions. The goal is simply to move more with less, i.e. maintain or increase the transport work with the same or less energy and emissions. The key logistical variables with impact on emissions and environment is ship size, frequency, trade, trade balance or imbalance and speed.



This requires setting up an efficient transport chain with the right type of vessel and the right size for the cargo volumes available for shipment. Further, it requires finding the right frequency, departure and arrival time and the right transit time. This is often determined by the value of the cargo, i.e. the capital tied up in the raw materials, semi-finished or finished goods.

The composition of the trade or the route has impact on the cargo base the vessel can draw from. Adding ports means access to more cargo, but also higher fuel costs, pilot and port fees.

Fleet planning can be done at three levels; strategic, tactical and operational: Strategic fleet planning has the greatest potential due to more degrees of freedom. At tactical level, the trading route is planned to utilize the available cargo capacity. Finally, at operational level, smart planning of voyages can set up a schedule that maximizes cargo and minimizes cost and or energy and emissions. Based on weather forecast and port slots.

Adjusting speed can be both a strategic and tactical decision.

7.1. Moving cargo from road to sea (or rail) reduces energy use and emissions

SUMMARY

Ships are the most energy efficient transport mode and the only meaningful means to move large volumes.

On short distances, e.g. within Norway or within Europe, ships compete with trucks.

Small bulk carriers, general cargo and container vessels emit around 70% less per transport work than long haul trucks.

Land based heavy duty transport has reduce emissions of NO_X and SO_X and will likely reduce also CO_2 as batteries and or hydrogen become commonplace also for heavy duty applications. Even if road transport becomes carbon neutral, environmental effects such as microplastic from tire abrasion and the effects from road construction remains. Also, less road traffic means less noise, road congestion and road accidents.

Goods and passengers should take the most energy efficient and environmentally friendly transport mode.

Ships are clearly the most energy efficient transport mode and the only transport mode capable of moving large cargo volumes. Therefore, many countries seek to shift cargo from land to sea. Despite these political intentions, waterborne transportation in Norway grew by 2.3% per year in the period from 1965 to 2015, compared to 4.6% for road and 1.4% for rail [Pilskog, SSB, 1 Aug 2017 | ↗]. ¼ of EU transport emissions come from heavy duty trucks and buses.

Vessels carrying cargoes in bulk, dry and wet, are the most efficient due to scale, high utilization of the main dimensions, simple cargo handling and low sailing speeds. Volume cargoes carried on ro/ro vessels weigh less and the efficiency per tonne cargo moved is therefore lower. These vessels should really be compared based on cargo hold volume or gross tonnage or a particular and representative cargo unit such as lane metres.

The below diagram (fig. 48) compares the carbon intensity (EEOI) of a number of smaller vessels typical for coastal short sea trades with land-based transport. Note that the carbon intensities below are for the smallest vessel class and global averages and based on carbon intensity factors from IMO [IMO 4th GHG study, 2021, p.225 | ↗]. Comparisons and case studies on the potential emission reductions by moving cargo from road to sea should be based on the specifics of the trade, regional conditions and with factors for the relevant vessel type.

The carbon intensity of road transportation varies. Long haul trucking is more efficient than last mile delivery by smaller trucks. The Norwegian average for heavy duty trucks (length ≥ 5.6 m) for 2019 was 88 g/t·km = 163 g/t·nm [SSB, Dec 2020 | ↗] while the average for new truck sold in 2019 in Europe was 57 g/t·km [ACEA, 2020 | ↗].

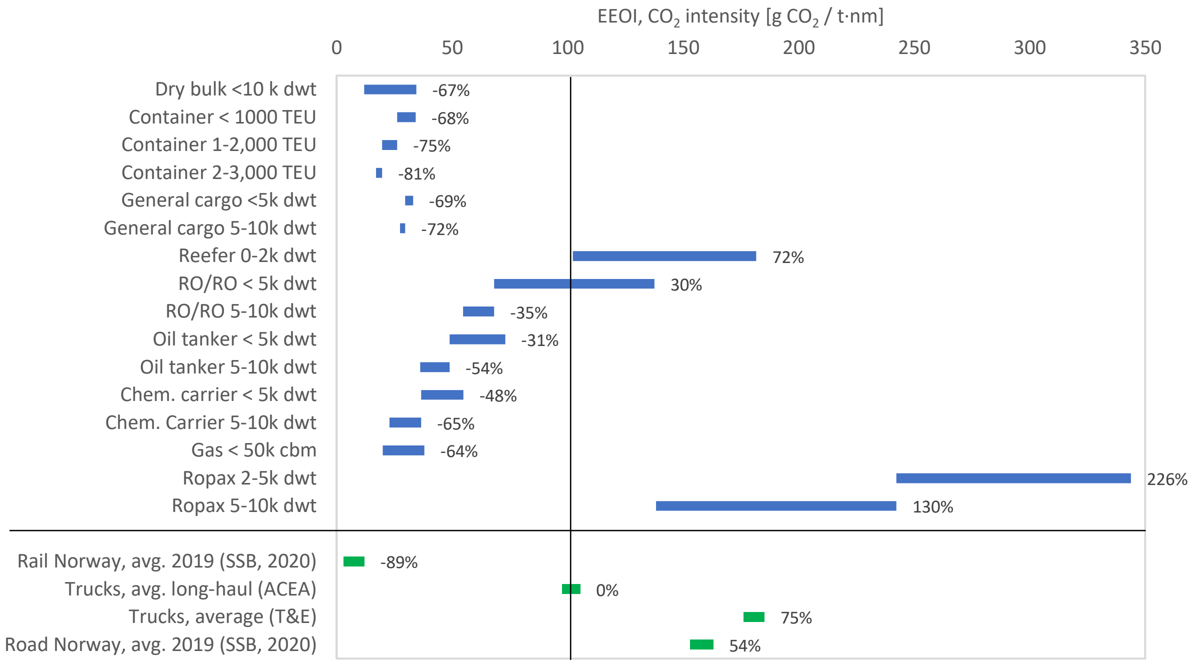


Figure 48: Carbon intensity of various vessel types and sizes vs rail and road transport options.

The vessels included are representative for the types and sizes engaged in coastal trade. Significant variation between individual vessels occurs due to technical and commercial factors partly outside the control of the operator. Note that rail in Norway is generally electric with near zero footprint; this is not the case elsewhere.

Small bulk carriers, general cargo ships and container vessels emit around 70% less than the most modern long-haul trucks!

Land transportation will likely reduce or eliminate GHG emissions as batteries and or hydrogen are expected to become common also for long-haul heavy duty trucks. To stay ahead of the truck in terms of GHG-intensity, seaborne transportation must continue to reduce energy use and emissions.

Sometimes, the sea route is shorter

On some routes, depending on the geography, the advantage of a more direct route comes on top of the lower emissions per kilometer.

The route from Tromsø to Rotterdam is around 15% shorter via the sea (2,500 vs 3,000 km) and the route from Bergen to Rotterdam is 45% shorter (1,050 vs 1,900 km). Other routes are much shorter on land: From Athens (Piraeus) to Rotterdam, the sea route is twice the distance (6,100 vs 2,900 km).

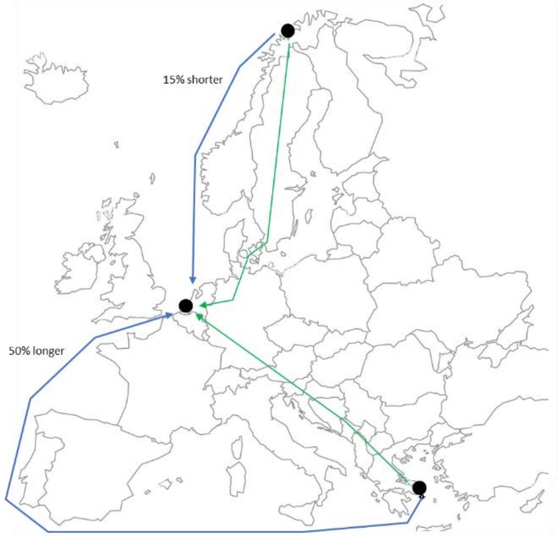


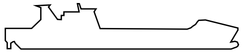
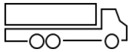
Figure 49: Distance over land vs distance via the sea.

Finally, the distance between other city pairs is very similar: E.g., from the Gulf of Bothnia to Rotterdam, the land distance is 2,350 km and the sea route is 2,500 km (5% longer) even when taking the short cut through the Kiel canal. A truck on this route will, however, have to pass through the cities of Stockholm, Malmö, Copenhagen, Hamburg, Bremen and Utrecht enroute. The environmental and social cost of passing through densely populated areas with enough traffic already, is not negligible.

Emission standards for NO_X, SO_X and PM

Ships are the most energy efficient transport mode. However, continuous efforts to improve energy efficiency and reduce emissions will be necessary to compete with the much stricter emissions standards for NO_X and SO_X applicable to land transportation.

Diesel for use in trucks landside use contains only one hundredth of the sulphur accepted in the cleanest marine fuels (10 ppm = 0.001% vs 0.1% for marine fuels in SECA). The Euro 6 NO_X-standard for truck engines is much stricter. Trucks must be expected to become emissions free within a decade. In 2016, the EC introduced uniform and stricter emission standards for non-road use, including inland waterway vessels [EC, 2016 | ↗]. Particulate matter are regulated directly, both by mass (PM) and particle numbers (PN), in addition to tighter emission limits for NO_X.

	 *Ships*	 *Inland waterway vessels*	 *European land-based transportation*
NO_X	In ECA: 2-3.4 g/kWh (from 2016)	EU Stage V: 0.40-1.20 g/kWh	Euro 6: 0.46 g/kWh (from 2015) [↗]
SO_X	In ECA: 0.1% sulphur (1,000 ppm)		10 ppm sulphur = 0.001% (from 2009)
Particles	Regulated indirectly	Yes; mass (PM) and number (PN)	

There is a research gap on particulate matter. Formation of particles is determined by the sulphur content and the combustion process [Winnes and Fridell, 2012 | ↗]. Further, the number of smaller particles may be more detrimental to human health than the aggregated particle mass.

To be truly sustainable in all ways, machinery and abatement technologies as well as alternative fuels must contribute to lower GHG as well as reduced NO_X, SO_X and particles in a life cycle perspective.

Moving cargo from land to sea moves the emissions farther away from people. While location does not matter for greenhouse gases, it does indeed for NO_X, SO_s and particles.

Other environmental advantages of sea vs road

Road transport is a major source of micro plastics, caused by abrasion of tires [Eunomia, 2014 | ↗], [Miljødirektoratet, 2021 | ↗]. Heavy vehicles wear down the asphalt and whirl up particles.

Traffic jams and accidents are part of everyday life in many cities and suburbs and less trucks will alleviate the pressure to the benefit of passenger traffic and short distance goods distribution, which ships cannot replace. To improve living conditions in Europe, noise from road traffic must be reduced, according to a recent EEA briefing [European Environment Agency, 23 Sep 2022 | ↗]

> *Even if trucks become carbon neutral, the environmental harm from micro plastics from chafing of truck tires remain, so does the noise, increased risk of accidents and traffic jams. Generally, trucks also operate closer to people as the main highways pass through or near places people live.*

Shifting cargo from land to sea can also alleviate pressure on existing roads and avoid construction of new roads, with negative climate impact from land use and habitat destruction.

7.2. Economy of scale: Ship size

SUMMARY

Ships are the most energy efficient transport mode and there is considerable economy of scale, both in construction and operation.

Also, the energy use and emissions are much lower for large vessels compared to smaller ones.

For these reasons, most vessel types have grown in size over the last decades. The average vessel afloat is now 40% larger than it was only 15 years ago.

Containerships continue to grow beyond 20,000 TEU and will likely be even more important in terms of cargo carried and emissions in the future.

Carrying a tone of cargo with a larger vessel generally reduces emission, provided that the capacity is in fact appreciated and utilized on the actual trade.

Data from IMO's 4th GHG study confirms the environmental advantage of larger ships [IMO 4th GHG study, 2021, p.225 | ↗]. E.g. carrying a tonne of cargo with the smallest ro/ro vessels (< 5k dwt,) emits 70-140 g CO_2/t·nm, while a ship in the next size category (5-10k dwt) emits only 30-70 g and 68 g on average.

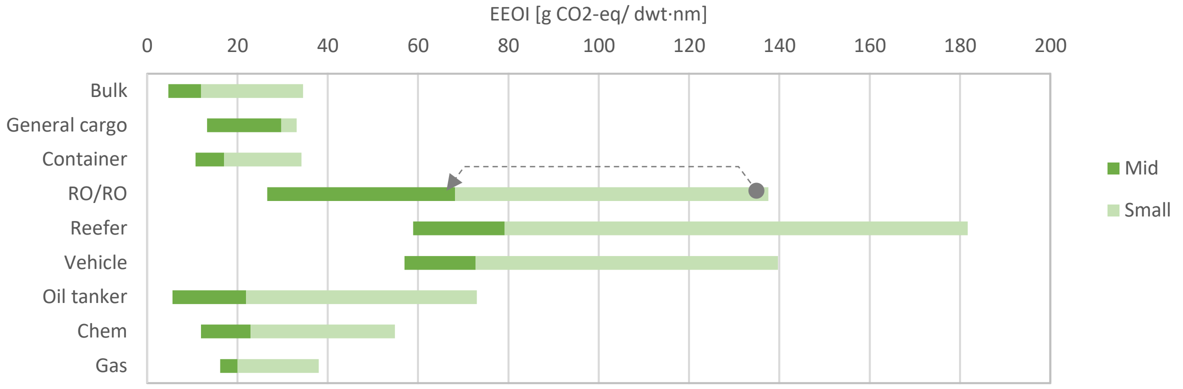
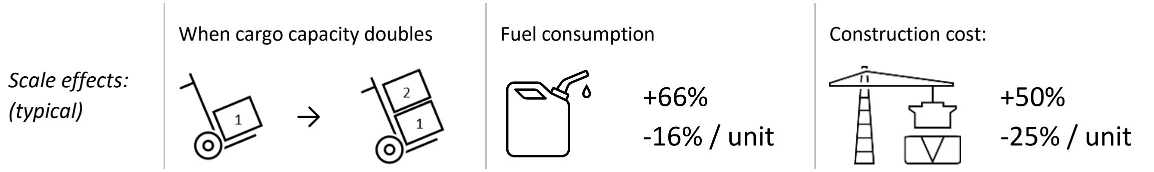


Figure 50: Carbon intensity (ranges) of various vessels types and sizes.

There are a few exceptions, as some size segments suffer from suboptimal main dimension ratios and hull forms. The largest and longest Panamax container vessels with unusually high L/B ratios are an example of this. Also, large vessels must be filled up to realize this scale advantage. Even with today's megacities and mega factories, many ports are better served by modestly large vessels. The high demand for container feeder vessels confirms this. A good AER and poor EEOI for the same vessel or trade or company can be explained by poor utilization.

Many vessel types have reached a size where further scaling does not pay off or is restricted by practical or commercial factors. Lindstad, Bø and Eskeland [2018 | ↗] has proposed the following rule of thumb based on analysis of multiple shipping segments, however, please note that the scale advantage depends very much on the vessel type and the starting point and is naturally stronger for small vessels. Typically, we see that when cargo capacity doubles, fuel consumption increase only by 66% while construction cost increase by 50%:



Vessel sizes have increased significantly over the last decades. From 2007 to 2015, a very active period characterized by a strong shipbuilding market motivated by the good freight markets up to 2008, average vessel size grew by 40%. Growth was particularly strong from 2007 to 2012, perhaps motivated by the strong freight market up to 2008 [Lindstad, 2017 | ↗].

The diagram shows the growth in average deadweight from 2007-12 and 2021- 15 [Lindstad et al., 2018 | ↗]:

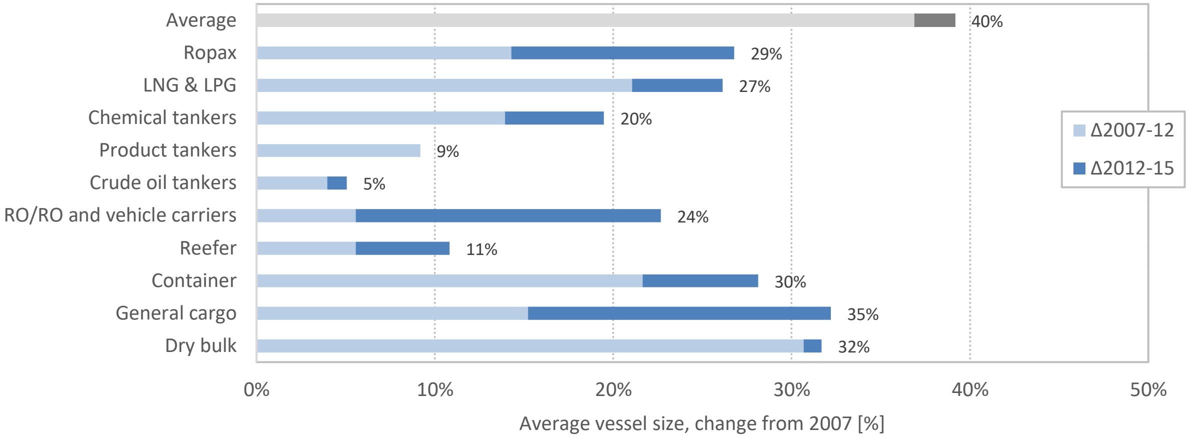


Figure 51: Increase in carrying capacity for various vessel types in two periods; from 2007 to 2012 and from 2012 to 2015.

Scale is not always appreciated in short sea shipping, where high frequency to reduce the need for factory inventories and storage as well as short transit times are important. Also, large vessels may not access smaller ports.

While larger vessels may be advantageous in theory, they must be filled up with cargo. The highest utilization reported for mega container vessels is around 0.90 [Maritime Executive Aug, 2019 | ↗]. This is where the difference between the two carbon intensity indicators becomes important. The AER is based on deadweight and will be better for large vessels regardless of the utilization rate. The EEOI on the other hand, is based on the actual cargo carried and will thus reflect the utilization rate of large vessel. See chapter 6.3 for details.

Will ship sizes grow forever? The case of oil tankers in the 1970's illustrate that practicalities set a limit to growth. The temporary closing of the Suez Canal motivated construction of larger crude oil tankers, culminating with Seawise Giant in 1981 at 565,000 dwt but the vessel was not a straight success as only very few ports could welcome the 458 m long vessel. Today's largest crude oil carriers, ULCCs, lift around 430,000 dwt but are rare and few compared to VLCCs (300-320,000 dwt).

Container vessels, on the contrary, continue to grow in size. The first container vessel took 58 units in 1956. 10,000 TEU on a single keel became reality by 2015 and 20,000 by 2017 [McKinsey 2017 | ↗]. At the time of writing, the largest container ship afloat takes almost 24,000 TEU. In terms of total emissions, though , vessels below 12,000 TEU still account for 85% of containership emissions in 2018 [MO 4th GHG study, 2021, table 81, p.446 | ↗].

In general, we see few signs indicating that the growth in average vessel size observed so far will continue [Lindstad, Eskeland, Borgen, Sandaas, 2019 | ↗].

7.3. Slow steaming

SUMMARY

Slow steaming is considered an effective and rapid way to reduce emissions from ships. However, noting that most vessels have slowed down already, the potential for further emissions reductions is less.

The effect of speed reductions hinge on a number of factors such as vessel type, hull form, current speed, weather and wind, energy demand for shipboard systems, energy demand in port, time at sea vs. time in port, machinery configuration, power transmission etc etc.

Through case studies, we find that the reduction is significant but that half the potential is already utilized. Further speed reductions will have negative impact on the required freight rate and require massive fleet expansion to keep supply constant.

Such newbuilding activity will give significant emissions which will cancel out the emission reductions in the first few years of operations.

Emissions should be regulated directly and not by way of a proxy parameter such as speed, to encourage innovation and ensure that the most effective and cost effective operational and technical measures are employed.

Speed is a key variable used to adjust the transport work of individual ships and the world fleet to the demand. It can also have great impact on fuel consumption and thus emissions and even daily running costs.

In 2011, SINTEF Ocean investigated the effect of speed and found that emissions can be reduced by 20-30% [Lindstad et al., 2011 | ↗]. This is similar to Corbett et al. [2009 | ↗], Seas at Risk and CE Delft [2009 | ↗]. A more recent study by CE Delft finds that emissions will drop by 13, 24 and 33% for 10, 20 and 30% speed drops [Faber et al., 2017 | ↗].

However, calculating the emissions reduction from slow steaming is far from straightforward. The effect depends on a number of factors such as vessel type, hull form, current speed, weather and wind, energy demand for shipboard systems, energy demand in port, time at sea vs. time in port, machinery configuration, power transmission etc etc. With this range of factors, it is clearly very difficult to estimate how much further speed reductions can give. Let us look at these factors and see how much slow steaming can help to cut emissions:

The required propulsion power is proportional to the speed to the power of three, approximately. However, there are exceptions to this rule that must be considered carefully when evaluating slow steaming, summarized as follows:

$$P = k \cdot v^X \quad \begin{cases} X \approx 3 \text{ for calm water around design speed,} \\ X > 3 \text{ for high speed ranges (high Froude numbers),} \\ X < 3 \text{ at low speeds (low Froude numbers)} \\ X \ll 3 \text{ at low speeds (low Froude numbers) when including added resistance from waves and wind.} \end{cases}$$

Based on X = 3, reducing speed by 10% will reduce power by 29%. Adjusting for the shorter distance travelled, the power reduction per nautical mile will be 19%.

At lower speed ranges, the coefficient will be significantly lower than 3, according to Berthelsen (DTU) and Nielsen (NTNU) who studied the speed-power relationship based on operational data from 88 tankers from 35,000 to 110,000 dwt [Berthelsen and Nielsen 2021 | ↗]. Ådland et al. come to similar conclusions even when the effect of wave and winds are excluded [Ådland, Cariou Wolff, 2020 | ↗].

Noting that most vessels sail slower than before (ref chapter 3.5) and run their engines on reduced loads (ref chapter 6.2), the effect of further speed reductions is less obvious in 2022 than it was in 2008. Take container vessels as an example: Ships carrying 3-12,000 TEU have reduced average speed by about 20% from 2008 to 2018 and now operate at 0.70 of their design speed [IMO 4th GHG study, 2021, table 82, p.446 | ↗].

While slower speed reduces propulsion power, the energy consumed by shipboard systems is constant and the vessel spends more time at sea. Also, the energy spent in port is not affected by slower speed, neither is the time required for loading and unloading.

As discussed in chapter 6.2, the emissions factors for NO_X, methane and black carbon vary with the engine load and is generally much higher at part loads. Reducing speed means spending more time at these part loads, resulting in unfavourable emission factors. Noting that the average engine load for the major three vessel types bulk, tanker and container, is already in the range 0.45-0.55 (ref chapter 6.2), further slow steaming will shift the average engine load to the very low end of the main engines operating range where the emission factors are very high. The problem of unfavourable emission factors can be avoided for newbuildings where the machinery can be tuned according to the expected power demand. However, the need for a power margin for rough weather will likely lead to low load operations also for newbuildings.

On average, vessels spend 4-9% of their annual operating time at anchorage [GEF-UNDP-IMO GloMEEP Project, 2020 | ↗]. This is unproductive time that could be better spent at sea. However, some idling before berthing will likely always be required to ensure utilization of port facilities and avoid delays int the supply chain.

Finally, the effect of slow steaming looks very different if there is overcapacity available or if new tonnage must be built to cover the transport demand. The abovementioned study by CE Delft finds that demand for new ships will be 10, 22 and 37% higher as a result of the proposed speed reductions of 10, 20 and 30% [Faber et al., 2017| ↗]. 10-20% speed reductions will, according to the paper, require new deliveries to grow back to the highest levels seen in the past decades. Larger speed reductions would require exceeding those levels for bulkers and small container ships. The energy, natural resources and emissions arising from massive additional newbuilding activity must be factored in.

If slow steaming requires massive newbuilding activity, it will have moderate or even negative environmental effects for the first few years, followed by reductions later.

To sum up, the saving in power will be larger than the saving in fuel consumption, which in turn will be larger than the reductions in emissions which again will be larger than the emissions per transport work (EEOI).

$$\textit{Effect of speed reduction:} \quad \Delta Power\ [kW] \; > \; \Delta Fuel\ [t/d] \; > \; \Delta GHG\ [t] \; > \; \Delta EEOI\ [g/t\cdot nm]$$

The conclusion is that slowing down will have positive, but varying effect on emissions depending on the starting point. Speed must be considered relative to the design speed or by the vessel's Froude Number and the hull form (prismatic coefficient). While 14-15 knots is fast for bulkers and tankers, it must be considered low for slender vehicle carriers vessels. A common speed limit for all vessels does not take these differences into account.

Emissions should be regulated directly and not by way of a proxy parameter such as speed, to encourage innovation and motivate use of effective operational and technical measures.

Finally, a fixed speed limit at sea breaks with the ideal of goal-based regulations. It does not honour the effects of operational practices, which often have very limited negative environmental effects and can be implemented immediately.

7.4. The Northern Sea Route between Europe and the Far East: Shorter, but not necessarily greener

SUMMARY

The Northern Sea route from the Barents sea to the Bering strait is much shorter; 10-40% shorter depending on the exact port of departure and arrival.

The effect on global warming, however, is not as crystal clear as first thought, due to the strong effect of black carbon. This can be mitigated by using clean fuels such as natural gas.

The case illustrates the importance of including all gases with global warming effects in such studies.

The Northern Sea Route (NSR) from the Barents Sea to the Bering strait offers a shorter route from Northern Europe to the Far East. The sailing distance is up to 40% shorter, however, transit times are not reduced as much due to slower speed, more complex navigation and likely waiting time for ice breakers. And research at NTNU and SINTEF Ocean finds that the much stronger global warming effect of black carbon emissions in the high north more or less cancels out the effect of less CO_2.

Traffic through the NSR is very limited; 30-40 complete passages annually [Centre for High North Logistics, June 2020 |↗]. The route is busiest in the months of July, August and September, as transit in autumn, winter and spring is more complicated and requires very high ice class notation and, likely, ice breaker assistance.

Marine traffic in the Arctic is growing by 75% in terms of distance sailed and by 82% in terms of fuel oil consumed [PAME | ↗]. There are two drivers for increased traffic through the Northern Sea Route; primarily exports of raw materials and energy from Russian ports such as Yamal and Dudinka, and secondly, the shorter distance between Asia and Europe.

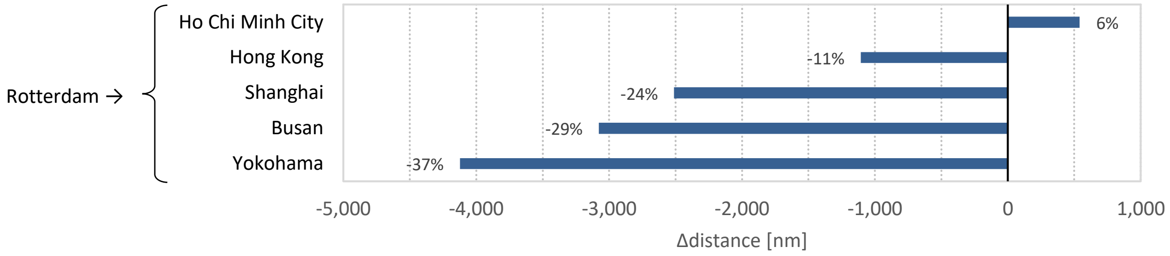


Figure 52: Difference in sailing distance with the Northern Sea Route

Normally, shorter sailing distance should result in less fuel consumed and less emissions. Two factors complicate the picture: Additional engine power is required to break the ice or move drifting ice floes during summer. Escort from ice breakers should also be considered when calculating total fuel consumption and emissions. Secondly, black carbon reduces the albedo (reflection) of the snow and ice and leads to enhanced melting.

The global warming potential of black carbon is five times higher in the Arctic than its global average. The global warming potential is 3.5 times higher on a twenty year timescale than in a hundred year perspective [Lindstad et al., 2016 | ↗].. While we normally focus on the hundred-year global warming potential, the short term effect is indeed relevant considering the rapid temperature rise and the urgent need to cut GHG emissions.

The global warming potential of black carbon is five times higher in the Arctic than in temperate climates; 1,700 vs 345 (GWP_{100}).

As discussed in chapter 6.1, the black carbon emissions can be up to ten times higher when engines run at part and low loads. This must be factored in. Using average emission factors for optimal engine load (e.g. NCR) will underestimate the black carbon emissions.

Lindstad, Bright and Hammer Strømman investigated the total global warming effect of Panamax and Capesize bulkers sailing the Northern Sea Route vs the Suez Canal between Europe and the Far East [Lindstad et al., 2016 | ↗]. With low sulphur fuel oil (0.50%S), the NSR gives lowest CO_2 but when BC is added, the Suez comes out with lower GHG. With MGO (0.1%S), NSR gives lowest CO_2 and the NSR and Suez comes out almost equal when BC is added. The two routes will thus have the same global warming effects. With LNG, the NSR gives lower GHG both in terms of CO_2 and when BC is added.

The key conclusion is that evaluations made based on only CO_2 can be very misleading. Emission factors reflecting actual engine load and the impact of black carbon on snow and ice must be factored in to find the greenest sailing route. At least one shipping company has ruled out the Northern Sea Route on environmental grounds [High North News, 2019 |↗].

The much higher global warming potential of black carbon in the Arctic confirms the need for geospatial emission inventories and including more than CO_2.

In 2021, IMO adopted a ban on use and carriage of Heavy fuel oil (HFO) in the Arctic from 2024. The ban was primarily motivated by the risk of oil spills to the cold and vulnerable Artic waters, noting the remoteness and long scrambling time for assistance in case of oil spills. A secondary effect will be the reduction of black carbon associated with residual fuels.

7.5. Weather routing

SUMMARY

Good weather routing systems depend on accurate modelling of the vessel's hydrodynamic and aerodynamic properties as well as the machinery.

Weather routing can reduce energy use by 3-5% and up to 4-8% on routes with rough weather e.g. in the North Atlantic.

Weather routing is important for vessels with sails and can increase the energy reduction due to sails considerably.

Weather routing systems evaluates the energy use of a particular vessel sailing at a certain speed from A to B based on the forecasted weather en route. Based on simulations of many different paths, it will recommend the route giving minimum fuel consumption.

The advantage is bigger in the Atlantic and Pacific Ocean where strong winds and high waves are more common, especially during winter. Weather routing can reduce fuel consumption by 3-5% [Zis et al., 2020 | ↗] and up to 4-8% based on route optimization on North Atlantic routes for a 134 m long multipurpose bulk carrier [Bentin et al., 2016 | ↗].

The quality of weather routing systems depends upon a good modelling of hydrodynamic and aerodynamic properties as well as the machinery onboard so that the vessel's response to the forecasted weather can be predicted reasonably accurately. To be applicable to the largest possible set of vessels, today's commercial weather routing software trades complexity and precision for generality.

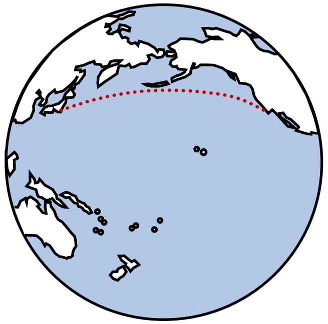


Figure 53: The great circle from Japan to the US West Coast offers shorter sailing distance but often rougher weather and a good example of a trade lane where weather routing will contribute positively to reduced energy and emissions.

The exact approach used by a given software is rarely known due to commercial interests, but such generic models typically take two various forms:

1. Using a fully data driven model such as neural networks require very large data sets for training, usually solved by retrieving historic data from many vessels. This approach will however neglect specific design and technology details for individual ships and new concepts, not exploiting such properties in the routing process.

2. Using a simplified parametric model, where the parameters are adapted using operational data from a particular vessel. However, to achieve convergence the number of parameters must be limited, not capturing important details and particular technological solutions.

Common for both approaches are their limited incorporation of cross-disciplinary knowledge of the vessel, and they are black box approaches. This prevents synergy effects from interdisciplinary development processes between ship designers, ship owners and operators when developing and planning for future use of low- and zero-emission maritime technologies.

Voyage planning must consider a number of other parameters than just fuel consumption. A survey among captains and chief officers found risk for cargo, crew and vessel to be the top priority, followed by arrival time and fuel consumption and cost [Rutesim project, 2020 | ↗].

For most vessels, the goal with weather routing is to avoid foul weather. For ships with sails, the goal is to find favourable winds. Weather routing used for this purpose can increase the energy saving with rotor sails from 36% to 53% crossing the Atlantic eastbound and from 14 to 28% when crossing the Atlantic westbound [Bentin et al., 2016 | ↗]

For both cases, the recommended path will be a compromise between favourable weather and sailing distance.

7.6. Policy implications

Transport emissions can be reduced by shifting cargo from road to sea or rail. Emissions and other environmental burdens should be assessed and compared for sectors but also across substituting transport alternatives. To support a model shift from land to sea, sea ports must remain close to population or industry centres with good hinterland connections.

The fleet of coastal general cargo and bulk vessels is old. Renewal or upgrade is critical to support the modal shift from land to sea. Standard designs can reduce costs but will not necessarily give the optimum designs in terms of energy and emissions.

Large vessels can deliver more cargo with only modest increase in energy use and emissions; however, the actual climate intensity depends on the filling rate and utilization. This confirms the importance of using EEOI rather than AER.

Speed can be an effective way to cut energy use and emissions, but not necessarily. The effect depends on the starting point, the ship type, weather and wind, hull form and machinery and the operation profile and energy use for ship systems at sea and in port. Reductions in transport work must be factored in, so must the emissions from ship building.

The enhanced warming effect of black carbon in the Arctic, Antarctic and other snow covered landscapes should be duly included by using region specific global warming characterization factors when analysing the environmental effects of marine traffic in such waters. This applies to the Northern Sea Route as well as Northern Norway and the Baltic Sea in winter. As an Arctic state, Norway has an obvious role to play here.

7.7. Sources and further reading

	Link
Berthelsen & Nielsen (2021): Prediction of ships' speed-power relationship at speed intervals below design speed.	→
Corbett, Wang and Winebrake (2009): The effectiveness and costs of speed reductions on emissions from international shipping.	→
Faber et al (2021): IMO 4th GHG study 2020.	→
Faber and Nelissen (2017): Regulating speed: a short-term measure to reduce maritime GHG emissions.	→
Lindstad, Asbjørnslett & Strømman (2011): Reductions in greenhouse gas emissions and cost by shipping at lower speeds,	→
Lindstad, Bright and Strømman (2016): Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation.	→
Lindstad, Bø and Eskeland in the texboook Marine Design XIII (ISBN: 978-1-138-54187-0): Reducing GHG emissions in shipping – measures and options,	→
Lindstad (2016): How the Panama Canal expansion is affecting global ship design and energy efficiency.	→
Lindstad (2015): Assessment of bulk designs enabled by the Panama Canal expansion.	→
PAME (Protection of the Marine Arctic Environment) a working gorup under the Arctic Council	→
Ådland, Cariou, Wolff (2020): Optimal ship speed and the cubic law revisited: Empirical evidence from an oil tanker fleet.	→

Photo: SINTEF Ocean.
Hybrid (computer and towing tank) model test of a slender bulk carrier with sails.
The wind forces are calculated by computer and transferred to the physical model by pulling the appropriate wires.

8. ENERGY USE AND ENERGY EFFICIENCY

SUMMARY

Reducing energy begins by mapping the major consumers and the drivers behind these.

Ship resistance and propulsive efficiency are the two major factors for most vessel types. Main dimensions and hull form should be designed for the expected weather and operation profile of the trade.

Although ships are the most energy efficient transport mode, shipping cannot rest on its laurels. In a world with very limited renewable energy (ref chapter 9.1), using less energy is paramount. The International Energy Agency (IEA) expects energy efficiency to contribute with more than 40% of the reduction in energy related greenhouse gas emissions over the next 20 years in their Sustainable Development Scenario [IEA | ↗].

> *Boosting energy efficiency is key to any decarbonization strategy*
> *Energy use must fall 4% Y/Y, twice the level achieved 2010-17.*
>
> Dr Timur Gül, IEA, 24 June 2021 [Forskningsrådet | ↗]

There are many ways to improve energy efficiency:

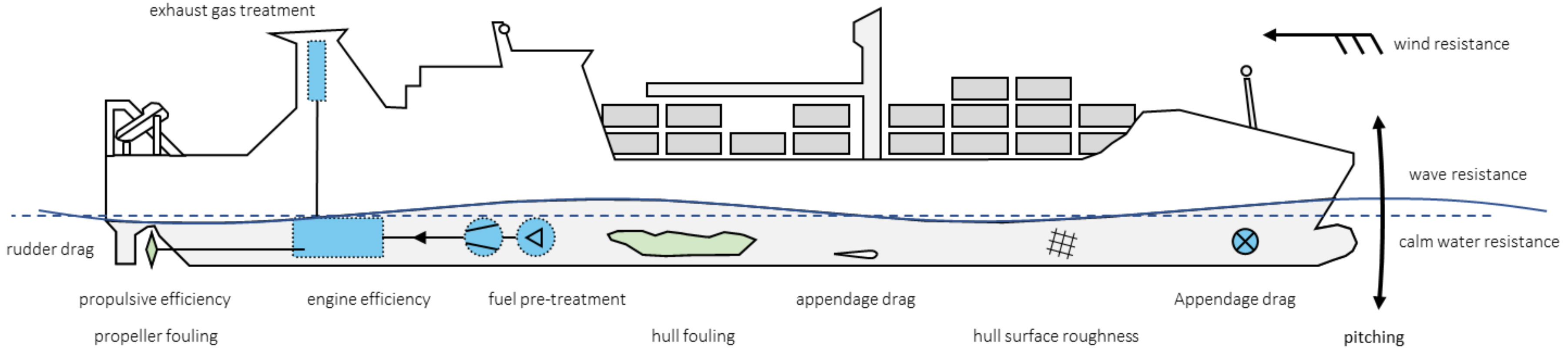
First, selecting the most energy efficient transport mode is essential to reduce emissions per cargo unit. Using larger vessels can also help, provided that the cargo flow is sufficiently large. Sending fewer but larger batches can make larger vessels feasible, if storage space is available at the production site and longer transit times and reduced frequency can be accepted (ref chapter 7.2).

The majority of vessels spend most energy on propulsion. The major factor influencing this is indicated on the illustrations on the next page. In this chapter, we discuss how propulsive power can be reduced through optimizing main dimensions and the hull form for realistic weather conditions (chapter 8.2), reduced frictional resistance (chapter 8.3) and use of various devices to improve propulsive efficiency (chapter 8.4):

Sails are, strictly speaking, not an energy saving device. Sails reduce the energy demand onboard by harnessing the energy in the wind.

Finding and sizing the engine and ensuring optimum load sharing between the engines installed is getting more and more attention, thanks to increased insight into the disadvantages of low load operation and more sophisticated control systems. Batteries can play a role here, also for larger vessels. GYMIR can be used to simulate this and find the right machinery configuration (chapter 8.6 and 8.7).

Significant amount of energy is also consumed by ships' ancillary systems at sea and in port. In chapter 2.5, we noted that emissions in port amount to 11% on average and 5-25% of the total for various ship types.



Main resistance components and energy consumers when sailing.

Energy consumed by ships' ancillary systems at sea and or in port.

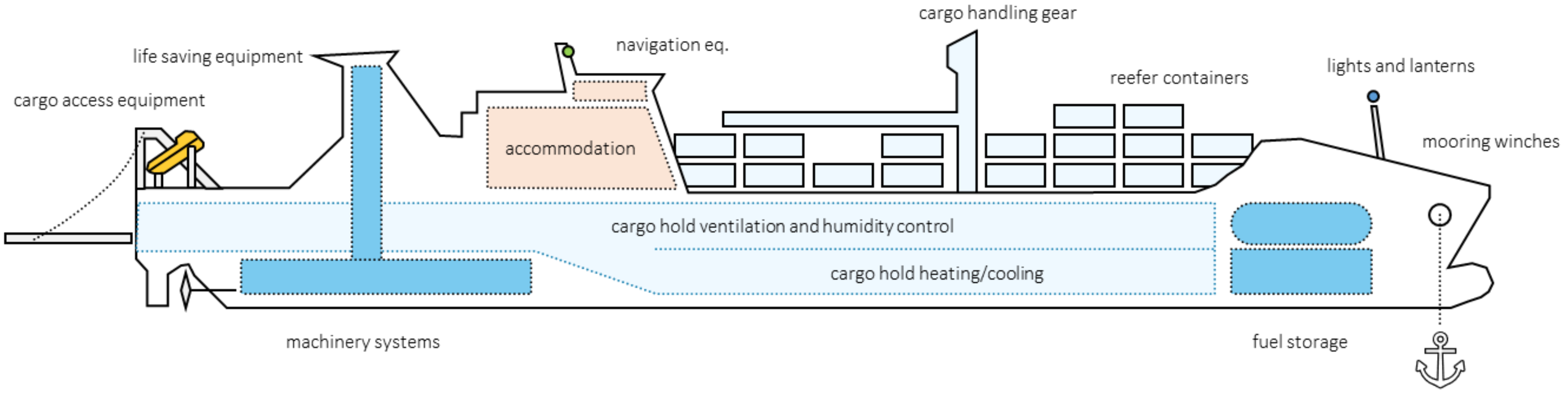


Figure 54: Drivers for energy consumption of ships (non-exhaustive list).

8.1. Development of energy efficiency 2008-2018 and predictions for the next decade

SUMMARY

Seaborne transportation is the most energy efficient transportation mode and the average carbon intensity has improved by around 30% measured based on actual transport work (EEOI).

IMO notes, in the 4th GHG study: «*The pace of carbon intensity reduction has been further slowing down since 2015, with average annual percentage changes ranging from 1 to 2%». Yet, it is committed to reach the 40% improvement by 2030, agreed in the 2018 GHG-strategy.*

There is considerable variation between the vessel types and sizes. Bulk, tank, container and ro/ro have improved the most.

Energy efficiency is a vital component in many of the roadmaps presented for shipping as well as other sectors.

As 96% of the world fleet burns heavy fuel oil (HFO) or marine diesel or gas oil (MDO/MGO) (ref chapter 3.3), CO_2-emisions are proportional to energy use and carbon intensity equals power intensity.

While this linearity has been true in the past, it will change in future with the advent of new fuels with varying carbon content. Indicators such as the Energy Efficiency Design Index (EEDI) and Energy Efficiency Operational Index (EEOI) appear to reflect the energy efficiency but are in reality reflecting the carbon intensity. In the future, with the advent of new fuels will less carbon content, energy efficiency and carbon intensity will not follow each other but develop independently. Therefore, more nuanced indicators will be needed, as we suggest in chapter 6.3.

Over the last decade, the energy efficiency of the world fleet has improved, both in terms of EEOI (Energy Efficiency Operational Index) and AER (Annual Efficiency Ratio). Note that the two tell quite different stories, for shipping overall and for various segments. The two key metrics, EEOI and AER, are discussed in chapter 6.3. In general, the EEOI and AER have improved for all vessel types by around 29% and 21% respectively. The improvements in carbon intensity of international shipping have not followed a linear pathway, and more than half have been achieved before 2012, according to IMO.

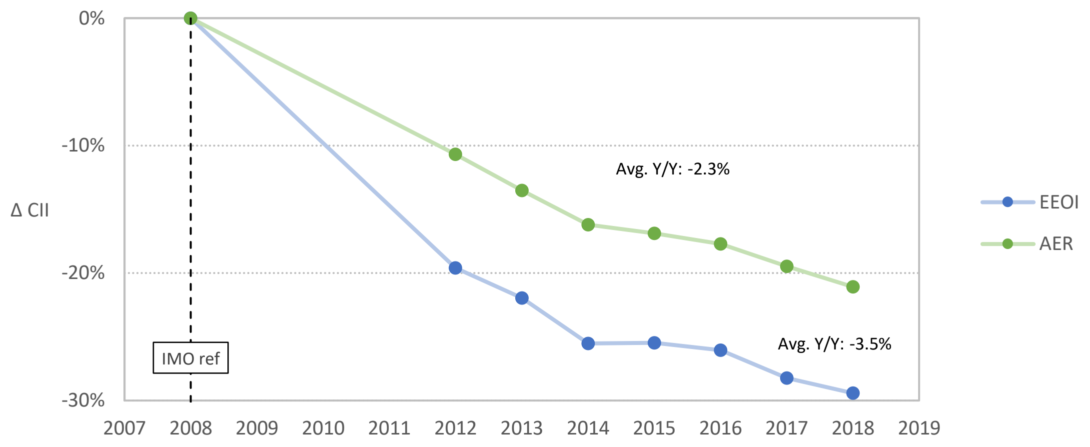


Figure 55: Change in carbon intensity since 2008

Some general conclusions based on the IMO 4. GHG-study can be made for each shipping segment [IMO 4th GHG study, 2021, table 59 and 62 | ↗]:

Bulk carriers: The most significant and consistent improvement is observed for dry bulk, with 40% lower EEOI and 31% lower AER. All size categories improve both the EEOI and AER, except for vessels above 200,000 dwt which sees 6% higher EEOI but 6% lower AER.

General cargo ships, a large and diverse group of mainly smaller vessels, have reduced the EEOI by 25% and AER by around 20% from 2008 to 2018. The smallest (below 5,000 dwt) vessels have not improved while the largest vessels (above 10,000 dwt) have higher EEOI in 2018 than in 2008. The segment has high average age, and the potential of fleet renewal is high. The pathway to decarbonizing small coastal general cargo ships presented in chapter 10.2 illustrates this.

Container vessels improve overall with 25% lower EEOI and 27% lower AER. The smaller vessels, up to 3,000 TEU, have higher EEOI but lower AER in 2018 vs 2008. Vessels carrying 3,000 to 14,500 TEU have improved EEOI by around 20%. Ultra large container vessels have been introduced after the 3rd IMO GHG report. If we compare the two largest vessel categories today (14,500-20,000 TEU and 20,000 TEU and above) with the largest category in 2008 (12-14,500 TEU), we see around 40% reductions in EEOI and AER alike.

Oil tankers have improved the EEOI by around 25% from 2008 to 2018. The smaller tankers, 5,000 to 60,000 dwt, had 5-12% higher EEOI in 2018 than in 2008 while vessels above 60,000 dwt improved their EEOI by 20-30% from 2008 to 2018. EEOI improved more than AER for both oil tankers and chemical carriers.

Chemical tankers are quite different from oil tankers as they carry many different fluids and spend more time in port. Again, the smaller vessels saw a deterioration of 10-20% in EEOI, while the largest chemical tankers, above 20,000 dwt, improved their EEOI, by 9% on average. Individual companies report reductions in CII as high as 34%-50% [Odfjell, 3Q 2021 | ↗].

RO/RO and vehicle carriers reduced EEOI by 40% and 15% respectively, mainly from 2008 to 2012. Two leading operators of vehicle carriers report improvements since 2008 as high as 35-40% and now emit 50-60 g/t-km [Wallenius Wilhelmsen, 2019 | ↗], [Höegh Autoliners, 2020 | ↗]. The automobile industry is under immense pressure to build emission free vehicles and emission free production and transportation can be a natural next step [e.g. DN, 23 June 2021 | ↗].

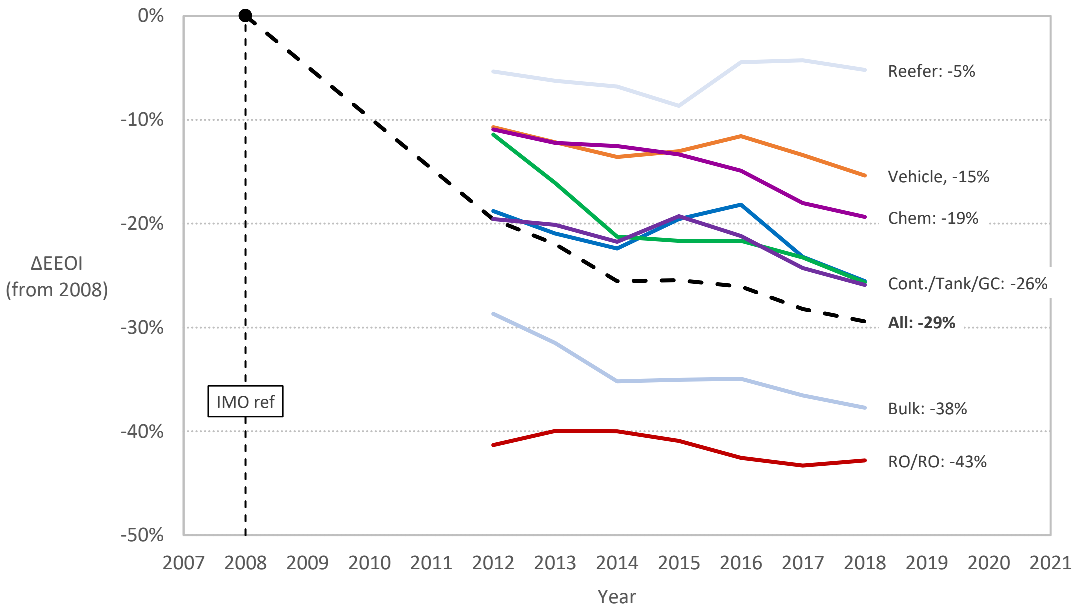


Figure 56: Development in EEOI since 2008 for some key shipping segments. Variations within the segments and between operators occur.

Can the improvement continue ad infinitum or will the energy efficiency train come to a stop? IMO notes that some of the energy efficiency measures hold limited further potential.

> *The pace of carbon intensity reduction has been further slowing down since 2015, with average annual percentage changes ranging from 1 to 2%, due to the limit in speed reduction, payload utilization, as well as the technical improvements of existing ships.*
>
> From IMO's 4th GHG-study (p. 18)

IMO agreed at MEPC 76 (June 2021) to continue lowering the CII by 1% annually from 2019 to 2023, then by 2% annually from 2024 to 2026. In total, this will give 11% from 2019 to 2026. The reduction rate for the last four years (2027-2030) will be agreed in 2026, but a minimum of 2% pa for the period 2027-2030 is required to reach 40% altogether [IMO, 17 June 2021 | ↗].

As explained in chapter 2.7, 40% improvement in CII by 2030 will not deliver substantial emission cuts in absolute terms, but rather 10% lower emissions with 1% trade growth and 15% higher emissions with 3% trade growth. Our calculations show that 60-70% better CII are required to cut emissions by 45% with 1-3% trade growth. Noting the challenges with alternative fuels such as large tank space, low supply and high cost, we believe the majority of the required reduction in CII must be realized by reducing the energy consumption.

> *In shipping, efficiency improvements make up two-thirds of emissions reductions to 2030 in each of our three scenarios, and 2050 it accounts for around 45% of abatement in the sector.*
>
> Bloomberg New Energy Outlook [↗]

8.2. Optimization of main dimensions and hull form

SUMMARY

Around 3,300 concepts and 8,000 models have been tested by SINTEF Ocean since the towing tank was built in 1939. Hull form optimization is still at the core of SINTEF Ocean.

Main dimensions are often set by convention and limited by infrastructure and or rule requirements. Breaking away from the mould can give significant savings.

The length of short sea vessels has often been limited. A study of coastal bulkers found that a 10 metre longer hull can reduce power per deadweight by around 15%.

The carbon intensity can be reduced by up to 25% for Supramax bulk carriers and by 15-20% for small coastal bulkers of around 5,000 dwt.

The saving depends on the speed and is higher for trades with high waves and strong winds. Few limitations on length, breadth and draught increases the possibilities to design a hull with minimum resistance.

If main dimensions cannot be tweaked, local changes to the bow and stern can change the waterlines to reduce added resistance in waves and improve seakeeping.

Once main dimensions are set, hull form, propulsion and detailed design optimization should be part of every design and newbuilding project. Novel tools for parametric models coupled with numerical tools makes it possible to apply holistic approach that considers the draughts, speeds and weather conditions relevant for the particular vessel's operation.

The main dimensions length, breadth, depth and draught (L, B, D and T) are often determined by convention and limited by various infrastructure and rule requirements. Finding the best combination of L, B and D and T for a given displacement is complicated and requires insight into the effect of each parameter, which can be very different in calm water and in waves.

Also, the main dimensions impact not only resistance but also stability, structural integrity, seakeeping, and construction cost. They are therefore, generally, always, a compromise.

Longer vessels will generally have lower wave resistance and better seakeeping characteristics due to a finer bow, less pronounced shoulders and lower block and prismatic coefficient. Length allows better inflow to the propellers as well. On the negative side, longer hulls require more steel and the increase in building cost is higher compared to extending the beam or depth. Longitudinal strength can be an issue for some vessels, notably bulk carriers. Length drives wetted surface area and frictional resistance, which is the key component for most vessels and certainly for bulky and slow vessels (ref chapter 8.3). Therefore, the advantage of a longer hull will commonly be more pronounced at higher speeds and in waves, but minor or even negative at slow speeds and in calm water.

Beam (B) has historically been limited by locks and canals. A reasonably wider hull allows lower block and prismatic coefficients. Large beam can reduce need for ballast water and thus reduce displacement.

Draught (T) is also commonly restricted by the depth in straits and ports. Draught has, typically, less impact on resistance than length and breadth. Larger draught gives lower block and prismatic coefficient. A deep draught gives room for a large propeller, which generally has better efficiency.

Air draught is restricting the size of volume carriers, i.e. vessels such as vehicle carriers and cruise ships as well as the stack height of container vessels. Air draught is also important for smaller vessels in coastal trade where bridges are more common.

The most important main dimension restrictions come from the most important ports or terminals as well as canals and seaways such as the Panama Canal, the Suez Canal, St. Lawrence seaway and the Kiel Canal, to mention a few. Shallow waters in Denmark limit the draught of vessels sailing to the Baltic Sea. Also, the Northern Sea Route is quite shallow.

In search for maximum cargo carrying capacity, many vessels are built with very high block and prismatic coefficients, at the expense of hydrodynamic performance [Utby, 2016 | ↗]. Studies by SINTEF Ocean and NTNU indicate that the emissions per transport work can be improved a lot by breaking away from conventional main dimensions.

Optimization can be done with regards to cost or environmental performance. We need economic incentives to make the most environmentally friendly vessels competitive also on cost.

For more than a century, naval architects have investigated the effect of hull form and fullness in particular, expressed by the block coefficient (C_B) or more accurately by the prismatic coefficient (C_P). Tests with systematic variations of a parent hull form has been made to this end and confirmed positive effects of low Froude number, low block and prismatic coefficients and high length to displacement ratios (slenderness) [Lindstad et al., 2018 | ↗].

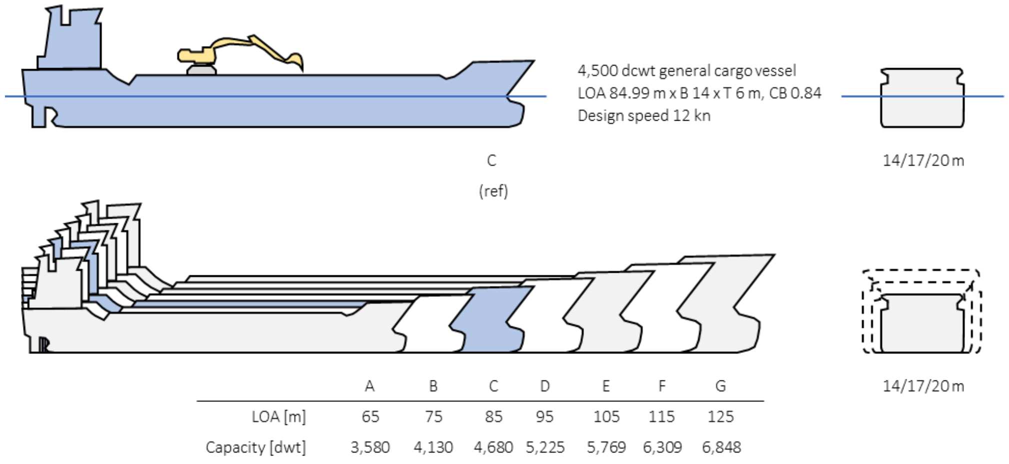
Yet, a study of tankers and bulkers built since 1970 found that the energy efficiency, measured by EEDI, had deteriorated for ships built the last two decades [Kristensen, 2011 submitted to IMO as EE-WG2/3]. Appetite for cargo capacity, low fuel prices and focus on calm water performance are likely explanations for this. Noting EEDI does not reflect added resistance from waves and wind and noting the added resistance from these forces, the EEOI has likely deteriorated even more than the EEDI.

By laying out the possible advantages, we hope owners and yards will look at main dimensions again, with fresh eyes, and optimize their designs not only with regards to cost, but also energy and emissions.

The discrete event simulation tool GYMIR was developed to evaluation different set of main dimensions and null forms a very early stage where the potential for emissions reductions is higher. Traditionally, model testing is undertaken late in the project where only minor tweaks can be done to the design.

The short sea case

Lindstad, Eskeland, Sandaas and Steen [2018 | ↗] investigated the possible advantages of unconventional main dimensions and slender hull forms for short sea general cargo vessels. They analysed variations of the standard hull with lengths from 65-125 and three breadths (14, 17 and 20) to see the effect of scale and main dimensions.



	A	B	C	D	E	F	G
LOA [m]	65	75	85	95	105	115	125
Capacity [dwt]	3,580	4,130	4,680	5,225	5,769	6,309	6,848

Figure 57: Variations of main dimensions and slenderness for a coastal general cargo vessel

First, the deadweight was varied to see the effect of scale; from 3,500 to 7,000 t and found considerable reductions in cost and power for the larger vessels. At 12 kn, a 7,000 tonner needs only 25% more power than a 3,500 tonner or 35% less power per deadweight. At 16 kn, the two needs roughly the same power so power per deadweight is halved. The scale effect is indicated by the arrow ① on the below diagram (fig. 58).

The positive effect of scale on both fuel consumption, emissions and costs is well known and the potential is biggest for the smallest vessels. However, in short sea shipping, large vessels are not always appreciated, as cargo owners prefer to ship many smaller lots at high frequency. Also, short transit time is necessary to compete with the truck, and this makes slow steaming less feasible than in deep sea shipping. It is therefore important to reduce emissions by simply optimizing the main dimensions.

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The researchers, therefore, for each hull length, analysed a version with the same deadweight as the reference vessel (4,680 t). The effect of such design optimization is indicated by the vertical arrow ② in the below diagram (fig. 58). The 4,680 dwt vessel can reduce fuel consumption and emissions by around 20% by optimizing the main dimensions, it was concluded.

From the diagram (fig. 58), we note that increasing the deadweight from 4,680 to 5,800 dwt (alternative E) reduces required power by 9%. The same 9% can be achieved by increasing the breadth from 14 to 17 m while keeping the cargo capacity constant. The breadth increase allows lower block and prismatic coefficient and eventually lower fuel consumption and emissions.

Power per deadweight drops more than cost per deadweight. Thus, building a large vessel is still a better option to minimize cost, with the fuel prices and other factors assumed in this study. Higher fuel prices and carbon pricing will, hopefully, change the picture.

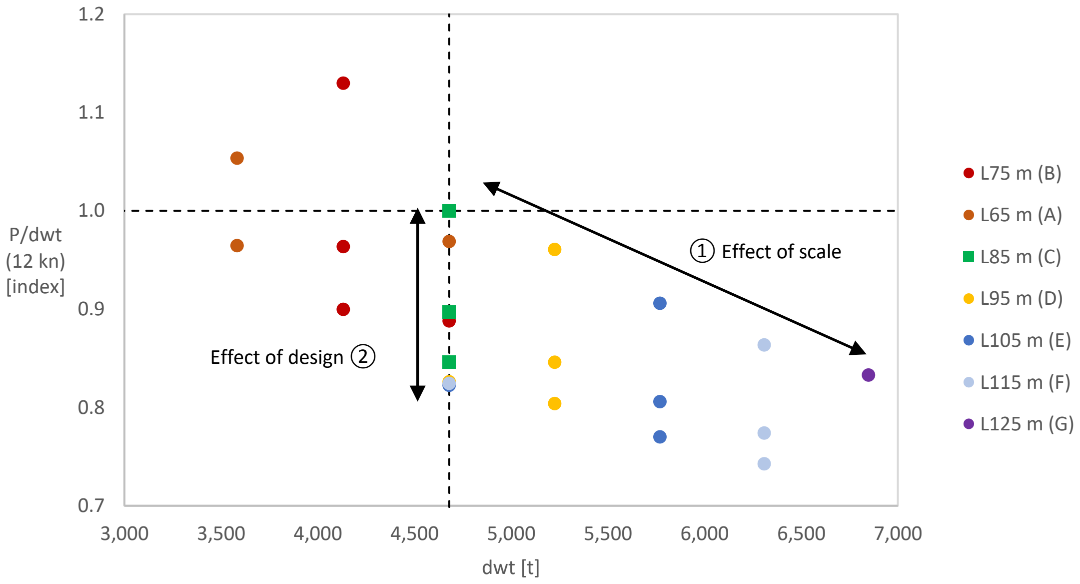


Figure 58: Propulsion power relative to cargo capacity [kW/dwt] for general cargo vessel designs resulting from variations in main dimensions and variations in cargo capacity.

The Supramax case

Supramax bulkers carries around 10% of global seaborne trade. There are around 7,000 bulk carriers from 35,000-100,000 dwt and these ships emit around 10% of shipping emissions [IMO 4th GHG study, 2021, table 81 | ↗]. Improvements to this type of vessels can therefore make a real difference on the total, global shipping emissions.

Lindstad, Borgen and Sandaas [2018 | ↗] have investigated the effect of slender hull forms by analysing the required power and total cost per transport work for a standard Supramax design and three variations of the parent hull form (as illustrated below). In all cases, deadweight was kept constant so that the larger main dimensions would give lower block coefficient.

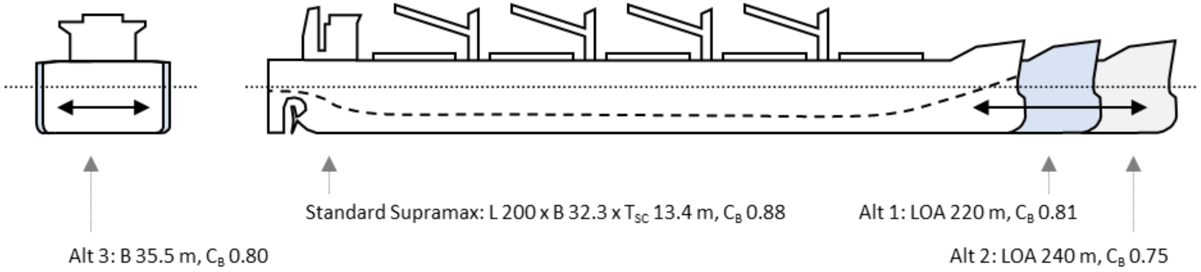


Figure 59: Variations of main dimensions and slenderness for a Supramax bulk carrier

In calm water, in terms of required power, the slender designs will outperform the standard only for speeds above 11 kn. In terms of cost, they will outperform the standard only for speeds above 13 kn. Hence, in terms of cost, the standard design is favoured although it will give higher emissions for speeds above 11 kn. Average speed for large bulkers (dwt > 35,000) was 11-12 knots in 2018 [IMO 4th GHG study, 2021, table 81 | ↗].

In 3 m waves, the slender designs will give lower emissions for all speeds and also lower cost. Emissions can be reduced by 10-25% depending on the design and speed, with the highest saving for the 240 x 32.3 m design at 15 kn speed.

If the analysis is based on a 50/50 mix of calm water and 3 m waves, all design alternatives will give lower emissions. Alt. 1 and 3 will giver lower cost for all speeds while alt. 2 will give lower cost for speeds above 13 kn.

To sum up, slender designs can reduce fuel consumption, fuel cost and emissions by 10-25% depending on the speed. After a desktop study, a model of the concept (OSBC-1) was tested in the towing tank to confirm the saving potential. The most important finding, however, is that the best design in realistic waves conditions, in terms of unit cost and emissions, is not identified if the analysis is based on calm water power predictions.

This confirms the importance of including power predictions for real sea states in estimates for power, emissions and unit cost. The study utilized the simulation tool GYMIR.

Calm water testing conditions for EEDI in its present for does not reward measures that reduce fuel consumption in realistic sea conditions with waves and wind.

Note that the analysis was based on fuel prices of 500 $/t. Higher fuel prices and possible carbon pricing will strengthen the business case for the slender vessels.

Håkon Utby analysed the main dimensions and hull form coefficients of bulk carriers around 80,000 dwt, known as Kamsarmax and Panamax. He comments that bulk carriers have, in general, been designed to minimize construction cost, maximize cargo intake at the expense of hydrodynamic performance. Utby found that lowering the block coefficient from 0.84 to 0.73 could shave 23% off the propulsion power [Utby, 2016 | ↗].

Reducing the block coefficient from 0.85 to 0.75 can reduce the energy consumption of a dry bulk carrier or tanker by up to 25%, depending on the speed and sea conditions.

Hull form optimization

Once main dimensions are set, hull form, propulsion and detailed design optimization should be part of every design and newbuilding project. Novel tools for parametric models coupled with numerical tools makes it possible to apply holistic approach that considers the draughts, speeds, and weather conditions relevant for the particular vessel's operation.

With multiple performance criteria and constraints, hull form optimization is full of conflicts and compromises, e.g.

1. A hull shape optimized for calm water resistance may behave sub-optimal in waves.
2. Optimization of hull lines for resistance typically conflicts with stability requirements.
3. Slender aftbody are beneficial for reducing resistance, but often results in lower hull efficiency, and may therefore have an adverse effect on propulsion performance.
4. Bulbous bows optimized for one speed and draught can drastically increase the resistance in other loading conditions and speeds.
5. A large propeller diameter can improve propeller efficiency, but too narrow tip clearance to the hull can give unacceptable pressure pulses, resulting in excessive vibrations and noise.
6. A narrow gap between the propeller and rudder improves hull efficiency but increases unsteady loads and risk of cavitation on the rudder especially at non-zero rudder angles.

There are countless other examples of contradictory optimization problems when considering the entire operational envelope of a vessel. Multiplied with the numerous operating conditions the vessel is expected to encounter this makes for a complex optimization problem.

The manual approach to hull form optimization by means of a trained eye, CFD analysis, simulations and model tests often reduce energy demand by 20-30% from first concept to the final design.

Fortunately, tools for simulation driven design optimization are in strong development and increasingly used, e.g. computational fluid dynamics (CFD) and seakeeping codes. Such tools allow analysis of a large number of design alternatives by automatic variation of key design parameters such as length, breadth, draught but also local details like for example bulbous bow geometry and appendage shapes and alignment.

Bow shape

While any and all modern vessels of some size would have a protruding bulbous bow, the vertical stem with a less pronounced bulb was reintroduced on a series of LPG-carriers built by Kawasaki for, inter alia, Bergesen and Solvang in 2004 [Kawasaki, 2004 | ↗]. The concept has since also been applied to many different vessel types including car carriers, cruise liners, general cargo vessels and large crude oil tankers.

A vertical stem (no. 2 from the left in the below illustration) allows a longer waterline and finer entrance angle. The move away from optimization for a single draught and speed towards optimization for a range of draughts and speeds speaks in favour of such a vertical stem.

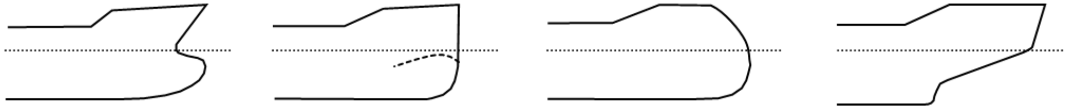


Figure 60:: conventional bulbous bow, straight stem with bulbous bow, Ulstein's X-bow and an icebreaking bow.

The advantage of a particular bow shape and bulb depends on the Froude number and will vary with the loading condition (draught and trim) and wave height and period. The overall effect can be estimated by simulating a full year of operations on the intended routes with GYMIR (ref. chapter 5.1).

In addition to added resistance in waves, the bow shape will influence seakeeping, momentary speed loss and speed variations, vibrations and noise and thus comfort onboard as well as water spray. These effects often lead to voluntary speed reductions.

Changing bow

The bulbous bow is designed for a given draught, speed and trim. It can be designed to perform well at one or a few sailing conditions. With increased slow steaming and generally more uncertainty, the current trend leans towards flexibility.

Yet, many designers and shipyards optimize the bulb and the hull as a whole for the guaranteed condition. A new bulbous bow can give significant savings if the vessel is now operating at a different draught or another speed than anticipated when the original bulbous bow was designed. The bow shape can be changed on existing ships during a normal or extended dry-docking. Such modifications have been popular for container vessels and car carriers [TU, 2015 | ↗].

Jon H. Leonhardsen analysed the energy saving potential of having a bulbous bow construction with fixed cross section but adjustable length, capable of changing shape to minimize resistance for the current sailing condition, i.e. speed, draught and trim. For a Panamax container vessel (LOA 230 x B 32.26 x T 10.8 m), he found that the possibility to change rapidly between seven bulbous bow shapes could save around 3% energy [Leonhardsen, 2017 | ↗].

Summary

Hull form optimization and propulsive efficiency is still at the core of SINTEF Ocean, more 80 years after the inauguration of the towing tank in 1939 [SINTEF Ocean | ↗]. Around 3,300 concepts and 8,000 models have been tested over the years. Initial design work and optimization using digital tools such as CFD comes on top of this.

SINTEF Ocean track record

Hull forms tested	Propellers tested	Potential
about 8,000	about 1,600	Up to 20-30%

The studies by Lindstad, building on the methods developed by SINTEF Ocean and NTNU, to estimate added resistance in waves suggest savings up to 20% for small bulkers in coastal trade and up to 25% for Supramax bulkers. Similar results (20-25%) are found by Haakon Utby, in his MSc thesis, for large bulk carriers. The metastudy by Bouman et al. (2015) concluded with savings up to 20% for hull shape optimization.

The most important finding from these studies is that including or excluding effect of waves and wind can change the conclusion completely. While one design may be better in calm water, another is better in the waves and wind expected on the intended trade. Excluding these effects – which is the norm today – can result in higher fuel consumption and emissions than strictly necessary.

Secondly; with cheap fuel and high newbuilding prices, we often see that the most cost effective dsesign is not the greenest and vice versa. Carbon pricing or fuel taxation can close the gap and make the greenest vessel the most competitive one.

Breaking away from convention and standard designs can reduce fuel consumption, fuel cost and emission by 10-25%.

Thirdly, the conclusions depend largely on the assumptions made on speed, draught, fuel prices as well as trade specific parameters such as weather and wind on the intended route. Solid insight into these external factors including forecasts is key to make good decisions.

8.3. Frictional resistance and effect of hull roughness and anti-fouling

SUMMARY

Frictional resistance is important for the calm water resistance of all vessels and clearly the most important resistance component for slow vessels.

Fouling of the hull can increase resistance significantly and its growth and effect on speed and power should be monitored.

Reliable methods for estimating the fouling effect have been lacking. SINTEF Ocean and NTNU have now developed methods to evaluate of effect of new anti-fouling coatings on friction.

Better coatings and timely hull cleaning can contribute significantly to reduce energy consumption and emissions from vessels already today, with minimum investment cost.

Other measures to reduce frictional resistance including hull roughness and air lubrication.

Friction or viscous resistance is a major part of the resistance for all vessels but more so for slow and full-bodied vessels such as bulk carriers and tankers while wave resistance is more important for fast and slender vessels such as ropax ferries, container carriers, ro/ro and cruise ships (ref chapter 6.4). As most vessels slow down, frictional resistance becomes more important for all vessels. To be precise, slow speed means low Froude number, i.e. low speed relative to the hull length.

Frictional resistance can be reduced in a number of ways:

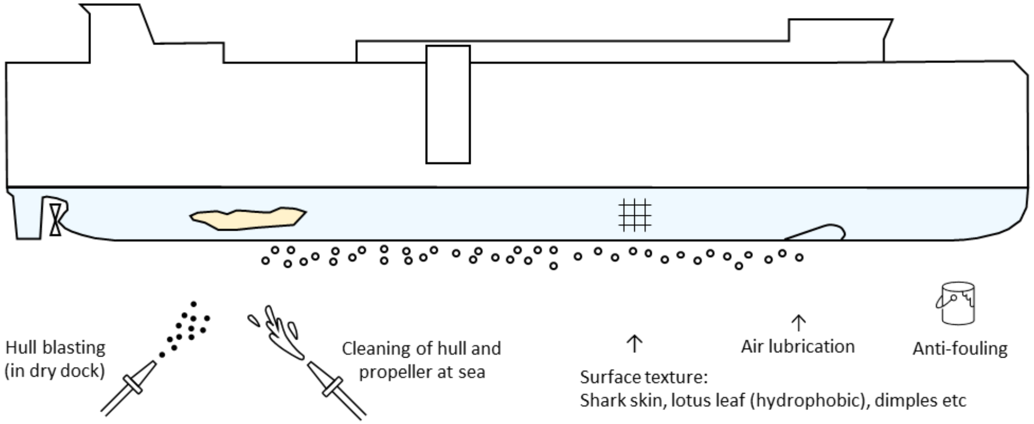


Figure 61:Measures to reduce frictional resistance, in construction and operation

Minimum wetted surface

Frictional resistance can be reduced at the design stage by selecting the main dimensions carefully.

While longer hulls generally improve seakeeping and reduce wave resistance, length drives wetted surface more than breadth and draught does. So, the optimum balance between low friction resistance (short length to minimize wetted surface area) and low wave resistance (long length to achieve fine entrance angles, slender bow, low C_B and C_P) can be found by analysing alternative hull forms over a year in the intended trade using GYMIR.

For a given displacement, the lowest wetted surface area is achieved with a high block coefficient. For a given set of main dimensions (L, B and T), the lowest wetted surface area is achieved with a low block coefficient.

Hull roughness and fouling

The surface roughness of the hull increases the frictional resistance and reduces the propulsive efficiency. Fouling was found to add 15-20% to the calm water power for a 2,500 TEU container vessel analysed from delivery to first special survey (5 years) [Ejdfors, 2019 | ↗]. The 4 GHG-study assumed an average 9% power increase due to fouling for all vessel types [IMO 4th GHG study, 2021, table 44, p. 407 | ↗].

Studies of fouling generally concludes that the fouling effect cannot be brought down to zero as some fouling remains. Secondly, the fouling effect returns faster after hull cleaning as the anti-fouling coating is less effective as time passes.

Anders Östman, Kourosh Koushan and Luca Savio wanted to know if a high quality coating could be applied only to the part of the hull where the shear stress is highest, and thus save money by accepting a poorer coating on the remaining hull. Unfortunately, they found that the increase in viscous resistance was roughly inversely proportional to the area coated with the best coating [Östman et al., 2019 | ↗].

The roughness can be split into two components: permanent and temporary roughness.

Permanent roughness is determined by the surface treatment of the steel plates during construction and later augmented by corrosion, mechanical damage (dents), accumulation of old coating. The permanent roughness can be reduced by hull blasting, using sand, grit or high pressure water in dry dock.

Temporary roughness is caused by biofouling and can be divided into slime, weed and shells [Townsin, 2003 | ↗]. Biofouling depend on the effectiveness of the underwater coating and generally increase with time in water. The anti-fouling coating is made to be most effective at a certain speed range. Higher speeds will wear down the coating faster while the self-polishing effect will be reduced at slower speeds.

Good understanding of the vessels' intended operations is essential to specify an effective anti-fouling coating. To be specific, this includes likely speed range, idling time, expected sea water temperatures and opportunities for hull cleaning along the route.

NTNU student Kristian Olaf Ejdfors analysed in-service data for a container vessel for five years from its maiden voyage to develop a method to isolate the effect of fouling [Ejdfors, 2019 | ↗]. Such methods are useful to determine when it is time to clean the hull and to check the effect of various types of anti-fouling paint.

Regular hull cleaning can give immediate reductions in energy use, lower fuel costs and emissions. It is available today with little investments. Reliable estimates of the advantage of hull cleaning can encourage more owners and operators to clean the hulls as the cost advantage can be documented.

Air lubrication

Bouman et al.'s analysis found savings around 5-10% with air lubrication systems and up to 20% in a few lucky cases. The effect of such systems depends on the speed and is generally higher for higher speeds.

8.4. Propulsive efficiency

SUMMARY

Required propulsion power is determined not only by the resistance but also by the propulsive efficiency.

The main factor is the propeller. Large diameter, low blade area and slow turning speed (RPM) give good efficiency.

Where propeller diameter is restricted or the propeller loading is very high, distributing the load on two propellers can pay off.

Controllable pitch propellers are generally inferior to fixed pitch propellers unless the operating profile is very mixed and the vessel is much exposed to rough seas.

Contra rotating propellers give high efficiency but the construction is complicated.

Tipped wings or end plates can also improve efficiency, but expanding the diameter is generally better.

The flow to the propeller can be improved by fins or ducts. Similarly, static or rotating fins can be installed in the flow aft of the propeller to regain some energy.

The effect of such devices depends on the hull shape and must always be investigated for the particular case with model test and or CFD. Scale effects are significant and can be studied by CFD and or by analysis of operational data from sister vessels in full scale operation.

The required main engine power of a ship is determined by its resistance and propulsive efficiency. Resistance is most affected by the main dimensions and hull form coefficients while propulsive efficiency is mainly determined by water flow into the propeller and the propeller geometry.

Best possible inflow to the propeller is ensured by the aftbody hull shape. A slim aftbody can reduce resistance but can give lower hull efficiency. A balance between minimum resistance and maximum propulsive efficiency must be sought.

Propeller design

Large diameter, few blades and slow turning speed (RPM) improve propeller efficiency. A deep draught helps to achieve this.

The propeller geometry is careful balance between high efficiency, complexity, blade strength, pressure pulses and noise levels. SINTEF Ocean have contributed to the design and tested 1,600 different propeller designs.

Fixed pitch propellers (FPP) have better efficiency than controllable pitch propellers (CPP), however, the possibility to adjust the blade angle can pay off when operating conditions change significantly from the design point, e.g. in rough seas. Good understanding of the vessels operating conditions is essential to find out whether a FPP or CPP is the best option for a new design. Simulations with GYMIR can be used to analyse each case.

Where the propeller diameter is limited, end plates or curved blade tips can suppress tip vortices allowing for more loading towards the tip. Depending on the original design, these propeller concepts can save a few percent.

Twin screw propellers may be advantageous to a single propeller with very high thrust load. Two propellers can deliver half the thrust each with a relatively large diameter. Twin screw propellers give better manoeuvrability and reliability.

Contra rotating propellers (CRP) increase propulsion efficiency by recovering part of the rotational energy losses from the forward propeller and due to better inflow to the aft propeller. The aft propeller will typically have smaller diameter and one more propeller blade than the forward propellers.

The construction with shaft-in-shaft has made CRP a costly and less popular option, despite its higher efficiency. The complex shaft arrangement can be avoided by having one pod and one shaft-mounted propeller. Perhaps the higher energy cost and environmental concern can give renewed interest?

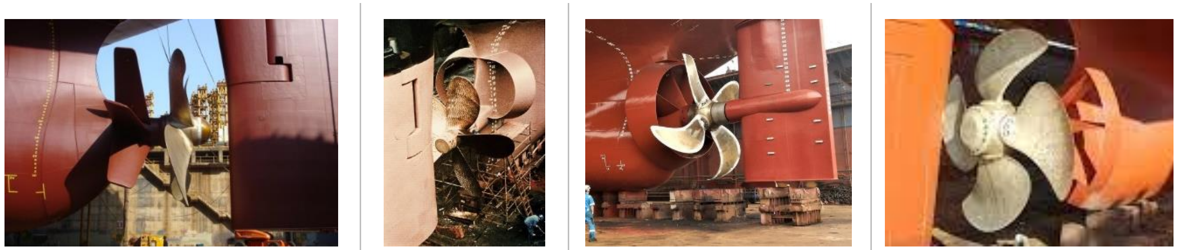
CRPs have been successfully fitted to vessels as diverse as a bulker (Juno, 1987), a VLCC (built by IHI for Idemitsu, 1993), a ropax (e.g. Hamanasu, 2004 and Sunflower Furano, 2017), a supply vessels (e.g. Ugland Juanita, 2013). Studies suggest 10% lower power for a 8,500 TEU container vessel [Pérez Sobrino, Mariano, 2013 | ↗].

Hydrodynamic energy saving devices

A range of devices to improve the flow before the propeller (pre-swirl) or regain energy aft of the propeller (post-swirl) exist. The effect of each depends on the aftbody hull shape, speed and the loading of the propeller. Generally, the potential is higher for propellers with high thrust load coefficient (C_{Th}) but any device must be designed and investigated for the particular case with model tests and or CFD.

There are large scale effects for most of these devices and the flow is complex to model with CFD. Also, the behaviour in real seas and non-ideal operating conditions (e.g. other speeds and draughts) are insufficiently researched. Model tests, model scale and full scale CFD as well as analysis of operational data can be used to estimate the effect of such devices, preferably in combination as all three methods have their strengths and weaknesses. Analysis of sister vessels in operation or a single vessel before and after can be useful, though it is complicated to compare these under identical conditions or make corrections for different loading condition and ambient conditions.

Pre-swirl devices are symmetric or can fitted to one or both sides of the hull.



Pre-swirl stator	Schneekluth duct	Mewis duct (Becker)	Energo Flow (Wärtsilä)

Figure 62: Pre-swirl devices

Post-swirl devices (below) try to recover the rotational energy.

Stator fins	Costa bulb and fairing cone	Propeller boss cap fins	Grim vane wheel

Figure 63: Post-swirl devices (below) try to recover the rotational energy. This is also beneficial for rudder cavitation.

Devices designed to save energy can also reduce noise, vibrations and rudder cavitation.

8.5. Wind propulsion

SUMMARY

Sails can once again contribute to propel large vessels across the oceans. Different types and a mix of very old and some new concepts are investigated and installed to vessels in both deep sea and shortsea trades.

The effect of sails depends on the sail type, sail area, vessel speed and prevailing wind conditions and is best estimated by means of simulation of e.g. a full year of operations on the intended trade. SINTEF Ocean has developed tools for both resistance modelling and weather routing for evaluation of sails.

Stability, coursekeeping as well as tolerances for static heel and dynamic roll and other ship motions and accelerations can limit the sail size and use.

If the above concerns can be successfully mitigated, sails can save 20-50% for many merchant vessels, especially in cases where the schedule and required estimated time of arrival (ETA) is flexible.

The saving is higher at slow speeds.

Sails can be retrofitted to existing ships if deck arrangements, stability and course keeping abilities allow.

Hear Anders Alterskjær and Anders Östman explain the role of modern sails in a SINTEF podcast 19 May 2022 [↗]

Harnessing the wind for propulsion was the norm until steam powered vessels took over from around 1880. More than hundred years later, several innovative projects are under development and a few cargo vessels have retrofitted sails recently.

The main advantage with wind is that is can be harnessed and utilized directly without the conversion losses and energy use in the supply chain that all other energy carriers suffer. Unlike alternative fuels, sails do not require any infrastructure and does not compete with other energy users for limited renewable power. Sails occupy weather deck space but does not reduce enclosed cargo hold space and does not increase the vessels gross tonnage.

The below sketch illustrates the different types of sails. The lift coefficient for each sail is indicated above, but keep in mind that the total thrust generated depends not only on the type but also on the wind speed and relative wind direction, and the drag coefficient in non-favourable wind directions. Note that some sails require some power to operate.

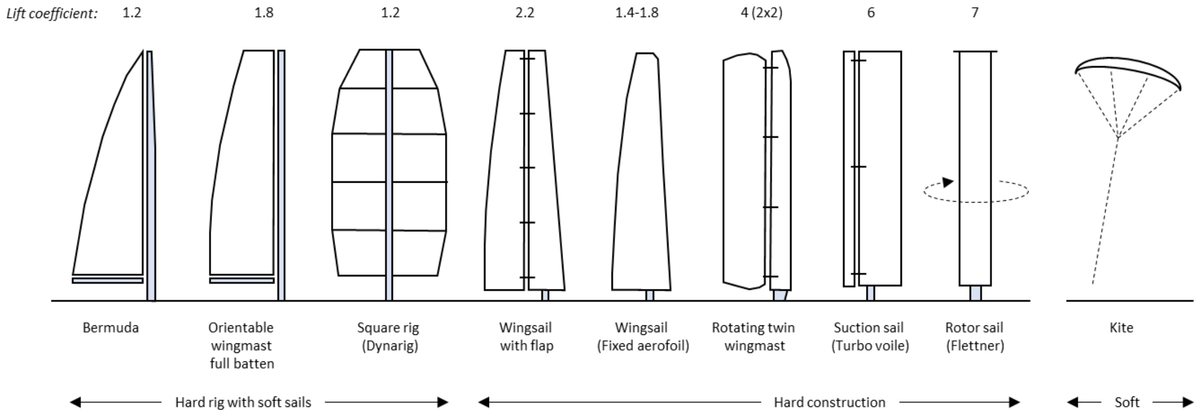


Figure 64: Different sail types adapted from Mathis Ruhl, 2019 [↗], by Jarle Kramer, Anders Østman and Gunnar Malm Gamlem.

In addition to the above sail types, a very novel concept has been under development in Norway for a decade: A vessel where the hull is shaped like an aerofoil and generates lift, known as Vindskip [↗]. The concept is indeed unconventional and will certainly face many challenges to materialize, yet, the company deserves praise for creativity and courage.

The effect of sails depends on the sail type and sail area, the vessel's speed and prevailing wind conditions in the trading area and is best estimated by means of simulations. The resistance model of the vessel must include the effect of drift, rudder, and heel angle. In addition, as the thrust from the sails vary with the weather, so will the thrust from the propeller. When the propeller load drops, the propulsive efficiency will generally improve, and this must be factored in.

Another important factor contributing to maximising the effect of sails is clever weather routing. While most vessels want to avoid heavy weather, sailing vessels need the wind. In addition to the hull's response to waves, weather routing systems for sailing vessels must consider the wind speed and angle of attack.

Coursekeeping and stability of the ship can in some cases limit the size of the sails. The control system of the sails needs to take these effects into account, and, in some cases, it may be beneficial to install larger rudders or additional keels for coursekeeping to balance the unwanted forces from the sails. Also, tolerances for heel, roll and other ship motions and accelerations in response to varying wind loads will limit the rig and sail area. Johanna Tranell found in her master thesis that Flettner rotors can reduce rolling significantly, especially in beam wind and waves [Tranell, 2021 | ↗].

Structural strength can also limit the sail area, especially for the largest vessels.

Very different estimates for the potential energy and emissions saving has been given: from 5% to 25% for a ro/ro vessel in coastal trade [Sea Cargo, Jan 2021 | ↗] to 90% for a trans-Atlantic vehicle carrier [Sjøfartstidningen, Dec 2018 | ↗].

From hybrid model tests of a slender bulk carrier with optimized main dimensions (see chapter 8.2), SINTEF Ocean and NTNU has verified fuel and emissions savings or around 40% at 10 knots speed and near 30% at 13 knots, on an operational basis (EEOI). In a life cycle perspective, the 40% saving drops to 30% when climate effects of shipbuilding is included [Lindstad, Stokke, Alterskjær and Borgen, 2022 | ↗].

NTNU and SINTEF Ocean has analysed and tested sails on large cargo ships to identify the potential of sails. The effect of sails is larger for ships sailing slowly; a study of sails on the route from Trondheim to Rotterdam found that sails could contribute 20% of the propulsion power if the ship sails at 16 kn and as much as 50% if the speed is reduced to 8 kn [Jarle Kramer]. The lower average operating speeds of ships (ref chapter 3.5) make sails more advantageous than before.

Sails can cover 20-50% of the propulsion power if the schedule and ETA (estimated time of arrival) is somewhat flexible, and the vessel has sufficient stability and course-keeping. The saving will of course depend on ship speed, prevailing wind conditions, course and vary with the seasons.

Applications: What ship types can benefit from sails?

Sails are best suited when the ship speed is low and when the schedule is flexible to cater for the hours or days with little wind. A more flexible schedule allows sail to cover a larger portion of the propulsion energy. The Swedish Oceanbird concept by Wallenius Marine, KTH, SSPA and others requires 12 rather than 8 days to cross the Atlantic [Oceanbird | ↗].

Studies at NTNU and SINTEF Ocean indicate that sails can be advantageous for vessels crossing the oceans as well as those sailing shorter distances along the coast. Sails are considered feasible for vessels as different as car carriers, short sea ro/ro vessels and deep-sea bulkers.

Success criteria for sailing vessels	Windy areas	Flexible schedule	Slow speed	Ample deck space	Good stability	Good course keeping

Vessels with ample deck space are best suited for sails, as the installation requires deck space and to avoid interaction effects between the sails, cranes, superstructure and outfitting. Bulk carriers and oil/product/chemical tankers are good candidates, while the installation is more complex on open hatch vessels. General cargo vessels typically carry deck cargo and thus sails will reduce the loadable deck area.

Finally, sails can be retrofitted to existing ships.

Design considerations

There are different types of sails and kites available for smaller and larger vessels, each with their pros and cons and applications. The following factors should be considered when selecting the type of sail [Anders Östman, Jarle Kramer, Anders Alterskjær]:

1. Efficiency: Lift/drag ratio, minimum angle of attack, effect at relatively high ship speeds, drag in head winds.
2. Interaction effects: Wing to wing interaction, interaction between sails and vessel superstructure and outfitting (e.g. cranes)
3. Installation: Deck space requirement and conflict with deck cargo, cargo hold hatches, cranes, deck equipment and helicopter winch area for pilot etc, as applicable.
4. Seakeeping: Vessel response to wind forces and tolerance for heel and roll.
5. Coursekeeping: Rudder(s) must be designed to counter the drift. Other appendages for coursekeeping such as keels may be useful.
6. Impact on propulsion and machinery: Propeller load, propeller efficiency at reduced propeller load, fuel efficiency of machinery at low and varying loads.
7. Operation: Complexity and robustness, wear and tear and maintenance needs, reliability, requirements for crew competence and working hours, conflict with visibility from bridge.
8. Conflict with shoreside infrastructure: Bridges (air draught) and cranes in port.
9. Structural integrity, especially for large sails.
10. Comfort (more relevant for vessels with passengers): Noise, turbulence, obstructed view.

To ensure passage under bridges and avoid conflict with shoreside cranes etc, sails should be foldable or retractable. This is particularly important for sails which cannot weather-vane (put to neutral position).

Water and wind scale differently and achieving Froude number similarity and Reynolds Number similarity simultaneously is impossible. To overcome this, SINTEF Ocean developed Real-time Hybrid Model Testing (ReaTHM®) where hydrodynamic forces are physical and aerodynamic forces are calculated before the two are combined [Sauder and Alterskjær, 2021 | ↗ and ↗].

Tests of a bulk carrier with sails at SINTEF Ocean found that when sails covered a significant portion of the propulsive power, the load on the propeller was reduced. This generally results in better propulsive efficiency. A controllable pitch propeller may be advantageous when the propeller load varies [Sauder and Alterskjær, 2021 | ↗ and ↗].

Model tests of rotor sails on a large bulk carrier

Rotor sails were tested on SINTEF Ocean's open bulk carrier design to quantify the effect on power as well as learn more about the implications of sails on coursekeeping and seakeeping [Sauder and Alterskjær, June 2021 | ↗]. At ship speeds from 10-17 knots and in wind speeds of 5, 10 and 20 m/s, the tests found that four (4) rotor sails could contribute 5-60% of the total thrust. From the polar diagram (in fig. 65), we note that the rotor sails are effective for apparent wind angles from 50-150°.

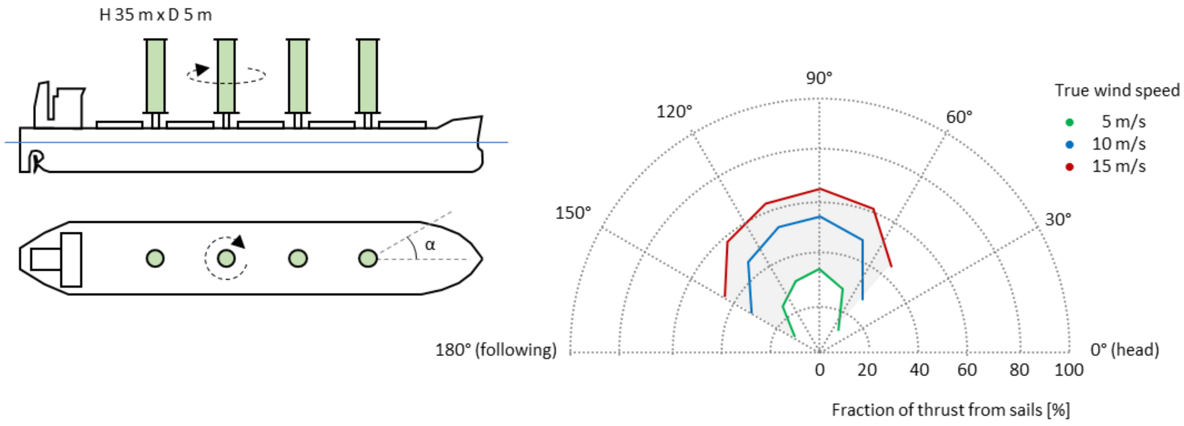


Figure 65: Key findings from hybrid testing of rotor sails for a bulk carrier.

Regarding sea keeping, we observed marginal heel and drift, but the required rudder angles to balance the transverse sail loads) were large; up to 20-25°. Rudders for ocean going merchant vessels are generally made as small as possible and their effect is enhanced by the velocity of the rudder slipstream, which is less pronounced with reduced propeller thrust.

The hydrodynamic resistance due to heel, leeway and rudder is rather limited, except when sailing close-hauled in strong winds.

The case vessel was a supramax with LOA 200 x B 32. X T 11 with a block coefficient of 0.70 based on LWL.

8.6. Machinery configurations

SUMMARY

To reduce emissions from onboard machinery further, the main engine(s), generator set, batteries and power transmission should be considered and optimized as a system rather than individual components.

The advantage or disadvantage of a particular novel setup should be evaluated in realistic conditions by long term simulation.

Discrepancies between theoretical and real reductions in energy use and emissions

An engine with high thermal efficiency is a good start to low fuel consumption. A marine two stroke slow speed diesel engine has a thermal efficiency of close to 0.5 while it is a bit lower for medium speed and high speed four stroke engines. An overview of thermal efficiencies for marine machinery is presented in chapter 9.4.

Multiple operation modes make it less straightforward to optimize the machinery. The power margin needed to overcome waves and wind can be significant. Further, significant market fluctuations result in large variations in speed, and thus in engine load. Finally, the need to reduce both GHG as well as other air pollutants complicates the task as the mechanisms to reduce one may come at the expense of another.

Recalling (from chapter 6.2) that many cargo vessels run at 40-60% engine load on average and noting that specific fuel consumption and emissions are higher at part loads, many vessels would benefit from a smaller main engine and a flexible machinery setup. The below schematic illustrates such an alternative machinery setup (right) with changes from the conventional setup indicated by yellow numbers. The output of the main engine (M/E) is reduced by one cylinder (①) and one genset is removed (②). A battery (③) is fitted to provide back-up power and ensure optimum load on generator sets and the main engine (only short periods of time). A PTO/PTI (④) enables the gensets and battery to contribute with propulsion power when needed and a controllable pitch propeller (⑤) gives more flexibility with regards to optimum engine and propeller speed.

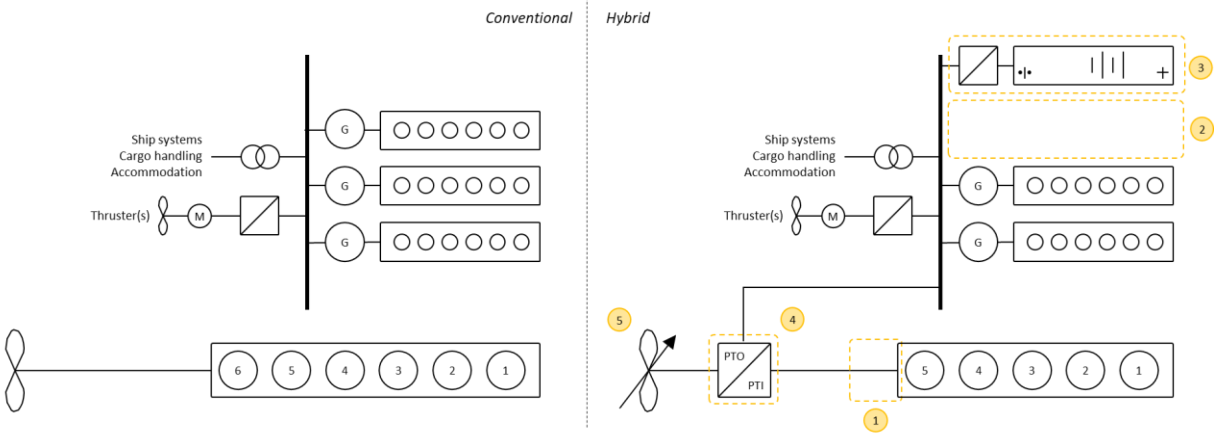


Figure 66:Example of how batteries can replace a generator set and reduce the required main engine output.

The novel configuration reduces installed power while increasing safety as the generator sets can propel the vessel in case of main engine failure (safe return to port). Such a setup will also improve the EEDI, but will the actual fuel consumption and emissions drop as much?

Lindstad and Bø have analysed and compared the two machinery configurations and finds that the hybrid setup will give lower specific fuel consumption for engine loads from around 0.50 to 0.70 [Lindstad and Bø, 2018 | ↗].

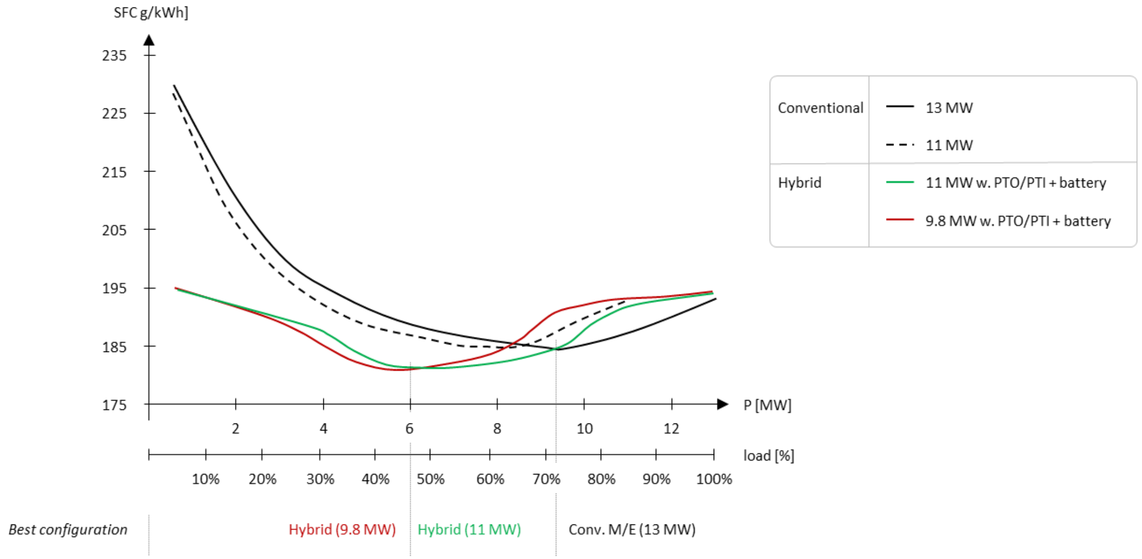


Figure 67: Specific fuel consumption vs engine load for various machinery configurations.

In the most frequently load range (45-55%, ref chapter 6.2), the hybrid machinery configuration can save 3 g/kWh or 0.5 t/d. The fact that the power difference in the above case was positive but marginal, confirms the need for careful calculation and optimization. However, the study also concluded that the setup giving the lowest EEDI does not necessarily give the lowest emissions.

The current EEDI-formula encourages reductions in main engine power while the power of the generator set is not factored in. Shifting power from the main engine to a less efficient generator can give higher fuel consumption and emissions.

The GYMIR simulation tool takes waves and wind into account and ensures that the actual specific fuel consumption and emission factors as well as transmission losses are used to calculated total fuel consumption and emissions. This gives a more realistic picture for the intended operation. The research by Lindstad and Bø shows that hybrid machinery setups can reduce both the design index and the operational index – but that the reduction in GHG emissions is generally less than the reduction in the EEDI score.

Installing a smaller main engine and one diesel generator less will reduce capital cost and maintenance cost and it thus attractive from an economic perspective. Only a detailed analysis of each case can document whether a hybrid machinery setup will give economic and or environmental benefits.

8.7. Hybrid power configurations: Combining engines and batteries on service vessels and cargo ships

SUMMARY

Batteries can be the main power source for small ships with small energy demand. If renewable energy is used to charge the batteries, GHG-emissions are reduced to almost zero.

Batteries can contribute to cut fuel consumption, emissions and cost in many other cases; in ships with fluctuating power demand, complex operating profiles, need for redundancy and immediately available power reserve.

Sizing of the battery pack requires careful analysis and optimization. The actual environmental advantage can be estimated by simulations of operations over long time.

Around 330 ship have batteries installed and plans are made for another 200. 71% of these have batteries in addition to conventional machinery [DNV AFI | ↗]. This confirms that batteries can be advantageous for many vessel types. Let us look at the possible use of batteries onboard ships:

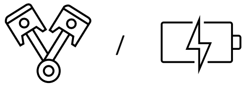
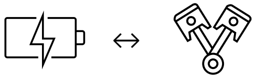
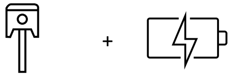
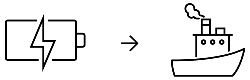
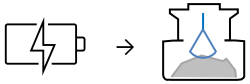
		Battery functionality	*Applications*
1		To power the entire vessel for a short period	Ships sailing through sensitive sea areas where emission free or quiet sailing is required for a short time period.
2		Peak shaving: Minimize specific fuel consumption	Ships with rapidly fluctuating power demand, on the main engine (propulsion) or D/G (ship systems)
3		To reduce installed power	Vessels with low average power demand but in need of a power margin for short periods only.
4		To provide redundancy and power reserve	Vessels with rapidly fluctuating power demand and need for large power margins for safety or convenience.
5		To aid cargo handling and recover kinetic energy	Ships with cranes and elevators: container feeders, general cargo ships, open hatch vessels and construction and supply ships

Table 4: Example of roles a battery can play onboard a vessel.

Case 2 and 3 above also reduce running hours of the engine(s) onboard, which reduces need for maintenance, overhaul and spare parts. Case 3 above gives the same environmental effects as case 2, but the motivation varies and the capacity of the batteries must be dimensioned differently.

Batteries have been combined with diesel engines in rail locomotives, where a fuel saving of 36% has been recorded [International Union of Railways, 2012 | ↗]

Batteries as single short-term energy source (case 1)

Even when batteries cannot power the entire ship for the entire voyage, batteries can allow emission free periods of navigation e.g. in and out of port and in particularly vulnerable waters. Examples include passenger, ropax and small cruise vessels. A modern state of the art explorer cruise vessel can sail up to four hours on batteries [Havila | ↗]

The batteries can be charged in port or by shipboard generators as fits. If charged by onboard generators, the environmental advantage depends on the vessel's machinery, specific fuel consumption and fuel.

Batteries for peak shaving (case 2)

Batteries can cover power fluctuations. This allows the generator set(s) to run at an optimum load with low specific fuel consumption and emission factors. It can also prevent one spare generator to idle nearly without load and thus reduce running hours and maintenance costs and spare parts.

This is known as peak shaving where the battery is charged and drained intermittently as power demand fluctuates.

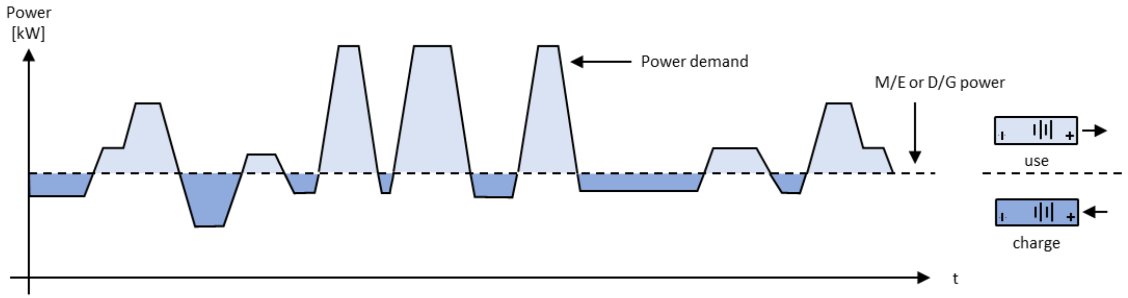


Figure 68: Power flux to/from a battery for a vessel with rapidly varying power demand.

Peak shaving is considered necessary for fuel cells which perform best when load variations are avoided.

Batteries to reduce installed power (case 3)

Recalling that many cargo vessels run at 40-60% engine load on average and noting that specific fuel consumption and emissions are high at part loads (ref chapter 6.2), many vessels can do with a smaller main engine. This will allow the vessel to run the engine at a more favourable (higher) loads and reduce investment costs and number of cylinders to overhaul.

A smaller main engine means smaller power margin for adverse weather. A shaft generator with power take in (PTI) allows the battery to supply additional power, but only for relatively short periods. Generator sets can deliver power if the power shortage continues for longer periods of time. An example case is discussed in chapter 8.6.

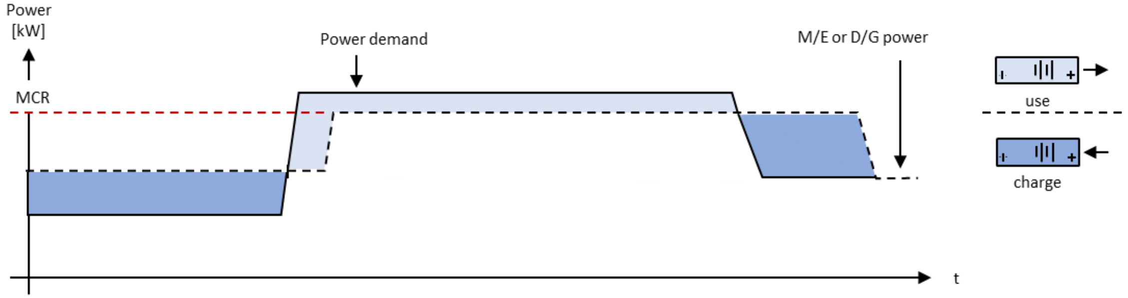


Figure 69: Power flux to/from a battery for a vessel where the main engine power cannot cover all operating modes.

Instant power reserve (case 4)

Some vessels need instant access to a power reserve and keep a generator running at low load or idling for this purpose. A battery pack can be useful to give time to start up a second generator when the power demand increases.

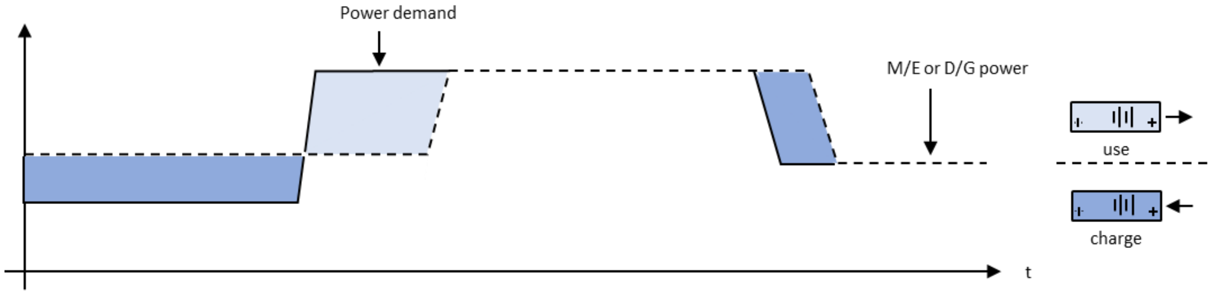


Figure 70: Power flux to/from a battery acting as spinning reserve.

A case study for a cruise vessel found that battery hybridization can improve the energy use of the electric propulsion by a few percent with both AC and DC switchboard, although the potential is greater with DC architecture [Ghimere et al., 2021 | ↗].

Batteries to power and recover energy from cargo handling gear and other intermittent consumers (case 5)

Cranes and other cargo handling gear have high and intermittent power demand which often will require a large or multiple generator sets running at, predominantly, low loads with unfavourable specific fuel consumption and high specific emissions.

Alternatively, a battery system can provide instant power and cover the demand peaks and thus contribute to better generator load with lower specific fuel consumption and emissions. Also, running hours and thus maintenance and spare parts for the generator sets can be reduced.

On top of this, electric winch motors can recover the energy when the crane is lowered and thus charge the battery.

In his M Sc-thesis, Jan Olav Øksnes found that one of two 960 kW generators sets could be put to rest if a 362 kWh battery was installed to work in tandem with one of the generator sets. This could reduce energy use by around 10% and maintenance cost by 50%, due to reduce running hours [Øksnes, 2017 | ↗].

Batteries are likely required to support future engines and fuel cells

In chapter 9 (and chapter 9.4 in particular), we will discuss the need for new or modified engines and fuel cells to use alternative fuels.

Many of these engines and fuel cells will be different from today's diesel engines. Gas engines, for example, respond slowly to power fluctuations and have – as of today – high methane slip at lower engine loads. Batteries can help in these cases.

Fuel cells perform best at stable loads and respond poorly to varying demand. High temperature fuel cells should ideally run continuously and avoid start and stops due to variation in power demand. Fuel cells will use electric power transmission from the fuel cell to the propulsion motor.

Other environmental burdens from hybrid vessels

Electricity in batteries have low transmission and conversion losses. With renewable energy, the GHG- emissions are low.

However, a full life cycle analysis is needed to evaluate the overall environmental impact of batteries on ships. Such an evaluation is important to identify the areas that will suffer from increased use of batteries, so that these impacts can be addressed and minimized.

In her MSc-thesis, Julie Galaan compared the life cycle emissions of an electric ferry with a conventional one. She found that GHG-emissions can be reduced by 89%. But the toxicity impacts except terrestrial ecotoxicity potential are higher for the battery electric alternative [Galaaen, 2020 | ↗].

Batteries require materials that are scarce, such as cobolt and litium. Resource depletion is considered one of the major environmental challenges along with global warming, persistent toxic substances and global warming [Costanza, 2014]

8.8. Policy implications

Ship designs must be evaluated in the expected operating conditions (speed, draught, trim, wave and wind) by the ship owners at the contracting stage and by regulators in rating schemes such as the EEDI, EEXI and CII. Current EEDI and EEXI reflects only calm water performance.

Some safety, port, commercial and other statutory requirements have become an unintended and involuntary barrier to more energy efficient and environmentally friendly vessels. Such barriers and disincentives should be reconsidered to avoid paragraph-vessels without compromising on safety.

Low emission vessels must not be penalized by higher tariffs in ports, channels, locks and fairways. The current system based on gross tonnage must be refined or adjusted to open up for longer and wider vessels if such modifications can give lower emissions.

Long term contracts and mechanisms for sharing risk, cost and profit between ship owners and charterers must be developed to align interests and overcome the current split incentive.

8.9. Sources and further reading

	Link
Bentin, Zastrau, Schlaak, Freye, Elsner and Kotzur (2016): A new routing optimization tool-influence of wind and waves on fuel consumption of ships with and without wind assisted ship propulsion systems.	→
Bertram and Schneekluth (1988): Ship Design for Efficiency and Economy.	→
Ejdfors, Kristian Olof (2019): Use of in-service data to determine the added power of a ship due to fouling.	→
Ghimire, Zadeh, Thorstensen and Pedersen (2021): Data-driven efficiency modeling and analysis of all-electric ship powertrain; A comparison of power system architectures.	→
Galaaen (2020): Comparative life cycle assessment of a diesel electric and a battery electric ferry.	→
Gjølme, Jens Christoffer: (2017) Estimation of speed loss due to current, wind and waves.	→
Leonhardsen, Jon Hovem (2017): Estimation of fuel savings from rapidly reconfigurable bulbous bows.	→
Lindstad and Eskeland (2015): Low carbon maritime transport: How speed, size and slenderness amounts to substantial caital energy substitution.	→
Lindstad, Eskeland, Sandaas and Steen (2016): Revitalization of short sea shipping through slender, simplified and standardized designs.	→
Lindstad, Mørch and Sandaas (2016): Improving cost and fuel efficiency of short sea Ro-Ro vessels through more slender designs – a feasibility study.	→
Lindstad & Sandaas (2016): Emission and fuel reduction for offshore support vessels through hybrid technology.	→
Lindstad & Bø (2018): Potential power setups, fuels and hull designs capable of satisfying future EEDI requirements.	→
Lindstad, Borgen and Sandaas (2018): Real performance in seaways and its impact on ship design.	→
Lindstad, Borgen and Sandaas (2019): Length and hull shape importance to reach IMO's GHG target.	→
Lindstad, Alterskjær, Sandaas, Solheim, Vigsnes (2017): Open Hatch Carriers: Future Vessel Designs & Operations.	→
Lindstad, Stokke, Alterskjær and Borgen (2022): Ship of the future – A slender dry-bulker with wind assisted propulsion.	→

LR (2020): Flettner rotor savings calculator (fuel and emissions savings calculator). →

Magnussen, Anna Karina (2017): Rational calculation of sea margin. →

Ruhl, Mathis (2019): Wing types efficiency →

Sauder (June 2021): Hydrodynamic testing of wind-assisted cargo ships →

Sauder and Alterskjær (30 June 2021): Hydrodynamic testing of wind-assisted cargo ships using a cyber-physical empirical method. →

Tranell, Johanna(2021): Seakeeping capabilities of sailing cruise and passenger vessels. →

Utby, Håkon (2016): Hydrodynamic optimization of bulk and tank ship hulls. →

Photo: BW LPG
LPG-carrier with LPG fuel tanks on deck

9. ALTERNATIVE FUELS

SUMMARY

Alternative fuels include fossil gases (LNG and LPG) methanol, biofuels (liquid and gaseous), hydrogen fuels (hydrogen and ammonia) and synthetic fuels also known as e-fuels.

The GHG effect of most of the new fuels will be determined by their production rather than their use. They should therefore be evaluated by their well to wake emissions (WTW) rather than tank to wake emissions.

We consider any fuel contributing to lower emissions than MGO to be a «low emission fuel» while «zero emission fuels» should reduce GHG by more than 85%. The criteria are not set in stone, and other definitions and criteria are used by others.

In the search for lower emissions, we must still evaluate all alternative fuels on other important criteria such as sustainability, possibilities to arrange them onboard, practicalities during operations and safety.

When energy demand has been reduced to a minimum, the energy needed should be renewable and have as low footprint as possible and be sustainable in every way. Clean energy is and will remain scarce (ref chapter 9.1), low energy use in production, refining and supply is important, together with high thermal efficiency in engines and fuel cells onboard.

As energy demand cannot be brought down to zero, some alternative fuels will be required to meet full decarbonization. For some cases, depending on the technical and operational measures available, alternative fuels may even be required to meet 2030-targets. In this section we will review the various energy carriers, or fuels, of interest for ships, and start with an overview of possible alternative fuels for maritime applications:

Terminology: Low, zero and climate negative fuels

The terms low and zero emission technology are frequently used, although there are no clear definitions and very likely different views on the qualifying criteria and thresholds. In the below illustration, we indicate the GHG-effect of the various alternative maritime fuels relative to MGO. The footprint of some fuels depends on the pathway and for biomethane, biodiesel, biomethanol and LNG we indicate a range, depending on the raw material, the production process and the logistics.

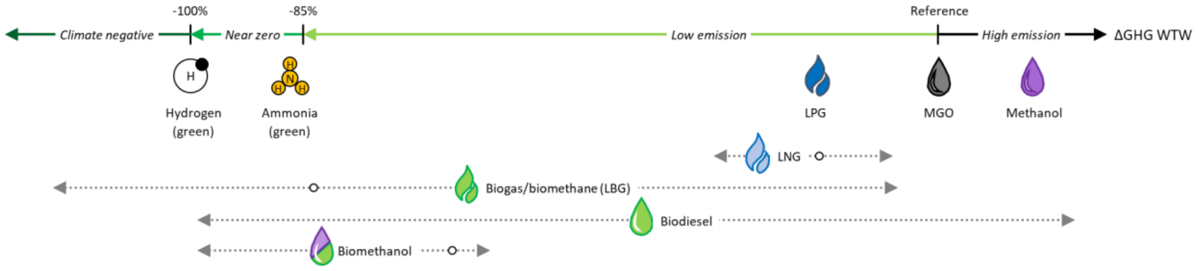


Figure 71: Overview and classification of alternative fuels.

No fuels have zero emissions, but how close to zero should they be to qualify as climate neutral? We suggest the above definitions and threshold for near zero at 85% below MGO. Climate negative fuels can cut emissions more than 100% (see chapter 9.2 and 9.11 on biogas).

Please observe that there are many different views on the terms low and zero emissions and no universally accepted definitions. Some are strict, some are pragmatic, and the interpretation will likely evolve with time. A lenient interpretation will lead to accusations of greenwashing, while a too strict interpretation may prevent support and interest in meaningful stepwise progress.

The table on the following page gives an overview of the various current and future maritime fuels with some key characteristic. Note that all fuels have their pros and cons and that the fuels that we commonly consider to be «green» will only be green provided that some key prerequisites are fulfilled. Note that *major advantages* and *major challenges* in the following table pertain to the climate aspect only; advantages and challenges concerning other environmental aspects as well as safety, handling and practical matters are note addressed later.

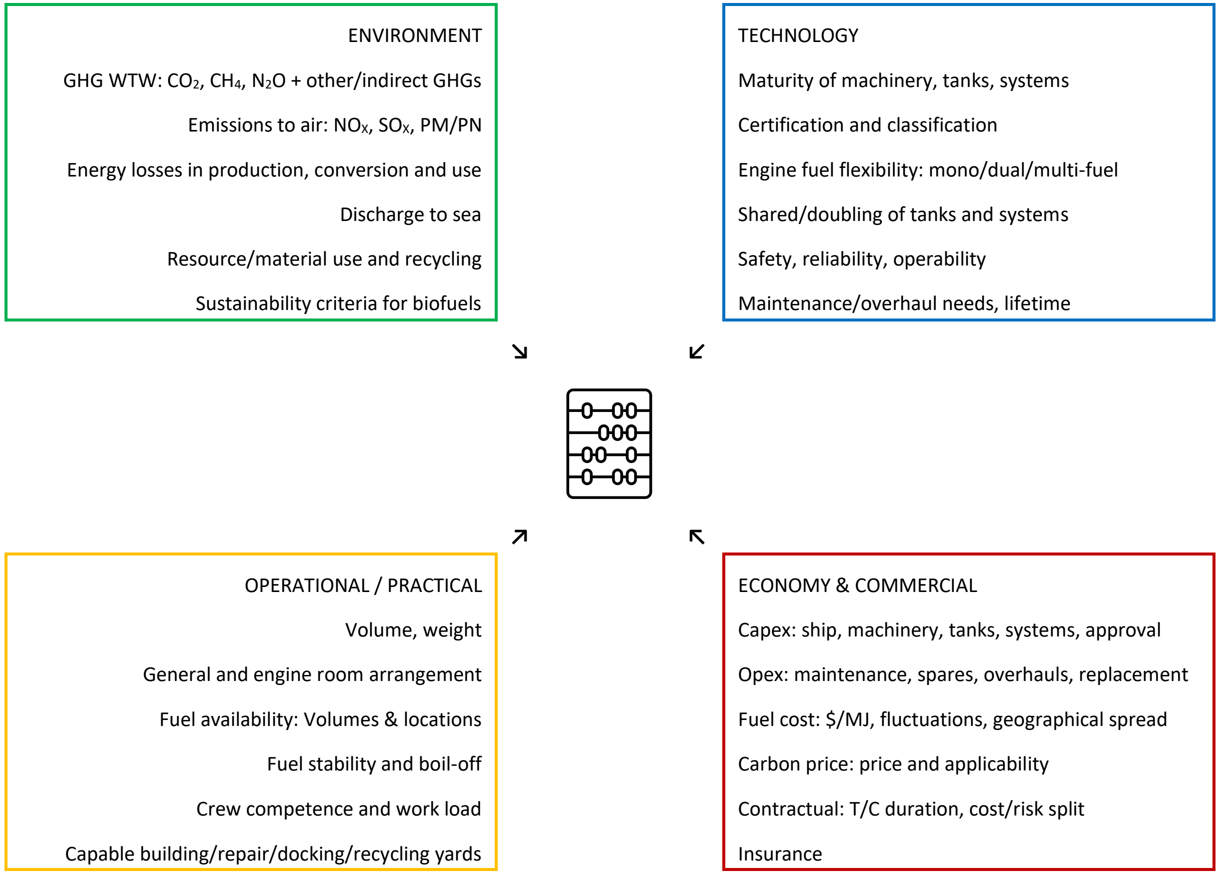
	Fossil oil fuels	*Fossil gas fuels*	*Biofuels*	*Hydrogen fuels*	*Synthetic fuels*
Variants	Heavy fuel oil (HFO) Low sulphur fuel oil (LSFO) Marine diesel oil (MDO) Marine gas oil (MGO) Methanol (CH_3OH)	LNG Ethane LPG	Biodiesel e.g. HVO, FAME. Biogas Biomethane (LBG) Biomethanol Bioethanol	Hydrogen (H_2) Ammonia (NH_3)	E-diesel E-methanol E-LNG E-LPG Dimethylether (DME) (CH_3-O-CH_3)
Production	Extracted from fossil sources and refined into fuel quality.	Extracted from fossil sources and refined into fuel quality.	Produced from sustainable, biological raw materials, wastes or biproducts.	Produced from natural gas or coal with CCS or electrolysis with renewable electricity or by pyrolysis.	Constructed from hydrogen and carbon sequestered from the air (DAC).
GHG WTW	High	Ca16% below MGO, but up to 30% possible if methane slip is eliminated.	Low, zero or climate negative.	Depends on the production; can give very high (45-65% above MGO) and near zero GHG.	Depends on the production.
Prerequisites for low/zero GHG WTW emissions	Onboard carbon capture (OCCS)	Elimination of methane slip in production, transport as well as combustion.	Sustainable biomass with no negative effect from direct and indirect land use change.	Green H_2 and NH_3: climate neutral electricity. Blue H_2 and NH_3: CCS.	Climate neutral electricity. Direct air capture (DAC).
Major advantage	No disruption.	Clean air. Available worldwide now. Stepping stone to biomethane and hydrogen.	Climate negative at best. Wastes as raw material (circular economy). Wide range of raw materials makes biofuel production possible in many locations.	H_2: Completely emission free TTW. Ammonia: Requires less storage than hydrogen (but more than MGO and LNG).	Can be used with existing machinery and systems.
Major challenge	High GHG emissions. NO_X, SO_X, PM and black carbon.	Methane slip (from LNG only); in production, distribution and combustion. Moderate GHG-effect, must therefore be combined with greener fuels.	Availability of sufficient volumes of sustainable raw materials. Indirect land use change (ILUC). Alternative use of crops for food. Complex supply chains.	High energy use in production and therefore low thermal efficiency overall. Ammonia *may* emit some N_2O. Storage and handling.	Very high energy use in production and therefore very low thermal efficiency overall.
Uptake (2018)	HFO: 64%. MGO 32% 	LNG 4%. LPG: very minor. 	Piloting. Miniscule volumes. 	Piloting. Grey variants only. 	N/A 

Table 5: Key characteristics of alternative fuels

Evaluation criteria for alternative fuels

The analysis of alternative fuels must extend beyond the environmental impact and the economy and should include most of the following criteria.

The below list is sorted alphabetically as the importance of each criteria will vary between users, countries and change over time as technology and the world develops. Note that the list is non-exhaustive, and that the relative importance of each criteria will vary from case to case.



ENVIRONMENT
GHG WTW: CO_2, CH_4, N_2O + other/indirect GHGs
Emissions to air: NO_X, SO_X, PM/PN
Energy losses in production, conversion and use
Discharge to sea
Resource/material use and recycling
Sustainability criteria for biofuels

TECHNOLOGY
Maturity of machinery, tanks, systems
Certification and classification
Engine fuel flexibility: mono/dual/multi-fuel
Shared/doubling of tanks and systems
Safety, reliability, operability
Maintenance/overhaul needs, lifetime

OPERATIONAL / PRACTICAL
Volume, weight
General and engine room arrangement
Fuel availability: Volumes & locations
Fuel stability and boil-off
Crew competence and work load
Capable building/repair/docking/recycling yards

ECONOMY & COMMERCIAL
Capex: ship, machinery, tanks, systems, approval
Opex: maintenance, spares, overhauls, replacement
Fuel cost: $/MJ, fluctuations, geographical spread
Carbon price: price and applicability
Contractual: T/C duration, cost/risk split
Insurance

Figure 72: Evaluation criteria for alternative fuels

9.1. Global primary energy mix and the share of renewable energy

SUMMARY

Sustainable energy with low footprint is a scarce resource and will likely be so for the next few decades. The share of renewables in primary energy has bare increased in the last 50 years.

This puts pressure on the use of renewable and low carbon energy.

Renewable energy must be put to use where it can cut emissions most effectively.

Energy use and conversion losses must be minimized, onboard vessels and in the production and supply chain.

Energy is a finite resource, and some energy is lost when energy is converted from one form to another. In world with growing demand for energy where the majority is covered by fossil sources, we must use whatever clean energy we have carefully.

Over the last five decades, primary energy supply has grown by around 2% annually, from 230 EJ in 1971 to 606 EJ in 2019.

The share of renewable energy is more or less constant: around 13-14% according to the IEA [IEA, 2021| ↗]. BP puts the share of renewable at 11% for 2019 [Our World in Data | ↗]. While the total energy demand has tripled, the renewable share has remained the same for the last 50 years.

Looking ahead, two scenarios by IEA and Shell suggests a renewable share of 42% and 67% in 2050 [IEA | ↗], [Shell sky | ↗]. Note that scenarios are explorations of what is required to reach certain goals, in this case global warming well below 2°C, not a forecast of the most likely future.

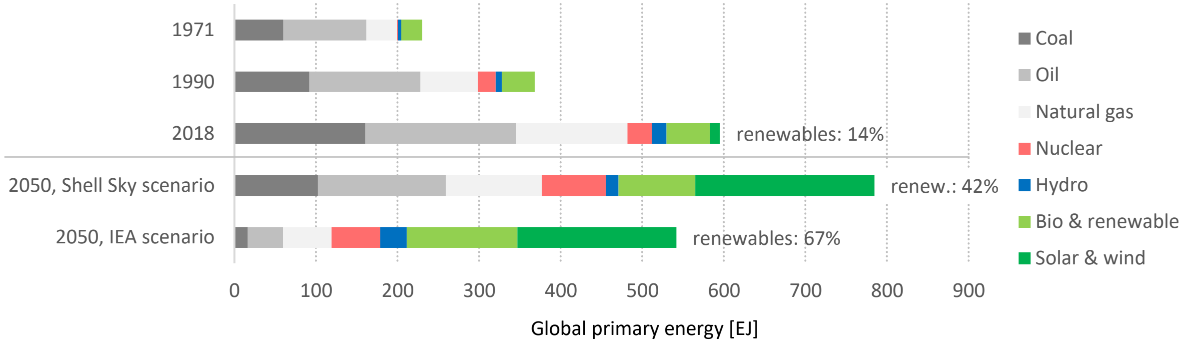


Figure 73:: Primary energy sources in 1971, 1990 and 2018 [IEA, 2021| ↗] and according to two scenarios for realizing net zero emissions by 2050 (IEA) and 2070 (Shell Sky).

The share of renewables is higher if we focus on electricity production only; 29% globally [IEA | ↗], 39% in the EU [Eurostat | ↗], 20% in the US [EIA | ↗] and 97% in Norway [NVE | ↗]. While Norway is blessed with hydropower for electricity generation, the share of renewables still drop to 50% when all energy consumption is accounted for [Energi Norge, 2022 | ↗]

The conclusion must be that renewable energy is scarce and will likely remain so for the foreseeable future. This requires all sectors to minimize energy demand and minimize conversion losses. For shipping specifically, the scarcity of renewable energy puts a big question mark on the energy intensive production of hydrogen, ammonia and synthetic fuels [Lindstad et al., 2021 | ↗].

As renewable energy is and will remain scarce, whatever clean energy we have must be used wisely, i.e. minimize demand and minimize losses. Renewable energy should be allocated to the sectors where it can cut emissions most effectively.

9.2. Emissions and energy efficiency well to wake

SUMMARY

Emissions from alternative fuels should be evaluated on their emissions and energy use well to wake (WTW), as argued in chapter 6.5.

LNG typically gives 6-16% lower GHG depending on the methane slip of the engine, but has the potential to cut GHG by up to 30% if the methane slip is eliminated and the conditions for recovering and producing LNG are good.

LPG does not suffer from methane slip and gives 17% lower GHG. LPG is one of the few fuels with higher energy efficiency than MGO; 45% of the energy required is delivered to the propeller.

A number of different biogas and biomethane variants exist with GHG savings from 20 to 200%. Biomethane can be blended with LNG to give the required saving.

Hydrogen and ammonia produced from natural gas without CCS increase GHG (by 66 and 45% respectively). Produced from electrolysis, these fuels will be as green as the electricity used in the process. The energy loss in production is high and only 20-26% of the energy required is delivered to the propeller.

Synthetic fuels consume 2.5-3 times the energy of MGO but can give zero GHG if only renewable electricity is used.

LNG, LPG and methanol nearly eliminates SO_X and particles. NO_X emissions are determined by the engine type and abatements systems used. Hydrogen produces only water vapour while ammonia will likely emit some N_2O.

Some fuels can give zero tailpipe emissions while the production will require lots of energy and give significant greenhouse gases. Conversely, biofuels are climate negative in the production phase. Therefore, emissions must be evaluated in a life cycle perspective (ref also chapter 6.5). Also, the high energy demand to produce new fuels such as hydrogen, ammonia and synthetic fuels means that the energy losses well to tank must be monitored and evaluated.

Referring to the diagrams below, the following conclusions can be reached. Note that the reference line and basis for comparison is MGO on a two stroke slow speed main engine. We assume the same thermal efficiency η 0.50 for all cases.

The emission factors WTT and TTW are taken primarily from the article *Assessment of Alternative Fuels and Engine Technologies to Reduce GHG* by Lindstad, Gamlem; Rialland and Valland [↗]. Supplementary values for blue hydrogen and ammonia from a study from LR and UMAS, Techno-economic study of zero-carbon fuels (2020) [↗] and values for HVO and FAME from EU JEC v4.

Oil fuels

Very low sulphur residual fuel (VSLFO or VLSHFO) has marginally higher emissions well to wake (+1%) while high sulphur residual oil combined with a scrubber gives marginally lower (-3%) emissions. In terms of energy use, high sulphur HFO requires less energy at the refinery.

E-diesel can be used without any changes to the infrastructure on shore or tanks or systems onboard. It can replace fossil diesel already today. With E-diesel, the shipping industry could become climate neutral – provided that the synthetic fuel is produced with renewable electricity. However, the energy spent in production is 3 times higher for E-diesel and only 14% of the energy used becomes available on the propeller, compared to 42% for MGO.

Methanol

The higher emissions in production (well to tank) cancels out the lower emissions onboard (tank to wake) and gives methanol from natural gas higher overall emissions; about 12% above MGO. Producing methanol from organic material cuts emissions by 65% compared to MGO. This saving is on level with other biofuels such as biomethane and bioethanol; all in the range from 60-85%. The footprint of biomethanol varies with the raw material and process and can be higher, as indicated by diagram 75 and 76.

Methanol from natural gas requires more energy to produce than MGO and only 31% of the energy required is delivered to the propeller compared to 42% for MGO. For synthetic methanol, the ratio is only 15% and thus around 1/3 of MGO.

LNG

LNG contains less carbon relative than liquid oils and thus gives about 25% less CO2, but this is partly offset by uncombusted methane (CH_4) known as methane slip. All told, LNG reduces GHG by 6-16% depending on the methane slip of the engine but has the potential to reduce GHG emissions by as much as 30% well to wake if methane slip is eliminated and the conditions for recovering and producing LNG are good. High pressure two stroke engines have minimal methane slip. On low pressure two and four stroke engines, the CO_2 cut is partly offset by high methane slip and the total GHG saving well to wake ends up at 6%.

The production emissions also suffer from methane leakages. E-LNG will have near zero GHG emissions, but a lot of the energy will be lost in the production; only 15% will be delivered to the propeller, compared to 42% for MGO.

LNG does not contain sulphur and thus eliminates SO_X. NO_X-formation depends on the engine. Low pressure engines will produce very little NO_X, well below the Tier III-limit, while high pressure engines will require EGR or SCR to meet Tier III.

LPG

LPG cuts GHG by 17% well to wake. LPG has lower losses from well to wake and thus makes better use of the energy; 45% of the energy is delivered to the propeller. LPG is thus a very good combination of low GHG and low energy losses well to wake.

Similar to LNG, LPG does not contain sulphur and thus eliminates SO_X while NO_X emissions depend on the engine. Low pressure engines will produce very little NO_X, well below the Tier III-limit, while high pressure engines will require EGR or SCR to meet Tier III.

Hydrogen fuels

Hydrogen can be produced from natural gas and coal without and with carbon capture and storage and by electrolysis of water. Ammonia is based on hydrogen. The footprint varies significantly based on conditions for production. Producing hydrogen and ammonia from natural gas increases emissions 45-65% compared to MGO. These production emissions can be captured and stored (CCS) to give near zero footprint; this option is not included in Lindstad's analysis.

CCS is considered a vital technology in most roadmaps to net zero emissions by 2050, yet the development is slow. In 2021, 40 million tonnes were captured from 27 facilities. Around 135 are in the pipeline, but 2,500 plants with 1.5 Mtpa capacity each is required to reach the 2°C target of the Paris Agreement [Global CCS Institute, 2021 and 2018 | ↗]. Shell's Sky scenario requires the construction of 10,000 large CCS plants by 2070 [Shell sky and Shell Energy Transition 2018 | ↗].

The footprint using electrolysis depends entirely on the electricity consumed. With climate neutral electricity, hydrogen can give zero GHG while ammonia will emit some N_2O and reduce GHG by nearly 90% well to wake. For practical purposes a 90% reduction in GHG can be considered very close to climate neutral.

Ammonia is a hydrogen carrier, giving lower emissions than liquid hydrogen but will likely emit some N_2O when combusted.

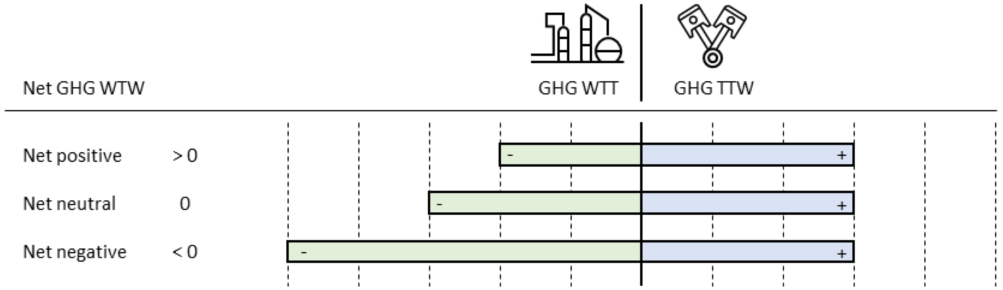
Hydrogen and ammonia can be produced and used with almost no GHG emissions, but this depends on either abundance of climate neutral electricity or very effective carbon capture and storage. None of these preconditions are currently met.

Even if renewable energy is available and the emissions are zero, producing hydrogen and ammonia by electrolysis is very energy intensive. Only 20% to 26% of the energy used along the value chain and onboard is delivered to the propeller vs 42% for MGO.

Almost the entire current hydrogen and ammonia production has very high emissions. Analysis and roadmaps indicate that just decarbonizing the current production will be a massive undertaking. Roadmaps and analysis of the fertilizer industry, the major hydrogen consumer, lay out scenarios with 10% of production from renewables by 2030 and 19% emission cuts [Fertilizers Europe, Feeding life, 2018 | ↗], [Dechema, 2022 | ↗].

Biomethane and liquid biofuel

Biofuels reduce GHG emissions because the organic material used to produce the fuel absorb CO_2 or avoid methane emissions from being released to the atmosphere. The total well to wake footprint of biofuels is the sum of the negative emissions in production and the normal emissions in combustion. When the prevented emissions exceed those from the combustion, the net GHG will be negative, and we label such fuels net negative or climate negative.



Biomethane for transport applications can be made from a range of raw materials. The net GHG emissions thus vary considerably. Standard values are given by the EU Renewable Energy Directive (EU RED II), IEA and IRENA inter alia. In political contexts and some regulations biofuels are simply defined as climate neutral for simplicity.

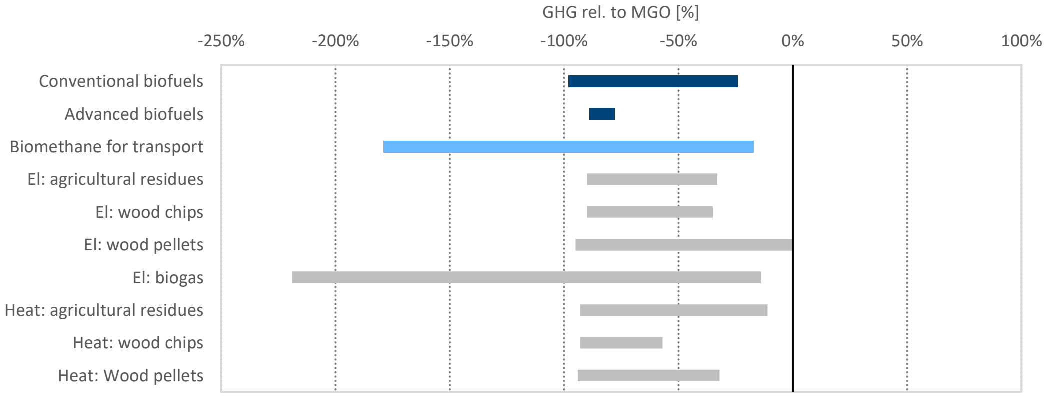


Figure 74: Net GHG relative to MGO for biofuels (source: IEA Technology Roadmap, 2017, table 7, page 51)

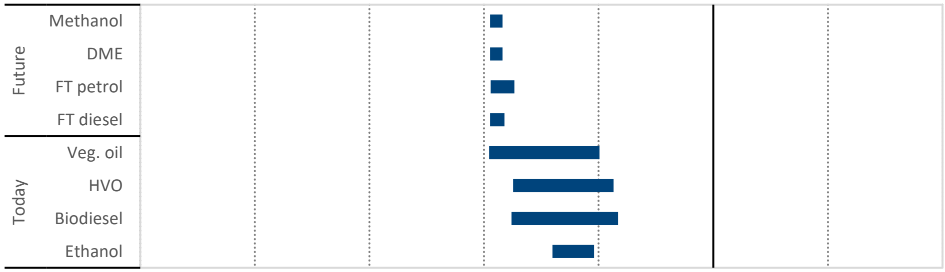


Figure 75: Net GHG relative to MGO for <u>*liquid*</u> *biofuels (source: EU RED II, 2018, annex V)*

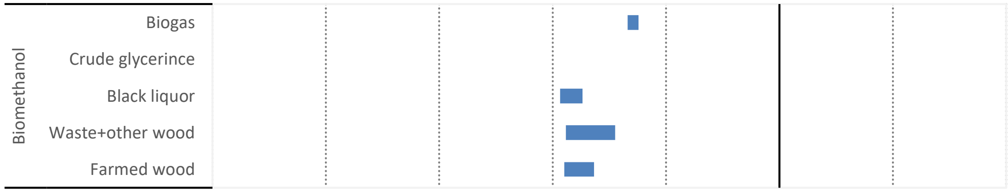


Figure 76: Net GHG rel. to MGO for <u>*biomethanol*</u> *(source: IRENA Innovation Outlook Renewable Methanol, 2021, page 59-64).*

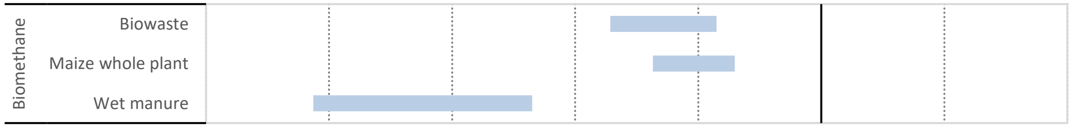


Figure 77: Net GHG relative to MGO for <u>*compressed biomethane*</u> *for transport (source: EU RED II, 2018, Annex VI)*

Due to the wide variation, the uncertainty and complexity of the footprint calculations and to stimulate the use of biofuels, they are often simply *defined* as climate neutral. Rather than setting the net GHG emission factor to zero, all biofuels should be evaluated based on the details of the raw material, production process and supply chain. Also, the combustion emissions should be measured to include possible methane slip from biomethane.

EU's Renewable Energy Directive requires the net GHG reduction to exceed 65% for biofuels and biomethane for the transport sector [EU RED II, article 29.10 | ↗]. Moreover, all biofuels must meet a range of sustainability criteria which are detailed in the same directive to avoid adverse climate effects from land use change, deforestation and competition with food production.

The biomethane options analysed by Lindstad et al. give a GHG saving of 70-80% well to wake. The liquid biofuel options analysed find good effect of biofuels based on maize (-85%) and barley (-58%) but negative effect of rapeseed (+28%) and palm oil (+239%!).

Emission factors WTT: From g/MJ to g/kWh

Well to tank emissions are generally given in g CO_2-eq./MJ i.e. based on the energy content of the fuel while tank to wake factors are calculated in g CO_2-eq./kWh. The latter takes the thermal efficiency of the engine or fuel cell into account and is thus case-specific and pertains to a certain machinery and system.

To calculate the total emission factor well to wake we must take the efficiency of the machinery onboard into account:

$$\frac{g\ CO_2\text{-}eq.}{kWh} = \frac{g\ CO_2\text{-}eq.}{MJ} \cdot \frac{1}{\eta} \cdot \frac{3600}{1000} = 14.4\ g/MJ \cdot \frac{1}{0.500} \cdot \frac{3600}{1000} = 104\ g/kWh$$

For MGO with 14.4 g CO2-eq./MJ and a machinery with efficiency 0.50, the emission factor WTT becomes 104 g/kWh. In our calculations of emission factors, we have assumed η 0.50 for all fuel options.s

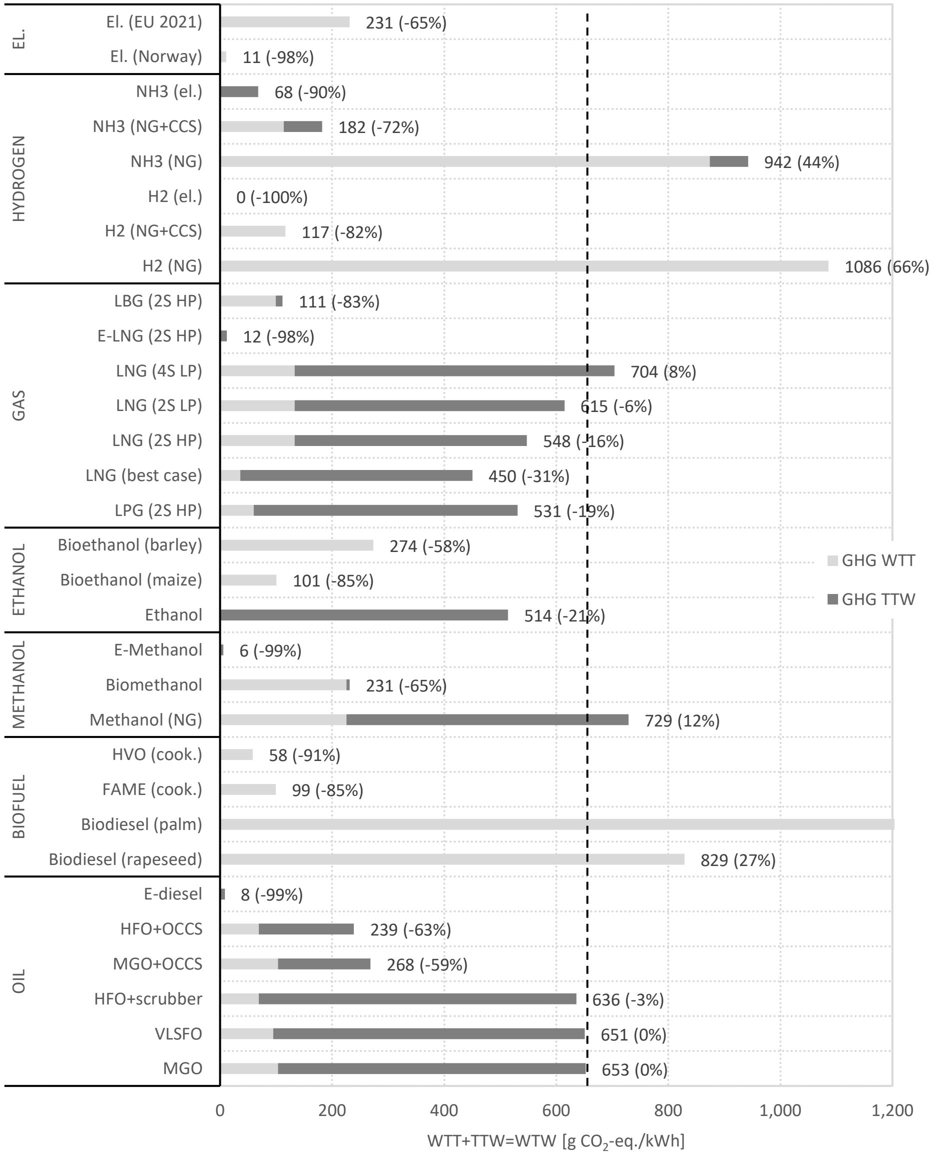


Figure 78: total GHG WTW. Difference from MGO indicated in brackets.

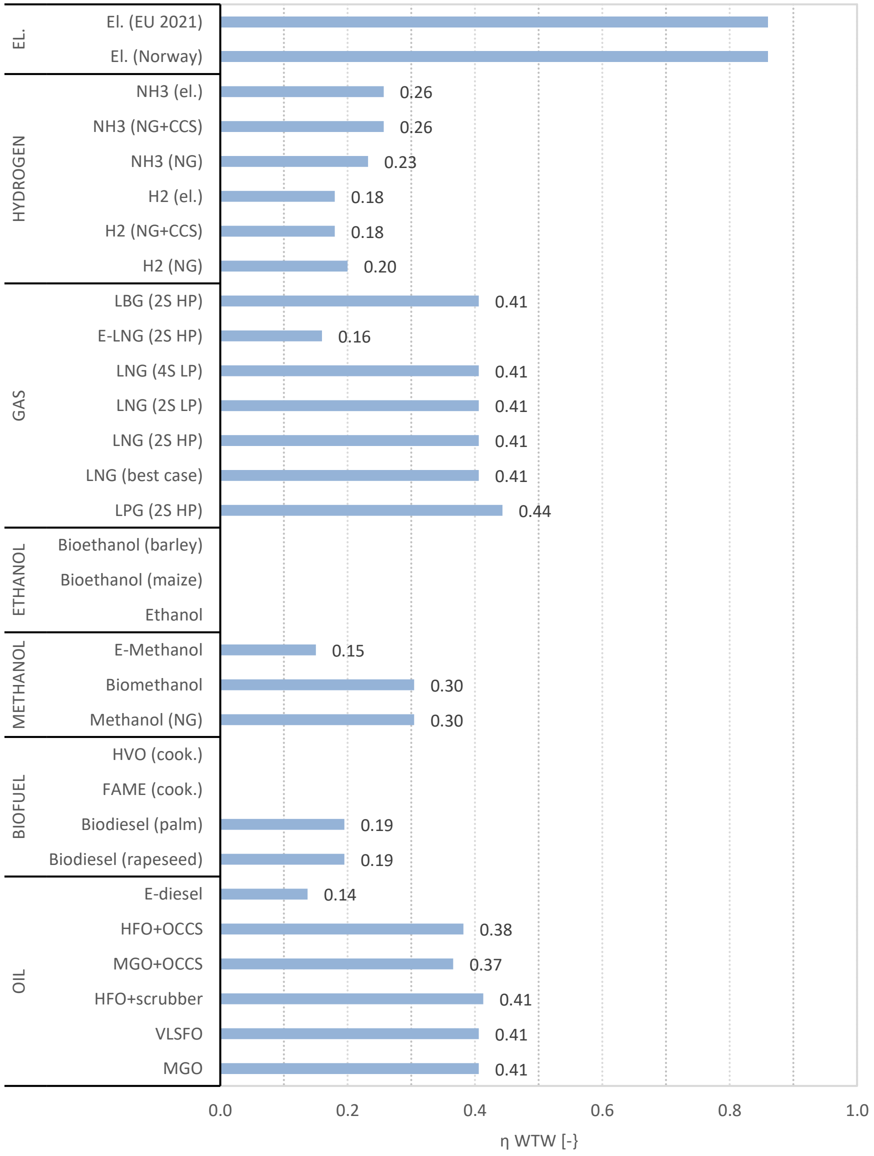


Figure 79: energy efficiency well to wake, i.e. conversion losses in production, supply and combustion.

9.3. Energy density and tank space requirements

SUMMARY

All alternative fuels occupy more space onboard. High speed vessels are sensitive to increased weights, while loss of cargo or passenger space is a concern for most ships.

Fuel consumption must therefore be minimized and more frequent bunkerings will likely be required to avoid reducing cargo capacity too much.

Main dimension restrictions must be challenged to allow lengthening, preferably, of the hull to accommodate the new fuels onboard. Bulky ships with high added resistance in real seas should be avoided.

All alternative fuels contain less energy per volume than liquid fuel oils, but hydrogen and LNG and LPG contain more energy per kg. Volume matters more than weight for most ship types, except high-speed vessels such as lightweight ferries and naval ships.

The transition to new fuels means loss of cargo space or larger main dimensions, if allowed by the ports, locks, canals, straits (ref chapter 8.2). Alternatively, the endurance will be reduced, or more frequent bunkering must be arranged for. Under all circumstances, this explains the need for minimizing energy demand.

The below diagram (fig. 80) is based on the energy content (LCV, MJ/kg) and density (ρ, kg/m³) of the fuels and the thermal efficiency (η) of the machinery. Many of the alternative fuels, notably LNG, LPG, ammonia and hydrogen, require sophisticated and spacious tank arrangements. All four gases can be carried in cylindrical pressure vessels, which occupy more space than prismatic tanks. The lost space around the tanks for insulation, inspection, piping, safety distances, access hatches etc comes on top of the below figures.

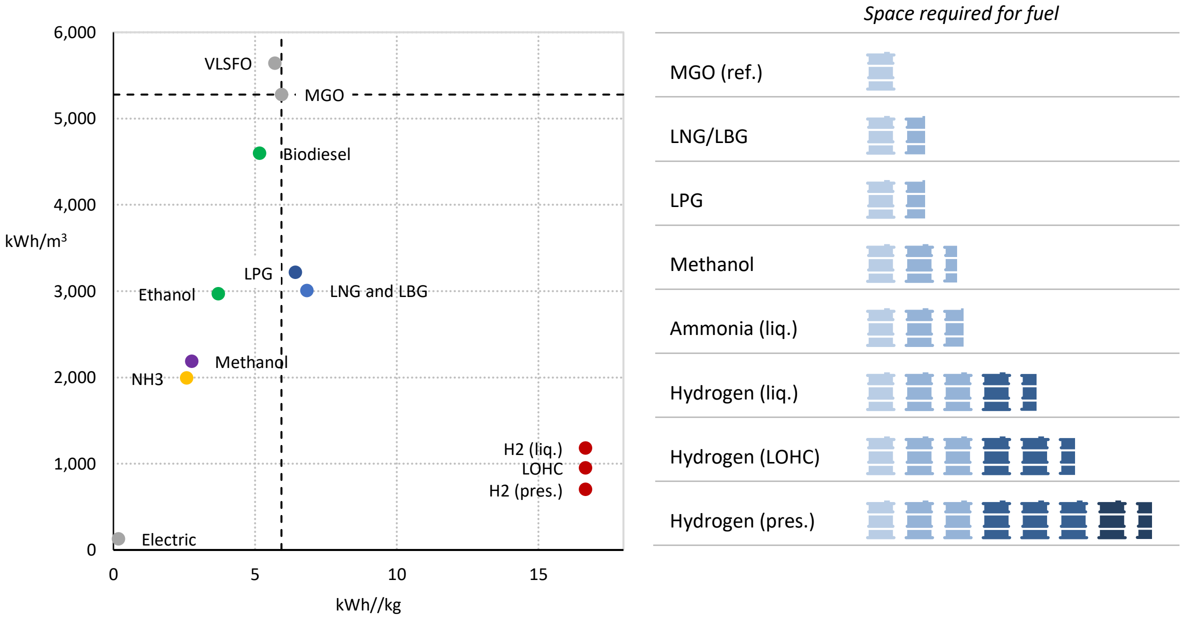


Figure 80: Energy density (volumetric and gravimetric) excluding effect of storage tank.

As a consequence of this, the transition to alternative fuels will require a larger vessel or reduce the cargo capacity unless shorter endurance and more or more frequent bunkerings can be accepted. Some vessels can carry fuel tanks on the weather deck if stability and the hull structure permits this.

Reference vessel on fossil fuels

Longer hull

Reduced cargo capacity

Figure 81: effect of new fuels with lower energy density.

Storage of oil fuels is quite straightforward with low requirements to the tank construction as well as handling procedures. Shipyards and crew alike have experience with building and handling storage of LNG. LPG, methanol and ammonia are primarily known to shipyards and deck officers as cargoes, and this can be a valuable basis for handling them as fuels as well. Hydrogen is likely the most complicated and unknown fuel.

9.4. Power conversion (i.e. engines and fuel cells) for alternative fuels

SUMMARY

Flexibility is key and the engine makers are working to develop multifuel engines.

To limit the complexity and optimise the combustion for each particular fuel, engines will likely be developed for dual or triple fuels only.

Large slow speed two stroke engines can already burn LNG, LPG, methanol and is developed further to take ammonia by 2024-25.

Medium speed four stroke engines are common for LNG and have been converted to burn methanol. Research is ongoing to take ammonia and hydrogen by 2022-25.

With the ongoing R&D, it is likely that the machinery side will be ready long before any fuel production of scale is on track.

Current medium speed engines from Wärtsilä can indeed blend in up to 25% hydrogen today. Hydrogen is not a fuel for the future; it is possible today!

In 2021, distillate and residual oil fuels dominate, some ships run on LNG and even fewer on LPG and methanol. Very minor volumes of biofuel and biogas are mixed in, in various pilot projects to check compatibility. We see continued interest in LNG for new vessels, increasing interest in LPG and sporadic interest in biogas, though few projects have been realized. The first projects exploring ammonia have been announced and a handful of hydrogen vessels are under construction.

In this landscape, until clear shipowner preferences emerge, policies are agreed, fuel prices can be forecasted with reliability and the fuel production facilities are indeed constructed, we believe that flexibility is the key. Flexibility means possibility to burn two or more fuels and possibility to convert the engine and vessel with minimal or reasonable work and cost.

The below diagrams illustrate compatibility of fuels and machinery. Green (🟢) signals commercially available, orange (🟠) under development, red (🔴) impossible (technically/commercially/practically).

	Two stroke engine	Four stroke engine	Fuel cell
MGO	🟢 3-80 MW. Slow speed (60-160 rpm). Three engine designs, numerous engine builders.	🟢 Up to 20 MW. Medium and high speed. Multiple makers.	🔴
Biofuel (liq.)			
Methanol	🟢 ME-LGIM 8-82 MW. 🟠 2025: low pres. Otto version.	🟠 2015: One 4S converted. 🟢 2022: W32 available, 3-9 MW 🟢 2023: ABC DZD up to 3.5 MW	
LNG	🟢 HP Diesel + LP Otto. 3-80 MW. Dual fuel	🟢 LP Otto cycle DF engine. LP LBSI pure gas engine. Up to 20 MW.	🟠
Biomethane (LBG)			
LPG	🟢 Available since 2018. 8-22 MWs		
Ammonia	🟠 2024/25: first engine. 2026: J-Eng plans 2S.	🟠 2022: Wärtsilä. 2024: J-Eng plans 4S.	🟢 SOFC, small scale (<1 MW). 🟠 Multifuel SOFC by 2025+.
Hydrogen	🟠 N/A	🟠 25% H_2-blend ok since 2015, larger blends likely ok. Research on pure H_2-engines with targeted launch 2025.	🟢 PEM, small scale (<1 MW). 🟠 Plans for 3MW by 2023.

Table 6: Engines and fuel cells available and under development for alternative fuels.

Gas turbines may also be relevant for some special marine applications. Gas turbines can burn 75% hydrogen today.

Internal combustion engines (ICE)

The diesel engine is the most important marine machinery today and will, pending developments under way today, be modified to take all fuels. While two stroke engines dominate in terms of horsepower, four stroke engines dominate measured by number of engines.

Variants of the high pressure two stroke slow speed engine are already in operation on LNG, LPG, methanol and ethane. A variant for ammonia is under development. We expect that the two stroke engine will be available for all fuels except hydrogen within few years and that the range of dual fuel engines will be extended in response to demand.

The four stroke engine is also suitable for most fuels and many engines builders have already developed engine variants for methanol and hydrogen and is working to develop engines for ammonia as well. In fact, some dual fuel medium speed four stroke gas engines have been able to burn up to 25% hydrogen for many years already. DF and even pure hydrogen engines are fully developed and commercially available in 2023. When running majorly on hydrogen, a combustion engine must likely be derated to limit temperatures and pressure.

Hydrogen is generally considered a fuel of the future, yet, in fact, there are multiple engine and fuel cell options available today. Some gas engines have been able to burn up to 25% hydrogen for many years already and pure hydrogen engines are commercially available in 2023.

The thermal efficiency (η) of internal combustion engines is around 0.50 for slow speed, two stroke engines, 0.40-0.50 for medium speed engines and down to around 0.40 for smaller versions with short stroke and higher speed (1,000-2,000 rpm), as indicated on the diagram below (fig. 82). Efficiencies at testbed conditions form an upper boundary of what can be expected. The thermal efficiency of future engines for alternative fuels are based on dialogue with makers and uncertain at the time of writing.

Many alternative fuels will require a pilot fuel to initiate the combustion; the percentage varies from 0.50-1.50% for dual fuel gas engines to around 3% for ethane and LPG engines and about 5% for methanol engines. The pilot fuel requires for future ammonia engines is not yet confirmed but indications say 5-8%.

Fuel cells

Fuel cells are electrochemical devices and work by combining hydrogen ions with oxygen ions. By using a membrane that block electrons the electrical current of electrons is routed externally and can be harnessed as DC (direct current) energy.

Fuel cells are quite versatile and can take hydrogen, ammonia and gas. PEM cells (proton exchange membrane) require pure hydrogen while SOFC (solid oxide fuel cells) crack ammonia and gas to hydrogen and are thus more robust and versatile.

Fuel cells with a combined output of 520 MW were installed in marine applications by 2018 [Shakeri, Zadeh and Nielsen, 2020 | ↗]. The growth from 2000 has been linear rather than exponential. While PEM cells are quite mature and are used in land transport, SOFC are still at a pilot stage.

Systems for fuel supply, control and load sharing between cells as well as water management for cooling are complex.

There are no current maritime installations above 1 MW of power, but several pilot projects are underway to demonstrate such capacities. Large fuel cell systems will be built as stacks of standard units of e.g. 200 kW. Scaling up from kW to MW is expected by 2022-23 [ABB, April 2020 | ↗].

PEM cells require very pure hydrogen and are sensitive to under supply or over supply of hydrogen. High temperature fuel cells are more robust with better tolerance for impurities.

The efficiency of a fuel cell varies between the different types and is also highly dependent on its auxiliary systems; hydrogen supply, air supply, cooling and humidification. Proton exchange membranes (PEM), a low temperature fuel cell can give 0.40-0.60 while the efficiency of a solid oxide fuel cells (a high temperature fuel cell) can be 0.45-0.60 and higher with waste heat recovery.

The efficiency of fuel cells is higher at part loads than at high loads. The efficiency is also high for stable loads. A fuel cell should therefore work in tandem with a battery to avoid rapid and frequent load fluctuations, and also to minimize the installed fuel cell power. The efficiency of high temperature fuel cells can be further improved if the waste heat can be utilized.

Contrary to the internal combustion engine, the efficiency figures for fuel cells are quite uncertain, since the lack of actual installations mean there is no comparable data and little experience from actual operations. The actual efficiency figures on fuel cells remain to be discovered as more installations come online and experience is gathered.

Type	*PEM* *Proton exchange membrane*	*PA* *Phosphoric acid*	*MC* *Molten carbon*	*SO* *Solid oxide*	*DM* *Direct methanol*
Electrolyte	MEA (Membrane electrode assembly)	Cilicon carbide matrix saturated with liquid phosphoric acid	Combinoation of alkali carbonates	Metal oxide	MEA (Membrane electrode assembly)
Fuel	H_2	H_2 LNG Methanol Diesel	H_2 LNG Methanol Diesel	H_2 LNG Methanol Diesel	Methanol
Internal reforming	No	No	Yes	Yes	No
Operating temp. [°C]	80-85	150-220	600-700	800-1,000	50-120

Thermal efficiency [%]	50-60	40	45-60	45-60	35-80
specific power [W/kg]	100-300	50-100	100-150	150-200	30-80

Table 7: key characteristics of different types of fuel cells [Shakeri, Zadeh and Nielsen, 2020 | ↗].

Fuel cells last shorter than engines [Ballard | ↗], [IEA, 2015 | ↗], [BeHydro | ↗]. Cells for mobility, with varying load, last even shorter than stationary cells running at constant load. Compared to engines, fuel cells require rare metals such as platinum and their construction and recycling will thus be more complex and increase demand for such metal, although research on alternative materials may change this.

Fuel cells have fewer moving parts and thus less wear and tear, however the complexity of multiple stacks and the presence of the BOP (balance of plant; auxiliary systems necessary for the operation of the fuel cell) means there are multiple sources for maintenance needs also with such systems. As of today, it is reasonable to say that maintenance will be different but not necessarily less.

Fuel cells creates less noise and vibrations than reciprocating engines; this will be appreciated in passenger and cruise vessels as well as research vessels. Also, fuel cells weigh less and occupy less space onboard than similar engines.

Thermal efficiency of engines, fuel cells and batteries

Thermal efficiencies are calculated based on specific fuel oil consumption at MCR informed by the engine makers [MAN | ↗], [WinGD |↗]. Efficiencies for future engines under development and fuel cells must be considered indicative and subject to confirmation.

The following diagram (fig. 83) indicates the power output available and under development by various makers for conventional and alternative fuels. Note that the versions for alternative fuels are under development and thus the figures are uncertain and best available indications at the time of writing.

Note that the total output from fuel cells and batteries can be increased by *stacking* the modular components and is expected to increase for both types in the years to come.

The first diagram (fig. 82)) indicates the typical thermal efficiency of various engine types. Note that the thermal efficiency varies with the engine load and can be improved with waste heat recovery.

The second diagram (fig. 83) confirm that within a few years, there will be engines for all alternative fuels. Rapid developments within fuel cells and battery systems can be expected.

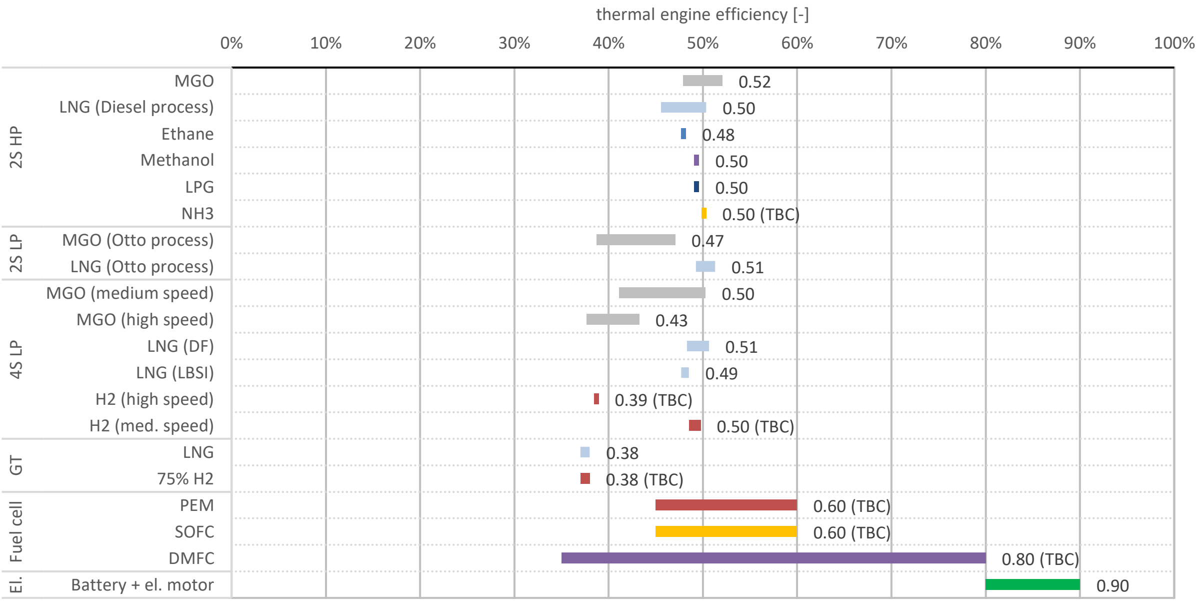


Figure 82: Thermal efficiency of various engine options.

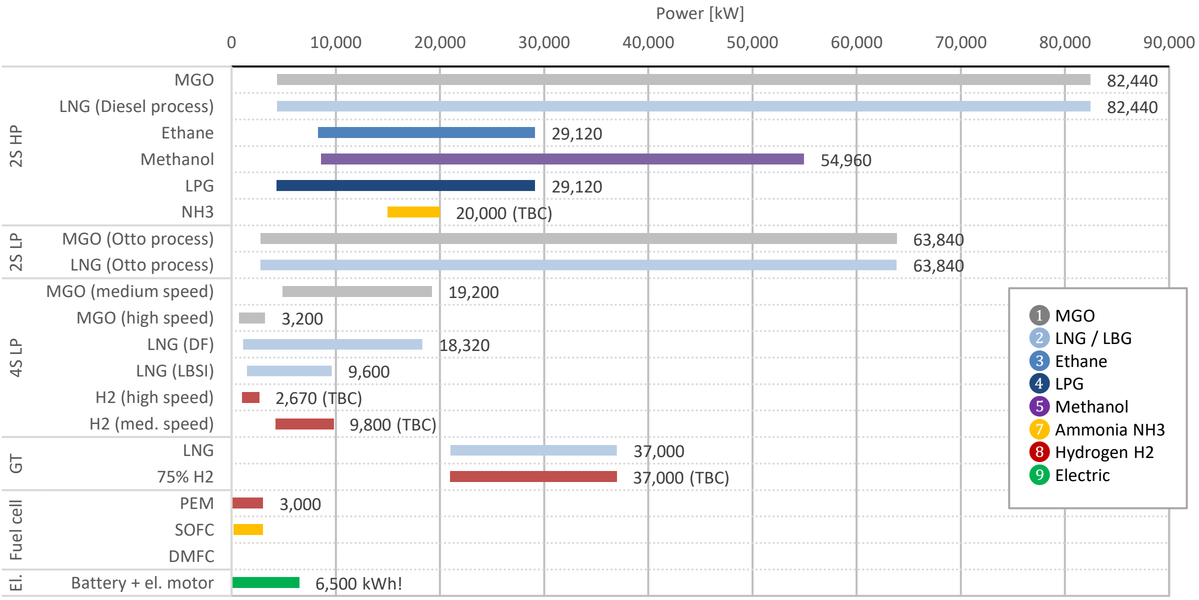


Figure 83: Power range for various engine options, indicative and subject to developments in the product portfolio of engine makers.

9.5. Safety

SUMMARY

Many of the new maritime fuels have low flashpoint and wider flammability limits.

Safety standards for alternative fuels are provided by the IGF Code, the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (2017).

The most important safety risks with alternative fuels can be summarized as follows:

	Boiling point	*Auto-ignition**	*Flammable range*	*Flashpoint*	*Safety risks*
MGO	160-400°C	260-370°C	0.5-7%	60°C DMX: 43°C	Fire
Biofuel (liq.)					Gives H_2S if degrading (toxic and corrosive) High acidity; wear on machinery.
Methanol	65°C	450°C	5-36%	Low (11°C)	Toxic Corrosive: Irritation to skin and eyes Inert gas asphyxiation
LNG	-162°C	650°C	4-14%	Low	Vapour flammability Inert gas asphyxiation Cryogenic brittleness and fractures Cryogenic burns
Biomethane (LBG)					
LPG	-26°C	372-428°C	9-20%	Low	Vapour flammability, Inert gas asphyxiation
Ammonia	-33°C	630°C	15-27%	High	Toxic Corrosive: Irritation, blindness, death. Cold burns from contact with cold ammonia
Hydrogen	-253°C	535°C	4-74%	-	Leakage in operation and by permeation. Cryogenic burns. Explosion Inert gas asphyxiation Ignition energy 1/10 of gasoline (0.02 mJ)
Batteries	N/A	N/A	N/A	N/A	Fire, thermal run away Explosion Gas and chemical leakages

Table 8: Fuel properties with importance for safety risks

*The auto-ignition temperature of gases depends on the air/gas ratio, thus a temperature range is given.

Regulatory

While the Marine Environment Protection Committee (MEPC) of the IMO works to reduce emissions, the safety regulations required for safe installation and operation are adopted by the Marine Safety Committee (MSC)

For vessels where the fuel is the same as the cargo, the construction standards are given by the IGC code; the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk. This applies to LNG carriers and LPG carriers.

Where low flashpoint liquids or gases are taken onboard as fuels only, the IGF code applies. The International Code of Safety for Ships using Gases or other Low-flashpoint Fuels adopted by IMO in 2017 contains mandatory provisions for the arrangement, installation, control and monitoring of machinery, equipment and systems using low-flashpoint fuels [IMO, 2017 | ↗]. It was developed with a focus on LNG and builds on the IGC Code but contains guidelines applicable to other fuels including hydrogen and ammonia through the procedure for *alternative designs*. The approach is goal based with functional requirements. The evaluation and approval will be based on the criteria of *equivalent level of safety*.

Standards for liquid hydrogen are being developed by IMO and the leading classification societies. Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk were adopted by MSC 97 [IMO, 2016 |↗] and guidelines have been developed by leading classification societies e.g. ClassNK in 2017 [ClassNK, 2017 | ↗].

In spring 2022, MSC is expected to adopt interim guidelines for use of fuel cells in ships [IMO, Sep 2021 | ↗]. The interim guidelines are intended to ensure safe and reliable delivery of electrical and/or thermal energy through the use of fuel cell technology and cover fire systems and gas/vapour detection inter alia.

9.6. Fuel demand from shipping

SUMMARY

Access to new fuels from energy majors will be crucial. 85% of the costs to decarbonize shipping will come in production and infrastructure for new fuels.

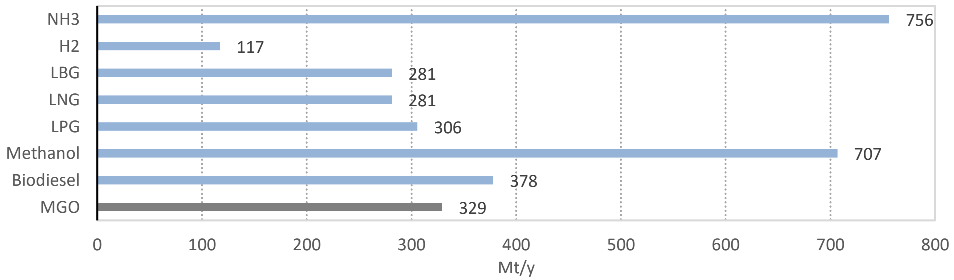
Decarbonizing shipping will require 280 Mt biomethane, 750 Mt ammonia, 120 Mt hydrogen or 700 Mt methanol or combinations of these, based on the energy demand in 2018.

This chapter presents the volumes required to decarbonize shipping in Norway, EU and worldwide with various alternative fuels.

It is important to understand the massive energy quantities required to fuel the shipping industry. A study by UCL found that 85% of the costs to decarbonize shipping will likely go into fuel production and infrastructure [UMAS/Carlo, 2020 | ↗].

The fuel demand for all shipping globally is about 330 mill t MGO-equivalents, equivalent to about 14 EJ (10^{18} J) and 4,000 TWh (10^9 kWh) [IMO 4th GHG study, 2021, p. 97 | ↗]. This is about 2.4% of the global energy demand. If energy consumed to extract and produce marine fuels are included, the share grows to about 2.8%.

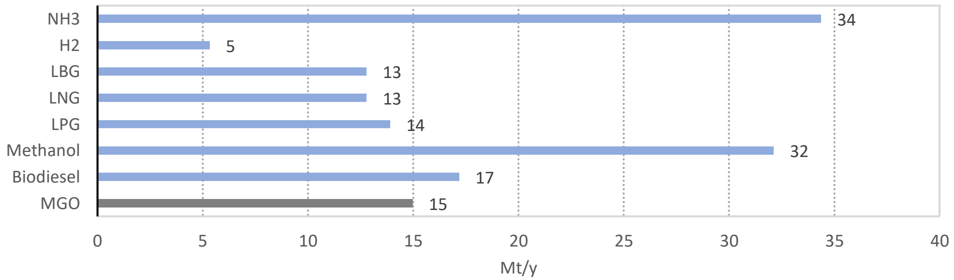
The below three diagrams indicate the volumes required if each fuel shall cover the entire needs from shipping, based on today's energy consumption, i.e. factoring in neither energy efficiency measures nor activity or fleet growth. Improvements in ship design, machinery and operations can reduce this. On a global scale, decarbonizing shipping will require 756 Mt ammonia or 117 Mt hydrogen, alternatively 281 Mt biomethane, 378 Mt biodiesel or 707 Mt climate neutral methanol.



All shipping (abt. 14.EJ)

Figure 84: Annual fuel demand if each fuel should cover the energy demand from all global shipping alone.

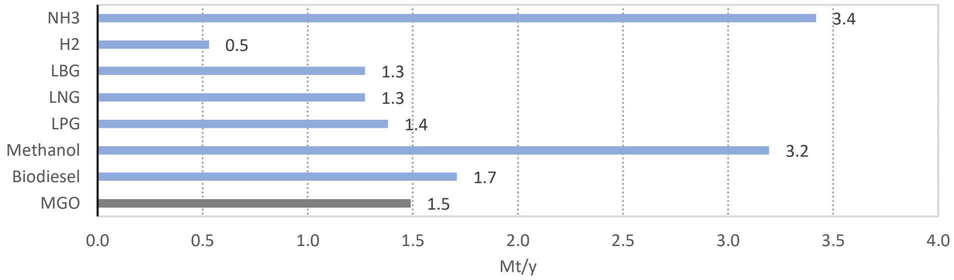
Alternative fuels will likely be introduced in regional or coastal shipping, it is therefore interesting to evaluate the energy demanded by intra-European shipping. The below is based on 15 mill t MGO-equivalents (0.8 EJ or 180 TWh). To decarbonize all intra-EU shipping, 13 Mt of biomethane will be required, alternatively 32 Mt sustainable biomethanol, 34 Mt ammonia or 5 Mt hydrogen.



Intra- European (EU/EEA) shipping (abt. 0.65 EJ)

Figure 85: Annual fuel demand if each fuel should cover the energy demand from intra-European shipping alone.

Finally, we estimate the demand for alternative fuels for Norwegian domestic shipping, based on the demand estimated in a Government white paper in 2017; Regjeringens handlingsplan for grønn skipsfart [Regjeringen, 2019 | ↗]. To change the fuel used by all ships sailing in Norwegian waters (EEZ; exclusive economic zone), around double the volumes will be required.



Norwegian (domestic) shipping (abt. 0.13 EJ)

Figure 86: Annual fuel demand if each fuel should cover the energy demand from Norwegian domestic shipping alone.

How does these energy volumes compare to the current and anticipated global production? The current production of various fuels is summarized in the below table, in million tonnes per year, EJ and TWh. The share from renewable energy is indicated where applicable. The table also indicates the energy demand in shipping vs the current global production, if a single fuel should cover the entire energy need of all shipping- Demand is based on the energy need in 2018, i.e. factoring in neither energy efficiency measures nor activity and fleet growth) relative to current production.

In addition to the energy demand tank to wake (i.e. energy content of the fuel), we estimate the energy demand well to wake, i.e. taking into account the energy consumed to produce the various fuels and compare this to the global primary energy production

It is also interesting to evaluate the energy required in production for each of the alternative fuels, as renewable and climate neutral energy is indeed a scarce resource.

	Current production				Shipping demand (based on 2018)				
	Mt	*EJ*	*TWh*	*Renewable*	*TTW [EJ]*	*TTW [Mt]*	*of current production*	*WTW [EJ]*	*of global primary energy*
Residuals	390	16	4,450	N/A	14.1	340	0.9 x	16.2	2.7%
Distillates	1,320	57	15,900	N/A		330	0.25 x	16.9	2.8%
Biodiesel	41	1.5	425			380	9 x	35	5.9%
Biofuels (liq.)		3.9	1,080						
E-diesel	0							50	8.4%
LNG	410	21	5,750	N/A		280	0.7 x	16.9	2.4%
Biomethane	29	1.4	400			280	10 x		
E-LNG	0							43	7.2%
LPG	330	15	4,200	N/A		305	0.95 x	15.5	2.6%
Hydrogen	94	11	3,100	<1%		120	1.25 x	35	5.9%
Ammonia	185	3.5	950	< 0.1%		750	4 x	27	4.7%
Methanol	98	2	540	< 0.2%		710	7 x	23	3.8%
Biomethanol	0.2	0.004	1.1			710	3500 x	23	3.8%

Table 9 Current production of various fuels (for all sectors irrespective of end users) and possible demand from shipping.

We find that if shipping should run entirely on e.g. hydrogen, the sector would need 1.25 times the current production. In the case of ammonia and methanol, shipping would require four and seven times the current global production. In the case of liquid biofuel, shipping alone would need 9 times what is produced today.

The conclusion is that fuel transition will require large volumes of new fuels Hydrogen, ammonia and methanol are not used as fuels to any large extent today. We therefore suggest that a transition happens gradually over some time to allow the production side time to scale up; we elaborate on this in chapter 9.15.

Gross energy demand for shipping including fuel production

As many alternative fuels requires a lot of energy to produce, it is important to consider the gross energy demand from well to wake. Let us take intra-European shipping as an example; the current fuel demand was about 15 mill t MGO in 2019 [EU MRV, 2020]. 15 Mt MGO has an energy content of 320 PJ or 90 TWh.

The below diagram (fig. 87) indicates the additional energy demand if European shipping shall use synthetic fuels, hydrogen or ammonia. Let us take hydrogen as an example: to get 90 TWh from an engine or fuel cell, the hydrogen must contain 180 TWh when we assume a thermal efficiency of 0.50. Producing hydrogen with an energy content of 180 TWh requires 266 TWh, so the total energy demand for the hydrogen case becomes 444 TWh.

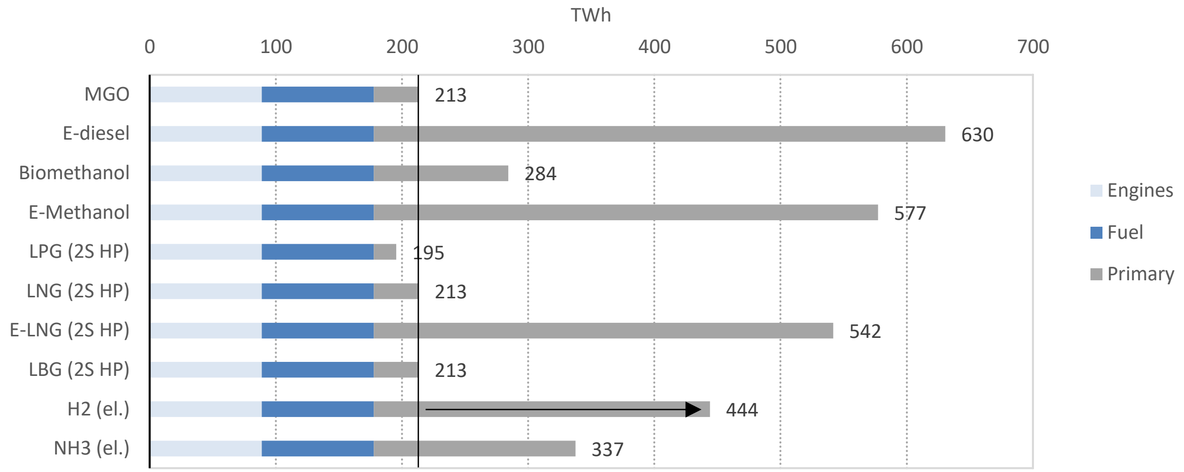


Figure 87: Energy required to the engines (blue), the energy content of the fuel (dark blue) and the energy required to produce the fuels (grey).

An increase of around 231 TWh (444 – 213) for hydrogen equals around 8% of European net electricity generation in 2021 [Eurostat | ↗]. If European shipping should run on synthetic diesel, the additional energy required (630 - 213 = 417 TWh) equals 15% of the European net electricity generation in 2020. A change to hydrogen or synthetic fuels will thus put significant additional pressure on the renewable electricity generation.

Changing to hydrogen or synthetic fuels will increase the overall energy consumption of the shipping sector from about 2.8% of global primary energy to 6-8%.

9.7. Electric vessels

SUMMARY

Batteries can be the main power source for small ships with small energy demand. If renewable energy is used to charge the batteries, GHG-emissions are reduced to almost zero.

Batteries will also eliminate local air pollution completely.

The low transmission losses well to wake suggests that electric power and batteries should be utilized wherever batteries can hold sufficient energy.

The large weight and size of batteries are a major concern for mobile applications. While weight are troublesome for airplanes, large volume are a disadvantage and hindrance for use in large vessels.

Learn about the possible future development in battery technology in a SINTEF podcast 8 September 2021 [Smart forklart | ↗]

Vessels with small energy demand sailing short distances with reliable and frequent access to shore power can be powered exclusively by batteries. The typical example is a small ferry on a fixed route. From the first electric ferry, Ampere, in 2015, there are 60 in operation and another 26 on order [Klimastiftelsen, Aug 2022| ↗].

The main advantage of electricity is the low conversion losses: While a combustion engine utilizes around half the energy of the fuel (ref chapter 9.4), an electric drive train utilizes 80-90% [Kifune and Zadeh, 2019 |↗]. All electric propulsion gives no emissions from onboard use and low noise. This is appreciated in pristine nature, populated areas, and busy ports.

Provided that the electricity used to charge the batteries is indeed climate neutral, electric power should be used wherever possible due to the low conversion losses onboard. Today, the global average footprint of electric power is 441 g CO_2-eq/kWh. There are significant variations between countries depending on, inter alia, their natural resources and energy consumption, indicated by the below map:

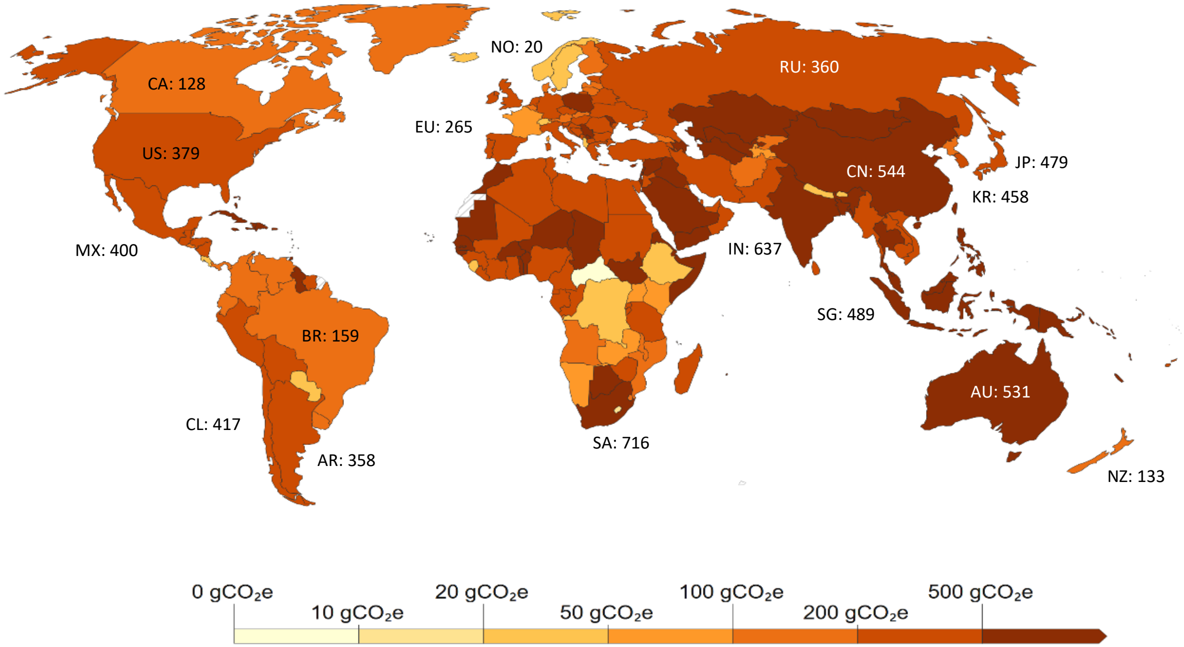


Figure 88: GHG- intensity map for global electricity production from Our world in data, 2022 [↗] based on Ember Climate (from various sources including the European Environment Agency and EIA)

These emission factors must be taken in when estimating the effect of electrification on global warming. Positive effects on local air pollution and energy efficiency applies regardless of the production method.

Today, the global share of renewable energy in the electricity mix is 29% and higher in the EU and lower in the US (ref chapter 9.1). Nuclear energy also contributes to lower the footprint of electricity, though nuclear energy has other environmental challenges. It provides almost 30% of the world's low carbon electricity [LSE, 2022 | ↗].

Batteries will make even more sense as renewable energy increases its share in the future and fossil electricity generation is replaced by hydropower, wind, solar – and perhaps nuclear energy.

Electricity footprint [g CO_2/kWh]	Global average [↗]	Hydro [↗]	Wind [↗]	Nuclear [↗]	Gas	Coal [↗]
	441	4-14	10-40	15-50	400-650	900-1100

Emissions in port can be eliminated with electric shore power. On a global scale, this can reduce shipping GHG by up to 6% (ref chapter 2.5) but have a very positive effect on the local air quality in and around ports.

Gothenburg was the first commercial port to offer shore power to ships in 2001 and the first facility in Norway was set up in 2011 [Opdal & Steen, Zero, 2012 | ↗]. In October 2021, there were around only 160 ports with electric shore power [Zadeh, Karimi and Sul, 2021]. With the FuelEU Maritime regulation, passenger/cruise ships and container vessels will be required to use shore power [EU, 14 July 2021 | ↗].

The main challenge with batteries is their weight and size. Batteries simply cannot hold the energy needed by large vessels. Therefore, only 24% of the electric vessels (130 ships) draw all their energy from batteries [DNV AFI | ↗] and most vessels use battery as supplementary power or to improve running of the generator sets (ref chapter 8.7).

Depending on the specification, batteries weigh 30-70 times as much as diesel and occupy 40-65 times as much space onboard. As battery technology evolves, these disadvantages will likely lessen somewhat.

9.8. Fossil, liquid oil fuels

SUMMARY

Residual fuels (high or low sulphur heavy fuel oil) fuelled 79% of ships in 2018. Scrubbers and development of low sulphur HFO can extend the use of HFO while concerns for oil spills and emissions of particles and black carbon are reasons to curb its use. HFO is banned in Antarctica, around Svalbard and from 2024 in the Arctic as well.

Use of distillate fuels (MGO, MDO) grew by 51% from 2012 to 2018 in response to the sulphur emission limits. The 2020 global sulphur cap and new ECAs will increase its use further.

MGO is the benchmark for analysing new fuels.

Blends of residual and distillate fuels with just the right sulphur content is developed by oil majors. These fuels behave like residual fuels when spilled and the risk of serious oil spills is not eliminated.

Fossil fuels have fuelled ships since the advent of steam ships in the mid-19th century. With the more energy efficient diesel engine, oil replaced coal and now provides 98% of maritime fuels [IMO 4th GHG study, 2021 | ↗].

Liquid oil fuels are convenient and safe because of high energy density, safety record, stability when stored and relatively straightforward storage and handling. Above all else, HFO and MGO are available everywhere and reasonable priced compared to all other fuels. In our analysis, marine gas oil (MGO) will be the benchmark for comparison.

Residual fuels (ISO category RME, RMG, RMK)

Residual heavy fuel oils provide 79% of the fuel consumed by ships in international traffic and 64% of all shipping in 2018 [IMO 4th GHG study, 2021, p. 97-98 ↗]. The majority (95%) of HFO is consumed by ship in international trade [IMO 4th GHG study, 2021, p. 119 | ↗].

If all ships worldwide should use only HFO, the demand would be about 340 mill t/y (14.1 EJ). This is about 90% of the annual production of HFO and crude oils of 390 mill t/y (16 EJ).

Residual oils with high sulphur content (> 1%) can be used onboard whips with a scrubber. This fuel oil has the advantage of low energy use in the refining process but requires a scrubber to reduce SO_X emissions. More than 3,000 large ships have such exhaust gas cleaning systems installed and another 1,500 are on order [DNV AFI | ↗]. Note that there is some concern about the environmental risks from discharge of scrubber wash water and many ports and coastal states have restricted the use of open loop scrubber.

Emissions and energy use for HFO	Thermal eff. (WTT·TTW=WTW)	Footprint WTT	Emission factor WTW
	0.87 · 0.50 = 0.435	9.6 g/MJ (-33%)	637 g/kWh (-3%)

The bunker suppliers have in recent years developed blends of residual and distilled oils that meet the sulphur requirements to avoid the use of scrubbers but still use as much residual oil as the emission limits permit. The energy use in production for these (very) low sulphur fuel oils (VLSFO) is higher.

Emissions and energy use for VLSFO	Thermal eff. (WTT·TTW=WTW):	Footprint WTT	Emission factor WTW
	0.83 · 0.50 = 0.417	13.2 g/MJ (-33%)	663 g/kWh (-3%)

Concern for fuel oil spills will likely reduce the acceptance for carriage of residual oils. Note that the refineries develop blends of residuals and distillates to meet the sulphur limit by blending in just the required share of distillate fuels. The behaviour of and damage from these new blends when spilled into cold water is unclear.

The campaign to ban the use and carriage of residual fuels is gaining ground: HFO is prohibited in Antarctica since 2011 and will be prohibited in the Arctic from July 2024 with some exceptions; Ships carrying HFO in protected fuel oil tanks can continue this practise until July 2029 and national states can give exemptions to national vessels until the same date [IMO PPR7, Feb 2020 | ↗].

Around 40-60% of the fuel consumption in the Arctic is HFO [ICCT, 2017 | ↗] [PAME, Oct 2020 | ↗] while the share is only 25% for shipping in the Norwegian sector of the Arctic [DNV GL, 2019]. Exports of LNG from Yamal explains much of the increase of shipping along the Northern Sea Route and the 80% increase in fuel consumption in the Arctic from 2016 to 2019 [PAME, Oct 2020 | ↗]

HFO has also been banned in the protected waters around Svalbard from May 2014, in the form of an obligation to use marine gas oil (DMA). This requirement will be extended to all territorial waters in the archipelago from 2022 and from 2024 for general cargo and coal carrying vessels to and from Longyearbyen [Sysselmannen | ↗], [Regjeringen, March 2021| ↗]. Norwegian authorities are also thought to consider declaring the entire Norwegian coast and sea areas an EABOUT

Another concern and argument against the use of residual fuels is the emissions of particles and black carbon emissions and the content of heavy metals and PAH (polycyclic aromatic hydrocarbons). While there are strong economic arguments to continue the use of HFO, the above risks and concerns will likely make this fuel the first to disappear from ships.

Advantages and disadvantages of residual fuels can be summed up as follows:

⊕	Availability and price Proven machinery and systems Low energy use and footprint in production (well to tank)
⊖	Tailpipe emissions; CO_2, soot, particles Need for scrubber to comply with SO_X emission standards Increased concern and restrictions on use of scrubbers and carriage of residual fuels Environmental impact if spilled to water

Distillates (ISO category DMX, DMA, DMZ, DMB)

The sulphur cap introduced by IMO, California and the EU since 2006 have motivated increased use of distillate fuels in ships. From 2012 to 18, use of distillate fuels grew by 51% and now (2018) make up about 32% of all maritime fuels and 17% of fuels consumed by international shipping [IMO 4th GHG study, 2021, p.7 | ↗]. The majority (63%) of distillate fuels is consumed by ships in national trades [IMO 4th GHG study, 2021, p.119 | ↗]. Talks with shipping companies sailing on Norway confirm this picture.

The use of distillates can only be expected to grow further with the entry into force in 2020 of the global 0.5% sulphur cap. MGO is used by most ships sailing with the Baltic Sea and North Sea after the ECA-requirements in 2006 and 2007. As the Mediterranean Sea becomes and ECA, we will see increased use of MGO – or other green fuels.

As indicated by the name, distillate fuels require more refining which increases the footprint from the production.

Emissions and energy use for MGO	Thermal eff. (WTT·TTW=WTW):	Footprint WTT	Emission factor WTW
	0.83 · 0.50 = 0.417	14.4 g/MJ	653 g/kWh

MGO will likely be the most important fuel in the decade to come as the majority of ships breaks away from residual fuels. Ships venturing into alternative fuels will likely use MGO as a back up fuel on dual fuel engines as. With MGO, tank and trace heating are not necessary, settling tanks can be omitted and the pre-treatment is simpler. Around 2.5-8.5 g/kWh will be required as pilot fuel for the various two stroke alternative fuel engines [MAN Marine Engine programme, 2021 | ↗]. Biodiesel can play the role of pilot fuel, as it is required in small quantities, to minimize emissions even further.

For this reason, MGO will be the benchmark for comparison of alternative fuels throughout this study.

If all ships worldwide should use only MGO, the demand would be about 330 mill t/y (14.1 EJ). This is about 25% of the annual production of distillate fuels of around 1,300 mill t/y (57 EJ) [BP, 2021 | ↗].

⊕	*Availability and price* *Proven machinery and systems* *Storage: high energy density, stability, simple tank arrangements*
⊖	*Carbon intensity* *Environmental impact if spilled to water*

9.9. Methanol (CH_3OH)

SUMMARY

Methanol was introduced as a marine fuel on methanol tankers to meet the sulphur emission limits.

Methanol is not a green fuel as it is currently produced from fossil fuels (65% from natural gas, 35% from coal) and gives higher GHG emission well to wake.

Only biomethanol and synthetic methanol can give GHG reductions. The GHG effect of biomethanol depends on the raw material and production process. Synthetic methanol requires a lot of climate neutral electricity.

It is available in more than 100 ports worldwide, but it is so far used almost exclusively by ships carrying methanol.

In 2016, the Norwegian methanol tanker Lindanger was the first ocean going vessel to use methanol as a fuel. Today, there are about 30 vessels powered by methanol and a number under construction or on order. So far, all ships burning methanol as a fuel also carry methanol as a cargo and have links to the methanol industry. This is set to change, when the twelve large container vessels ordered by Mærsk hit the water [Maersk | ↗].

The total methanol consumption was estimated for 2018 to 160,000 t [IMO 4th GHG study, 2021 | ↗]. Although this is next to nothing (0.02%) it proves that methanol works and that there are rules for approval and practices for bunkering.

Emissions

The problem is that methanol is not a green fuel unless it is produced from renewable electricity (synthetic methanol) or from sustainable bio feedstocks (biomethanol). The current production from natural gas gives 12% more GHG when production emissions are included (well to wake). Methanol does not contain sulphur, and this is currently the only environmental argument for using methanol produced from natural gas.

65% of current methanol production is based on natural gas reformation and 35% based on coal gasification. Only 0.2% of the methanol produced today is biomethanol [IRENA, 2021 | ↗]. The below factors apply to grey methanol:

Emissions and energy use for methanol (NG)	Thermal eff. (WTT·TTW=WTW):	Footprint WTT	Emission factor WTW
	0.63 · 0.50 = 0.31	31 g/MJ (+17%)	729 g/kWh (+12%)

Biomethanol can be produced from sustainable biomass such as forestry and agricultural waste and byproducts, sewage, solid municipal waste and black liquor from the pulp and paper industry. Depending on the feedstock, byproduct generation, production process and final use, the well to tank footprint varies from -65 to -35 to g CO2-eq./MJ [IRENA, 2021 | ↗]. With the standard engine efficiency of 0.50 applied throughout our analysis, we conclude that the biomethanol can reduce GHG by 65% to 95%.

Emissions and energy use for biomethanol	Thermal eff. (WTT·TTW=WTW):	Footprint WTT	Emission factor WTW
	0.63 · 0.50 = 0.31	-65 to -35 g/MJ	35 to 250 g/kWh

Synthetic methanol is near climate neutral but requires a lot of energy in the production; nearly three times as much as MGO and only 15% of the energy reaches the propeller shaft compared to 42% for MGO. In world with very limited renewable energy, such energy losses seem hard to justify.

IRENA estimates the production cost for fossil methanol to 100-250 USD/t and the cost for biomethanol to be 320-770 USD/t while synthetic methanol costs 800-1600 USD/t with CO2 from BECCS or 1,200-2,400 if DAC is used [IRENA, 2021 | ↗]. The low carbon methanol variants thus costs at least 3-7 times as much as fossil methanol.

With NO_X-emissions above the Tier III level, a modest reduction in GHG tank to wake and increased GHG well to wake, methanol can only be considered a green fuel when sufficient volumes of biomethanol is blended in.

The low carbon methanol variants cost at least 3-7 times as much as fossil methanol according to IRENA. The cost gap will narrow when a carbon price is added to fossil methanol and process improvements reduce the cost of biomethanol.

Around 5-10% pilot fuel is required, and some SO_X and PM are caused by the use of pilot fuel and lubricating oil. Emissions of NO_X is determined by the engine type rather than the fuel and typically reduced by 60% [TNA, January 2021].

Production, infrastructure, and availability

Methanol is a petrochemical feedstock used to produce plastics, paints, carpets, textiles, medicines, and other everyday products. It can be used as a fuel directly or in various forms e.g. dimethyl-ether (DME). Around 1/3 of the methanol is used as a fuel today. Global production was around 98 mill. t in 2019. Around 65% is based on natural gas and 35% on goal gasification.

Methanol is available in more than 100 ports worldwide including the main bunkering hubs [Methanol Institute | ↗]. Despite global availability, all methanol powered vessels have so far been linked to the methanol industry. The first bunkering from a bunker barge were reported in May 2021 [Motorship, 14 May 2021 | ↗].

Maersk's intent to run eight vessel on methanol changes this and the expected demand for the series of twelve container vessels is 540,000 t annually, more than three times the total use by ships today.

Only 0.2% of current methanol production is climate neutral, says IRENA. Sustainable production of methanol requires abundant renewable electricity, direct air capture and sustainable biomass.

If all ships worldwide should use only methanol, the demand would be about 700 mill t/y (14.1 EJ). This is about 7 times the annual production in 2019 (1.9 EJ). It would also increase the energy required to fuel shipping from 16.9 to 22.5 EJ or 2.8% to 3.8% of global primary energy.

Technology

Methanol's key advantage is the minimal modifications required to the engine. Due to the low energy content and low density compared to MGO, fuel tanks and fuel piping cross section must be around 2.5 times. Finding space for such big pipes in an existing engine room can be challenging.

Both two and four stroke engines can be built or converted to run on methanol. MAN has developed an engine specifically for methanol, the ME-LGIM and sold more than 100 engines over a few years [Kjeld Aabo, May 2021]. The engine is currently available from 7.4-16 MW (the G60 range) and will likely be expanded upon demand, e.g. a methanol version of the G95 will be built for Maersk's large container vessels by 2024 [MAN Aug 2021 | ↗]. Despite more pilot fuel required, the specific fuel consumption is the same as the ME-C engine when adjusted for calorific value.

Existing engines can be converted, as demonstrated onboard the Stena Germanica in 2015. The well proven Wärtsilä 32-engine is modified for methanol and available from 3 to 9 MW [Wärtsilä, 2022 | ↗. Engines with spark plugs are also considered suitable for methanol.

Methanol is corrosive so tanks and engines must be constructed accordingly, and corrosion inhibitors and special coatings will be required. Methanol is toxic and must be contained in double wall piping with leak detection and ventilation arrangements.

Methanol is a liquid under ambient conditions. Avoiding the need for cooling or pressure to liquefy the fuel saves energy and makes storage less complicated.

Mærsk said the additional capex for methanol was 10-15% for the future feeder vessels ordered [Maersk, 24 Aug 2021 | ↗].

Summary

Methanol is available with regulations and practices for handling. Machinery and systems are mature. The Achilles of methanol is the production; methanol is only as green as the production of the fuel itself.

⊕	Engines available Fuel available in select locations worldwide, around 100 ports. Low capex on ship side
⊖	12% higher GHG emissions WTW for fossil methanol, only biomethanol and synthetic methanol reduces GHG. Synthetic methanol requires a lot of climate neutral energy in production. Needs after treatment to meet Tier III limits for NO_x.

9.10. Liquefied natural gas (LNG)

SUMMARY

LNG offers modest GHG reductions (6-16% depending on engine's methane slip) but is available today. Engine makers work hard to eliminate the methane slip.

LNG is the natural building block towards climate neutral hydrogen and climate negative biomethane and deserve political backing not only as a transition fuel, but as an enabler of biomethane and hydrogen. Biomethane can replace LNG completely, production volumes pending, while up to 25% hydrogen can be blended in today.

LNG ensures clean air with no SO_X or particles and little NO_X, with the right engine. This is particularly valuable in coastal areas, ports and populated and sensitive regions.

Natural gas is a gaseous mix of hydrocarbons such as methane (CH_4), ethane (C_2H_6), propane (C_3H_8) and butane (C_4H_{10}). It is commonly liquefied to -163°C and known as liquefied natural gas (LNG). Compressed natural gas (CNG) is rarely used on vessels.

Unlike liquid fuels, there is no commonly agreed specification, nor any ISO-standard for LNG and LPG. Therefore, the chemical composition and thus the energy content depend on the geographic origin and refining.

Natural gas has been used as fuel on LNG-carriers since the inception of this vessel type as the boil off gas from the cargo tanks would otherwise be a problem for such vessels [Robert Ffooks, 1993 | ↗]. In 2000, the first LNG-powered ferry, Glutra, was put in service in Norway, in 2001 two offshore vessels, in 2011 a product tanker, in 2013 two ropax ferries, in 2015 a container vessel and in 2018 a cruise ship. By the end of 2022, LNG fuels about 350 vessels in addition to nearly all LNG carriers, and there is more than 500 more on order. It is a popular choice for cruise ships and, interestingly, oil tankers.

LNG is forecasted by LR and UCL to make up 10% of marine fuels in 2030 while DNV have long been more optimistic and predicts 20% in 2030 and 40% in 2040 and 2050 [LR/UCL, 2014 | ↗], [DNV GL ETO 2019 | ↗]. Politically, LNG has lost much of the support it enjoyed a short decade ago as a clean fuel. Today, many consider LNG to be acceptable only as a bridging fuel or a replacement for coal [IEA, 2019 | ↗].

Emissions: GHG

The footprint of LNG varies and is also highly debated. The emissions from production depend on the natural gas resource, the extraction methods, flaring, leakages from production and transport, the ambient temperature, the distance to market and other factors.

A review of life cycle analysis of LNG finds WTT-factors from 4 to 30 g CO_2-eq./MJ [Equinor, Gasum, Gasnor, UMAS, DNV, Brynjolf et al, 2013, Gilbert et al 2018]. The spread is significant. Norwegian LNG has a quite low footprint WTT: Cradle to gate emissions for Snøhvit is only 3.8 g CO_2-eq./MJ and other Norwegian small scale LNG producers achieve a footprint of about 5 g. Electrification of Snøhvit can reduce the production emissions to less than 1 g/MJ [Equinor | ↗]. The average methane emissions from gas production worldwide is 0.23% but only 0.03% on the Norwegian continental shelf [Gardarsdottir, 25 August 2021 | ↗].

The below footprint WTT estimated by Lindstad to 18.5 g CO_2-eq./MJ; 28%above MGO. The below emission factor WTW is based on combustion with minimal methane slip. Today, such low methane slip is achieved in high pressure diesel engine, but is also expected in future low pressure engines.

Emissions and energy use for LNG	Thermal eff. (WTT·TTW=WTW):	Footprint WTT	Emission factor WTW
	0.83 · 0.50 = 0.42	18.5 g/MJ (+28%)	550 g/kWh (-16%)

The engine type used has also significant bearing on the GHG emissions of LNG. Methane slip has been reduced but is still significant from some engines and generally higher at part load (see chapter 6.2). For low pressure engines, two and four stroke engines alike, the methane slip is still significant, although it has fallen in recent years. Measurements onboard vessels with various types of DF and pure gas engines by SINTEF Ocean found that the methane slip is still 4-7 g/kWh [Ushakov & Stenersen, 2019 | ↗], which translates to 119-209 g CO_2-equivalents per kWh, based on GWP_{100} factors from AR6.

New technology is being developed to reduce the slip further; Wärtsilä suggests that 1 g/kWh should be possible for low pressure engines [Wärtsilä, 6. April 2020 | ↗]. Many of the improvements envisaged to reduce methane slip will become available for existing engines.

The methane slip is very low from high pressure engines; 0.2±0.1 g/kWh at the contract point and up to 0.3 at part loads [MAN ES, engine programme, p. 14 | ↗], [MAN, 30 Jan 2020 | ↗]. Unfortunately, high pressure gas injection is costly, capex in particular, and therefore less popular then the low pressure alternative. Also, the high pressure gas engines emit more NO$_X$ and require SCR or EGR.

Engine makers have reduced methane slip considerably, nevertheless; the average rate is still high enough to cancel out a large portion of the CO$_2$-saving. Fixing the methane slip would reduce greenhouse gases and ensure clean air – today!

What is the potential of LNG? We note that many life cycle analysis find quite advantageous WTT footprints for LNG: from 4 to 10 for LNG [Gilbert et al, 2018 | ↗], [UMAS, 2018 | ↗], [Brynjolf et al, 2014 | ↗], [DNV, 2019 | ↗]. LNG is produced in Norway with a footprint below 5 g CO$_2$-eq/MJ [Gasnor, 2022], [Gasum, 2022], [Equinor | ↗]. If LNG with an advantageous footprint of 5-10 g CO$_2$-eq./MJ well to tank can be sourced and combusted in an engine with nearly no methane slip, LNG can reduce GHG emissions by about 30% and give emission factors WTW from 450 to 480 g CO$_2$-eq./kWh.

Emissions from production, distribution and combustion of LNG can be reduced if careful measures to curb methane slip along the value chain is implemented. The LNG footprint also varies between regions Rather than using global average values, each batch of LNG should be assessed on the basis of its production pathway and with ship-specific emission factors reflecting the machinery and systems onboard.

Emissions. No SOX, no particles and little NO$_X$

LNG gives no SO$_X$ and almost no particles. The NO$_X$ emissions depend on the combustion process i.e. the engine type.

Low pressure engines give NO$_X$ below Tier III levels while high pressure engines need SCR or EGR to reduce NO$_X$ formed by the high temperature combustion. NO$_X$ emissions were found to be 0.9 g/kWh from lean burn spark ignited engine and 1.9 from low pressure DF engines – well below the Tier III limit of 3.4 g/kWh [Ushakov, Stenersen and Einang, 2019 | ↗].

High pressure engines, give much higher NO$_X$; around 10 g/kWh in Tier II-mode and 2 g/kWh with EGR active. Keep in mind that while Tier III engines *can* reduce NO$_X$, they are only obliged to do so when in ECAs, and for reasons of economy, ships will likely run in Tier II-mode outside ECAs, with five times the NO$_X$-emissions. Only around 1/6 of international shipping takes place in SECA (ref chapter 2.9) and the areas where Tier III applies are even smaller.

LNG should therefore be appreciated for ships sailing in coastal waters and at berth. While GHG should be addressed through global regulations and with a view to minimize the emissions from well to wake, regardless of where they place, local emissions should be regulated at local level and minimized where it matters most.

Unlike GHGs, where shifting emissions from one country to another or from one part of the value chain to another, moving emissions away from populated or sensitive areas makes good sense.

While the CO_2 reductions with LNG is positive but limited, the avoidance of soot including black carbon can have a positive effect if LNG replaces residual fuels in the high north. We noted in chapter 6.1 that black carbon has a GWP_{100} factor of 1,700 in the Arctic and 345 worldwide; thus reductions of black carbon should be a priority here. See also chapter 7.4 where the climate impact of the Northern Sea Route is discussed.

Production, infrastructure, and availability

LNG is now available as a marine fuel primarily in Europe, but also in the Middle East, Singapore, Far East and US East Coast and Caribbean [DNV AFI | ↗]. Other locations can be served with bunker barge; 21 in Europe, 3 in Japan and Korea, 3 in Singapore and 3 along the US East Coast. Small volumes can also be supplied by truck.

With variations in emissions well to tank between producing countries, significant leakage from grids in some countries and noting that the transport of LNG from producer to consumer have significant impact, users of LNG should be aware of the difference in footprint between suppliers.

If all ships worldwide should use only LNG, the demand would be about 280 mill t/y (14.1 EJ). This is about 70% of the annual LNG production in 2021 (516 Gm^3, 21 EJ). The energy required to produce LNG is roughly the same as for MGO so a switch to gas would have no impact on the shipping sectors overall energy consumption.

Technology: Machinery, storage and fuel systems

LNG must be cooled to -163°C to liquefy and must be stored at this temperature onboard. This requires thick insulation and most ships carrying LNG as a fuel have cylindrical tanks, which occupy more space onboard. Cylindrical pressure vessels are also generally preferred to allow pressure to build in case of low activity or idling, though new and innovative prismatic concepts are developed. This improves the space utilization onboard. Experience with cryogenic storage and handling can be useful for hydrogen.

A range of engines options from a number of engine makers exist for LNG; two and four stroke, low and high pressure, compression and spark ignited, dual fuel and pure gas. Pure gas engines avoid the need of double systems for fuel pre-treatment and injection and will achieve slightly better specific fuel consumption than the dual fuel versions.

High pressure engines working according to the diesel principle, like MAN's ME-GI engine, will have negligible methane slip and high thermal efficiency, both on gas and diesel. The engines comply with Tier III-levels in gas mode, but require EGR or SCR in diesel mode.

The technology has clocked 1.7 mill hours on LNG [MAN | ↗]. The high-pressure fuel system is costly, both in terms of capex and opex, with short overhaul intervals for the gas compressors.

Low pressure Otto-cycle engines, on the other hand, have higher methane slip but complies with Tier III without pre- or aftertreatment. It is also cheaper in terms of capex and opex. Four stroke versions are available from a number of makers. Two stroke low pressure Otto engines were until recently only made by WinGD. In July 2021, MAN received its first order for its equivalent engine, the ME-GA type [MAN, July 2021 | ↗].

Dual fuel engines seem to be preferred by ship owners. If we keep LNG-tankers apart, around 80% of the gas fuelled vessels have dual fuelled engines while only 10% are limited to gas only [DNV AFI | ↗]. This indicates owners' appreciation of fuel flexibility to mitigate risks related to new fuels.

Summary

LNG can reduce GHG by 16% well to wake, if methane slip is avoided. If LNG is sourced from locations with low footprint in production, the GHG effect can be up to nearly 30%.

This may seem insufficient, but LNG is available today, it can be mixed with biomethane and hydrogen (up to 25%) already today. It eliminates SO_X and particles including black carbon. The technology and infrastructure can be used for biomethane and will likely be a good starting point for hydrogen.

The most pressing issue remaining is the elimination of methane slip from some engine types.

⊕	Can give moderate to significant reduction in GHG. Can be introduced today and thus give near immediate effect and be a steppingstone to hydrogen and biomethane. Clean air: No SO_X, no NO_X (with low pres. engine), no soot/PM. Regulations available, strong safety record.
⊖	Methane slip cancels out some of the CO_2 advantage (low pres.). Cryogenic storage, double wall piping, space requirements

9.11. Biomethane (LBG)

SUMMARY

Biogas and biomethane can be made from many very different raw materials. In Scandinavia, wastes and residues from forestry, fishing, aquaculture and farming are good starting points for biogas production. Waste streams (black water) and organic garbage from municipalities are other sources.

The footprint varies accordingly. The GHG-advantage varies from zero to 220%!

With such a diverse raw material base, biogas can be made many places. The potential for scaling up production are uncertain and questioned, although some reports confirm sufficient volumes for shipping can be realized.

Biogas are made from organic material. The indirect effect on land use and competition with edible crops are two key sustainability concerns for biogas and biofuels in general.

Biogas can be produced from a range of organic raw materials and waste from farm, forest, fishery and humans; both sewage and municipal waste. The climate effect depends on the raw material, the production and the logistics involved and varies considerably. There are also sustainability concerns for some of the raw materials pertaining to indirect land use change and their alternative use.

Biogas contains 45% to 75% methane [IEA, 2020 | ↗]. The rest, primarily CO_2 must be removed to produce biomethane which can be used to power ships. Biomethane and LNG can utilize the same infrastructure and systems on shore and onboard and mixed in storage tanks. bio

Several shipping liners trial use of biomethane, but the use is so far limited. The IEA roadmap sees a major role for biofuels together with ammonia, and the net zero scenario assumes 7% of maritime energy to come from biofuels by 2030 and 20% by 2050 [IEA, 2021, p. 137 | ↗].

Emissions

As explained in chapter 9.2, biomethane and the other biofuels, reduce GHG emissions because the organic material used to produce the fuel absorb CO_2 or avoid methane emissions. Biomethane can be made from a range of raw materials with GHG reductions from 20 to 200%, as indicated by the below diagrams [EU RED II, 2018 | ↗]. There are two key take aways: first; the very high saving potential, and second; the significant variation and dependence on the raw material and process.

The two biomethane alternatives included in Lindstad's paper (and our summary of GHG WTW in chapter 9.2) indicate a 70-80% saving. EU's Renewable Energy Directive requires GHG reductions above 65% for biofuels and biogas for the transport sector [EU RED II, article 29.10 | ↗].

Emissions and energy use for biomethane	Thermal eff. (WTT·TTW=WTW):	Footprint WTT	Emission factor WTW
	0.83 · 0.50 = 0.42	Varies	110-180 g/kWh (-70 to -80%)

LBG can be blended with LNG to reduce the GHGs as much as required. With the biomethane type analysed by Lindstad et al. (with 83% lower GHG than MGO well to wake), blends of natural gas and biomethane can give substantial GHG reductions.

Sustainability criteria for biomethane

The biological material used to produce biomethane and liquid biofuels can cause deforestation or reduce arable land thus reduce food production. Therefore, biofuels must meet a range of sustainability criteria, e.g. those included in the recast Renewable Energy Directive [EU, 2018 | ↗]. Biomethane can also be produced by collecting methane from landfills, sewage and waste from farms and fisheries. It will thus turn waste into energy.

Production of biomethane can have positive side effects such as improvement of soil structure and reduced use of mineral fertilizers.

Production, infrastructure and availability

Biogas is produced by anaerobic digestion of biomass. The wide range of raw materials makes production of biogas possible in many locations. Yet, current production volumes are very minor: Worldwide, around 400 TWh, corresponding to 1.4 EJ or about 400 Mt/y) [IGU, 2021 |↗] and only parts of this is upgraded to biomethane suitable for transport applications.

In 2017, there were only seven (7) active LBG-plants worldwide; one in Sweden, Norway and the Netherlands and two in the UK and US but many more under construction and planning [Dahlgren, 2020 | ↗].

Biogas can be produced from many different types of wastes and organic materials and the IEA estimates the potential biogas and biomethane production to 8,500 TWh (equal to 31 EJ and 610 Mt/y) [IEA, 2020 | ↗]. CE Delft concluded that raw materials for biogas can be found everywhere and estimated the potential production of biomethane in 2030 to 40 - 120 EJ [CE Delft, 2020 | ↗].

If all ships worldwide should use only biomethane, the demand would be about 280 mill t/y (14.1 EJ). This is many, many times more than the current production, but less than the potential production estimated by the IEA and CE Delft.

Clearly, other sectors would also want a share of the available biomethane, not least heavy and long-haul transport (trucking, trains etc) and other sectors where electricity is impractical. Gas covers 25% of the EU's power generation and biogas can be useful here too.

Very small production volumes are often cited as a barrier for biogas and biomethane, despite that various reports see a significant potential for future production.

The Nordic countries all have the resources to make biomethane; fish, farm and organic waste in Norway, forestry waste in Sweden and Finland and biproducts from farms in Denmark. All countries have municipal waste and sewage and the production benefits from a mix of raw materials. Biomethane currently flies below the radar and receives little political attention in Norway. The situation is better in Sweden and Denmark.

Technology

As noted above, biomethane can use the same tanks, systems and machinery as natural gas, which are already available. The safety risks and regulatory regime will also be the same as for LNG operations.

Summary

There are certainly pitfalls with biomethane, e.g. deforestation and a uncertainty with regards to their GHG effect. Yet, biomethane can cut GHG significantly and be climate negative at best. It is also available today, can be used together with LNG or replace LNG, depending on available volumes, availability and economic factors. Therefore, and as they can be readily used already today, biomethane deserves more attention and support.

The combination of LNG, biomethane and hydrogen is a flexible and robust way to cut GHG.

⊕	Unbeatable GHG effect, with the right raw material and process. Raw materials for biomethane are available anywhere. Turns waste into energy (circularity) Can replace, be mixed and used intermittently with LNG.
⊖	Sourcing of organic material can cause deforestation and reduce arable land and compete with food production.

9.12. Liquefied Petroleum Gas (LPG)

SUMMARY

LPG cuts GHG by 17% well to wake.

It is the fossil fuel with lowest energy use in production

LPG is a relatively new fuel in marine applications and only used by LPG carriers for a few years' time.

Storage, machinery, and systems are available. Also, safety measures and procedures for handling are available through the IGC and IGF-codes

LPG is a produced from wet gas and consists of propane (C_3H_8) or butane (C_4H_{10}) or a mix of the two. It is well known as a cargo and has over the last few years become a fuel for a number of large LPG carriers as well, lead by the conversion of a VLGC by BW LPG. Today, less than a hundred vessels, all LPG-carriers, can run on LPG.

Emissions

With more carbon relative to hydrogen, LPG emits more CO_2 than LNG but less than diesel. These figures are based on the carbon content and adjusted for the energy content of LPG and assumes the same efficiency of the machinery. LPG does not contain methane and therefore does not suffer from methane slip.

LPG has the lowest GHG emissions among the fossil fuels and the best energy efficiency well to wake (ref the diagrams in chapter 9.2.

Emissions and energy use for LPG	Thermal eff. (WTT·TTW=WTW):	Footprint WTT	Emission factor WTW
	0.91 · 0.50 = 0.45	8.3 g/MJ (-42%)	540 g/kWh (-17%)

LPG does not contain sulphur and thus eliminates SO_X. NO_X-formation depends on the engine. Low pressure engines will produce very little NO_X, well below the Tier III-limit, while high pressure engines will require EGR or SCR to meet Tier III.

Production, infrastructure and availability

Around 330 million tonnes of LPG are produced annually. 60% is separated from oil and natural gas extraction while the remaining 40% is a coproduct of the and oil refining [WLPGA 2021 | ↗]. Around 1/3 is traded by sea [Clarksons, 2020 | ↗]. LPG is therefore available worldwide, but not necessarily as a marine fuel.

If all ships worldwide should use only LPG, the demand would be about 305 mill t/y (14.1 EJ). This is about 90% of the annual current production.

Technology

In ambient conditions, LPG is a gas, but only requires low pressure to liquefy, e.g. 18 bar at ambient temperatures or 5-8 bar in semi-refrigerated tanks (-10 to -20°C). Cylindrical pressure vessels handle pressure build up from boil off gas better and are generally preferred for storage. LPG does not rely on cryogenic tanks and fuel supply systems and is thus easier and less costly to install and handle.

MAN reports sales of 100 ME-LGIP-engines [MAN | ↗]. Conventional diesel engines can be converted to burn LPG, as demonstrated by BW LPG recently. With very low methane number, the engine must be derated significantly to avoid knocking. In practical terms, it means more cylinders or larger bore compared to an engine running on MGO or LNG.

Tanks and systems for LPG can be a good starting point for ammonia with regards to temperature and pressure, while the pipe dimensions should be increased to compensate for ammonia's much lower heating value.

Safety

LPG is heavier than air and will accumulate if leaked. The gas must be carried in double wall piping and arrangements for gas detection, ventilation and purging are required.

The long experience from handling LPG as a cargo under the IGC-code lays a good foundation for handling LPG as a fuel, although additional training and certification of engineers will be required for ships without previous experience with LPG.

Summary

There are low energy losses in the production and LPG can cut 17% of GHG. Engines and systems are available, so are rules and regulations for design and operation.

⊕	*Well known as a maritime cargo.* *Low energy use well to wake.* *Engines and systems available*
⊖	*Low methane number requires derating of engine.*

9.13. Hydrogen (H_2)

SUMMARY

Hydrogen gives no harmful emissions onboard and the environmental impact is determined by the production. H_2 from natural gas gives more (+65%) GHG than MGO well to wake while H_2 from electrolysis with renewable electricity can give zero emissions also in production.

The energy use well to wake is high for both production methods: Around two times MGO.

Low carbon hydrogen can be produced from natural gas once CCS becomes available. The footprint will then depend on the carbon capture rate.

The first H_2-plants are planned for 2024, although with very, very small capacity.

Engines are under development and fuel cells will be scaled up to the size required for small ship. Storage for hydrogen seems to be the most challenging technical piece, considering the need for compact and safe storage.

Hydrogen is an interesting, but challenging fuel for the transport sector. It ignites and burns easily, is explosive in concentrations above 4% and burns in concentrations from 4 to 75%. On the positive side, it is very light and disperses easily if leaked to air.

Most importantly, hydrogen emits only water vapour: No CO_2 or other greenhouse gases, no NO_X, SO_X or PM. Marginal amounts of particles may come from lubrication oil. Pilot fuels are likely not needed as hydrogen ignites and burns well alone.

Hydrogen will be introduced onboard ships in Norway with the ferry Hydra (first half of 2022) and two smaller ro/ro vessels built by Wilh. Wilhelmsen for shuttling between offshore bases on the Norwegian west coast. From 2024 or 2025, four ferries connecting Lofoten with Bodø shall run at least 85% on hydrogen [TU, 19 Jan 2021 | ↗]. A Dutch river barge, Maas, carrying containers is fitted out with an 825 kW fuel cell and 500 kWh battery to run on hydrogen in 2021 [Future Proof Shipping | ↗]

Many key industry nations have worked out hydrogen strategies and Korea has even enacted a law to firm up its hydrogen ambitions. The first approval in principle was awarded to a 20,000 m^3 liquid hydrogen tanker in 2020 [The Naval Architect, Oct 2021].

The IEA net zero scenario assumes 2% of maritime energy to come from hydrogen by 2030 and 17% by 2050 [IEA, 2021, p. 137 | ↗]. Shell forecasts hydrogen to cover 1% of global energy by 2040 and 6% by 2070 [Shell's Sky scenario, 2018 | ↗] while DNV is more optimistic and suggests 5% in 2050 [DNV ETO 2021 | ↗]. While the numbers from IEA and Shell are *scenarios*, DNV presents a *forecast*.

Emissions well to tank from hydrogen production

H_2 give no emissions in combustion (tank to wake) so the critical part is therefore the production. Hydrogen from natural gas gives 60% higher emissions well to wake than MGO. Both steam methane reforming and electrolysis requires a lot of energy; only around 20% of the energy reaches the propeller shaft compared to 42% for MGO.

Emissions and energy use for H_2 (grey)	Thermal eff. (WTT·TTW=WTW):	Footprint WTT	Emission factor WTW
	0.44 · 0.50 = 0.22	150 g/MJ	1,086 g/kWh (+66%)

H_2 from electrolysis is as green as the electricity that is used in the process. Hydrogen is therefore only climate neutral or low carbon when produced by electrolysis with renewable electricity (green hydrogen) or nuclear electricity (pink hydrogen). Less than 1% of the current hydrogen production is renewable [IEA, 2022 | ↗].

Emissions and energy use for H_2 (green)	Thermal eff. (WTT·TTW=WTW):	Footprint WTT	Emission factor WTW
	0.40 · 0.50 = 0.20	near zero	near zero

Below, we will explain the other possible production avenues for hydrogen. Hydrogen produced from natural gas by steam methane reforming is the most mature method but gives very high GHG emissions. If CO_2 is captured and stored permanently, hydrogen can be produced from coal and natural gas with low emissions. The capture rate is not yet confirmed; modern technology can likely capture 90% or more [Gardarsdottir, 25 August 2021 | ↗] while some studies say the realistic capture for coal gasification will be only 60% [Li et al, 2022 | ↗].

Experience with hydrogen as a rocket fuel indicate that significant volumes of hydrogen leak from production and transport. Increased concentrations of hydrogen in the atmosphere may also have a global warming effect, and research is underway to estimate the effects of this [Derwent et al., 2006 | ↗]. With high hydrogen prices, such losses are also an economic concern.

Energy loss well to tank with electrolysis and fuel cell

Shakeri, Zadeh and Nielsen analysed the challenges with hydrogen and fuel cells [2020 | ↗]. They estimate the total efficiency to be highest for pressurised hydrogen and LOHC; around 0.30 and 0.29 respectively. Liquefaction of hydrogen requires cooling to 253°C; the energy use increases the losses and gives η ≈ 0.25. Even higher losses occur when hydrogen is converted to ammonia and back; this lowers the total energy efficiency to 0.20.

Production, infrastructure, and availability

Hydrogen can be produced from different raw materials and by different methods. Many of the production technologies are familiar and proven. A colour scheme is used to identify the different ways to make hydrogen:

	H	H	H	H	H	H	H	H	H
Colour	*Black or brown*	*Blue*		*Grey*	*Blue*	*Turquoise*	*Grey*	*Green*	*Pink*
Raw material	Coal		Biomass	Natural gas			Water		
Process	Gasification			SMR or ATR		Pyrolysis	Electrolysis		
Prerequisite	N/A	CCS	-	-	CCS	-	Fossil electricity	Renew. electricity	Nuclear electricity
GHG WTT	High!	Low	Net zero	High	Low	Near zero	High	Near zero	Near zero
Maturity	High	Medium		High	Medium	Low	High		
Share of production	About 20%			About 80%	< 1%	R&D		< 0.1%	

Table 10: Various routes to hydrogen

In 2021, around 94 million tonnes were produced, almost entirely from natural gas, but also from coal [IEA | ↗]. Only four production sites use carbon capture and storage today [Bloomberg NEF, 2020]. Without CCS, the footprint of today's H_2 production is high; about 900 million tonnes CO_2 [IEA | ↗]. Scaling up based on natural gas and coal without carbon capture and storage is clearly not good for global warming.

If all the announced plans for production of low emission hydrogen are realised, the global annual production can reach 24 Mt by 2030, i.e. around 25% of the current production [IEA, 2022 | ↗]. Scaling up production to replace the current production of fossil-based hydrogen and also providing the volumes of hydrogen required by the steel industry and transport sector is clearly a massive undertaking. Keep in mind that – taking a holistic approach – we should replace the current fossil H_2-production first, before making renewable hydrogen for new applications.

Electrolysis was used in Norway since 1927 but was discontinued for economic reasons. Less than 0.1% of global dedicated hydrogen production today comes from electrolysis [IEA, 2019 | ↗]. Producing today's volumes of hydrogen from electricity would require 3,600 TWh, more than the total electricity generation in the EU (2,900 TWh), according to the IEA [IEA, 2019 | ↗].

Worldwide, around 40-45% of the hydrogen goes to ammonia [IEA, 2019 | ↗], [IRENA , 2022 | ↗]. In the future, Bloomberg foresees demand from steel, cement, the petrochemical industry, power generation as well as long haul and heavy transport including shipping. This is good news, as the costs and efforts for development and scaling can be shared with many other sectors. The first ferry service, Hjelmeland-Nesvik requires 150 kg hydrogen per day [Norled, Oct 2021]. Hydrogen will be supplied by truck from Germany until local production is established [TU, 15 July 2021 | ↗].

In Norway, Equinor has long been working to realize hydrogen with CCS. Together with BKK and Air Liquide, Equinor plans to produce 6 t/d at Mongstad from 2024 for the Topeka vessels. The investment is said to be 1 bill NOK [TU, May 2021]. 10 t/d is required for the Vestfjorden service [Energi Norge, Nov 2020 | ↗]. 6 and 10 t are less than one percent of what is required to power all Norwegian domestic shipping (estimate: 1,450 t hydrogen daily). This illustrates the scale, work and investments required to make hydrogen a meaningful energy carrier.

The first cargo vessel on hydrogen will be fuelled with pressurized hydrogen in a containerized solution to allow fast bunkering in both ends of the pendulum will be established for delivery from late 2023 [Statkraft, June 2021 | ↗].

In addition to production, infrastructure for distribution including ship to ship bunkering is completely lacking. Hydrogen can to some extent build upon LNG infrastructure, however, the difference in properties between the two gases should not be underestimated, e.g. boiling point, flammability and explosion risk.

Safety

Due to its small size, hydrogen escapes easily and even permeate. As hydrogen is flammable in concentrations from 5 to 75% and burns easily [H_2 tools | ↗], systems for containment, gas detection, venting and purging must be arranged. Sparks, high temperature surfaces and ignition sources must be avoided. If leaked, hydrogen is light and escapes and disperses quickly.

Technology: Practical storage is a bottle neck for increased use of H_2

Hydrogen can be stored under pressure (PH_2) or liquefied (LH_2) in insulated tanks or on the surface (adsorption) or within (absorption) of metals and chemical compounds. Liquefied hydrogen and hydrogen stored in organic oil (LOHC; liquid organic hydrogen carrier) are the two most interesting options for ships. Combinations of pressure and temperature can also be used, so called cryo-compressed tanks with temperatures from -120 to -196°C.

Pressurized storage (up to 700 bar) are built up by an array of long cylinders arranged in a container frame. Careful stacking of the cylinders helps to maximise the volumetric utilization, yet pressurized storage take too much space, the tank weight is too high and the large number of bottles, valves and connections are impractical and expensive.

At -253°C, hydrogen is compressed 800 time to 71 kg/m^3, yet it still takes up 4-5 more times than MGO, adjusted for energy content. Thick insulation, tank fittings and voids around the tank adds to this volumetric inefficiency. At such low temperatures, some hydrogen will boil off and the tank must handle some pressure increase. Cryogenic tanks have so far been spherical but prismatic tanks will utilize the space onboard a vessel much better. Prismatic tanks can likely be developed based on LNG-tanks.

The first shipment of liquefied hydrogen took place in February 2022, from Australia to Japan.

Embedding hydrogen in organic liquid (LOHC; liquid organic hydrogen carriers) is a novel storage alternative under development currently. The liquid can be stored in prismatic tanks designed for organic oils, at ambient temperatures and pressure. Avoiding large volumes of pure hydrogen avoids many of the safety risks and the operational difficulties with boil off and pressure build up. The hydrogen loaded liquid will have 80% of the energy of pure liquid hydrogen; 57 vs 71 kg/m^3 or 6,840 vs 8,500 MJ/kg [Hydrogenius | ↗]. Hydrogen stored in organic liquids still require 5.6 times the space of MGO.

If LOHC proves successful, many of the safety risks and impracticalities of handling hydrogen is dealt with. And the equipment cost can be drastically reduced. The significant conversion losses are a fundamental disadvantage with LOHC.

Technology: Machinery or fuel cells for hydrogen

Fuel cells were long considered synonymous with hydrogen, but the last few years have seen established makers of dual fuel, medium speed four stroke engines launching ambitions to redesign existing engine lines for hydrogen.

While many considers hydrogen as a future fuel, four stroke engines for dual fuel or pure hydrogen are commercially available today.

ABC, Bergen Engines and Wärtsilä are all developing engine variants for hydrogen. An Otto engine on H_2 must likely be derated compared to the LNG version. Fine tuning of the combustion is necessary to achieve acceptable pressure levels and temperatures and thus NO_X-formation [Portin, 18 May; Portin, 26 May].

Some dual fuel gas engines have been able to burn blends with up to 25% or even 40% hydrogen for many years already and Wärtsilä is testing increasing blends of H_2/LNG with a view to test 100% H_2 on four strokes engines of both the Otto and Diesel principle and release such an engine by 2025. [Portin, 18 May; Portin, 26 May].

The first dual fuel hydrogen engine from ABC is installed in a tractor tug due to enter service in the port of Antwerp from 2023 and ABC have both dual fuel and pure hydrogen engines commercially available, under the BeHydro label.

To sum up, both dual fuel and pure hydrogen four stroke engines will be available from multiple makers within a few year.

Summary

The car industry is building up experience with production and handling of hydrogen, but it is yet unproven in maritime applications. Safety and handling procedures are available. Only grey hydrogen with much higher GHG well to wake is available, so hydrogen does not make sense just yet. Production of green or blue hydrogen must begin. Some pilot projects are under planning and construction.

⊕	No harmful tailpipe emissions. Can be used with internal combustion engines (four strokes) as well as fuel cells. Can give very high efficiencies on fuel cells.
⊖	Energy intensive production. Requires large storage volumes, cryogenic storage. No operational experience yet.

9.14. Ammonia (NH_3)

SUMMARY

Unlike hydrogen, ammonia gives N_2O and NO_X and is not entirely without emissions tank to wake. The amount of N_2O is unknown at this stage. Noting the very high GWP of N_2O, it must be minimised as only a few grams will make ammonia as polluting as fossil fuels.

If ammonia is produced without emissions (well to tank), the total GHG can still be reduced by 89%.

Today, ammonia is produced by reforming natural gas. This process gives 45% higher GHG emissions well to wake.

The energy use is also high (1.6-1.8 times MGO), yet lower than for hydrogen.

Engines are under development and ready from 2024. Fuel cells can take ammonia, but with lower efficiency than for hydrogen, considering the need to crack (convert) NH_3 to H_2.

Ammonia receives lots of interest and support, despite the technical challenges with solid oxide fuel cells and the toxicity.

85% of all ammonia is used to produce synthetic nitrogen fertilizer [IRENA , 2022 | ↗]. It is also used to produce plastics, explosives synthetic fibres and in refrigeration, mining and water treatment. With no carbon and three hydrogen atoms, it is also an interesting hydrogen carrier and thus a potential fuel.

Ammonia has for some years received a lot of positive attention. DNV's energy transition outlook forecasts ammonia to constitute 25% of maritime fuels in 2050 [DNV ETO 2019 |↗]. The IEA roadmap sees a major role for ammonia, together with advanced biofuels [IEA, 2021, p. 61 | ↗]. In its roadmap to net zero, the net zero scenario assumes 8% of maritime energy to come from ammonia by 2030 and 46% by 2050.

Indeed, the shipping industry is moving to realize ammonia with approval in principle to several design projects at major shipyards as well as research projects on engines and fuel cells. Several ship design projects working to obtain approval in principle cover container vessels, gas and tankers and shall be realized by 2024-25 [The Naval Architect, March 2021, p. 6 and 29 | ↗],

Emissions

Ammonia is today produced primarily from natural gas without CCS (72%) and coal (22%), naphtha and fuel oil. Less than 0.02 Mt of 185 Mt (0.011%) was produced renewably in 2021 [IRENA, 2022 | ↗]. The colour scale that is used for hydrogen can be used for ammonia, as ammonia is a form of hydrogen. Unlike hydrogen, Ammonia is not entirely emissions free and will emit N_2O and NO_X; the volumes of these exhaust gases are not yet known. The current production of ammonia thus gives very high emissions well to tank; about 45% more than MGO.

Emissions and energy use for NH_3 (grey)	Thermal eff. (WTT·TTW=WTW): 0.48 · 0.50 = 0.24	Footprint WTT 120 g/MJ (+740%)	Emission factor WTW 942 g/kWh (+45%)

Climate neutral ammonia is produced from renewable hydrogen using nitrogen that is separated from air. Climate neutral ammonia thus depends on climate neutral hydrogen production. Produced without emissions, ammonia can reduce GHG well to wake by 90%.

Emissions and energy use for NH_3 (green)	Thermal eff. (WTT·TTW=WTW): 0.53 · 0.50 = 0.26	Footprint WTT near zero	Footprint WTW 68 g/kWh (-90%)

Note that although ammonia is produced from hydrogen, it requires less energy to produce than liquid hydrogen as the liquefaction is very energy intensive.

In high pressure engines, the nitrogen in ammonia will give not only N_2O but also NO_X. MAN intends to handle this with EGR as they do for LNG-engines. Keep in mind that while Tier III engines can reduce NO_X, they are only obliged to do so when in ECAs and for reasons of economy, ships will likely run in Tier II-mode outside ECAs.

Unlike hydrogen, ammonia gives N_2O and NO_X and is not entirely without emissions tank to wake. Fine tuning of the combustion or after treatment are therefore required to eliminate or minimize N_2O and NO_X from ammonia.

The need for quite significant pilot fuel volumes, MAN suggest 5-8%, will give some soot in the exhaust. Hydrogen will manage without or use gas as pilot fuel, so while ammonia and hydrogen are commonly both described as zero emissions fuels, there are indeed differences, although they may be minor.

Production, infrastructure and availability

Around 185 mill tonnes are produced annually. One tenth of this is traded internationally and ammonia is therefore a maritime cargo and thus a chemical compound well known to the shipping companies carrying it [International Fertilizer Association, 2022 | ↗].

Ammonia for fertilizer were produced by electrolysis in Norway until the 1960/70's, and until 1993 in Glomfjord, but replaced by gas reforming which was cheaper. Yara now intends to shift its production back to electrolysis, at a cost 2-4 times higher than with steam reforming, pending financial support from Norway [DN, 9 April 2021 | ↗]. The scale of this shift is herculean; Yara will require electrolysis capacity of 450-500 MW, while the global aggregated electrolysis output is only 100 MW today. Together with partners, Yara intends to supply ammonia for ships as a side stream [DN, 8 Dec 2020 | ↗]. All going well, production can be ready in 5-7 years time [Yara, 16 Aug 2021 | ↗].

Globally, existing and announced projects for low and near zero carbon emission ammonia production can give nearly 8 Mt/y [IEA, 2021 | ↗] or 15 Mt/y by 2030 [IRENA , 2022 | ↗]. This is just a fraction of the current production (185 Mt/y) and also just a fraction of the forecasted demand from the maritime sector which IRENA estimates to 197 MT by 2050.

Production, supply, bunkering infrastructure for Ammonia is lacking, but due to similar properties as LPG, it is expected that ammonia can use systems built for LPG, both on shore and on board, and be transported in LPG-carriers. Amoi as a liquid at 8 bar or above and at ambient temperature, or at atmospheric pressure at -33°C.

Ammonia has its challenges; it is toxic, colourless and corrosive. While LNG fuel tanks are stainless steel or 9% nickel steel, ammonia must be stored in high manganese steel tanks. The toxicity puts strict requirements to safety and may limit the use on certain vessel types or trades.

If leaked, an ammonia vapour will disperse and require evacuation of people from the surrounding areas. Storing of ammonia close to large population centres may be considered too risky and ultimately prevent storage and supply of ammonia from ports near cities. Bunkering in remote industrial ports and from bunker barges is therefore advised.

Ammonia production takes about 45% of the global hydrogen consumption. The production cost of renewable hydrogen represents 90% of the production cost of renewable ammonia [IRENA , 2022 | ↗].

Technology: Internal combustion engines for ammonia

Ammonia can be burnt in a conventional engine or in fuel cells.

Both two and four stroke engines for ammonia are under development. Ignition can be by compression or spark plugs. Slow combustion and the presence of nitrogen in the fuel will give NO_X in the exhaust, which will require EGR or SCR to meet Tier III emission levels. A scrubber to wash away unburnt ammonia and derating is likely required.

The long quenching distance also leads to incomplete combustion and the formation of unburnt ammonia in combustion chamber crevices [Motorship, May 2020 | ↗]. The unknown volumes of the highly potent greenhouse gas N_2O will be a serious threat to ammonia's viability as a green fuel and warrants further optimization. Only 2-3 g/kWh of unburnt N_2O will give GHG emissions on par with a diesel engine, when multiplied with the GWP_{100} for N_2O of 273 [IPCC AR6WG1, Chapter 7, page 1017].

Considering the poor combustibility of ammonia, slow speed, two stroke engines will likely be a good concept to achieve high efficiency, complete combustion and low ammonia slip. However, adjustments must be made to cater for different physical and chemical properties. MAN expects more pilot fuel (perhaps 5-8% compared to 1.5% for LNG).

MAN is banking on this and is aiming to have a variation of the ME-engine available from 2024 and make retrofit kits to convert any ME-engine. The major conversion will be in the fuel systems, storage and service tanks and piping [MAN/Aabo, 19 May 2022]. Machinery and systems for gas engines with liquid fuel injection (i.e. LPG and methanol rather than LNG and ethane) are considered the best basis for ammonia due to similarities in the storage and fuel gas supply system.

Wärtsilä initiated combustion tests in March 2020 with a view to develop both DF and spark ignited four stroke engines for ammonia, ready for the first installation in 2023 [Wärtsilä, March 2020 | ↗], [Kaj Portin, 18 May]. "Whereas with hydrogen you have high combustibility, and fast flame speeds at stoichiometric ratios, ammonia does not burn very well and slows down the combustion process at higher concentrations", explained Kaj Portin [Motorship, May 2020 | ↗]. Wärtsilä believes ammonia must be used with MGO or biodiesel as pilot fuel to ensure proper combustion [Portin, 18 May].

Interestingly, considering their history with low pressure LBSI engines, Bergen Engines is considering the high pressure diesel concept in their R&D for ammonia [Bergen/Skarbø, 19 May].

Japan Engine Corporation is working with NYK to launch a tug with a four stroke ammonia engine by 2024 and an ammonia carrier by 2026 [NYK, 26 Oct 2021 | ↗]

A regulatory framework and class rules will need to be developed for ammonia a marine fuel [Wärtsilä, March 2020 | ↗],

Technology: Fuel cells for ammonia

Fuel cells can be used to convert the chemical energy in ammonia to electricity. Fuel cells are discussed in chapter 9.4 and 9.13 and only the special characteristics of fuel cells for ammonia are discussed below.

Solid oxide fuel cells (SOFC) can take ammonia directly while PEM-cells require a cracker to convert ammonia to H_2 before the cell, at a loss of 22% [The Naval Architect, June 2018 | ↗]. SOFC will likely be used in stationary applications while PEM-type seems more fit for transport applications as the PEM-type can handle load variations and require shorter time to start.

SOFC operates at very high temperatures (800-1,000°C) and takes long time to heat up and also long time to accommodate load variations. SFOC are therefore best suited for continuous and stable base loads. If waste heat recovery (WHR) can be utilized and under ideal conditions.

Eidesvik and Odfjell are working to realize fuel cells for ammonia on offshore supply and parcel tankers. Eidesvik will install 3 MW SOFC type fuel cell [Eidesvik].

SOFC are likely ready for final testing in 2028. No systems are ready for marine applications and there are question marks with regards to the ceramic materials' tolerance for vibrations.

Summary

Unlike hydrogen, ammonia will likely give N_2O and NO_X and is not entirely without emissions tank to wake. Its GHG advantage depends on the production; renewable electricity or carbon capture and storage is required to produce ammonia with low footprint. Engines and fuel cells are under development.

⊕	Occupies less space than hydrogen onboard. Easier storage than hydrogen. Can be used with two stroke diesel engines. Can be used with high temperature solid oxide fuel cells directly
⊖	N_2O must be eliminated, and NO_X must be reduced to Tier III-levels. Toxic and corrosive, significant health hazards if leaked. Current production methods give much higher emissions than MGO, well to wake. Cannot be used with PEM-cells, due to impurities.

9.15. Fuel transition strategies

SUMMARY

The table sums up some facts and their consequences for alternative fuel strategies.

Fuel transition strategies should be based on gradual and increasing blend-in of climate neutral fuels, employ dual or triple or multi fuel engines, consider the energy demand to produce the fuel and – critically – start with fuels that are available so that GHG is reduced quickly.

This gives the supply side time to scale up and establish the required global infrastructure. It also gives the vessels flexibility and ensures continued sailing even if/when the new fuel is unavailable; either temporarily or in a certain trading area.

Now that we have reviewed the possible future maritime fuels, we will try to be concrete and present some promising fuel transition strategies that adequately address the challenges we have observed in the initial chapters, such as the need for deep, rapid and sustained emission cuts while at the same time observing the scarcity of climate neutral primary energy and thus the importance of energy efficiency also when it comes to fuel production.

The following elements must be considered when drafting a fuel transition strategy:

1		Global warming depends on the atmospheric concentration of GHG and thus accumulated emissions rather than annual emissions Rapid but modest emission reductions can contribute to reduce GHG and avoid tipping points.
2		All alternative fuels take up more space (ref chapter 9.3) and cost more. Energy consumption onboard should therefore be minimized to maximise cargo capacity and minimize fuel costs.
3		New fuels will, initially, be available in few locations or depend upon complex supply chains. Dual or multi fuel engines can increase the operational range allow redeployment and increase second hand value.
4		Novel technology onboard may fail more frequently, at least initially. Redundancy and access to a secondary fuel reduces offhire risk.
5		Alternative fuels cost more. Blends of climate neutral and conventional fuels can minimize the fuel bill avoid dramatic overnight cost spikes.
6		Production facilities will, initially, have limited production capacity. Gradual increase from small to larger volumes gives landside production side time to scale up.
7		Infrastructure for fuel distribution requires land, is costly and takes time to establish. Same or similar fluids and gases (e,g. biomethane in LNG-tanks) with modest blend in of alternative fuels can utilize existing infrastructure and speed up the transition.

Based on the above key elements, we believe that a strategy based on multiple fuels with a gradual transition from today's fossil fuels (e.g. LNG) to greener fuels (e.g. biomethane) is the best and most realistic way forward. The preference for dual fuel engines is confirmed by the fact that 4 of 5 LNG-fuelled vessels can also burn diesel [DNV AFI | ↗]. A gradual transition can happen with *intermittent* use of a green fuel and a conventional (fossil) fuel or by *blending* in a certain share of the greener fuel.

Recalling from chapter 2.1 that GHG emissions must peak before 2025 to avoid global temperatures above 1.5°C and that emissions must drop by about 45% before 2030, we conclude that alternative fuels must be phased in as quickly as possible. Noting also that the global temperature increase is determined by the concentration of greenhouse gases and which in turn is determined by *accumulated* emissions rather than *annual* emissions, we conclude that an early transition is better than a late transition. While this may seem obvious, it the time aspect is often forgotten, and we note with concern that many seem to prefer to commit to zero emissions in 2050 rather than more moderate reductions in 2030 or 2040.

> *We see four success criteria for fuel transition strategies: Fuel transition strategies should be based on gradual and increasing blend-in of climate neutral fuels, employ multi fuel engines, consider the energy demand to produce the fuel and – critically – start with fuels that are available so that GHG is reduced quickly.*

Fuel transition strategies should be based on dual or triple fuel machinery. The basis fuel must be widely available throughout the operating area of the vessel to ensure continuous operation while the new fuel should be blended in or used intermittently as much as possible. A gradual transition seems more realistic than a hard shift, considering both availability and fuel prices.

This approach is suggested in other sectors; the IEA foresees hydrogen to be blended into the natural gas network as well as retrofitting gas fired power stations to co-fire with hydrogen and retrofitting coal fired power plants to co-fire with ammonia [IEA, 2021, p. 75-76 | ↗]

Feasibility assessment of alternative fuels

The near-term feasibility of each alternative fuel is a product of the fuel availability and the technical readiness level (TRL) i.e. availability of machinery, storage tanks and systems. This can be summarized by the below illustration. Note that some fuels can use different types of engines or fuel cells or boiler and thus the TRL will vary between them and develop over time.

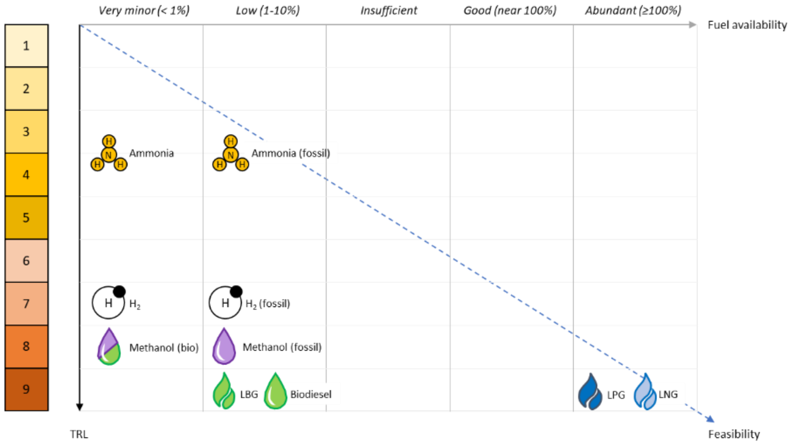


Figure 89: Near-term feasibility of alternative fuels based on technical maturity and fuel availability.

Based on this, conclude or assume that biomethane can be phased in from 2026, biomethanol and synthetic fuels from 2027, hydrogen and ammonia from 2030.

Further, we assume that all alternative fuels are blended in starting at 5% and growing at 5% pa to a maximum share of 75%. Adding only 5% per annum allows the production side to scale up. We limit the maximum share to 75% because it will take a long time to build up a supply network to make all alternative fuels as widely available as fuel oils.

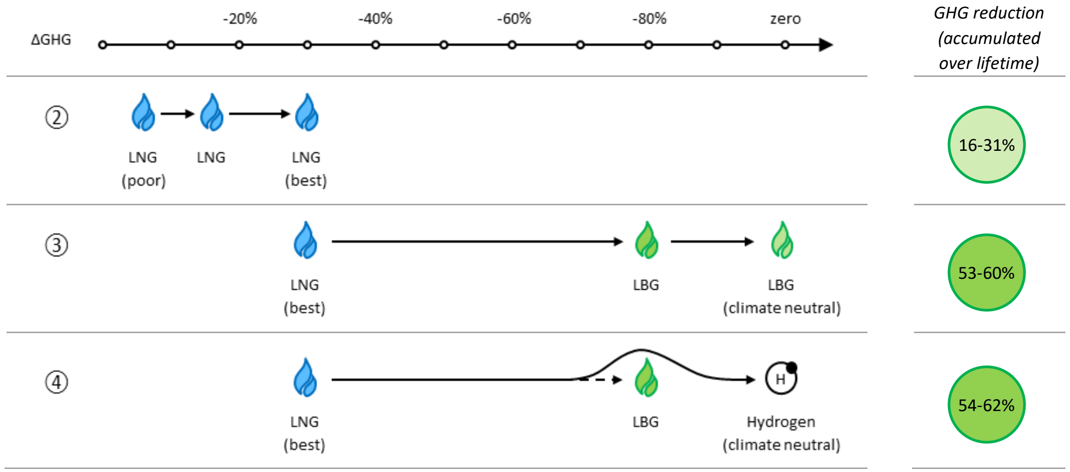
Alternative fuel pathways

To be concrete, we analyse and suggest four pathways (no. 2-5) building on LNG as basis fuel and four pathways (no. 6-9) starting with MGO. The various alternative fuels are placed from left to right (in the below illustration) to indicate their emission reductions potential well to wake.

The continuous arrows indicate the suggested transition for each pathway while the dotted arrows indicate transitions that are technically possible, and thus indicates the flexibility to move further or between fuels. E.g., referring to transition strategy 4, we note that LNG can be combined with both hydrogen and biomethane.

Note that other combinations than the below eight are also possible.

We evaluate the climate effect of each fuel transition pathway by the GHG emissions reduction accumulated over the lifetime for a vessel constructed today, i.e over 30 years from 2025 to 2054. The reduction relative to MGO is indicated in the circles.



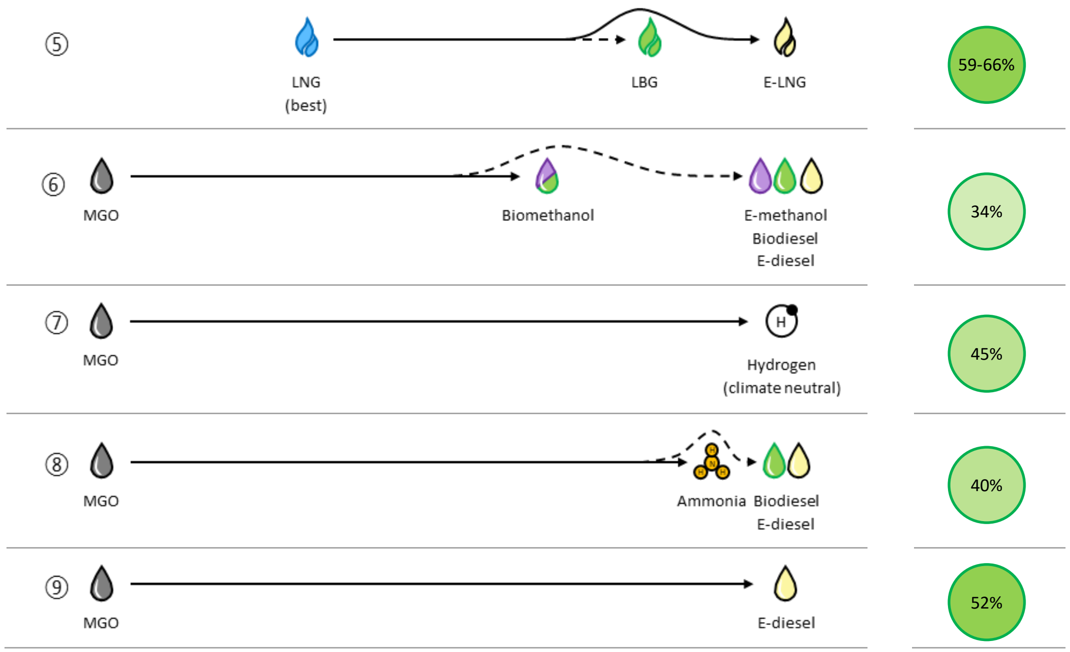


Figure 90: Eight fuel transition pathways.

Based on the assumed phasing in schedule, we note that strategy 5 (LNG + synthetic LNG) gives the highest climate effect. The disadvantage of synthetic fuels is the high energy losses in production and thus synthetic fuels can only be recommended when or if renewable energy becomes abundant.

The fuel transition strategies based on LNG give very good climate effect as the LNG reduces the emissions from the first day of operation and the successive phasing in of biomethane or hydrogen or synthetic LNG contributes to reduce the emissions year on year. Depending on the footprint of the LNG used, pathway 3 and 4 cuts GHG by 53-60% and 54-62% respectively.

Biomethanol, pathway 6, gives good results because biomethanol is available early but with only 65% lower emissions WTW, the total effect is limited to 34%. Better types of biomethanol can make pathway 6 better.

Interestingly, the pathways with hydrogen (pathway 7) and ammonia (pathway 8) do not give the highest climate effect due to the late introduction of these fuels. If hydrogen is phased in faster, e.g. starting at 10% in 2030 and increasing its share by 10% every year until it covers 90% of the energy in 2038, the total climate effect increases to 63%. The same phasing in schedule for ammonia will give accumulated total emissions 53% below MGO. With this phasing in schedule, strategy 7 and 8 matches strategy 3-4.

Interestingly, the fuel transition pathways building on LNG reduces GHG more over the next three decades simply because LNG gives a head start. If green fuel becomes temporarily unavailable, LNG will be a better backup fuel than MGO and ensure moderate emission reductions until the vessel can bunker the green fuel again.

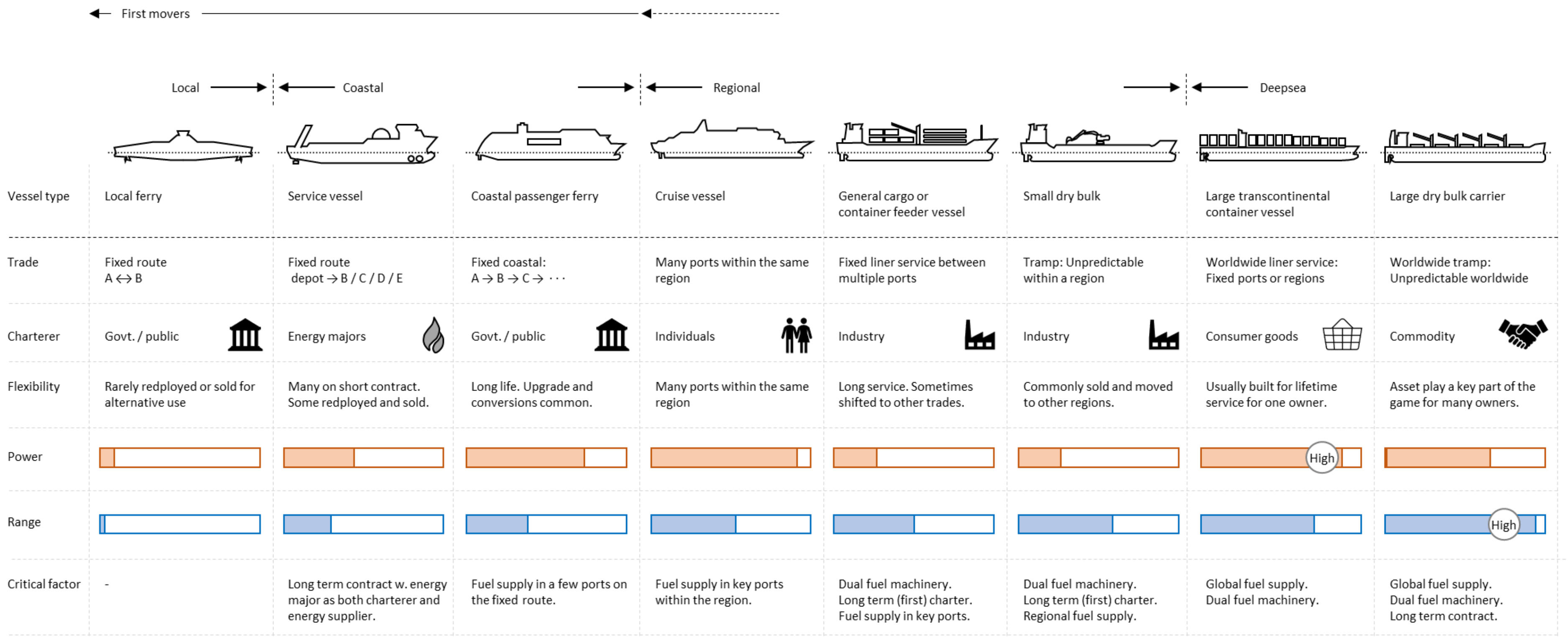
First mover segments

Some vessels are better positioned to take up alternative fuels early, with less disadvantages, risk and cost. Vessels with higher requirements to flexibility, both in the daily operations (e.g., unknown destinations) and over the vessel's lifetime (e.g. the need to redeploy the vessel to other trades or sell the vessel) will likely change to alternative fuels later.

The first mover cases are characterized by low energy use, short sailing distances and predictable operations. The type of charterer or end customer also matter.

Bulk commodities where price is the first, second and third criteria will likely move last, unless their charterers extend their sustainability policies to the transportation leg as well. Although we see some charterer initiatives towards this end, the majority of dry bulk vessels will continue to win contracts based almost exclusively on price.

For manufactured goods shipped in containers, the transportation cost is only a small fraction of the total cost of the total product cost. This could make container vessels one of the most promising segments for alternative fuels, and other environmental measures. On the negative side, more than half of the vessels operated by many of the major container liners are chartered in from tonnage providers, which may not afford the same long term perspective and optimization and tailoring of individual vessels to specific trades and ports.



Vessel type	Local ferry	Service vessel	Coastal passenger ferry	Cruise vessel	General cargo or container feeder vessel	Small dry bulk	Large transcontinental container vessel	Large dry bulk carrier
Trade	Fixed route A ↔ B	Fixed route depot → B / C / D / E	Fixed coastal: A → B → C → ···	Many ports within the same region	Fixed liner service between multiple ports	Tramp: Unpredictable within a region	Worldwide liner service: Fixed ports or regions	Worldwide tramp: Unpredictable worldwide
Charterer	Govt. / public	Energy majors	Govt. / public	Individuals	Industry	Industry	Consumer goods	Commodity
Flexibility	Rarely redployed or sold for alternative use	Many on short contract. Some redployed and sold.	Long life. Upgrade and conversions common.	Many ports within the same region	Long service. Sometimes shifted to other trades.	Commonly sold and moved to other regions.	Usually built for lifetime service for one owner.	Asset play a key part of the game for many owners.
Power							High	
Range								High
Critical factor	-	Long term contract w. energy major as both charterer and energy supplier.	Fuel supply in a few ports on the fixed route.	Fuel supply in key ports within the region.	Dual fuel machinery. Long term (first) charter. Fuel supply in key ports.	Dual fuel machinery. Long term (first) charter. Regional fuel supply.	Global fuel supply. Dual fuel machinery.	Global fuel supply. Dual fuel machinery. Long term contract.

Table 11: Overview of some very different shipping segments with key characteristics that explain their eligibility as first movers into alternative fuels.

9.16. Policy implications

Alternative fuels as well as other green measures should be evaluated in a life cycle perspective based on well to wake emissions (WTW) to avoid carbon leakage. The need to address the totality when making decisions and policies must be reconciled with current conventions on territory-based national emission reporting.

Mindful of the need for deep, rapid and sustained emission cuts, alternative fuels should be evaluated based on their emissions reduction potential *and* near-term feasibility. The climate effect should be measured by accumulated GHG over a relevant time period rather than the annual emissions in a given year so that the feasibility and realistic phase-in schedule is reflected.

Metals and other materials required for batteries, fuel cells and catalysts are scarce. Sustainability standards from mining to fabrication should be developed and referred to in shipbuilding contracts, including labour conditions and pollution to soil and water.

Less than 1% of the current production of hydrogen, ammonia and methanol is produced from renewables with low well to tank emissions. Switching to these fuels is meaningless until low emission versions of hydrogen, ammonia and methanol becomes available.

Climate neutral electricity on batteries should be used wherever possible, noting the low conversion losses in production (compared to hydrogen, ammonia, methanol and synthetic fuels) and onboard. However, electrification lends itself only to very specific cases with low energy demand, i.e. small engines and short sailing distances with frequent charging. Electrification only makes sense in regions with (abundant) renewable or low carbon energy.

Biogas including biomethane can give substantial GHG reductions if made from the right raw materials. Production should be established based on waste streams, residues and organic crops from soil and sea, mindful of conflicts with food production, deforestation and land use change.

LNG can deliver up to about 30% lower GHG well to wake, if methane slip is eliminated in production, distribution, and use. Research to curb methane slip must be a priority. Gas engines built for LNG can burn biomethane (LBG) and blends of LNG and hydrogen to reduce the GHG-intensity further.

With realistic assumptions for the availability and phase in of hydrogen and ammonia, fuel transition strategies building on LNG offers the bet climate effect for vessels built today, measured by the total accumulated GHG emissions for a vessel sailing from 2025-2054.

Hydrogen and hydrogen-derived fuels such as ammonia and synthetic fuels can give (near) zero emissions from tank to wake but demand more energy in production than today's oil fuels. Emissions from production of these fuels are determined by the electricity used in the production, if produced by electrolysis.

Most alternative fuels take up more space. Unless the vessels set aside more space for fuel, vessels must bunker more frequently. Hence, alternative fuels must be made available in many key ports. Ports must facilitate simultaneous bunkering and cargo operations to avoid longer port stays.

The combustion engine, developed in the late 19 century, is reliable, well known and robust and available today. Pending successful technological developments expected within 2024-25, it can use nearly any fuel including climate neutral fuels and is already available in mega watt-size. GHG policies should target emissions - not the engine.

Hydrogen can be blended with LNG or biomethane. A strategy based on blend- in rather than replacement can help the uptake of hydrogen as well as other alternative fuels and allow time to scale up production capacity.

Fuel transition strategies must be built from zero with gradual annual increase in volumes to support experience building and gradual increase of fuel production capacity. It should be built on multi-fuel engines to allow continues operation regardless of fuel supply disruptions.

9.17. Sources and further reading

	Link
DNV: Alternative fuels insight (AFI).	→
European Commission: European Alternative Fuels Observatory (EAFO).	→
Hannah Ritchie and Max Roser, Our world in data (2020): Renewable energy.	→
Hwang, Jeong, Jung, Kim, Zhou (2019): Life cycle assessment of LNG fueled vessel in domestic services.	→
IEA (2021): Total primary energy supply by fuel, 1971 and 2019.	→
IEA (2021): Net zero by 2050, a road map for the global energy sector.	→
IEA (International Energy Agency): Renewables.	→
IEA (International Energy Agency): Global hydrogen production CO2 emisions and average emissions intensity…..	→
IEA (2022): Global hydrogen review	→
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IRENA (2022): Innovation Outlook: Renewable Ammonia	→
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LR and UMAS (2020): Techno-economic assessment of zero-carbon fuels	→
Shakeri, Zadeh and Nielsen (2020): Hydrogen fuel cells for ship electric propulsion.	→
Shell (2018): Shell Sky scenario.	→

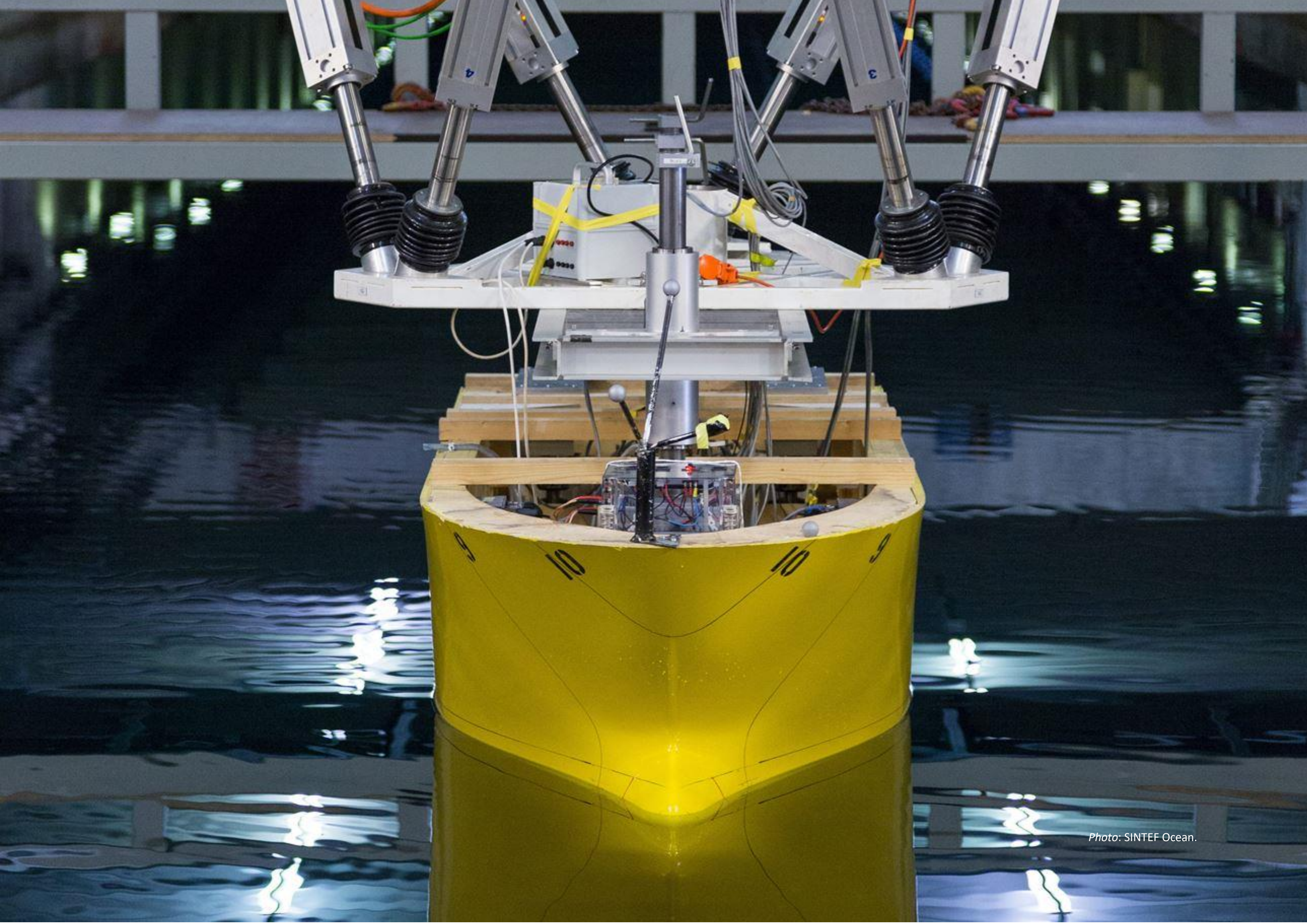


Photo: SINTEF Ocean.

10. SEA MAPS FOR KEY SHIPPING SEGMENTS

SUMMARY

In chapter 4, we laid out a procedure to decarbonization with four steps. Chapter 7, 8 and 9 explained many of the measures, their potential and applicability.

There are some key messages in this report; 1) there is no silver bullet so we need to consider and apply a range of measures. 2) the effect of a particular measure depends on a number of factors and must be evaluated by appropriate tools for the case at hand.

Despite of this, we will in this chapter lay out two decarbonization strategies for two very different vessel cases; a small general cargo ship in coastal trade with short sailings and frequent port calls and a large bulker sailing between continents with industry or agricultural commodities.

We will now use the measures discussed in chapter 7, 8 and 9 as building blocks to illustrate possible pathways for two very different vessel cases; a small general cargo vessel in a fixed coastal liner trade and a large bulker sailing tramp worldwide.

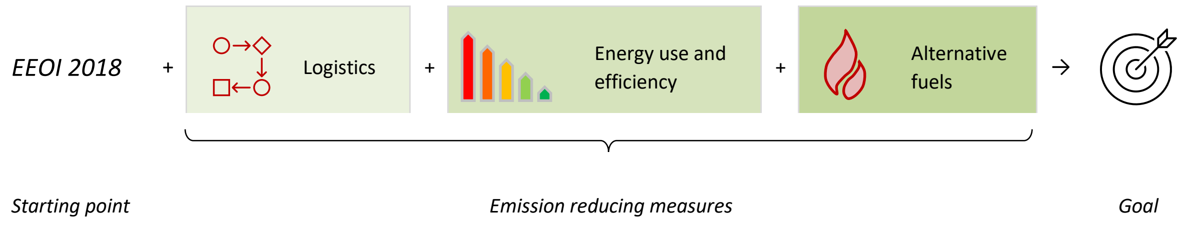
These pathways are realistic combinations of technology, operational practices and alternative fuels that fulfil the GHG goals discussed in chapter 2. The purpose is to illustrate the use of the Smart Maritime framework for generating decarbonization maps or strategies.

A key message in our report is that all technologies, operational procedures, and alternative fuels all have a role to play.

There is no silver bullet and certainly no one size fits all to greener shipping. The effect of a certain technology, say rotor sails, will be significant for some ships on some trades but insignificant for others. To find the effect for a particular case vessel, detailed analysis preferably by simulation of a full year of operation is required, as explained in chapter 5.1. Yet, in the following case examples, we estimate the effect of the various measures rather bluntly to illustrate how the path to zero emission shipping can look like.

We must stress that the percentages are indicative and approximate. Also, note that percentages cannot always be added; if a better hull form and a better engine both cuts 15%, the total is 28% (0.85 x 0.85 = 0.72). This is discussed in a paper from 2012 by Balland, Erikstad and Fagerholt [↗]. In some vessel cases, two very different technical solutions can address the same energy loss or inefficiency and thus be mutually exclusive.

The starting point is determined by the internal analysis of the entity (the shipowning or operating company) while the goal is determined by the external analysis. The starting point varies between shipping segments and particular operators. Some segments and companies have made significant progress from 2008 and have a shorter distance to go to 2030 and 2050, as explained in chapter 8.1.



The goal is 65% lower carbon intensity in 2030 and 85% lower by 2050, in line with the analysis in chapter 2.7. This will give absolute emission cuts of 45% by 2030 with a growth in seaborne trade of 3%.

The pathways to green shipping are presented to show possible combinations of technology and fuels. A key conclusion is that large reductions are possible, first in energy use, then by using alternative fuels.

10.1. A number of factors determine the decarbonization strategy

SUMMARY

Each vessel case is quite unique in terms of possibilities and restrictions. We suggest three questions as guidance to narrow in on the most relevant technologies and fuels.

The first relates to the abundance of renewable energy while the other two relates to the operations and the current fleet.

Chapter 7, 8 and 9 presented a number of technologies and alternative fuels that can cut emissions. The most cost effective and feasible combinations of technology, operational measures and alternative fuels depends on a number of factors and must be ascertained by individual case by case analysis based on specifics of the vessel and the trade it is servicing.

Yet, some factors will have significant bearing on the most fruitful pathways to zero emission shipping. When crafting a decarbonization strategy, one should consider the following key questions:

Will renewable energy become abundant?

Can the vessel and operations be tailor made for – and locked to – a particular trade?

Is the time right for building new vessels or upgrading the existing fleet?

Asking these questions can help to narrow in on the most suitable technologies and fuels. We discuss these briefly below and analyse the relevance of some technologies and fuels in light of these factors.

Will renewable energy become abundant?

On a global scale, we argued in chapter 9.1 that renewable energy will remain scarce. In corners of the world, however, the situation may be different and there may be stranded power without access to the central grid. With plans for significant growth in wind and solar power, renewable energy will or may become abundant - but when? And where?

This is not a matter of availability only, but also about energy prices. If renewable energy is scarce, it will be expensive and thus energy intensive fuels will be expensive. The question of abundance of renewable energy is therefore key for the selection of alternative fuels for the future.

Can the fleet be tailor made for – and locked to – a specific trade or service?

Another key strategic decision to be made is whether tonnage can be built or modified for a particular trade or service.

Unconventional main dimensions, hull forms, machinery and outfitting can bring significant emission cuts, but it can also restrict the use of the vessel and make it less attractive to charterers and second-hand buyers. These vessels may have a significant advantage on some trade lanes but be prohibited from sailing on other trade lanes. The predictability of the trade and long term contracts are therefore key to thing outside the box.

This dimensions affects both the choice of fuel and the array of available energy saving measures. The ability to build partnerships and secure long-term charters opens up for tailor making while the economic risk of building stranded assts.

Based on these two factors; abundance of climate neutral energy and degree of optimization and trade lock-in, we place the possible alternative fuels in one of the following four quadrants. The fuel of choice depends on the operator's view on these two factors.

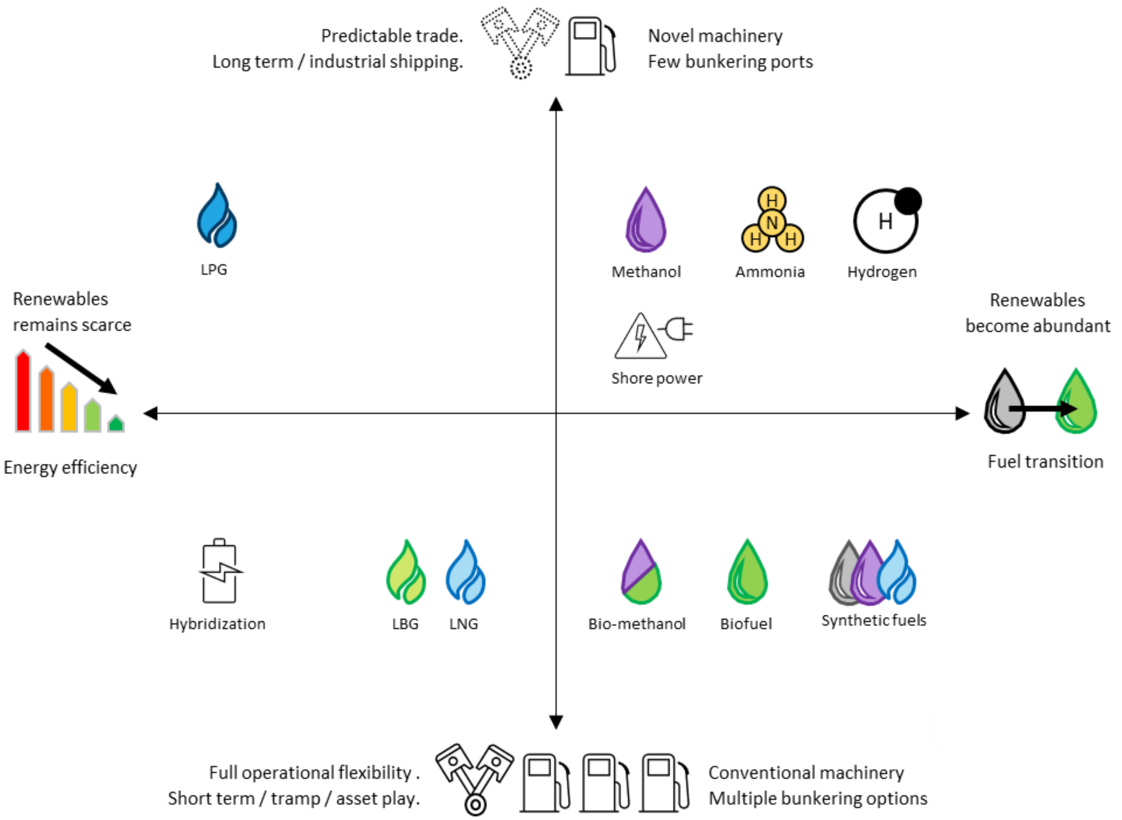


Figure 91: Categorization of alternative fuels based on future scenarios.

Is the time right for building new vessels or upgrading the existing fleet?

Finally, scrapping and building new vessels carry an environmental and economic costs. Rule number one in the waste hierarchy is to avoid waste by extended lifetime, repair and upgrading [SINTEF | ↗].

The age profile of the fleet affects the selection of energy saving technologies as well as alternative fuels. Young vessels with many good years left in service should be converted and retrofitted to lower energy use and emissions. The list of technologies suitable for retrofitting is shorter, but still has many good options.

The position of the shipowner with regards to building new or upgrading existing fleet influences the selection of energy saving technologies as well as alternative fuels. Some technologies can only be economically applied to newbuildings, while others are add-ons which can be fitted alongside or in dry dock.

Based on vessel age and degree of optimization and trade lock-in, we place the possible technical measures in one of the following four quadrants. The applicability of each measure depends on the operator's view on these two factors.

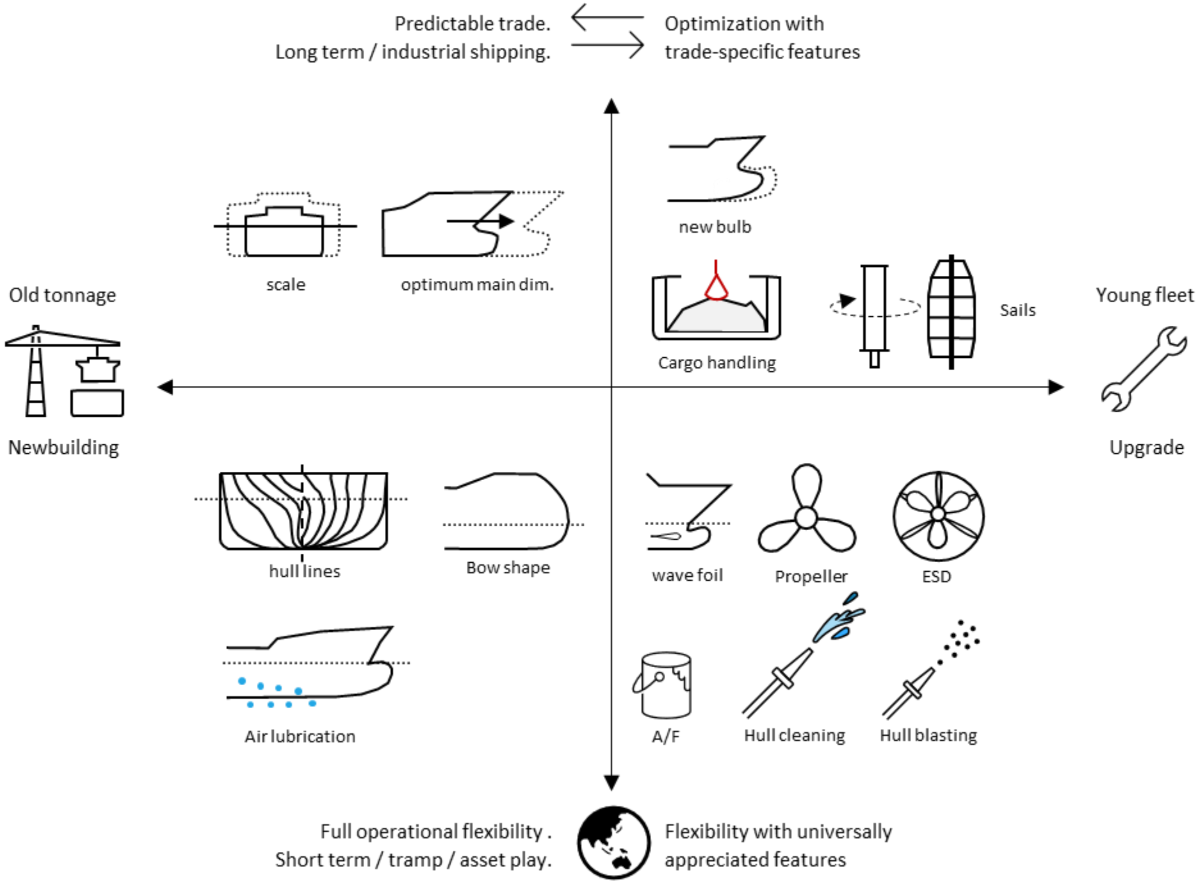


Figure 92: Categorization of environmental technology based on future scenarios.

Note that the fuels and technical measures in the two diagrams are only a selection. The idea is to illustrate how the three questions posed can be used to find the most relevant fuels and technologies. The analysis can be extended and tailored for different vessel types and cases.

10.2. Sea map to decarbonizing short sea general cargo vessel

SUMMARY

General cargo vessels are important for local trade many places. They are small, versatile and flexible and often sail for decades. The fleet is old and the energy demand quite small, i.e. these are ideal first movers on alternative fuels (ref chapter 9.15).

We apply the four-step method to find the most suitable improvements in logistics, technical measures and alternative fuels.

Geared general cargo vessels are interesting early mover candidates due to relatively small energy demand, short transit time between ports and limited geographical operating area. Our case vessel runs from the European continent to ten Norwegian ports from Risavika (Stavanger) to Hammerfest.

LOA	140 m
Tonnage	10,000 GT
DWT (scantling)	12,000 t
Cargo capacity	bale: 15,000 m^3
Roundtrip	Świnoujście to Hammerfest, 4,200 nm
Main engine	5,500 kW
Speed	10-15 kn, typically 12-13
Fuel	LNG and hydrogen
Machinery	DF engine
Sail	Yes, rotor sails
Batteries	For peak shaving and port entry/exit

Reorientation

First; small general cargo vessels and container feeder vessels have not improved their EEOI from 2008 to 2018, in fact, EEOI has deteriorated by around 10% for the largest general cargo subsegment and container vessels up to 2,000 TEU segment [IMO 4th GHG study, 2021, table 59 and 62 | ↗]. Although there are notable exceptions to this, vessels in this segment must therefore, on average, realize the entire 40% from now to 2030 to contribute to the IMO-goals and 60-70% to comply with the IPCC recommendations.

The smaller vessels below 5,000 GT may escape mandatory annual improvements to CII imposed by the IMO. However, as coastal shipping is competing with land-based transport options for cargo, further improvements in climate intensity is necessary if ships shall remain ahead of the truck in a future where the truck is expected to become emission free thanks to either batteries or hydrogen.

Although trucks may become emission free, ships will always be ahead in terms of energy use per ton cargo moved – and make important contributions toward cleaner cities without traffic congestion.

Owners of coastal tonnage are typically family owned and small enterprises, with small technical departments – but very passionate and hands on. General cargo vessels are diverse; in size, cargo and trade. Smaller general cargo vessels are generally old and the need for fleet renewal is evident. With old hull forms, machinery and equipment the potential for improvement is good. Unfortunately, fleet renewal has proven difficult.

General cargo vessels sail along the coast with frequent port visits. Clean air with minimum NO_X, SO_X and particles from the exhaust is therefore important for this vessel type. Access to city ports is essential for the competitive position of short sea shipping and this access can be jeopardized by dirty exhaust. A rapid transition to cleaner fuel is therefore needed.

Logistics

General cargo vessels are versatile and can take almost any type of cargo. We see possibilities for increasing cargo hold utilization; by adding ports, making slack in the schedule to add inducement calls and seek new cargo owners outside the current customer portfolio.

As noted, many general cargo vessels are old and the required fleet renewal presents an opportunity to build larger vessels; provided that the cargo base supports this. Larger vessels can reduce energy use by 25% (ref chapter 8.2).

Reducing speed from the design speed can reduce power and emissions, but drastic reductions will likely be counterproductive as the added resistance from waves and wind is rather constant, hotel load and port consumption is also constant (ref chapter 7.3). Slower speed will also increase transit time and make sea transport less competitive with trucking.

Weather routing has limited impact given the short sailings and limited room for circumventing bad weather but will be essential to maximise the sail power.

Energy efficiency

The current coastal fleet is old, and the improvement potential is considerable, especially on machinery.

Main dimensions can be optimised if port restrictions and conventions permit. Some safety and other regulatory standards are also prohibiting optimum main dimensions, and these must be challenged. Here government contribution is needed. We see a potential for 10-20% energy reductions (ref chapter 8.2).

The sea margin of small vessels sailing in the rough waters of the North Sea and Norwegian Sea can be determined by simulation of alternative, optimized hull forms. Studies indicate that longer and more slender vessels will perform better in waves.

Energy use can be reduced by fitting rotor sails, cutting 10-20%. The simplicity and robustness of rotor sails make them the preferred type for geared general cargo vessels. Conflict with cargo cranes must be avoided and the sails must be tiltable to ensure access under bridges and ports.

Specific fuel consumption has improved over the last decades and a modern main engine will have higher thermal efficiency. 15% is realistic, e.g. a drop from 210 to 180 g/kWh [IMO 4th GHG study, 2021, p. 277 | ↗]. Fuel consumption and emissions at part loads are particularly improved. Replacing a pre-2000 engine means that NO_X will fall from Tier 0 to Tier II-levels, and Tier III inside NECAs.

From a not so good starting point, there is good potential for improving the energy efficiency of short sea vessels. For old vessels, we expect as much as 15% on main dimensions and machinery each.

Batteries for peak shaving and short emission free sailings, e.g. in and out of port, will reduce the consumption of the main engine and contribute to clean air in and around ports and silent approaches e.g. at night.

Deeper draught to make room for larger propellers are difficult for ships needing access to shallow draught ports. Twin screw with lighter load on each propeller and enhanced manoeuvrability should be considered.

Alternative fuels

Relatively low energy demand, fixed and limited operating area and frequent port calls make coastal general cargo vessels ideal for new fuels such as hydrogen (ref chapter 9.13). As first movers, however, their owners and operators want a safe fallback option if hydrogen is not available, prohibitively priced or the vessels fuel system for hydrogen fails.

Pure hydrogen engines or large fuel cells are a few years away and climate neutral hydrogen is not yet available. General cargo vessels can be built with gas engines and prepared for later conversion to hydrogen. This allows use of LNG today and blends up to 25% as soon as H_2 becomes available and larger percentages as hydrogen production picks up. Alternatively, biomethane can be mixed in. This gives operators at three fuels (hydrogen, biomethane and LNG) plus MGO to play with.

With 10% of emissions during port stays (ref chapter. 2.5), electric shore power will help. There are more than 3,000 ports in Norway, of which 32 are considered key ports [Kystverket | ↗]. As general cargo vessels visit very many of these ports, it will take time until shore power becomes available throughout. Clean exhaust will thus depend on the vessel's own machinery during the majority of the port stays.

Summary

Overall, the segment has not reduced its carbon intensity from 2008 to 2018. Fleet renewal lowers energy used by about 3 ·15%. To reach 2030 targets, 77/20 blend of LNG and H_2 is needed, assuming 3% shore power. To lower GHG to 85% below 2008-levels, the share of hydrogen must increase to 65% with 32% from LNG.

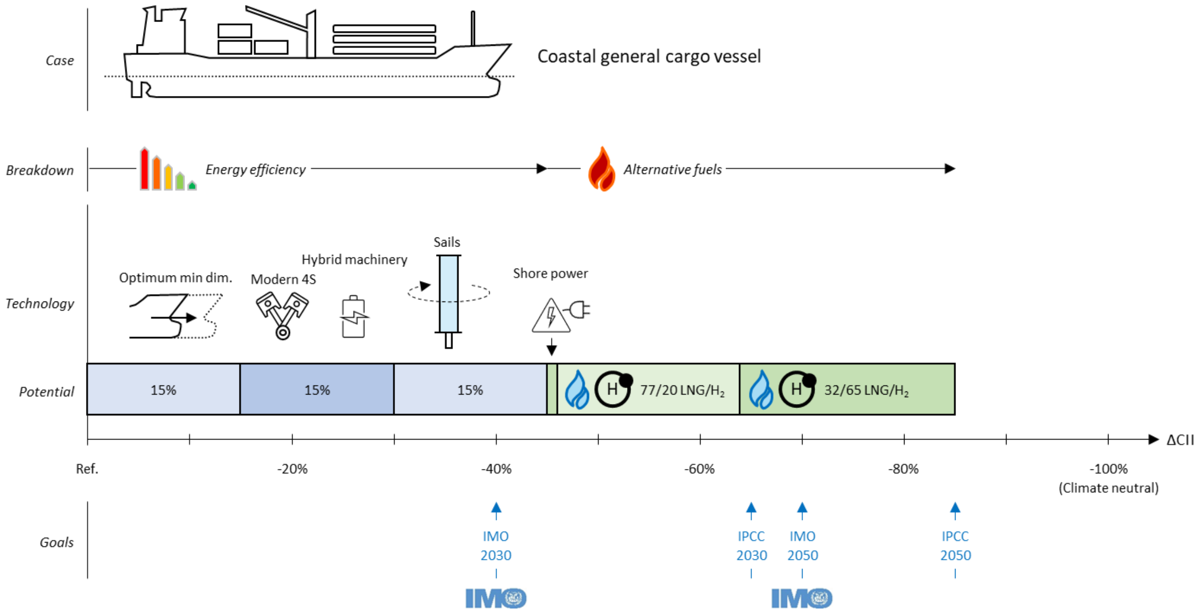


Figure 93: Sea map for coastal general cargo vessels, showing how various GHG reduction goals can be reached by a combination of measures.

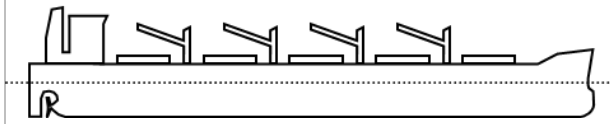
10.3. Sea map to decarbonizing dry bulk vessels in worldwide tramp trade

SUMMARY

On the other end of the spectrum, we find large dry bulk carriers transporting commodities. Their operation is characterized by uncertainty, price pressure, asset play and cyclical demand and earnings.

The dry bulk sector is enormous: Around half of seaborne trade is dry bulk cargoes (ref chapter 3.1) and the sector emits 18% of shipping's GHG (ch 2.1). Findings solutions for this segment is critical to reduce shipping emissions altogether.

LOA	200 m
Tonnage	36,000 GT
DWT (scantling)	63,000 t
Cargo capacity	bale: 78,000 m^3
Roundtrip	Port Hedland (Aus) - Shanghai, 3,300 nm Brazil-China, 11,050 nm
Main engine	8,500kW
Speed	11-14 kn
Fuel	LNG and biomethane
Machinery	DF engine
Sail	Yes, robust rotor sails
Batteries	Yes, for energy recovery from cranes



Reorientation

Dry bulk tonnage is very standardized, subject to immense price pressure and many are on charter to commodity traders. Vessels change hands and asset play is common. This calls for standardized tonnage which can fit in nearly any dry bulk trade. Sadly, this practice of standardization is also a barrier to tailor making and optimization. Flexibility and low cost is key to success.

Yet, we see signs of change, especially in cases where the charterer is engaged. Partnerships or long term contracts with key cargo owners is key to challenge the standardization and put some extra efforts into the design and outfitting.

Although dual fuel machinery and blend-in fuel strategies (suggested below) will give some flexibility, the high capex means that optimized tonnage should stay on the intended trade. As green shipping becomes appreciated elsewhere and alternative fuels become available, options for redeployments and sale will open, perhaps after 2035.

Dry bulk improved its EEOI by almost 40% from 2008 to 2018. All size classes except vessels above 200,000 dwt improved. This give many bulk vessels a head start, but the importance of further emission reductions is clear – and the cost and flexibility pressure make the task challenging.

Logistics

Iron ore, coal and grain are the most important ones, but there are around 40 types of cargoes; agricultural products, timber and forest products, fertilizer, steel products and scrap steel, petroleum coke, bauxite, cement and more. The long range of cry bulk commodities and a global economy opens up for taking backhaul cargoes. Yet, most dry bulk carriers sail empty almost half the time.

Energy efficiency

The study by Lindstad et al. referred to in chapter 8.2 concluded that 10-25% can be shaved off emissions by optimizing main dimensions. The key to unlocking this potential is collaboration with charterers and ports.

Energy use can be reduced by fitting rotor sails, cutting at least 10-20% and perhaps more. Sails are perhaps more difficult to fit on geared vessels. The interaction effects between cranes and sails should be studied to find the best arrangement of the sails. Sails can be fitted between hatches with arrangements for tucking them away in port

In terms of machinery, a dry bulker is as straightforward as it gets. Two speed, long stroke, slow speed machinery is used. Marginal reduction in specific fuel consumption can be achieved by opting for even longer strokes and slower turning, if large propellers can be fitted. Port days are few and port emissions are low, only 6% (ref ch 2.4). Geared vessels use some energy in port and can benefit from batteries to recover energy when the crane is lowering the grab.

Large propeller can increase propulsive efficiency by a couple of per cents

20% lower power demand should encourage owners to break away from standard main dimensions. Rotor sails reduce energy use – and cost – and will likely be even better when/if slow steaming remains the norm.

Finally, at slow speed and a full hull with large wetted surface area, frictional resistance is important. A smooth and clean hull surface is important and can be achieved with good anti fouling, hull cleaning when necessary and regular blasting at class renewal in dock.

Alternative fuels

Sailing from anywhere to anywhere with the risk of being rerouted en route means that dry bulkers cannot rely on a fuel that is available only in a select few ports. Bulkers will not transition to a low carbon fuel until it is very widely available, alternatively the vessel can have dual or even triple fuel machinery to remain flexible and unlimited in its operation.

The dry bulk segment is also very competitive with immense pressure on freight rates. While some have long term contracts, most are exposed to the brutal spot market and owners must minimize capex.

A dual fuel gas engines with the option to run on biomethane, LNG or even MGO meets these two requirements. Biomethane can be manufactured anywhere as the raw materials are organic residues and wastes available from any population or rural area. 10% biomethane is needed in 2030 and 80% in 2050. 10% is not much and such a soft start should be well within reach for many.

Summary

Efforts from 2008 to 2018 make the next decade easier for bulk carriers: Already 38% below the 2008 reference line, there is still potential for optimization of main dimensions and hull form. Use of sails and control with hull roughness and propulsive efficiency can bring bulkers another 20% down.

LNG can cover 90% in 2030 but only 20% in 2050, with biomethane making up 10% and 80% respectively, to comply with the IPCC-goals.

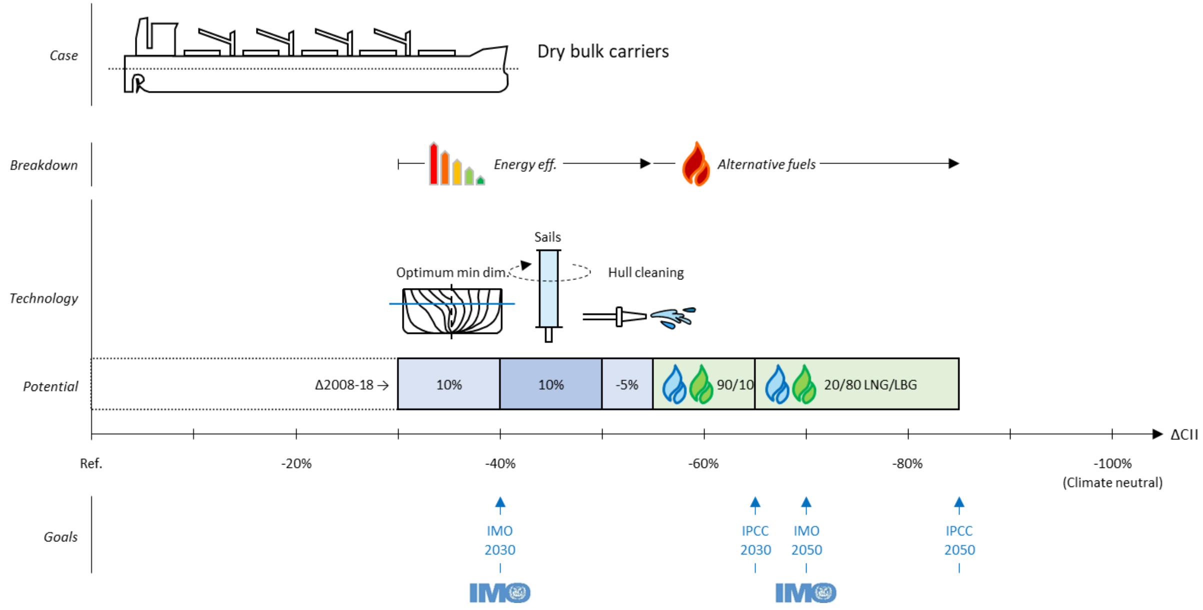


Figure 94: Sea map for dry bulk carriers, showing how various GHG reduction goals can be reached by a combination of measures.

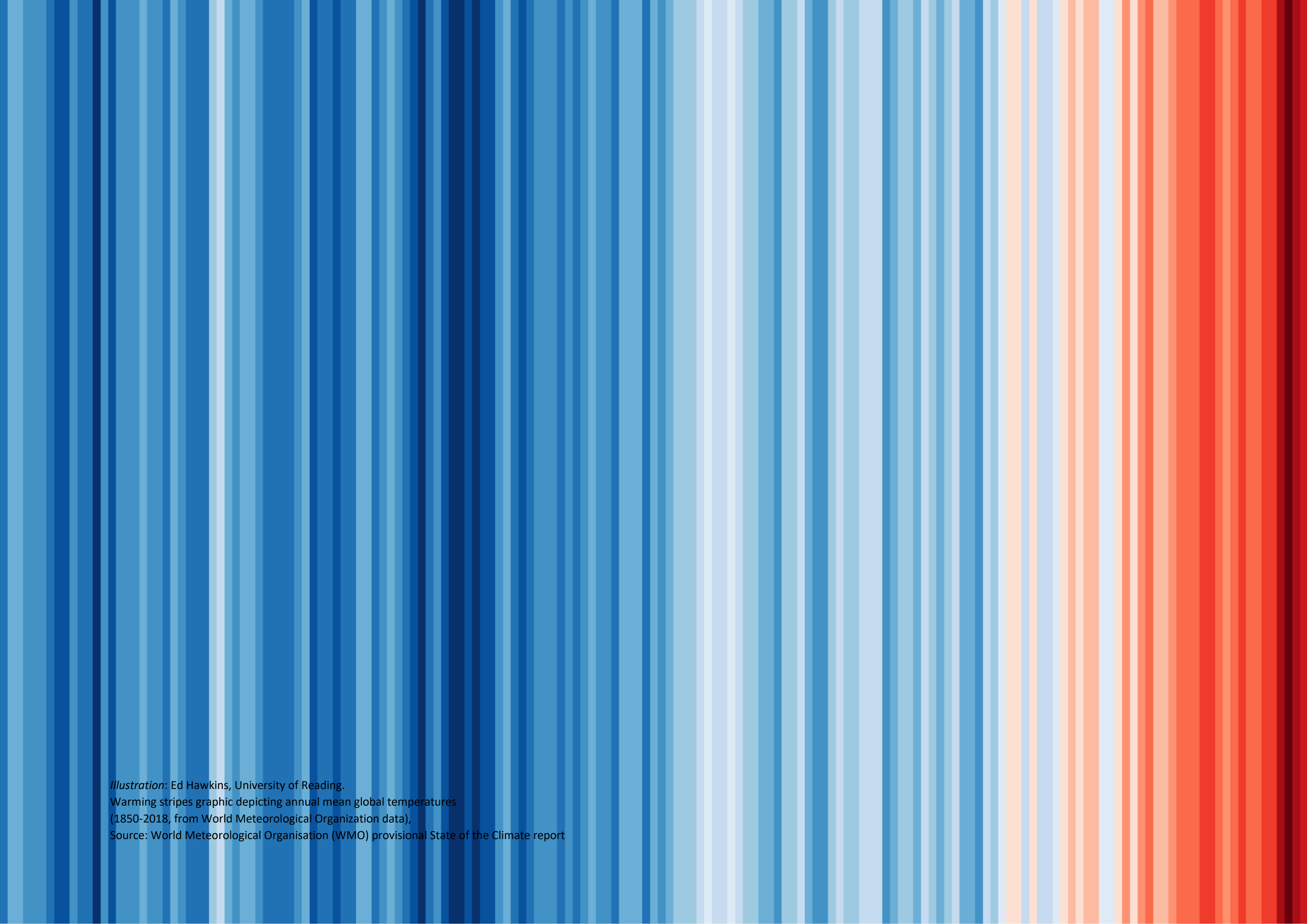


Illustration: Ed Hawkins, University of Reading.
Warming stripes graphic depicting annual mean global temperatures
(1850-2018, from World Meteorological Organization data),
Source: World Meteorological Organisation (WMO) provisional State of the Climate report

11. ABBREVIATIONS

abatement cost	Cost per emission reduction [e.g. USD/t CO_2]. (Norwegian: tiltakskostnad).
AER	Annual Efficiency Ratio. See chapter 6.3.
Aframax	Oil tanker with approximately 100-120,000 dwt cargo capacity.
AIS	Automatic Identification System, information system to identify and track vessels including their identity, type, position, course, speed, navigational status and other safety-related information. Also used as basis for stating emissions e.g. in the IMO GHG-studies and emission inventory models such as MariTEAM (IMO | ↗).
albedo effect	Albedo is an expression of the ability of surfaces to reflect sunlight (heat from the sun) (Norwegian Polar institute | ↗).
BC	Black carbon, an indirect greenhouse gas. See chapter 2.2, 6.1 and 7.4.
capex	Capital expenditure (investment).
carbon intensity	Carbon or greenhouse gas emissions per activity, e.g. CO_2 per transport work. See CII.
carbon leakage	Shifting of emissions from onboard use to the production phase.
CCUS	Carbon capture, utilization, and storage (IEA | ↗).
CCS	Carbon capture and storage (IEA | ↗) (SINTEF | ↗).
CFD	Computational fluid dynamics, computer-aided analysis of hydrodynamic (and aerodynamic) flows.
CH_4	Methane, a potent greenhouse gas (GWP_{100} 29.8±11, GWP_{20} 82.5±25.8), ref chapter 6.1.
CII	Carbon Intensity Indicators, ratio of greenhouse gas emissions by transport work (IMO MEPC resolutions 335-339(76) | ↗).
climate negative	Emissions reduction above 100% (see chapter 9.2 and 9.11 on biomethane).
CNG	Compressed natural gas.
CRP	Contra rotating propellers, two propellers in line turning opposite directions to improve propulsive efficiency (see chapter 8.4).
DAC	Direct air capture, extract CO_2 directly from the atmosphere (IEA | ↗).
DE	Diesel electric, power generation by engine (commonly, but not necessarily, a diesel engine) and electric power transmission.
DCS	Data collection system, an IMO instrument for reporting of fuel, emissions and transport work (IMO | ↗)
DF	Dual fuel, engines capable of burning two fuels. See also multi fuel.

displacement	Total weight of a vessel [t] or volume of submerged underwater body [m^3].
DWT	Deadweight, a measure of vessels' capacity for cargo, consumables including fuel and water ballast.

E	Exa, SI-prefix, 10^{18}.
ECA	Emission control area.
EEDI	Energy Efficiency Design Index (IMO | ↗).
EEXI	Energy efficiency existing ships index, an equivalent to EEDI for existing ships.
energy density	Energy per volume [e.g. J/m^3].
EEOI	Energy efficiency operational indicator (IMO | ↗) (IMO MEPC.1/Circ. 684, 17 August 2009 | ↗).

G	Giga, SI-prefix, 10^9 (one billion).
GEVA	Greenhouse gas per value added [Jørgen Randers, 2012 | ↗].
GDP	Gross domestic product.
GHG	Greenhouse gas [CO_2-equivalents].
GT	Gross tonnage, a function of the moulded volume of all enclosed spaces of the ship (IMO | ↗).
GWP	Global warming potential, a factor to convert and compare the GHG-effect of other greenhouse gases to CO_2. Unless otherwise specified, the timescale used is 100 years (GWP_{100}) and factors taken from IPCC, WG1AR6, chapter 7, table 7.15 (page 1017).
GWP_{100}	GWP for a timescale of 100 years, the most commonly used horizon.
GWP_{20}	GWP for a timescale of 20 years i.e. focusing on the near-term effects.

HFC	Hydrofluorocarbons, a group of very potent greenhouse gases.
HFO	Heavy fuel oil, e.g. RME, RMG, RMK. (ref ISO 8217), also known as residual fuels.
H_2	Hydrogen.

ILUC	Indirect land use change.
IGU	International Gas Union.
MO	International Maritime Organization, the UN body for shipping (London/International).
IPCC	Intergovernmental Panel on Climate Change (Genève/International).

IRENA	The International Renewable Energy Agency, established 2011.
kn	Knot, 1 nm/h = 1.852 km/h.
Kyoto gases	The main six greenhouse gases: carbon dioxide (CO_2), methane (CH_4), nitrious oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexachloride (SF6).
LCA	Life cycle assessment.
LBG	Liquefied biogas or biomethane, methane produced from biological raw materials, wastes or byproducts.
LCV	Lower calorific value, the energy content of fuels [kJ/kg, MJ/kg].
LNG	Liquefied natural gas, primarily methane.
LPG	Liquefied petroleum gases, mixes of propane, butane and other hydrocarbons.
LH_2	Liquefied hydrogen.
M	Mega, SI-prefix, 10^6, (one million).
MariTEAM	Maritime Transport Environmental Assessment Model), emission inventory model developed by NTNU and SINTEF Ocean (see chapter 5.3).
MARPOL	IMO's International Convention for the Prevention of Pollution from Ships.
MEPC	Marine Environment Protection Committee, one of IMO's five main committees (IMO | ↗).
MCR	Maximum continuous rating, the maximum power [kW] an engine can deliver continuously.
MDO	Marine diesel oil, DMB (ref ISO 8217).
MGO	Marine gas oil, e.g. DMA, DMZ (ref ISO 8217).
MSC	Maritime Safety Committee, one of IMO's five main committees (IMO | ↗).
Multi fuel	An engine capable of burning several (more than two) different fuels. See also dual fuel.
MRV	An EU instrument for reporting of energy, fuel, emissions and transport work (EU DG CLIMA | ↗).
N_2O	Nitrous oxide, a potent greenhouse gas GWP_{100} 273±130, GWP_{20} 273±118), ref chapter 6.1.
NCR	Nominal continuous rating, the optimal operating condition for an engine, typically 85-90% of max continuous rating (MCR).
NDC	Nationally Determined Contributions, national plans to reduce national emissions and adapt to the impacts of climate change to be updated and communicated every five years, normally, although COP26 agreed for strengthened NDCs also in 2022 (IPCC | ↗) (COP26 | ↗).
NH_3	Ammonia.

nm	Nautical mile (1,852 m).
NOOA	National Oceanic and Atmospheric Administration (US).
NO_X	Nitrogen oxides; NO, NO_2, N_2O_3, but mainly NO_2.
NSR	Northern Sea Route; a sailing route from the Kara Gate or the Strait between the Cape Zhelaniya and Franz Josef Land in the west to the Cape Dezhnev in the East (near the Bering Sea) [PAME | ↗].

OC	Organic carbon.
OCCS	Onboard carbon capture and storage: Systems for capturing CO2 from ship's funnel for onboard storage and delivery to shore for permanent storage.
open hatch	Geared dry bulk vessel, introduced in 1969, with box-shaped cargo holds and large hatch openings to facilitate efficient handling of timber, pipes, steel coils and other project cargoes.
opex	Operating expenditure.

PAH	Polycyclic aromatic hydrocarbons (Folkehelseinstituttet | ↗).
pax	Passenger.
PEM	Proton exchange membrane, a type of fuel cell considered most suitable for mobile applications.
PFC	Perfluorcarbons, a group of very potent greenhouse gases.
PH_2	Pressurized hydrogen.
PM_{10}	Particulate matter with diameter < 10 µm (µm = 1/1000 mm, 1/1,000,000 m).
$PM_{2.5}$	Particulate matter with diameter < 2.5 µm (µm = 1/1000 mm, 1/1,000,000 m).
ppm	Parts per million.
Roadmap	A plan or strategy intended to achieve a particular goal.
RO/RO	Roll-on/roll-off.

Scenario	A coherent, internally consistent, and plausible description of a possible future state of the world.
Specific energy	Energy per weight [J/kg].
SF6	sulphur hexachlorides, a group of very potent greenhouse gases.
SFC	specific fuel consumption, the fuel consumption of an engine per kWh produced [g/kWh].
SMR	Steam methane reforming, process for producing hydrogen from natural gas.
SOFC	Solid oxide fuel cell, high temperature fuel cell with high efficiency but limitations in operations.

SO_X	Sulphur oxides; primarily SO_2 and SO_3.
SRL	System readiness level, an index of the maturity and availability of complete systems rather than individual components.
Suezmax	Oil tanker with approximately 165,000 dwt cargo capacity.
Supramax	Geared dry bulk carrier with 50,000 to 60,000 dwt capacity. (Store Norske Leksikon | ↗).

T	Terra, SI-prefix, 10^{12}, (one trillion)
t·nm	tonne nautical miles, measure for transport work.
TRL	Technology readiness level.
TTW	Tank to wake: Emissions, other environmental effect or energy use arising onboard the use from use.
tier I, II or III	Emission limit standard for NO_X for marine machinery (IMO | ↗).
TRL	Technology Readiness Level, an index of the maturity and availability of technology under research and development see e.g. NASA (↗) or EARTO (↗).

Ultramax	Dry bulk carrier with 60-65,000 dwt capacity. Cargo cranes.
UNCTAD	United Nations Conference on Trade and Development (Geneva, Switzerland).
unit cost	Total cost per unit (tonne, TEU, RT, m^3 or passenger) per nautical mile .

WTT	Well to tank: Emissions, other environmental effect or energy use from production, refining, conversion, transport, bunkering etc before the fuel is onboard the vessel. WTT emissions fall within scope 3.
WTW	Well to wake: Emissions, other environmental effect or energy use during the whole life cycle taking all emissions along the fuel's value chain into account.

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