Technology space

4 TECHNOLOGY SPACE

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

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

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

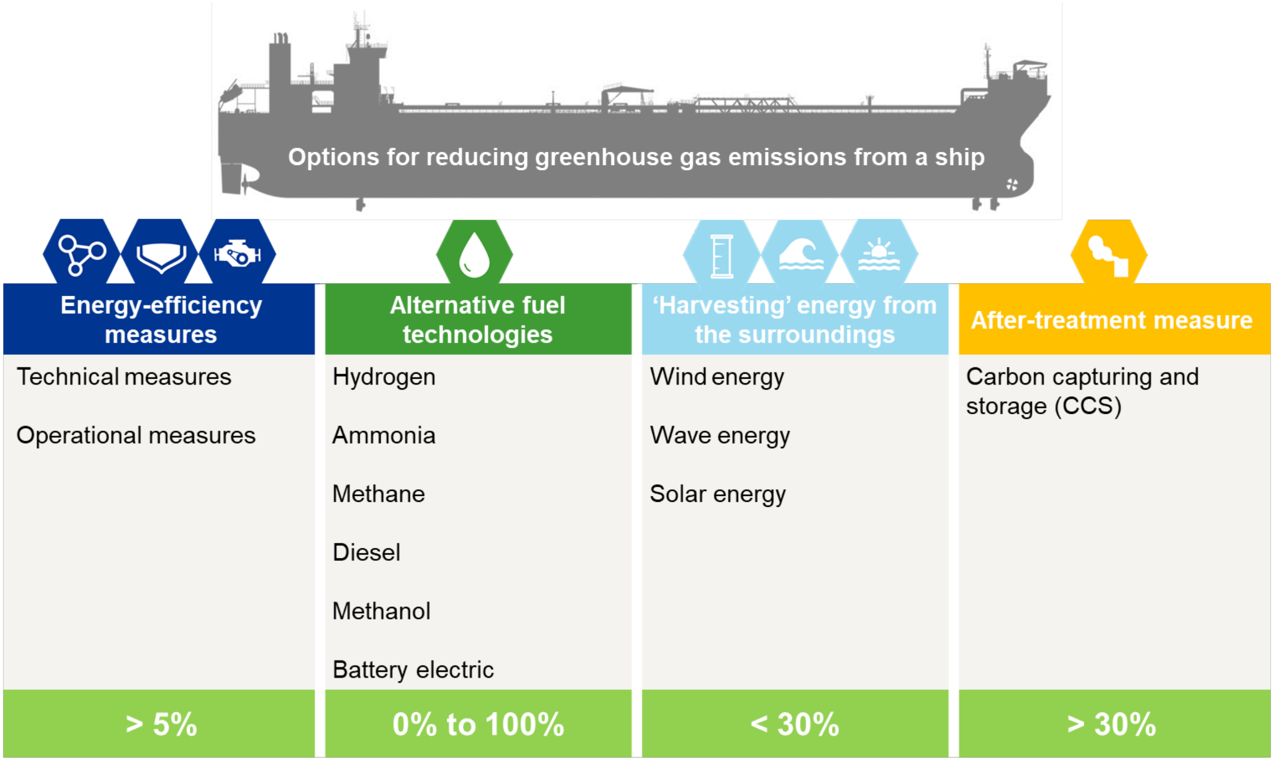
The technical applicability of various abatement measures will vary greatly for different ship types and trades. Newbuilds will have more options available than ships in operation. Vessels in the deep-sea segment have fewer fuel options compared with those in the short-sea segment.

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

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

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

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



Energy-efficiency measures	Alternative fuel technologies	'Harvesting' energy from the surroundings	After-treatment measure
Technical measures	Hydrogen	Wind energy	Carbon capturing and storage (CCS)
Operational measures	Ammonia	Wave energy	
	Methane	Solar energy	
	Diesel		
	Methanol		
	Battery electric		
> 5%	0% to 100%	< 30%	> 30%

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

4.1 Energy-efficiency measures

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

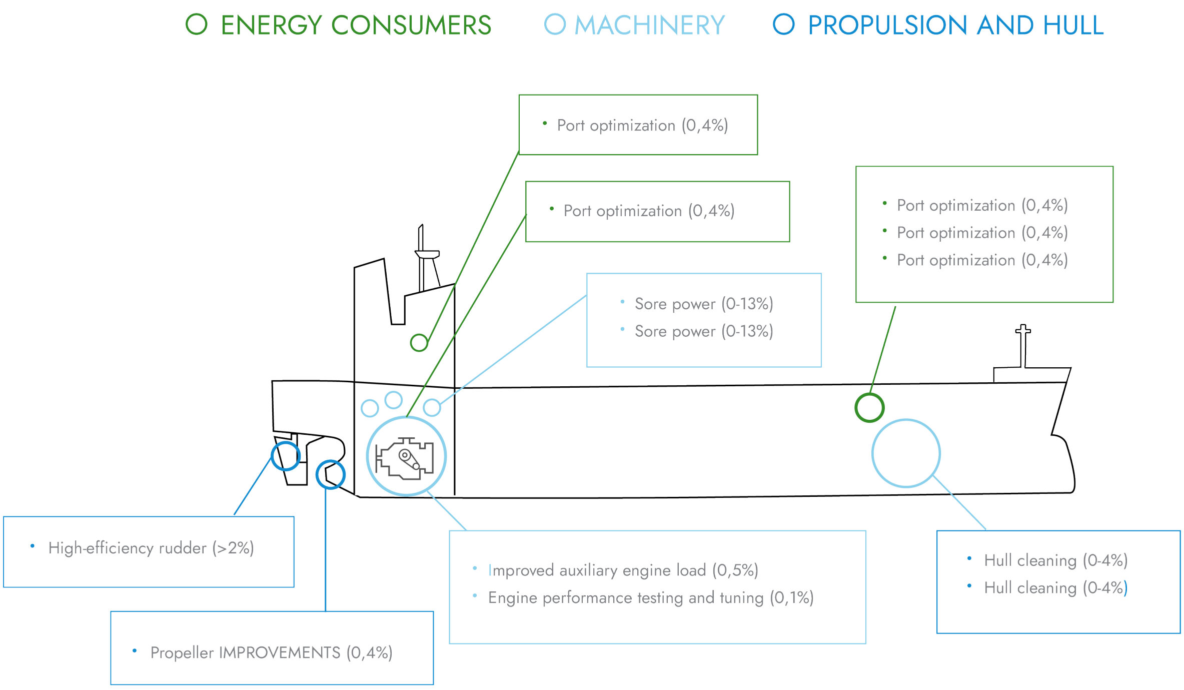
Several studies have investigated barriers to uptake of energy-efficiency technologies in shipping (e.g. DNV, 2012b; DNV GL, 2017c; Acciaro et al., 2013; Rehmatulla et al., 2015; Rehmatulla & Smith, 2015). Findings indicate the importance of financial and technical barriers, managerial practices, and legal constraints. For each energy-efficiency technology, very specific challenges and barriers will need to be identified and considered.

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

4.1.1 Technical measures

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

Abatement measures such as air lubrication systems, and various hull and machinery measures, are currently emerging[33]. Figure 4-2 categorizes some relevant technical measures into three main groups – energy consumers, machinery, and propulsion and hull – and gives an indicative range of CO_2-reduction potentials for each measure, based on DNV's Abatement Insight database. The emissions-reduction potential for each measure strongly depends on factors such as ship type, size, operational profile, technical conditions/status, and age (e.g. DNV GL, 2016, 2017a). Consequently, ship-specific modelling and assessment will be needed to build a robust decarbonization improvement plan. Such improvement plans will be required by the enhanced SEEMP requirements, a short-term IMO policy measure to regulate GHG emissions from shipping (see Chapter 3).



CPP: Controllable pitch propeller

(Source: DNV Abatement database

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

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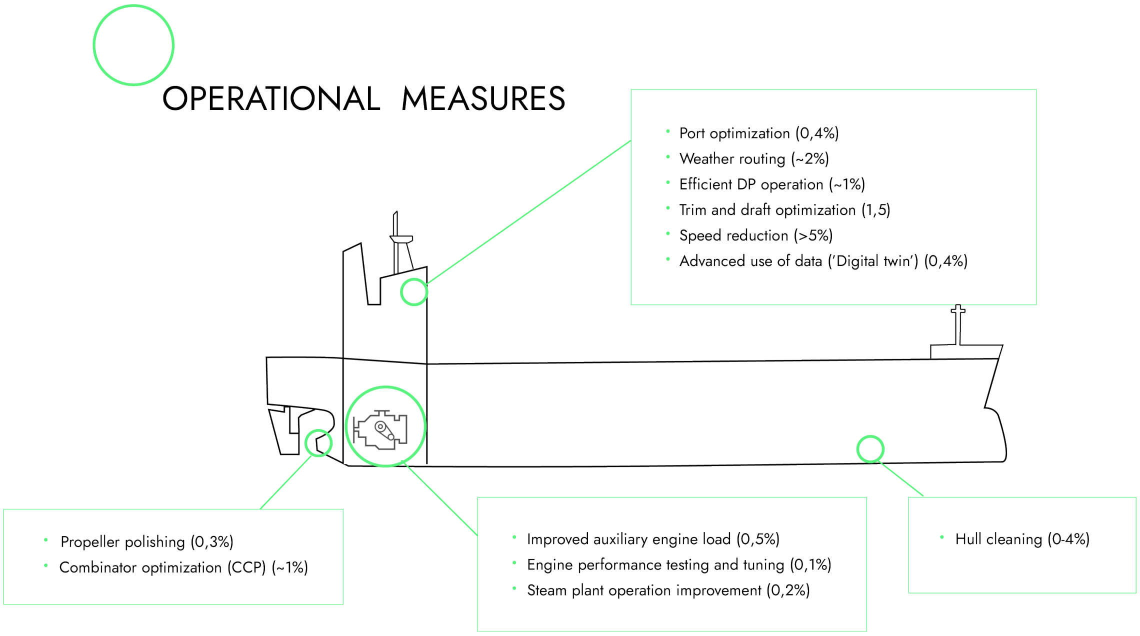
[33] For instance, see "Fuelling Transition: Tracking Technology Uptake": https://www.hellenicshippingnews.com/fuelling-transition-tracking-technology-uptake/

4.1.2 Operational measures

Operational measures relate to the way in which the ship is operated and maintained. They include measures such as optimized trim and draft, hull and propeller cleaning, better engine maintenance, and optimized weather routing and scheduling. In contrast to technical measures, operational measures typically do not require significant investment in hardware and equipment. They generally have low investment costs and moderate operating costs. Implementation of many of these measures is attractive for purely economic reasons, and many also require execution of programmes involving changes in management and training. Digital technologies are expected to facilitate improved information flow and be important for untapping the full potential of operational measure. One effective operational measure with a large fuel-saving potential is to reduce vessel speed (e.g. Lindstad et al., 2015; DNV GL, 2017c; CE Delft, 2012, 2017a; DNV GL 2018b,c). Part of the speed reduction can be absorbed in current transport systems through reduced time in port, and improved coordination and synchronization between ship and port to avoid waiting in port, with the extra time being used to slow steam (e.g. Longva, 2011; Andersson, 2017; Jia et al., 2017). Otherwise, timetables and schedules must be changed, and more ships deployed to maintain the total transport capacity. A large GHG-reduction potential related to better ship and port synchronization – for example just-in time arrival – has been reported (e.g. Longva, 2011, Jia et al., 2017).

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



CPP: Controllable pitch propeller

(Source: DNV Abatement database

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

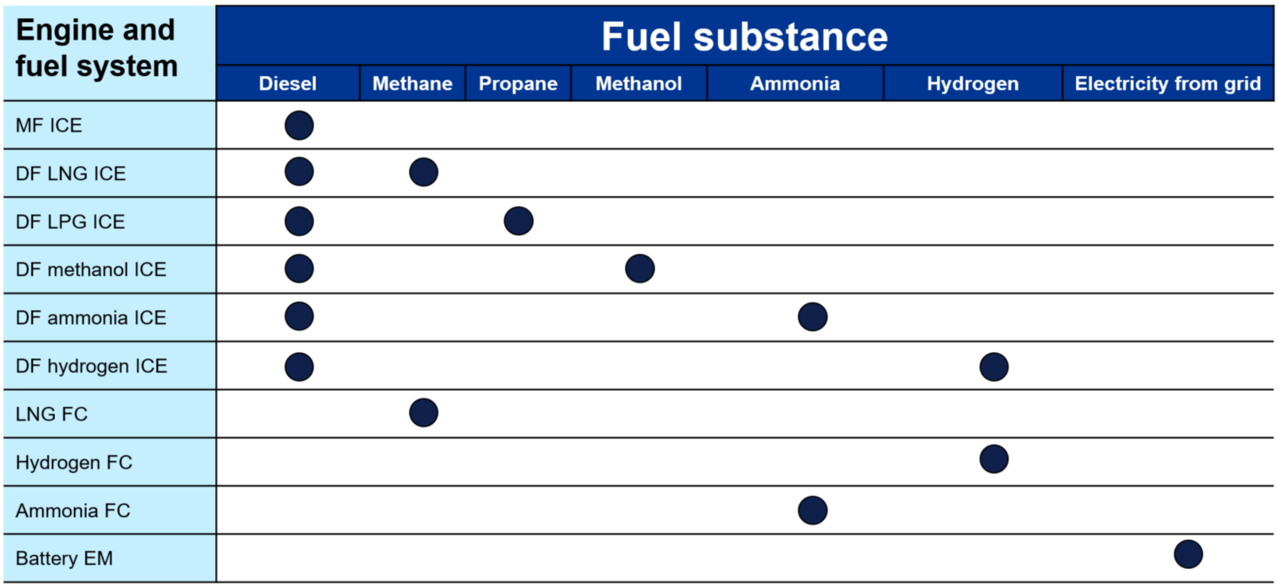
4.2 Alternative fuels for shipping

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

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

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

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



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

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

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

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

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

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

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

4.2.1 Current uptake of alternative fuels

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

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

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

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

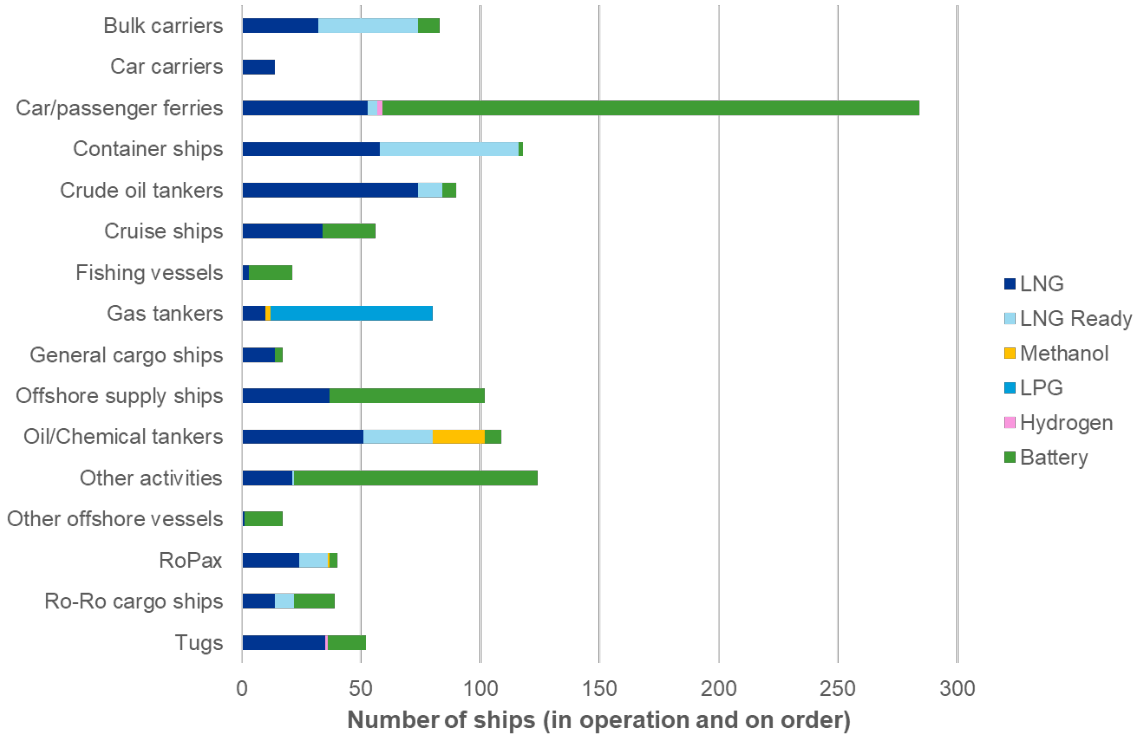

Figure 4-5 Status on uptake for selected alternative fuels in June 2021, ships in operation and on order. (Data: DNV Alternative Fuels Insight platform). 'LNG Ready' is a term used to indicate vessels that have prepared for a future retrofit to LNG as a fuel.

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

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

4.2.2 Barriers to uptake of alternative fuels

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

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

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

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

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

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

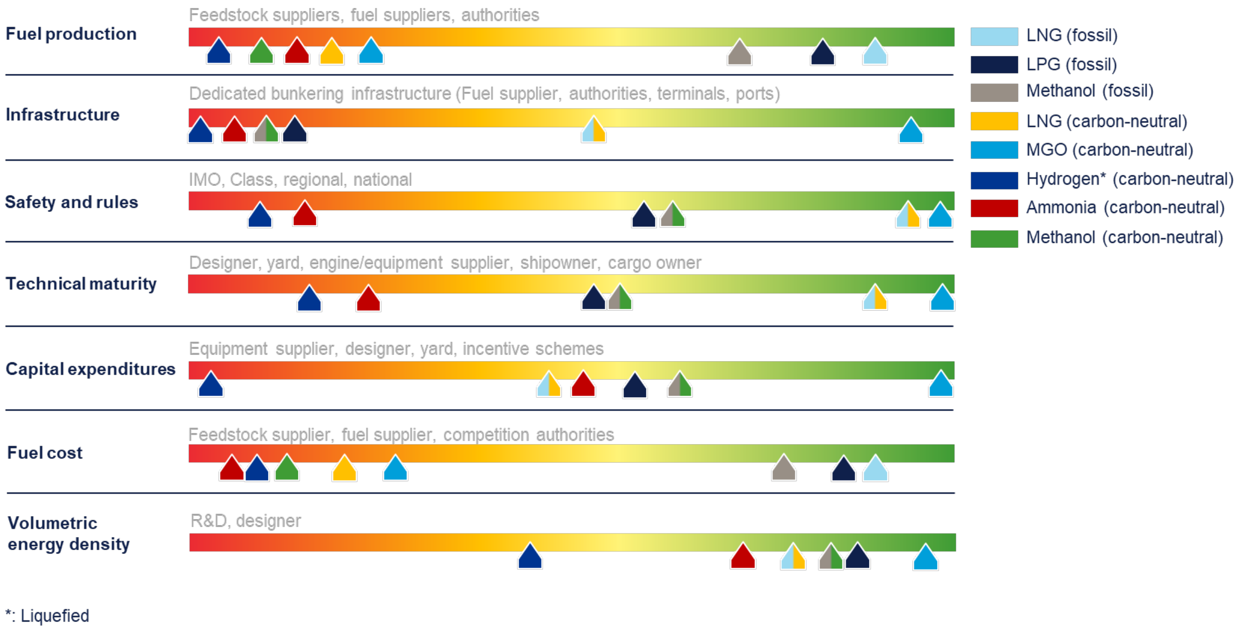

Figure 4-6 Indicative status of key barriers for selected alternative fuels (based on DNV GL, 2020b).

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

Volumetric energy density

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

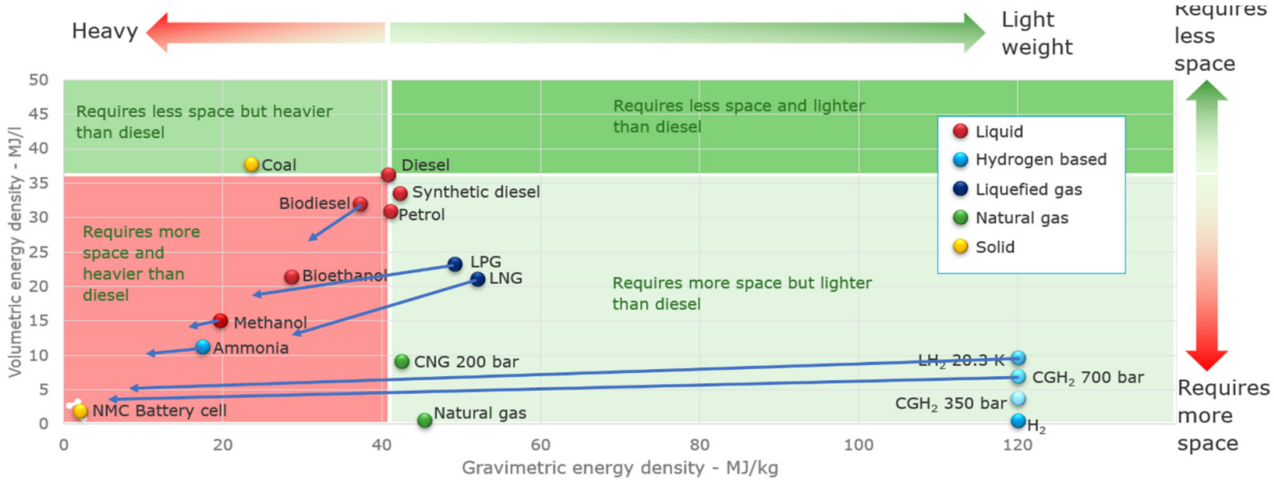

Figure 4-7 Comparison of gravimetric and volumetric storage density for fuels (DNV GL, 2019b). The arrows represent the impact on density when taking into account the storage systems for the different types of fuel (indicative values only).

Infrastructure and fuel production

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

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

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

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

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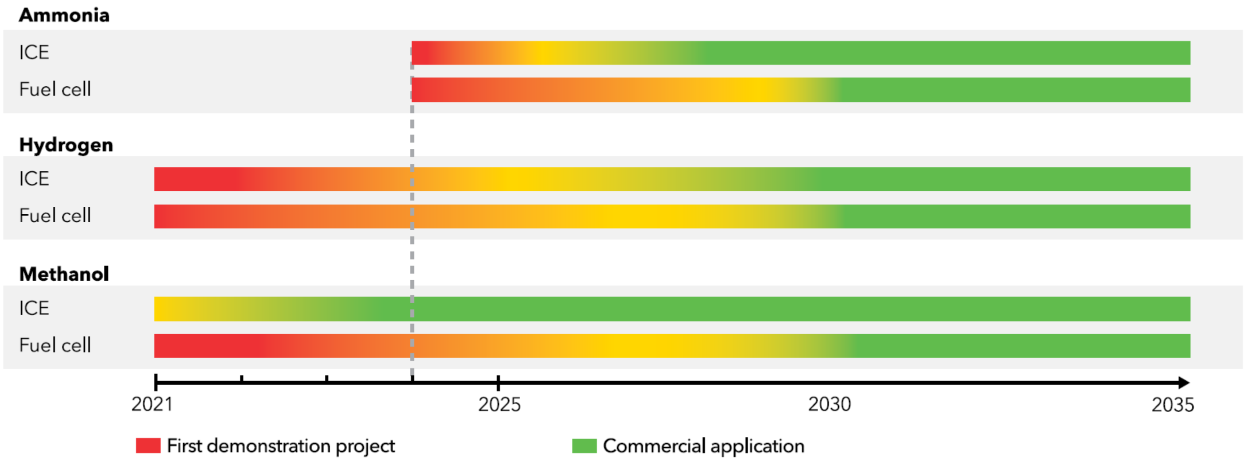
[39] DNV Alternative Fuel Insight (AFI) platform: https://afi.dnvgl.com/Map

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

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

Technical maturity

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



Key: Internal combustion engine (ICE)

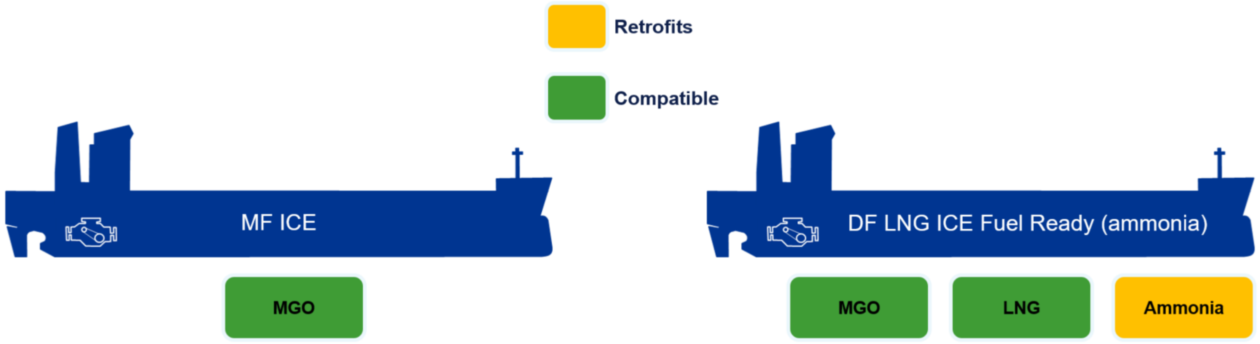
Figure 4-10 Timeline for expected availability of alternative fuel technologies - our best estimate for when these may be available for onboard use (DNV, 2021a).

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

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

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

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



MGO, marine gas oil; LNG, liquefied natural gas; MF, mono fuel; DF, dual fuel; ICE, internal combustion engine

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

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

4.3 Harvesting energy from the surroundings

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

4.3.1 Wind energy

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

4.3.2 Solar energy

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

4.3.3 Wave energy

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

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[41] The International Windship Association: https://www.wind-ship.org/en/category/wind-propulsion-technology-providers/

[42] https://vpoglobal.com/2021/03/09/deltamarin-bar-technologies-and-cargill-present-windwings-virtual-showroom/

[43] https://www.ship-technology.com/news/wallenius-wilhelmsen-wind-powered-roro-ship/

[44] https://news.trust.org/item/20201209130140-yjblo/?utm_campaign=inDepth&utm_medium=inDepthWebWidget&utm_source=homepage&utm_content=link1&utm_itemId=20201209130140-yjblo

[45] https://www.marineinsight.com/types-of-ships/auriga-leader-the-worlds-first-partially-propelled-cargo-ship/

[46] https://glomeep.imo.org/technology/solar-panels/

[47] The wave power history: https://www.bluebird-electric.net/wave_powered_ships_marine_renewable_energy_research.htm

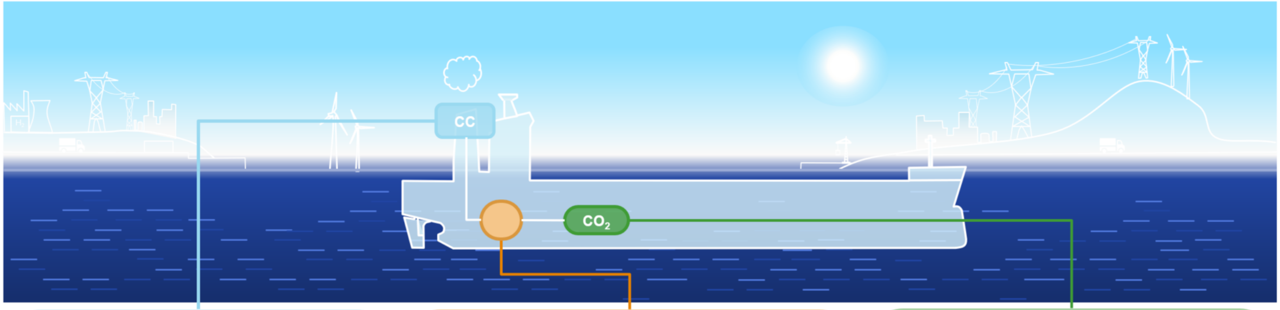
4.4 Carbon capture and storage (CCS)

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

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

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

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



Carbon capture system

CO_2 from the exhaust gas is captured at a dedicated carbon capture unit. Depending on the carbon capture system a significant share of the CO_2 is removed.

Treatment system

The CO_2 by-product is treated and converted into storage conditions.

Storage

The treated CO_2 stream is stored on board in dedicated containers as:

- Solid (adsorption)
- Gas (compressed, e.g. for short routes)
- Liquefied (typical CO_2 transport conditions)

When entering port the CO_2 is discharged.

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

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

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

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