Key takeaways from ABS' *Pathways to sustainable shipping*

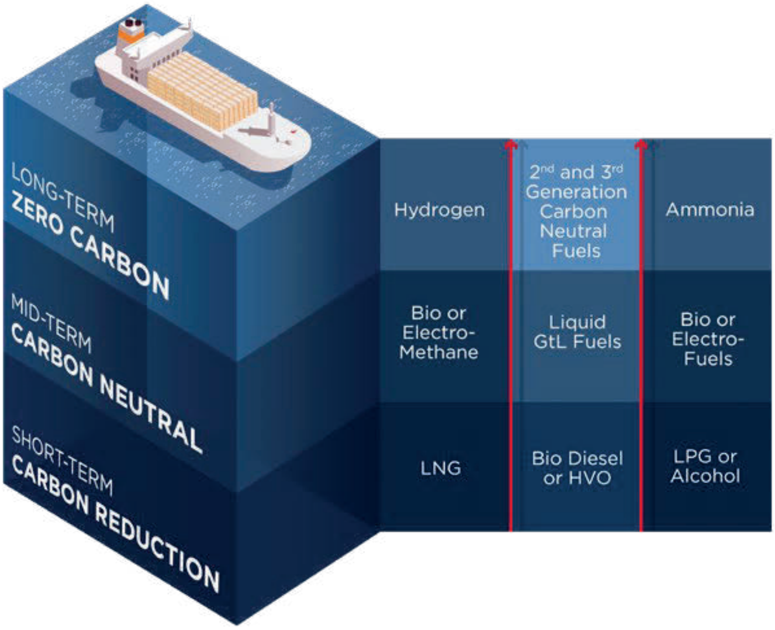
Not enough?

by Przemysław Myszka

We've been reporting on the topic of cutting down the sea shipping industry's carbon intensity for a long time now and have done so from multiple angles – technological, financial, regulatory, and even political. One of the latest analyses comes from the American Bureau of Shipping (ABS) which has investigated alternative fuel pathways toward reaching the International Maritime Organization's (IMO) greenhouse gas (GHG) emission reduction target: down to half of what was emitted in 2008, by 2050 (meaning to 460.5 million tonnes). Whereas there are a plethora of more or less mature technologies that promise to supply low- or zero-carbon bunker, that alone won't be sufficient. More worryingly, implementing measures that would slow global warming, in line with the +1.65 centigrade goal (with a 50% probability) set forth by the International Energy Agency (IEA) in its Sustainable Development Actions (SDA) scenario, hence limit the demand for shipping fossil fuels (even carried in the holds of a green fleet), probably won't get the job done either. That said, one is inevitable, ABS observes, "[…] there is consensus that adapting to the new rules and challenges aimed at lowering its collective carbon footprint will be another period of uncertainty driven by disruptive environmental legislation, and defined by the innovative solutions which emerge."

ABS' research revolves around three non-mutually exclusive pathways: light gas fuels; heavy gas oil and alcohol; and bio/synthetic. These are structured into the framework of two scenarios, base (with and without the adoption of less carbon-intensive fuels) and the so-called Accelerated Climate Action (ACA). Both are informed by the projections made by the Intergovernmental Panel on Climate Change, with the latter assuming the implementation of IEA's SDS and their impact on the world trade of dry and liquid bulk as well as containerized goods. ABS has partnered with Maritime Strategies International (MSI) to calculate how international sea shipping will fare carbon-wise by 2050 under these scenarios, all in order to, "[…] reference available carbon-reduction strategies and inform the shipping industry as it enters the uncharted waters of the […] emissions challenge."

Fig. 1. Three fuel pathways to carbon-neutral and zero-carbon shipping



Source for all figs. and tabs. (except Fig. 12): American Bureau of Shipping's Pathways to sustainable shipping

Light gas fuels

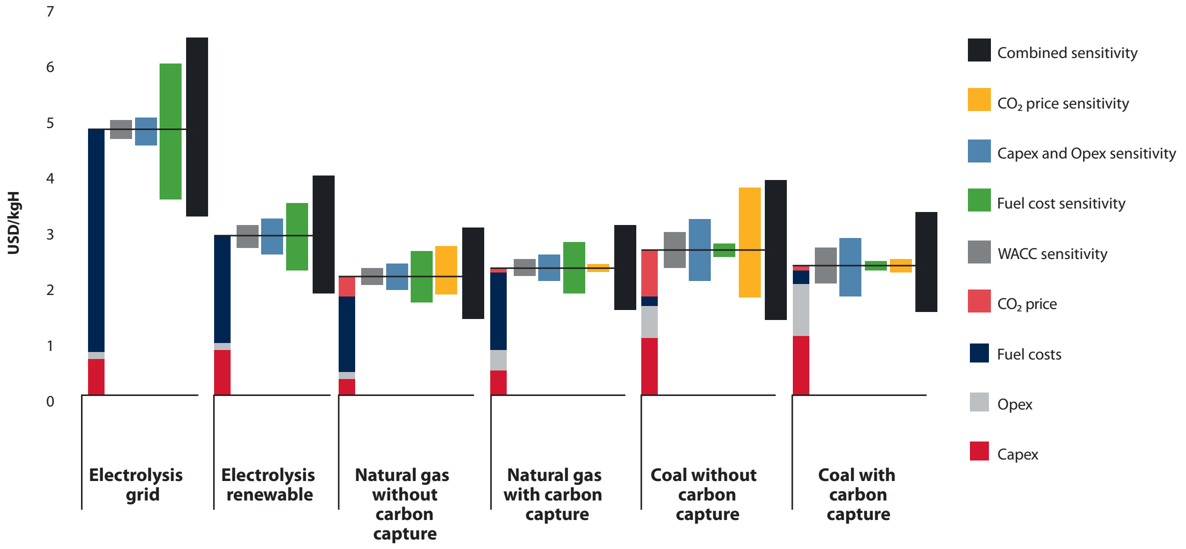
This category comprises fuels made of small molecules with low-carbon-to-hydrogen (C/H) ratio such as hydrogen itself but also liquefied natural gas (LNG) along with its variations depending on how they're produced, e.g., synthetic natural gas (SNG) or renewable natural gas (RNG).

Compared to other future fuel candidates, LNG has over the past several years established itself as a fairly mature bunker not limited to the gas carrier segment. On paper, LNG promises a CO_2 emission reduction of up to 21% vs heavy fuel oil (HFO), provided that methane doesn't slip from engines (an issue for any shipowner going for a low-pressure Otto cycle engine and who also makes no investment in methane oxidation catalysts and other exhaust gas after-treatment systems). The carbon footprint of LNG can be further lowered by blending it with liquefied gases that have been sourced in a more renewable way, a solution already explored in Sweden through the addition of sustainable liquefied biogas (LBG) produced in Lidköping (e.g., by using LBG, the ferry line Destination Gotland wants to achieve a climate goal of reducing its CO_2 emissions by 70% by 2030). According to a 2011 analysis prepared by the Gas Technology Institute, RNG produced from waste biomass (e.g., agricultural) has the potential to offer up to 2.5 quadrillion British thermal units/year, the equivalent of what the half of homes in the US consume. SNG can be produced from biomass, too, yielding >90% methane by volume mixtures and with the same physical and chemical properties as fossil natural gas. Biomass can be used to source SNG/RNG at an efficiency of up to 70%. There's also the coal-to-SNG option, though, the conversion results in more CO_2 emissions than burning coal, so additional measures would have to be implemented to make it climate-friendly such as carbon capture and sequestration (CCS). Alternatively, there's the power-to-gas lane to explore where hydrogen can be used to react with CO_2 to produce methane or SNG/RNG, or when hydrogen is used to upgrade low-quality biogas. The 4-9% (hydrogen by energy) hydrogen-compressed natural gas blend can be used either in internal combustion engines or in fuel cells (obviously, the eco-friendliness of this method depends on the energy source used to produce hydrogen). Because LBG, SNR, and RNG do not significantly differ from LNG, they can be used as drop-in bunker necessitating no engine or fuel system modifications. Lastly, SNG/RNG biomass facilities can be set up in or nearby ports, thus cutting transport-related emissions (the Lidköping plant is located some 360 km away from the Port of Nynäshamn where Destination Gotland's ships are bunkered).

Although still a fossil fuel, LNG was very much praised in the past; maybe not as the ideal solution but far better than oil-based bunkers – to the extent that the European Commission (COM) rushed a few years ago to entwine the whole EU with LNG infrastructure (within the sustainable energy security package, which included a non-legislative strategy for LNG and gas storage). Fast forward to present times and one gets the impression that LNG is already passé; instead, the new COM has put hydrogen in the centre of attention of its European Green Deal.

Having said that, the story behind hydrogen is no breaking news; it has always been portrayed as the silver bullet. In all fairness, it's a solution that also repeatedly came with its set of caveats. As things stand today, the production of hydrogen is very carbon intensive: from 10t CO_2/1.0t H_2 when natural gas is used (75% of world hydrogen output), up to 19t for coal (23%). Some 275mt oil equivalent of hydrogen is produced annually, roughly 2% of the global energy demand. The allure of hydrogen is that it can be zero-carbon if "only" produced with renewable electricity.

Fig. 2. Hydrogen production costs for different technologies in 2030[1]



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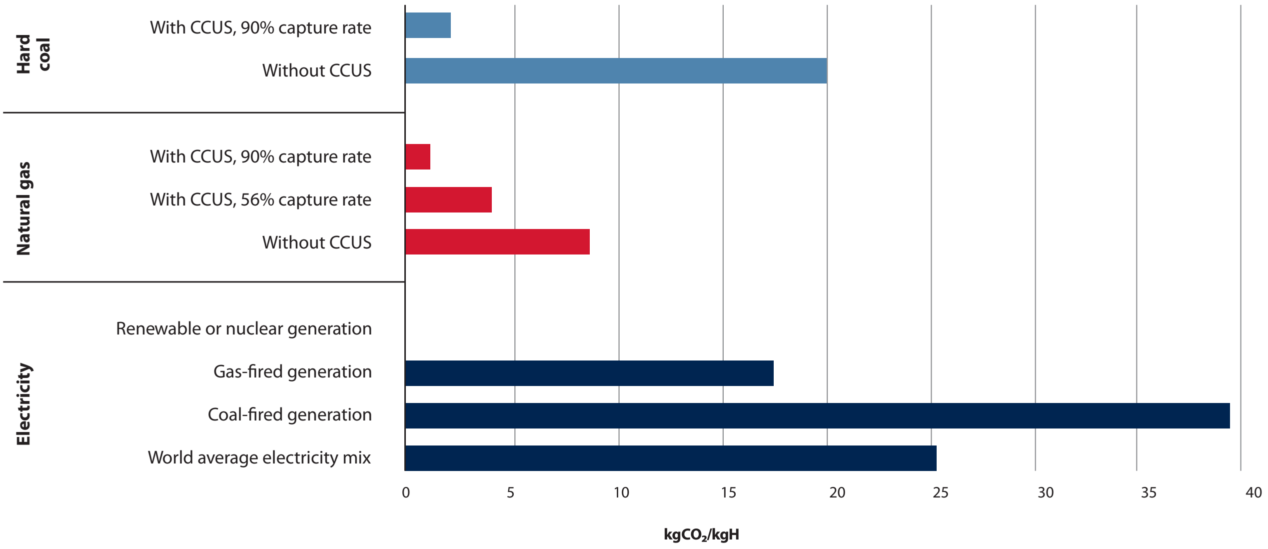
[1] *WACC – Weighted Average Cost of Capital*

Fig. 3. Carbon intensity of hydrogen production with and without utilizing Carbon Capture Utilization and Storage



With 120.2 MJ/kg it has the highest heating value among potential bunkers. On the other hand, its energy density per unit of volume (compressed at 700 bar) is only around 15% that of diesel, requiring either larger tanks on-board vessels, at the expense of other areas not to mention new ship design altogether, or more frequent refuelling. That's the reason why different projects are looking into storing hydrogen in solid-state materials (e.g., silicon pellets) or exploring the full cell avenue. Next, authors of *Pathways to sustainable shipping* underline, the cost of transporting and distributing hydrogen can be three times as high as its production. Concerning the former, it needs to be liquefied (by cooling it below -253°C, which consumes more than 30% of the energy content), or transported as ammonia or in liquid organic hydrogen carriers (LOHC); both are cheaper than liquefaction, though, the costs of conversion and reconversion are significant. Hydrogen can diffuse into certain materials, including some types of iron and steel pipes, increasing their chance of failure, as well as leak through seals and fittings more easily than natural gas. Hydrogen is also invisible to the naked eye, colour- and odourless; therefore, any leaks and fires can be hard for the crew to spot. “Hydrogen has been used industrially for decades, therefore protocols for safe handling have been developed. However, they remain complex compared to those of other fuels,” ABS authors note, also adding, “Wide adoption of hydrogen as a marine fuel will necessitate further development of safety protocols and potentially alleviation of public concerns.”

Lastly, as this also pertains to other alternative marine fuels, there's no established supply chain for getting hydrogen to ships' tanks. A concept for transporting, storing, and delivering it has yet to be developed, a discussion how to do that probably repeating the one around LNG, including the chicken or the egg dilemma, i.e., what's the best way to match demand and supply (in reality meaning who'll be bold enough to invest in a hydrogen-run ship and who in H_2-bunkering services).

Fig. 4. Cost of delivering hydrogen or ammonia produced by electrolysis from Australia to Japan in 2030

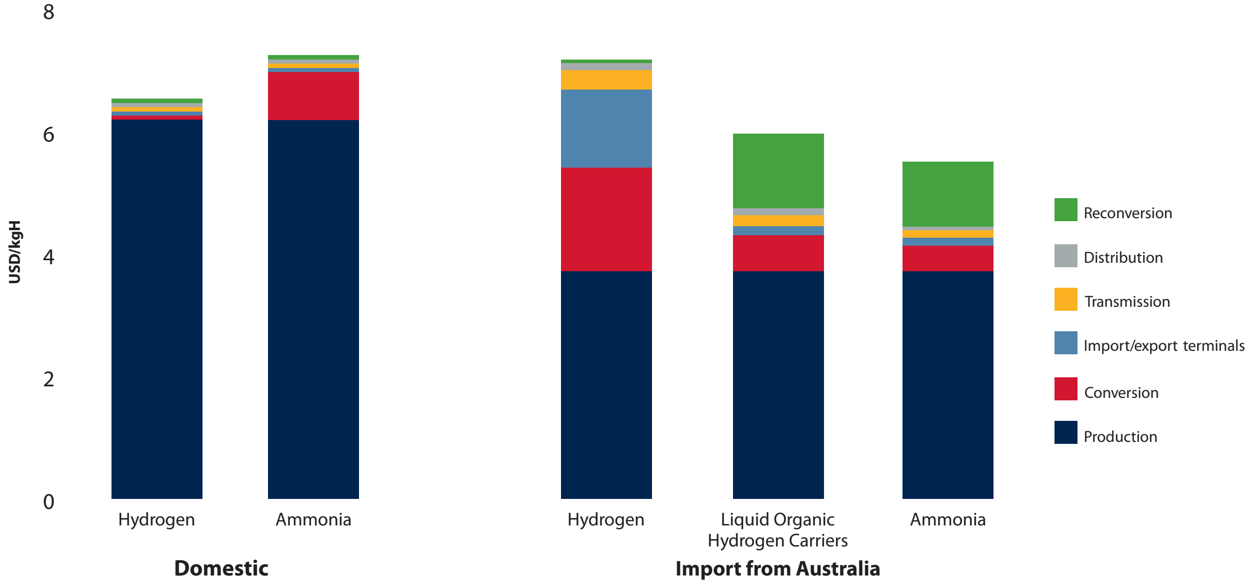
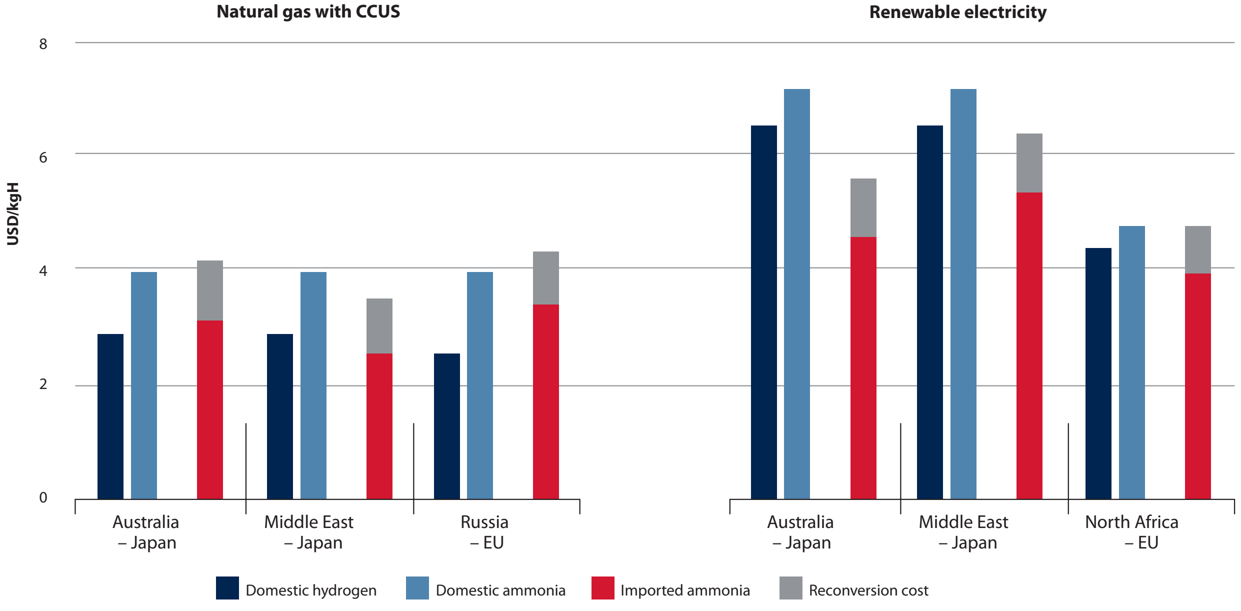


Fig. 5. Comparison of delivered hydrogen costs for domestically produced and imported hydrogen for selected trade routes in 2020



Heavy gas & alcohol fuels

This group consists of fuels based on larger molecules than the light gas group as well as having less favourable C/H ratio eco-wise.

Interestingly, while liquefied petroleum gas (LPG) has considerably penetrated the private vehicle market in certain countries (e.g., around 14% of cars in Poland run on it, 9% in Italy, and 7% in Latvia), the shipping sector has to this day been reluctant to give it a try. Unlike LNG, this non-toxic and not harmful to soil or water by-product of natural gas processing or oil refining can be liquefied at low pressures and ambient temperature, making it possible to store and transport in pressure vessels at around 18 bar or semi-pressurized/refrigerated tanks at five to eight bar and -10 to -20˚C. LPG has a lower C/H ration than diesel, thus its burning results in lower CO_2 emissions. For instance, using LPG in the ME-LGIP engines reduces CO_2 emissions by up to 18% and particulate matter by 90%, compared to HFO, according to MAN (the first commercial ME-LGIP engines were installed in two of EXMAR's very large gas carriers in 2019; on behalf of BW LPG, MAN has also retrofitted four MAN B&W 6G60ME-C9.2 HFO-burning engines to 6G60ME-C9.5-LGIP LPG-propelled DF ones). The lifecycle GHG emissions of LPG have been reported to be 17% lower than those of HFO or marine gas oil (MGO), on a par with LNG. The carbon footprint of LPG can be further axed by bunkering bio-LPG, a by-product of biodiesel production, purified to make it identical in composition to conventional LPG. Bio-LPG can be produced from a variety of feedstock, including agricultural waste and residue, wood, and vegetable oils. Since end-2016, Neste has been running what's said to be the world's first bio-LPG production facility, part of the company's renewable product refinery in Rotterdam. Neste's bio-LPG is used in transportation, residential and commercial heating, and as a drop-in biofuel in marine applications. Unlike LNG, however, current two-stroke LPG engines will need to employ exhaust gas recirculation (EGR) to control rising temperatures during combustion or selective catalytic reduction (SCR) systems to treat the exhaust gas in order to comply with Tier III NO_X emissions regulations (there's some evidence that four-stroke engines can be efficient enough to ensure compliance without the need for after-treatment).

Tab. 1. GHG emissions of HFO, MGO, LPG, and LNG (kg CO_2eq/GJ)

	HFO	MGO	LPG	LNG (Qatar)
Well-to-tank	9.79	12.69	7.15	9.68
Tank-to-propeller	77.70	74.40	65.50	61.80
Total	**87.49**	**87.09**	**72.65**	**71.48**

Methanol, primarily produced from natural gas and already widely used in the chemical industry, is an alcohol fuel with low C/H ratio, which can offer similar CO_2 emission reductions as natural gas. Its low-reactivity requires the presence of an ignition source (pilot diesel injection in dual-fuel engines) to ignite the fuel-air mixture. The energy content of methanol is comparatively low, creating issues with how much bunker can be actually stored on-board a ship (e.g., deep-sea vessels would require two-to-three times more frequent bunkering). On the plus side, it is liquid in ambient conditions which simplifies storage. It also has a lower adiabatic flame temperature than diesel, which can reduce the peak cylinder temperature and limit NO_X formation during combustion. Methanol contains no sulphur and requires limited modifications to the engine and fuel supply system compared to LNG. "In 2019, Marinvest announced that two of its vessels using the ME-LGI engine accumulated more than 50,000 operating hours using methanol and showed a slight improvement in fuel conversion efficiency compared to baseline diesel operation. […] Engines that use direct fuel injection have shown very little methanol slip," ABS' authors write in *Pathways*. Similar to LNG and LPG, there's also bio-methanol, sourced from a variety of feedstock, most commonly from natural gas but also more renewable sources like wood, municipal solid waste, waste CO_2, and sewage water.

While the light gas group has its 'top of the class' in the form of hydrogen, here the same can be said about ammonia, "a disruptive, zero-carbon fuel that has the potential to enter the global market relatively quickly and significantly contribute to meeting the GHG reduction target for 2050 set by the IMO," ABS highlights. Just as methanol, ammonia has been on the market for years, predominantly used as a fertilizer as well as a building block for the synthesis of pharmaceutical and cleaning products. Although ammonia is nowadays produced from hydrocarbon fuels, renewable sources can be used to make hydrogen from the electrolysis of water and then synthesized to ammonia, making it what's called an electro-fuel. More importantly, it's an electro-fuel that is characterized by zero-carbon intensity during production or use, as it is free of carbon (and sulphur, for good measure).

Ammonia has a higher energy density by volume than hydrogen and is easier to liquefy – at 8.6 bar and at ambient temperature or, alternatively, by bringing it below -34°C; it can also be carried in liquid form at ambient temperature, typically compressed to around 18 bar. As such, C-type or prismatic tanks can be used for storage. Moreover, ammonia requires significantly lower re-liquefaction energy compared to hydrogen or LNG. It also has a narrow flammability range, thus isn't considered an explosion hazard. Yet, ammonia can be toxic in concentrated form and very reactive. That's why the International Gas Carrier Code specifies strict requirements on the materials that can be used to contain ammonia, alongside the design features that a plant needs to have in order to minimize the risk of exposing personnel to poisoning. Gases other than natural gas can be used as fuel, according to the International Code for the Construction and Equipment and Ships Carrying Liquefied Gases in Bulk (IGC) as well as the International Code of Safety for Ships Using Gases or Other Low Flashpoint Fuels, granted safety isn't compromised; however, the use of cargo identified as toxic is explicitly prohibited by IGC.

Tab. 2. Well-to-tank emissions for ammonia by energy source for the production process (g CO_2eq/MJ)

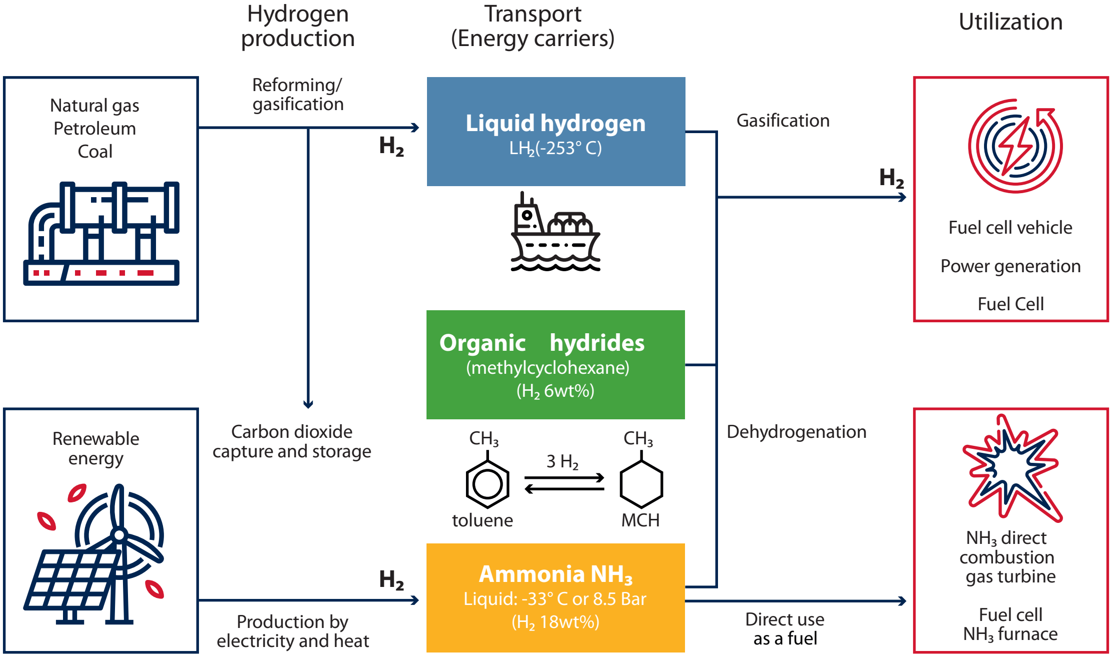
Electricity source	Production	Transmission and distribution	Total
Municipal waste	18.31	0.42	**18.73**
Hydro	20.46		**20.89**
Nuclear	45.23		**45.66**
Biomass	45.77		**46.20**

Ammonia is a low-reactivity fuel, requiring a pilot injection; on the flip side, it's conducive to spark-ignition combustion. Ammonia has a high heat of vaporization, helping to control NO_X formation. Then again, this may be offset by the fuel-bound nitrogen, which may increase nitrogen oxide formation. The MAN ME-LGIM dual-fuel engine, designed for running on methanol and diesel, can use ammonia instead of the former, following slight modifications to the fuel delivery system to supply ammonia at 70 bar and inject it into the cylinder at 600-700 bar.

The 2012 study *Developing Fuel Injection Strategies for Using Ammonia in Direct Injection Diesel Engines* showed that combustion with ammonia results in similar or lower NO_X formation than diesel and two-to-six times lower CO_2. If injected into the cylinder during the exhaust valve event, however, ammonia slip can occur; this can be avoided in high-pressure direct-injection systems that inject fuel late in the compression stroke. Nonetheless, SCR will have to be used for ammonia engines to comply with NO_X emission regulations.

Identically to hydrogen, ammonia can be burned in internal combustion engines or used in fuel cells (discussed in more detail later in the article). In the latter case, hydrogen contained in the molecule needs to be extracted, and high-temperature solid oxide fuel cells (SOFC) can be a more efficient and compact solution than the polymer electrolyte membrane (PEM) technology. ABS notes in this regard, "There are also other advantages of using ammonia in SOFC, such as the high electrical efficiency achievable, the absence of NO_X production and the lack of vibration. However, SOFC currently have a […] very high comparative cost. […] An additional shortcoming […] is the sensitivity of the solid oxide ceramic materials used to heat gradients, which cause relatively long and careful start up and shut down procedures, which often last for hours." To avoid that, SOFC plants should operate continuously, coupled with an energy storage system (batteries) to balance load demand fluctuations.

Fig. 6. Hydrogen and ammonia production and use

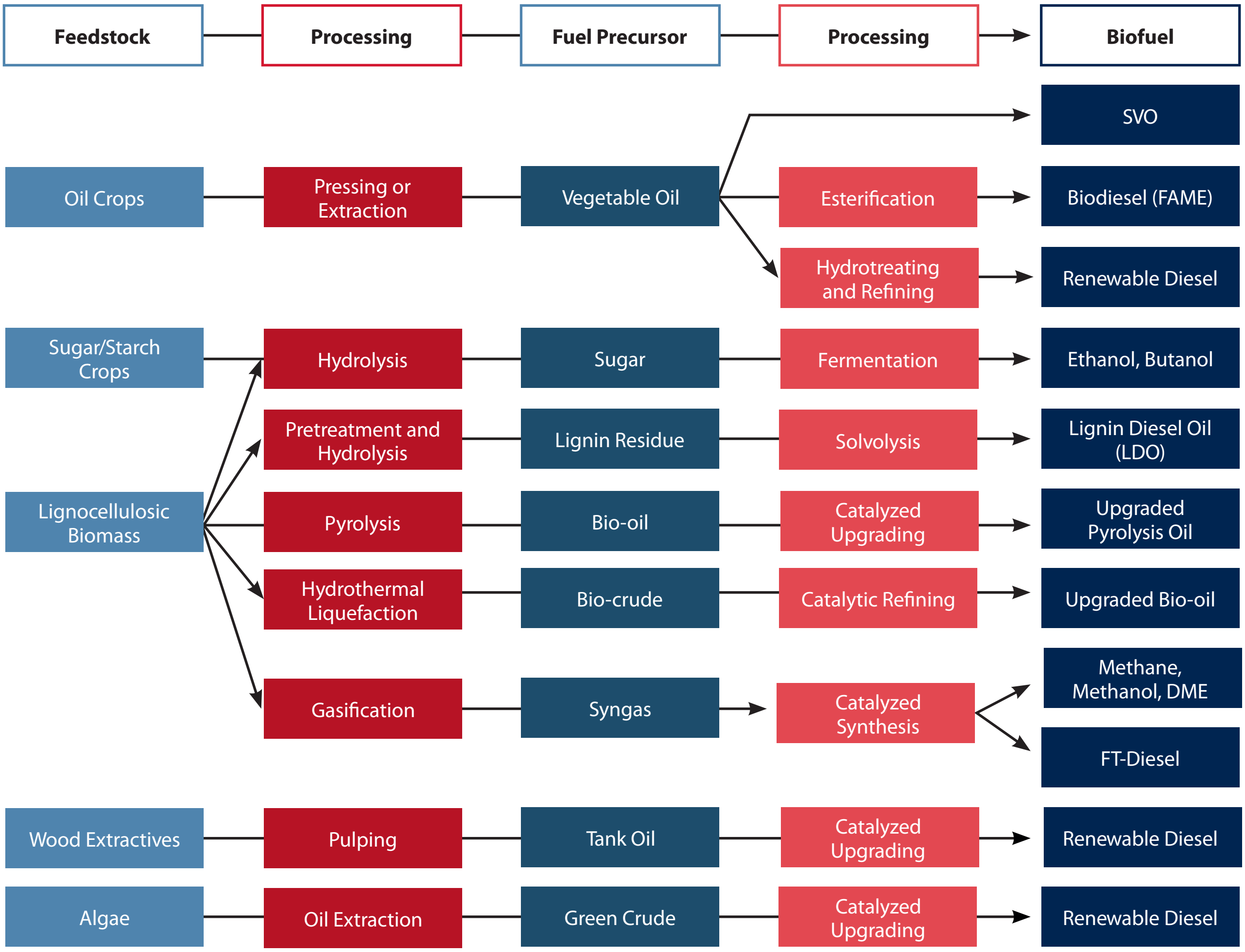


Bio/synthetic fuels

These are fuels similar in proprieties to diesel but sourced renewably. This makes it easy to use them as drop-in bunker as well as take advantage of the existing transport and bunkering infrastructure and services. "However, the carbon reduction potential, economics, and viability of different biofuels depend on their source feedstock and production pathways," ABS notices.

Fatty Acid Methyl Ester (FAME) is the most common first-generation biodiesel, characterized by a higher cetane number than diesel, which promotes autoignition and may reduce the ignition delay and noise during combustion. FAME is produced from a variety of plant and animal feedstock, including canola, soybean, coconut, palm, corn, rendered beef, poultry litter, and used cooking oil. It has a higher flash point (149°C) than diesel and a high cloud point which may result in clogging of fuel filters and lines and poor fuel flow below 32°C. While FAME is non-toxic and has good lubricity properties thanks to which fuel pumps and injectors are protected against wear, it's also biodegradable, degrading in the presence of water, and has low oxidative stability, meaning FAME breaks down over time, forming peroxides, acids, and other insoluble compounds; oxidation can also lead to bacterial growth in tanks and sludging of fuel lines, filters, and injectors. There are certain trade-offs to consider when blending FAME and diesel, ABS cautions, such as when fuel-bound oxygen can decrease carbon monoxide and non-methane hydrocarbon emissions in blends up to 20% but which, at the same time, increases NO_X formation. Larger blends also lead to the degradation of fuel filters and oil sludging. The International Council on Combustion Engines published in 2013 its *Guideline for Ship Owners and Operators on Managing Distillate Fuels up to 7.0 % v/v Fame (Biodiesel)*, which includes recommendations such as avoiding >6-month-long storage, especially of biodiesel in isolated individual unit tanks, and implementing fuel condition monitoring. Overall, ABS voices its scepticism toward first-generation biofuels, "The production of first-generation biodiesel generally results in high fuel cost due to the limited supply of feedstock and competition from the food, pharmaceutical and cosmetic industries. In addition, the feedstock supply for biodiesel is significantly less than petroleum diesel, so present biodiesel production cannot fully replace the consumption of diesel. Based on these limitations, biodiesel can be used in blends, but as a long-term solution, it would be economically

Fig. 7. Overview of biofuel production pathways from different biomass feedstocks



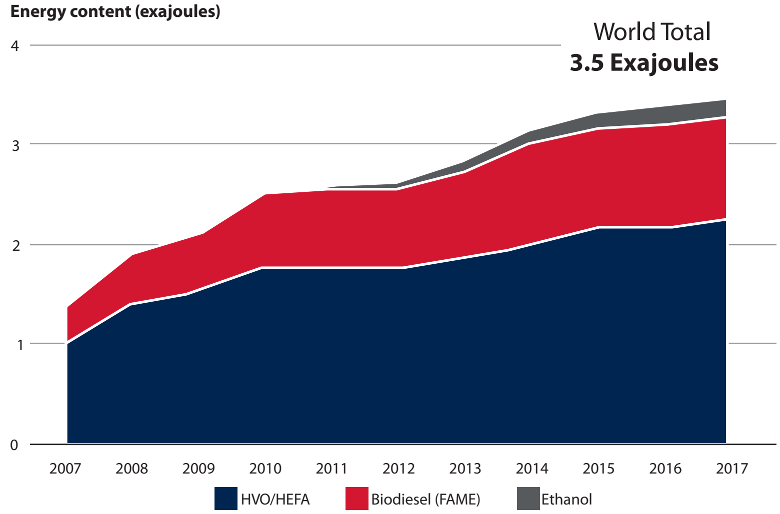
and logistically unattractive to use it as a large-scale marine fuel."

Hydro-treated vegetable oil (HVO) represents the second generation of biofuels (i.e., those not produced from food crops). HVO comes from plant oils or animal fat through hydrotreating and refining. Hydrogen is used to remove the oxygen from oil to avoid FAME's oxidation issues. A mixture of paraffin, HVO is free of sulphur, esters, and aromatics (which form soot precursors). It has a very high cetane number, a heating value that is slightly higher than diesel, and good stability for storage. Combustion with HVO results in 28-46% fewer particulate emissions and Filter Smoke Number (FSN) than diesel as well as 5-14% lower NO_x formation. Less CO_2 is emitted, too, following HVO's better C/H ration than diesel. Overall, specific fuel consumption is 3-4% lower (but 4-5% higher volumetric consumption since HVO has a lower density than diesel). Alike FAME, however, the capacity for producing HVO is limited. Because it's dependent on access to renewable feedstock, HVO prices can vary greatly depending on the source and season (palm oil cost $1,250/t in February 2011 vs $650/t in 2016; cooking oil $720/t in January 2013 vs $400/t in 2016). A number of companies in the Baltic are already using HVO, i.a., the Port of Södertälje to propel its two new reach-stackers, APM Terminals Gothenburg to run the container handling equipment (incl. over 40 straddle carriers), or the Port of Norrköping for its machinery and car fleet. Then there's GoodShipping Program, an initiative dedicated to decarbonizing ocean freight, i.a., by scaling up the supply and use of low carbon marine biofuel oils. In March 2019, the organization, together with IKEA Transport & Logistics Services and CMA CGM, bunkered the shipping line's container carrier biofuel derived from forest residues and waste cooking oil. According to GoodShipping Program, its product is expected to deliver 80-90% well-to-propeller CO_2 reduction vs fossil equivalents. In addition, the product eliminates sulphur oxide (SO_x) emissions – and does so without any requirement for engine modifications.

Syngas ($CO + H_2$), converted biomass under high temperature and pressure in the presence of oxygen, is another alternative. It can be either directly used in internal combustion engines or further processed to liquid form. Although synthetic diesel, a high-quality clean fuel, demonstrates reductions in regulated emissions in comparison to diesel, its production and refining are energy-intensive.

Syngas can also be converted to dimethyl ether (DME), a colourless, non-toxic, and low-carbon content gas, easy to liquefy and transport. "Combustion with DME has been experimentally tested on automotive heavy-duty diesel engines […]. The results verified that the absence of carbon bonds and the presence of oxygen in the fuel eliminates soot formation and enables engine optimization for minimizing NO_x formation and fuel consumption," ABS reports. Because DME has a higher cetane number than diesel, the ignition delay is decreased, resulting in less pressure during combustion, hence lower noise. On the other hand, DME has lower energy content than diesel as well as low viscosity and lubricity, requiring the use of additives to avoid supply line leakages and surface wear of moving parts. That said, DME production is ramping up, e.g., in China as a replacement/supplement for propane (up to 5mt/year); other facilities are also coming online (Japan, South Korea, Brazil) or are in the pipeline (Egypt, India, Indonesia). In the Baltic, Sweden is experimenting with BioDME produced from waste streams from pulping. Last but not least, DME production doesn't require large-scale plants.

Fig. 8. Global trends in ethanol, FAME, and HVO production in 2007-2017



Tab. 3. Comparison of energy and sulphur content, and cost of alternative fuels

	HFO	MGO	LNG	FAME	HVO	Ethanol	Methanol
Lower Heating Value (MJ/kg)	39.0	43.1	47.1	37.1	44.1	26.7	19.9
Sulphur (% m)	<3.5	2	–	–	–	–	–
Cost ($/t)	290	482	270	1,040	542	503	464

Tab. 4. Storage requirements of different fuels

	MGO	Methane	Ethane	Propane	Butan	Hydrogen	Ammonia	Methanol	Ethanol
Flashpoint (°C)	>60	-188	-135	-104	-60	–	132	11	16
Boiling point (°C 1 bar)	180-360	-162	-86	-42	-1	-253	-33	65	78
Density (kg/m^3 liquid)	900	450	570	500	600	76.9	696	790	790
Conventional or cryogenic pressurized tank	CONV	CRYO	CRYO	CRYO	CRYO	CRYO	CRYO	CONV	CONV
Secondary tank barrier required	NO	YES[1]	YES[1]	YES[1]	YES[1]	YES[1]	YES[1]	NO	NO
Additional cofferdam or hold space requirements	NO	YES	YES	YES	YES	YES	YES	YES	YES
Volume comparison MGO (energy density)	1	1.78	1.41	1.66	1.40	4.16	2.45	2.44	1.82

[1] *Except type C tanks*

Carbon capture and sequestration, hybrid electric power, fuel cells, DC systems, just-in-time and optimum ship routing

ABS identifies a set of additional measures the sea shipping industry will have to implement in order to hit the IMO's GHG goal.

Carbon capture and sequestration (CCS) aims to tackle the inherent issue of CO_2 formation as a complete combustion product in proportion to the carbon content of fuel. The plan is to absorb CO_2 into a solid or liquid. Next, in the desorption/regeneration step, CO_2 is selectively desorbed, resulting in a flow of pure CO_2 gas and the regeneration of the original capture absorber for further use. In a pioneering trial, Mitsubishi Heavy Industries has installed a CCS unit on a very large crude carrier. The system comprised four towers (each roughly the size of a scrubber) and liquefaction and storage facilities, an additional 4,500t in total. The plant was designed to produce methane or methanol by combining hydrogen from water electrolysis with the captured CO_2. The initial capture rate was 86%. The entire CAPEX came at around $45m, out of which the CCS installation cost $30m and the methane/methanol plant $15m.

More and more shipping lines are also equipping their vessels with batteries, either for hybrid or purely electric propulsion (the former are optimized for a narrow operating range in order to maximize the number of discharge cycles, while the latter for a wide operating range). Although lithium-titanate (LiT) batteries have lower cell voltage and specific energy than the more commonly known lithium-ion (Li-ion) ones, they aren't troubled by Li-ion's ageing problem, hence the technology is more promising for the sea shipping industry (today's marine batteries have a life cycle of 7-10 years, which according to ABS should be extended beyond 15 years). Irrespective of the chosen solution, the organization also cautions, "Batteries can be a source of catastrophic failure resulting in dangerous and possibly life-threatening consequences. Battery packs must undergo rigorous testing in order to ensure benign failure modes. As general guidelines, the battery should not emit particle or any toxic and hazardous gases. Care must also be taken in manufacturing, transporting, using and recycling of batteries. Many safety standards exist to define the level of danger from batteries; safety tests include penetration, crash, thermal stability, overcharge/discharge, and externals short." A number of companies have already blazed the battery trial (incl. Scandlines, ForSea, Color Line, Blidösundsbolaget, Waxholmsbolaget, the Swedish Transport Administration, Västtrafik, and FinFerries in the Baltic); SEACOR Marine has hybridized its diesel platform supply vessel SEACOR Maya with a Li-ion system (operational within 90 days), saying that her average fuel consumption went down by one-fifth.

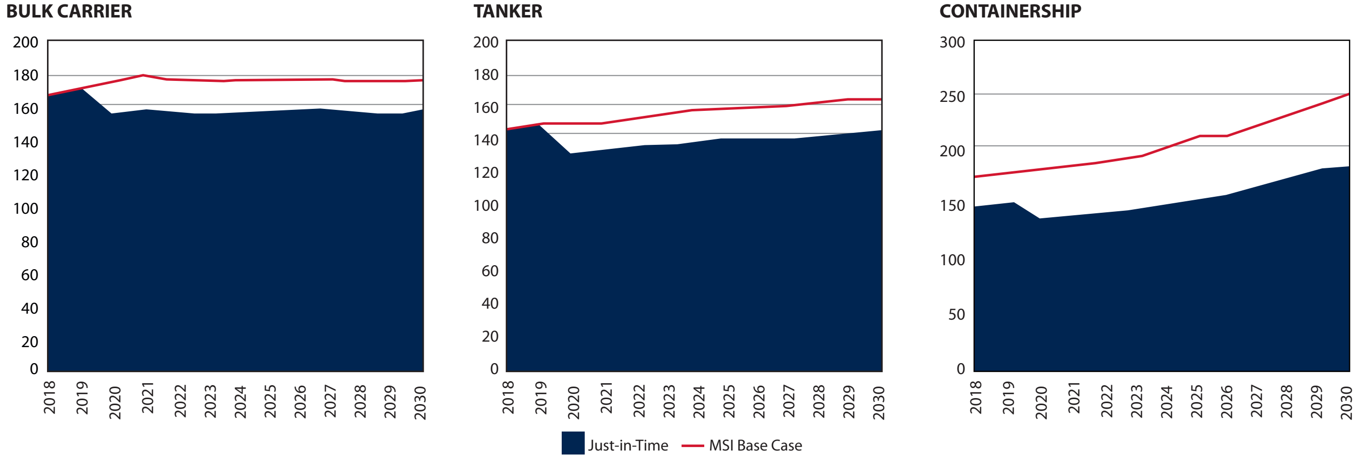
Just like batteries, fuel cells are also electrochemical devices that supply DC power. In contrast to batteries, the fuel and oxidant are stored outside the cell and brought into it as the reactants are consumed. In essence, fuel cells are energy converters, not storages (that's why it's faster to refuel them than recharge/replace batteries; however, both operate within a DC system, so that fuel cells can be accommodated into a hybrid electric architecture). While the already-mentioned SOFC technology seems better suited for ammonia fuel cells, ABS also highlights its competitor, the polymer electrolyte membrane (PEM) solution characterized by lower operating temperature range (<100°C vs 650-1,000°C for SOFC), small size, high efficiency, and wide operating range. That said, there's a set of challenges – other than the cost of producing and transporting hydrogen or ammonia – standing against the widespread use of fuel cells, which includes the cost of exotic materials (e.g., platinum for electrodes) or sensitivity to impurities but, above all, the so-called balance of plant, an accessory system required to operate the fuel cell (fuel and air processing; thermal and water management; electrical controls; protection; and AC-DC conversion). Balance of plant can take up to 10-20% of the fuel cell output for low- and high-pressure systems, respectively. Then again, combined with heat recovery, fuel cells can achieve system efficiency of up to 85% vs 30-55% for diesel engine-generators. Once an issue, because fuel cell performance weakened with time, the lifetime of fuel cell systems has been improved to the extent suitable for marine applications. Currently, however, the unit cost of a fuel cell system can be up to 10 more expensive than competing power generation technologies.

Quite a few projects have been initiated to bring the fuel cell technology onto the market. ABS' own initiative, SF-BREEZE, was tasked with designing and building a high-speed passenger ferry with hydrogen-fuelled PEM fuel cells for operation in the San Francisco Bay. ABS is also involved in developing a prototype hydrogen fuel cell unit to power on-board reefers. The Norwegian ship technology company Havyard Group is working to design, certify, and deliver a large-scale hydrogen power solution that can be retrofitted onto a ro-pax. Wärtsilä is said to develop the world's first big-scale ammonia fuel cell for ships. The Finnish company will take part in the ShipFC project the aim of which is to install a 2 MW-big ammonia fuel cell on-board Eidesvik's currently LNG-run offshore vessel *Viking Energy* by 2023 (Wärtsilä has also carried out combustion trials using ammonia to assess its potential to serve as ship fuel and is investigating several other alternatives, including synthetic methane, hydrogen, and methanol). The ShipFC consortium believes that an ammonia fuel cell of that magnitude will make it possible to sail on clean energy for up to 3,000 hours/year. Tokyo Kisen Co. and e5 Lab are working on developing the design and regulatory baseline for a hydrogen fuel cell-powered tugboat, possibly in operation in 2022. Last but not least, Ballard Power Systems has presented a modular 100 kW PEM fuel cell stack that can be used in various combinations to provide power (main or auxiliary) and redundancy needed by a vessel.

Direct current (DC) distribution is another technological solution that promises to improve fuel efficiency. DC energy sources, fuel cells and batteries, can also be directly connected into the ship's electrical systems via power-electronic converters (PEC), producing additional fuel savings. Nevertheless, ABS notes, "It is only in the past few years that full DC networks have been used in small vessels. New systems require crew training, awareness, and familiarity. Also, the supporting components do not have a long history of operations in marine environments (operability, reliability and historic data for failure rates)."

Technology can also aid shipowners in optimizing ship routing. Analysis of various data sets (ship performance, weather, ocean currents, etc.) can be used to adjust vessel speed in order to avoid unnecessary anchorage, which is often the result of ships speeding in the hope of arriving before others, only to get stuck in a queue waiting for a free berthing slot, meanwhile burning bunker to keep on-board systems running. According to models prepared by ABS' partners from MSI, just-in-time shipping (incl. an average 5% reduction in speed, and assuming no impact on cargo-carrying capacity and no adjustment to the size of the fleet) can deliver 10-11%/year CO_2 emission savings. However, it might be hard to enforce a global speed reduction scheme, not counting the toll this might take on importers who will have to increase their inventories to accommodate the longer delivery time (according to research carried out by Erasmus University Rotterdam – following the slow steaming practices introduced by shipping lines in response to the negative impact on trade of the financial crisis of 2007-2008 – while liners could achieve fuel savings of up to around $70m, shippers would accrue $170m in inventory costs).

Fig. 9. Potential reduction of CO_2 emissions with just-in-time shipping vs baseline (million tonnes)



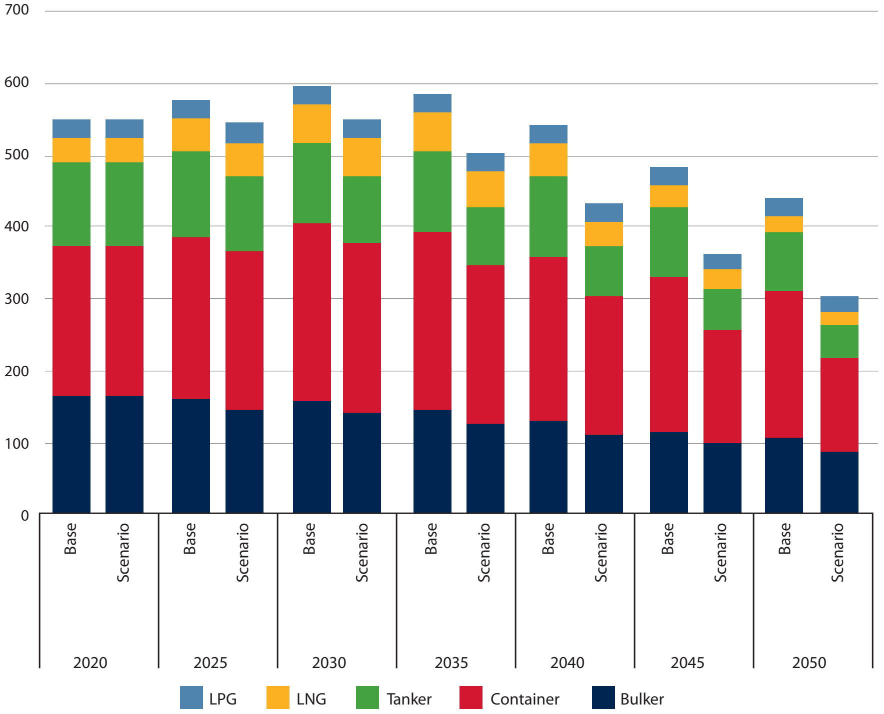
Given the superfluity of alternative fuels that can take shipowners and operators to the other side where the grass is in fact greener, how come ABS arrives at a conclusion that transitioning sea shipping toward climate-friendly operations, by means of exchanging one bunker for another, won't be enough to get the industry to the IMO's 2050 goal? "Based on the projected fuel mix for the five vessel segments analysed in this study, shipping can meet the IMO's target to reduce CO_2 emissions per transport work (g CO_2/dwt/nm) by 70 percent by 2050, relative to 2008. However, to achieve a 50 percent reduction in absolute CO_2 emissions (ton), the market share of petroleum fuels will need to be further reduced by 2050 (below 40 percent)," ABS clarifies.

It ultimately boils down to two issues. First, lowering as much as possible the share of fossil fuels in the 2050 demand mix. This may be quite a challenge from a tonnage renewal perspective, as demonstrated on an exemplary dry bulk carrier company that gradually mixes its fleet (HFO, MDO, LNG, biofuels, putting slow steaming on top of it all). "With so many combinations of options on the table – and more certain to emerge in the next few years – devising a sustainable fleet-wide decarbonization strategy that meets company goals is complex; more so, when each ship requires a bespoke solution that fits its age and operating profile, etc.," ABS stresses.

Tab. 5. Key ship types, gross tonnage, number, and typical emissions (g CO_2/dwt/nm)

Type	Total gross tonnage (million)	Total no.	Emissions
Dry bulk carrier	482	11,536	3-9
Oil and chemical tanker	352	8,681	2.5-7.5
Container ship	246	5,170	6-19
LNG carrier	58	518	6-11
LPG carrier	21	779	7-15
Other	221	40,620	N/A

Fig. 10. CO_2 emissions by ship type (million tonnes)



Tab. 6. Lowering the carbon intensity of a bulk carrier company

- Fleet of ten bulk carriers: 10 x 80k dwt built in 2010 (prior EEDI)
- Operating profile: 50% laden, 35% ballast, 15% idle
- Newbuildings are assumed with negligible fouling, whilst existing vessels with a fouling allowance

Timeline	Fleet composition	Main engine fuel	Auxiliary engine fuel	Speed (knots)	Carbon intensity[1]	Reduction in carbon intensity vs baseline
2019: ten vessels, prior to the 2020 sulphur cap	10 x 80k dwt	HFO	MDO	13	4.4	BASELINE
2020: after the sulphur cap	10 x 80k dwt	MDO	MDO	13	4.5	+2%
2021: slow steaming	10 x 80k dwt	MDO	MDO	12	3.2	-27%
2025: replacement with three EEDI III LNG vessels[2]	7x 80k dwt 3x 85k dwt	MDO LNG	MDO LNG	12	2.82	-36%
2030: replacement with two EEDI III biofuel vessels[3]	5x 80k dwt 3x 85k dwt 2x 85k dwt	MDO LNG BIOFUEL	MDO LNG BIOFUEL	12	2.23	-49%

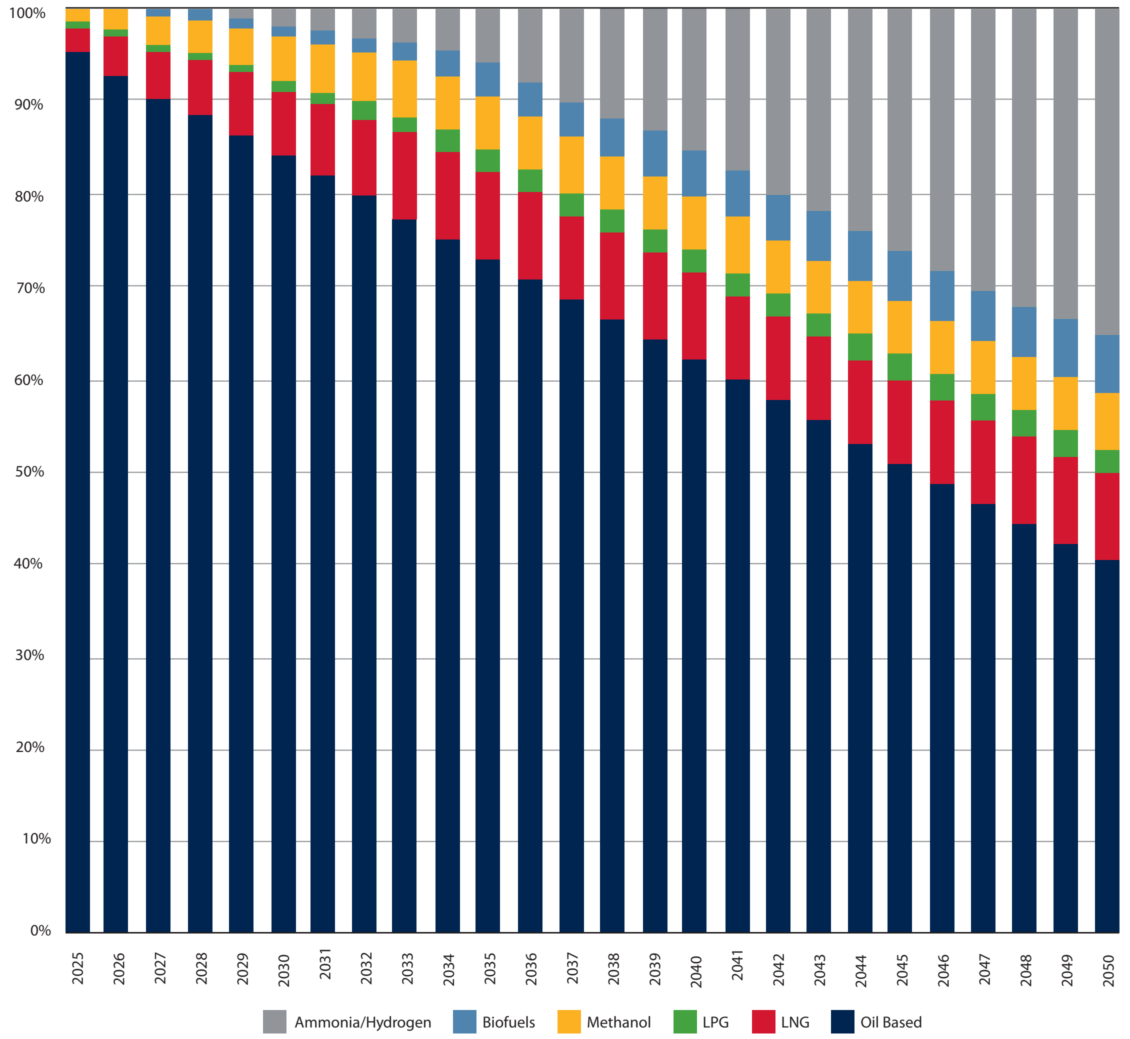
[1] *Calculated as an average of the fleet; CO_2 emissions per transport work – calculated using nominal deadweight, not cargo carried*

[2] *The newbuildings are assumed with a 20% gain in specific fuel oil consumption (SFOC) and a 5% gain in power from design optimization*

[3] *The newbuildings are assumed with no gain in SFOC and a 10% gain in power from design optimization; the carbon factor is assumed as 0.4 for the biofuel*

Second, the global demand for sea shipping, hence how much GHG will be emitted from taking goods from point A to B. This might be the biggest unknown, particularly if one ventures to predict how much will be traded in three decades from now. The foundations can be a little shaky, including the decoupling of trade and GDP; growing demographics don't necessarily have to contribute to greater consumption (either because future cohorts are poorer than generations born in the 20th century, a trend already

Fig. 11. Projected marine fuel use to 2050



visible, or because they chose to lead more sustainable lifestyles); alternative models of production will kick in, notably 3D printing which could lead to both less transportation and products with a longer lifespan; reshoring much of today's production; embracing the circular economy model; electrifying, automating, and having access rather than owning private cars; socioeconomic havoc wrecked by climate change and other black swans; whatever the development of Artificial Intelligence will bring, also factoring in the emergence of a Superintelligence which may come up with solutions beyond the grasp of humankind – for good or ill of our species.

Fig. 12. Projected economic cost of the coronavirus pandemic[1] and climate change[2] (trillion US dollars)

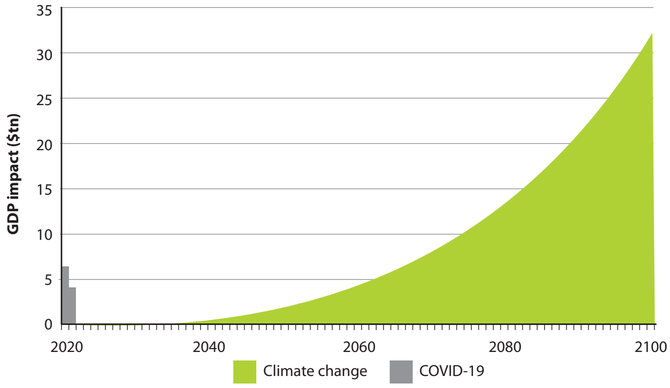
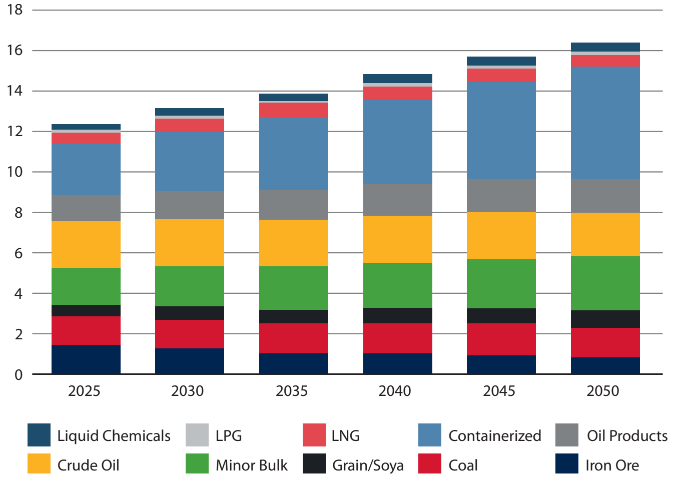


Fig. 13. Trade growth by key commodity (billion tonnes)



[1] *According to the International Monetary Fund*

[2] *According to the Organisation for Economic Co-operation and Development*

Source: AFRY

Fig. 14. Iron ore seaborne trade (million tonnes)

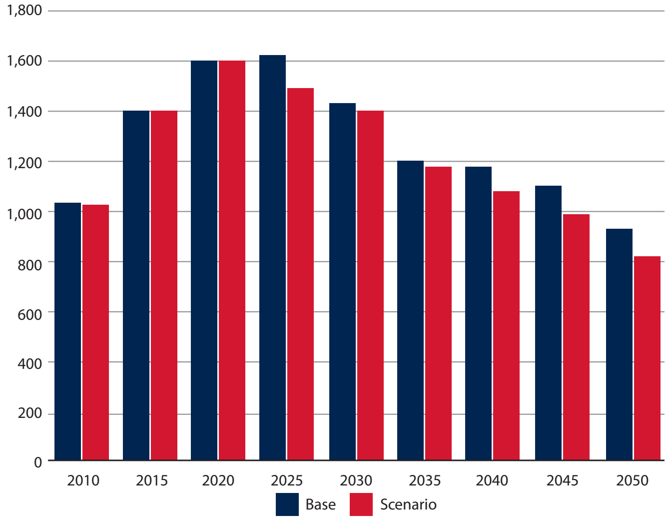


Fig. 15. Coal seaborne trade (million tonnes)

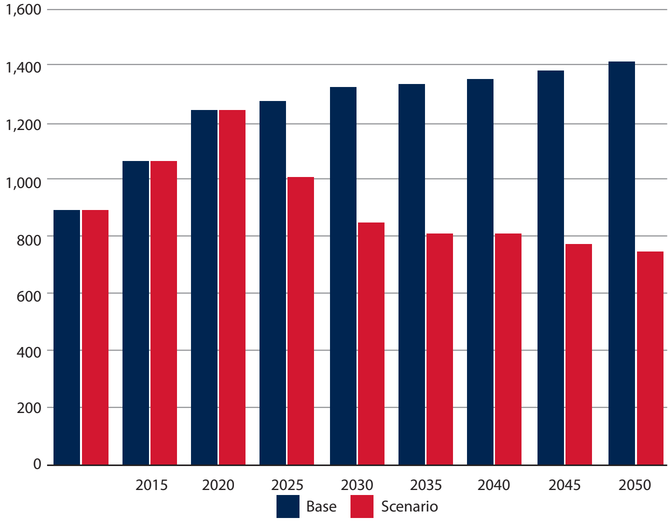


Fig. 14. Iron ore seaborne trade (million tonnes)

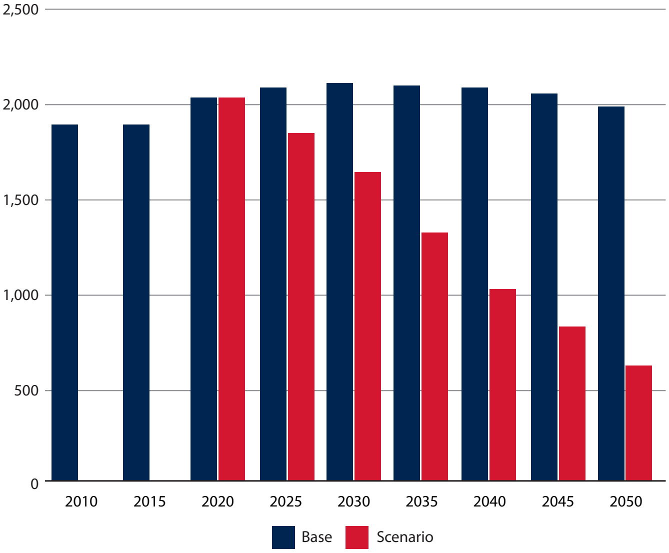


Fig. 15. Coal seaborne trade (million tonnes)

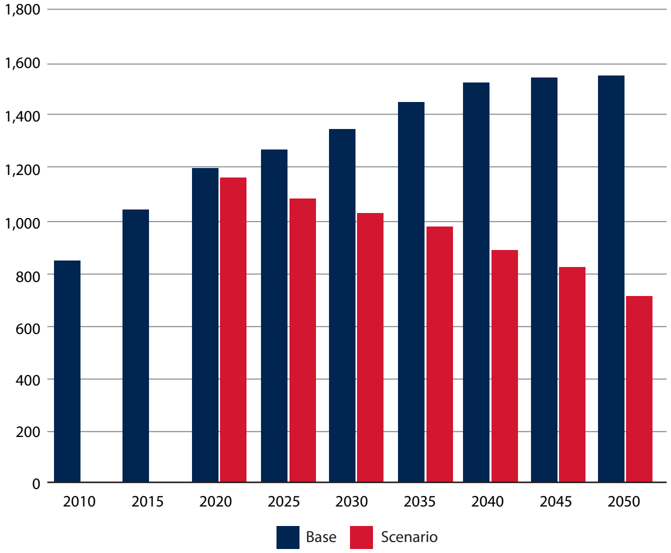


Fig. 18. Edible oil, in- and organic chemicals seaborne trade (million tonnes)

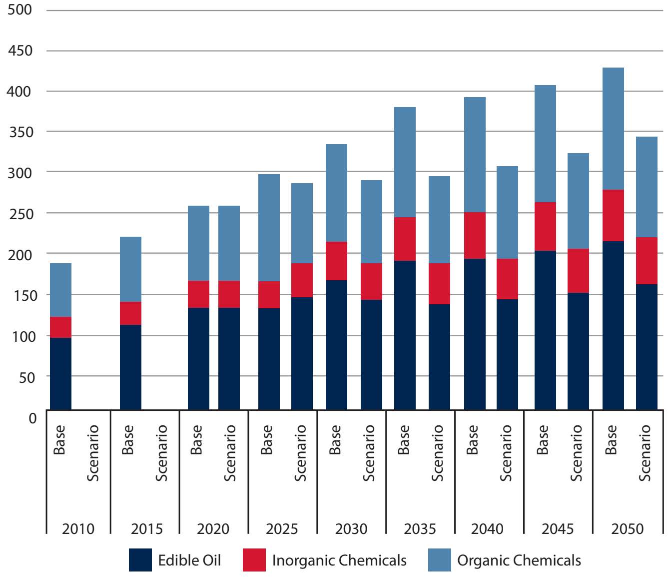


Fig. 19. Global container trade evolution (million TEUs)

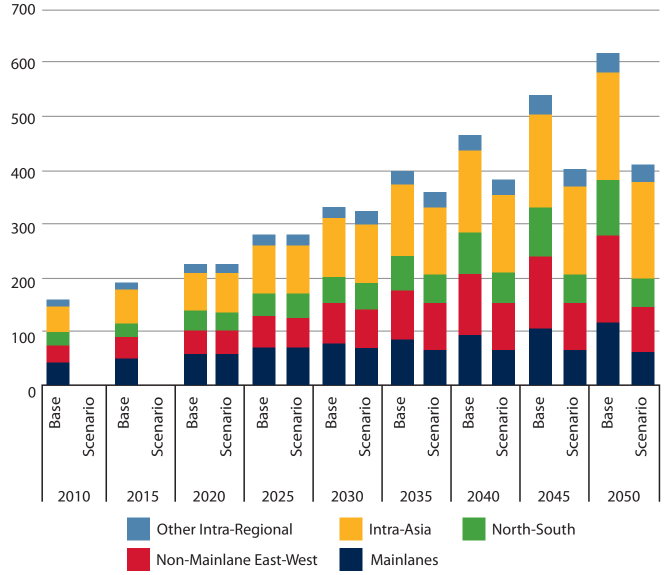


Fig. 20. LNG imports by region (million tonnes)

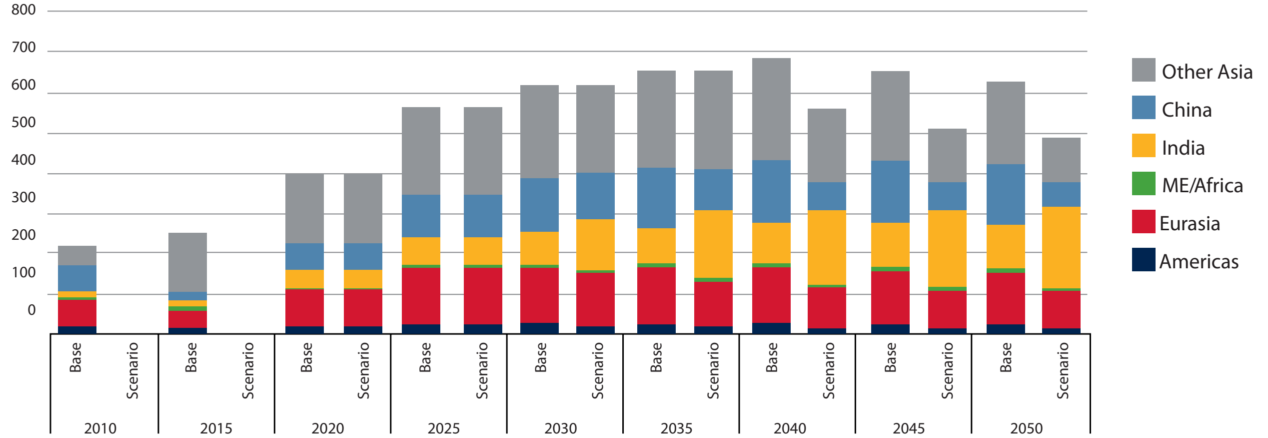


Fig. 21. LPG imports by region (million tonnes)

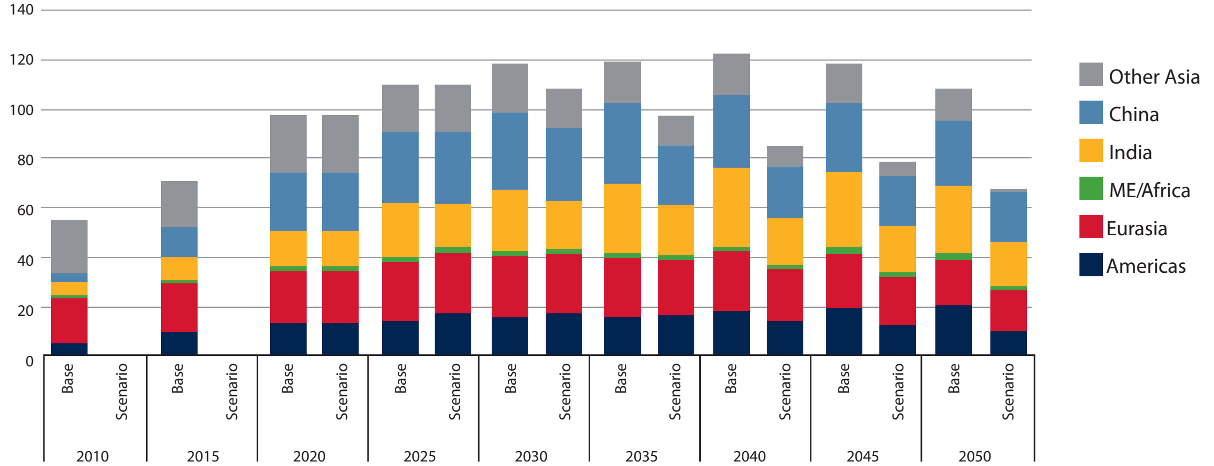


Fig. 22. Fuel consumption by ship type (million tonnes heavy fuel oil equivalent)

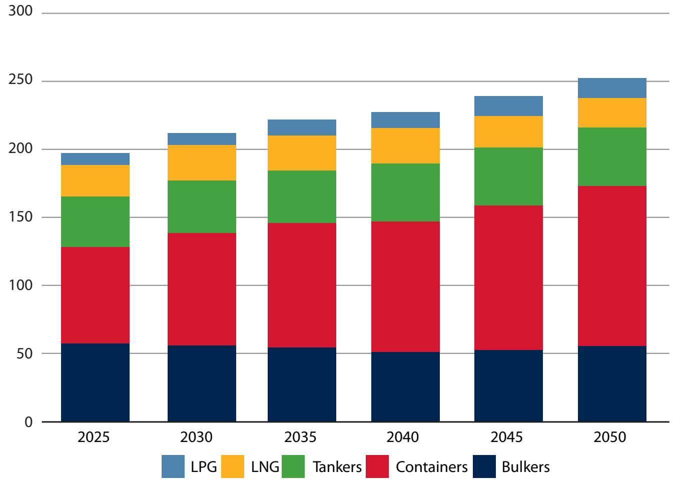
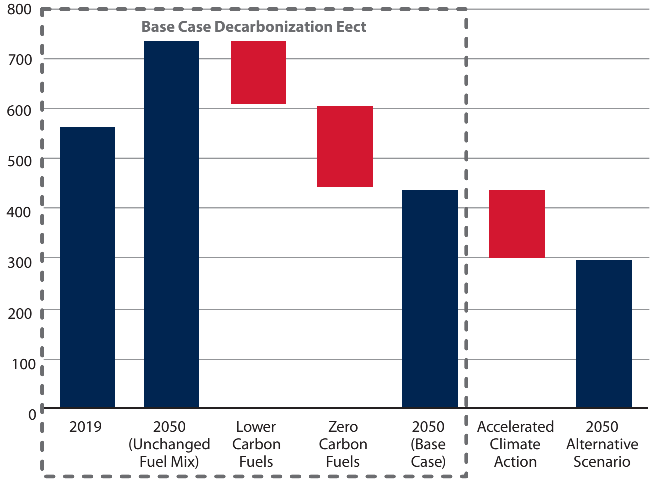


Fig. 23. Key vessel segments pathways to decarbonization (million tonnes CO_2)



Survival of the fastest and greenest

At the end of the day, it appears that decarbonizing sea shipping isn't within the full reach of the industry itself. As blunt as it may sound, greener shipping also means less shipping. "As with any large-scale industry transition, success will not come easily or without the significant disruptions that pose unique and unprecedented challenges and opportunities, especially for early adopters," ABS sums up its *Pathways to sustainable shipping*.

"Early adopters," seem to be the keywords here. It may as well mean "survivors." After all, combating climate warming isn't about the survival of planet Earth, in the past, it handled far worse disasters than us, but a liveable future for all earthlings, with or without sea shipping.