ALL AT SEA

METHANOL AND SHIPPING

INDUSTRY BACKGROUND FROM LONGSPUR RESEARCH

25 January 2022

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ALL AT SEA – METHANOL AND SHIPPING

The shipping industry is likely to be driven towards decarbonisation by the twin pressures of customer demand and regulation. Leading shipowners are already making significant strides in the right direction. Solutions are varied but are driven by considerations of emission reduction potential, fuel density, useability and cost. We think hydrogen and methanol stand out as key solutions in a market worth $105bn per annum with methanol taking an immediate role as commercially and technically viable today.

Pressure growing to reduce shipping emissions

Shipping represent 3 - 4% of global greenhouse gas emissions, roughly equivalent to Germany's emissions. However, unlike Germany, the proportion is set to grow. A combination of tighter emission regulation from the International Maritime Organisation (IMO) and decarbonisation initiatives from some of the major fleet owners means that we see a major drive to adopt low emission solutions. This creates a two-way pressure for decarbonisation and we think that pressure will increase in the years to come. Notably, the IMO will review its current 50% decarbonisation target in 2023 and it is difficult to see this resulting in anything other than tougher targets.

A number of viable routes to decarbonisation

There are a number of viable routes to marine decarbonisation including batteries, biofuels, hydrogen and hydrogen carriers. Batteries are only really suitable for short voyages; perfect for ferries and bumboats. The hydrogen-based options are liquified hydrogen, ammonia and methanol. All currently rely on natural gas for production but can be produced with the emissions captured to create "blue" fuel or, better still, using renewable energy to produce "green" fuel although ammonia has remaining N2O emission considerations. Only methanol dual fuel engines are currently available.

Multiple factors influence choice of solution

We think issues of energy density, emissions, useability and delivered cost will drive outcomes. Energy density is the reason battery use is limited for long distances. Methanol and biofuels are the best low emission options for density. Hydrogen is the lowest emission fuel followed by green methanol. Useability is important and the caustic nature of ammonia is an issue for this fuel. Methanol perhaps excels here given its ability to decompose harmlessly if spilled. Finally, the levelized cost of energy for suggests hydrogen is the outright winner in terms of cost at the point of fuel creation. However, what matters is the delivered cost. Hydrogen requires pressurisation and pressurised storage, increasing costs. By comparison, methanol can use existing fuelling infrastructure with minimal disruption resulting in a lower delivered cost.

Industry background from Longspur Research

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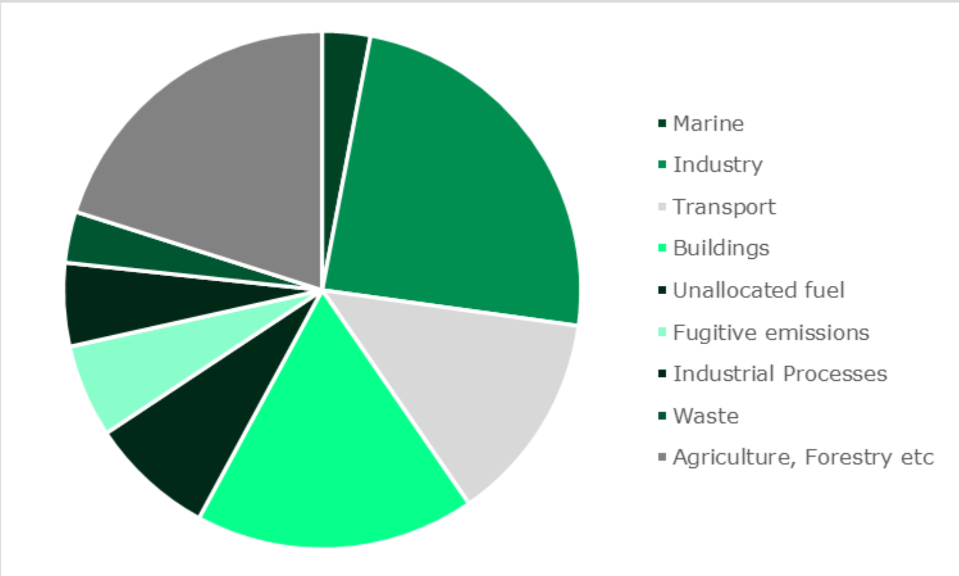
MARINE INDUSTRY EMISSIONS

The marine industry emits approximately 1 billion tonnes of carbon dioxide (CO_2) annually and accounts for around 3 - 4% of total global greenhouse gas (GHG) emissions. This is equivalent to the total annual CO_2 emissions of Germany. The IMO forecasts these emissions to grow by approximately 130% from 2008 levels by 2050 with no further decarbonisation efforts.

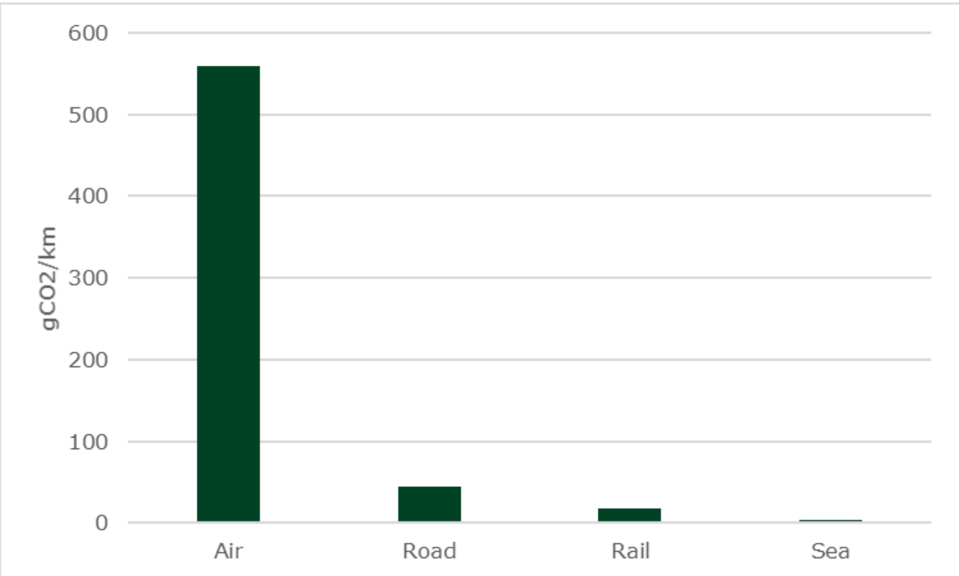
Marine Emissions vs Global Total Emissions



Source: Climate Watch, the World Resources Institute, IMO

The bulk of emissions are CO_2, but other greenhouse gases are emitted including methane and nitrous oxide (N_2O) with 100-year global warming potentials relative to CO_2 of 21 and 310 times respectively. Additionally, acid rain gas SOx and ozone layer damaging NOx are emitted. Despite these emissions, shipping remains the lowest emission form of transport per kilometre travelled.

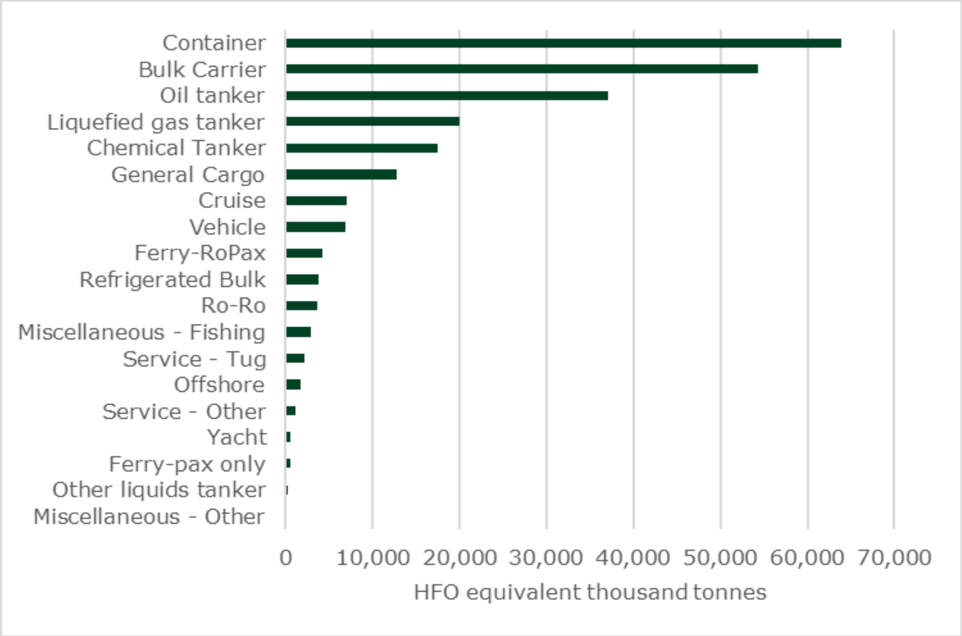
CO2 emissions per km



Source: CMS

The vast bulk of fuel consumption is from long distance larger vessels with container ships, bulkers and tankers together making up 80% of all fuel consumption.

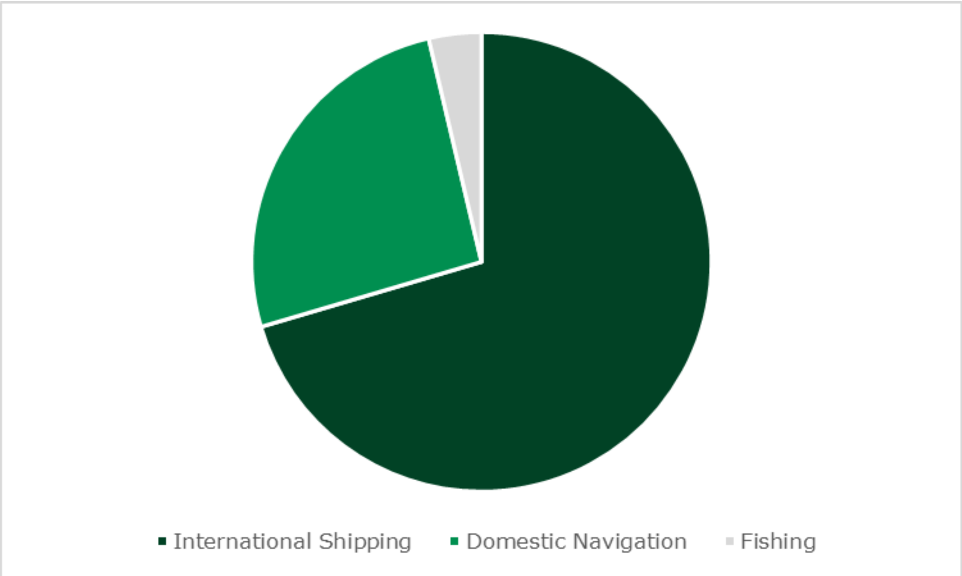
HFO-equivalent fuel consumption



Source: IMO

These figures are reflected in the overall split between international shipping, domestic navigation and shipping.

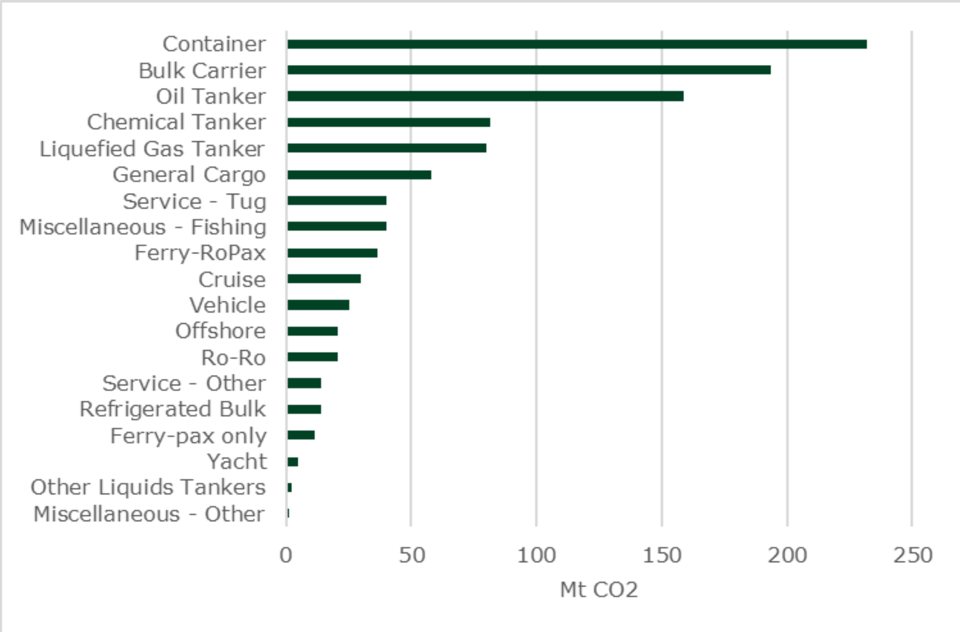
HFO-equivalent fuel consumption by range related grouping



Source: Fourth IMO GHG Study 2020 (2018 data)

Not surprisingly this is broadly matched in emissions although with larger vessels often having better emission characteristics the grouping above accounts for 70% of CO2 emissions.

CO2 Emissions by vessel type



Source: IMO

In terms of an addressable market for low carbon fuel alternatives we see the key market as being international shipping less a major element of oil and gas tankering. Clearly in a net zero world there will be less seaborne trade in fossil fuels. The IEA estimates that to reach net zero we will need to consume 25% of today's oil production. We therefore assume demand from oil and gas tankers is scaled back by this amount to get a total international shipping fuel demand of 178mt HFO equivalent annual consumption. In theory this figure is likely to grow with international trade although this growth can be partly offset by efficiency improvements. With a global 20 ports average bunker price of US$595/mt this gives a total addressable annual market of US$105bn.

SHIPPING FUEL REGULATION

The global approach to addressing GHG emissions from the shipping industry has been led by the International Maritime Organisation (IMO), a United Nations specialised agency for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. The original purpose of the IMO was the prevention of marine pollution by oil, resulting in the adoption of the first ever anti-pollution convention, the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1973. This has since changed to include air pollution and emissions from ships culminating in the introduction of Annex VI of the MARPOL treaty in 1997 that has been amended numerous times since the turn of the century to align with increased awareness of the negative effects of GHG emissions on both the climate as well as population health.

Global shipping is responsible for 90% of world trade and according to the UN is expected to grow almost 4% a year out to 2023. The point here is that is often overlooked is that emissions from shipping grows alongside global trade. Therefore, under similar conditions the 3rd IMO GHG study predicts an increase in shipping emissions between 50% and 250% by 2050. Whilst there is no one size fits all solution, there is significant untapped potential to reduce shipping emissions cost effectively. In order to do this, the industry needs to shift to zero and low carbon fuels, alongside technical and operational energy efficiency measures and improved resource use. The IMO has been actively engaged in a global approach to further enhance ship's energy efficiency and develop measures to reduce GHG emissions from ships, as well as provide technical cooperation and capacity-building activities. This global approach detailed below in conjunction with other strategic policy from international organisations and governments such as the Emissions Trading System (ETS) Directive commissioned by the European Union (EU), as well as strategy and investment from Action groups formed from the private sector, will help reach the IMO's target and makes the possibility of tougher targets realisable.

NOx AND SOx REGULATION

The original MARPOL Annex VI introduced in 2000 by the IMO limited the use of Nitrous oxides (NOx) as well as Sulphur Oxides (SOx) and prohibited the use of specific Greenhouse gases (GHG) such as chlorofluorocarbons. This originally regulation limited the SOx content of the fuel to 3.5% as well as the emission of NOx to 17 g/kWh for ships with engine's rated speeds of 130 rpm or less and 9.8 g/kWh for ships with engine's rated speeds of 2,000 rpm or more. In the years that followed, the IMO has continued to update regulations in an attempt to reduce emissions with each subsequent regulation (IMO Tier II and Tier III) continuing to lower SOx and NOx emissions.

As a result, the shipping industry emits 80% less NOx and 89% less SOx than it did prior to the initial regulation in 2000. Importantly, this initial regulation and subsequent amendments didn't limit GHG emissions and, according to the Fourth Greenhouse Gas Study (2020), the emissions from greenhouse gases from the shipping industry exceeded one billion tonnes a year in 2018.

From 1st January 2020 ships are only allowed to use fuel with a very low sulphur content under rules set out by the IMO. The new limit of sulphur oxide (SOx) content is 0.5% compared with the previous limit of 3.5% and the IMO estimates this will lead to an annual worldwide reduction of approximately 8.5million metric tonnes of SOx, reducing SOx emissions from ships by 77%. It is worth noting that there are stricter conditions of 0.10% SOx content of ship fuel for areas including the Baltic Sea, the North Sea, the US Caribbean Sea and the North American area including designated coastal areas that have been classified by the IMO as Emissions Control Areas (ECAS).

Reducing SOx emissions will limit incidences of acid rain and other forms of air pollutants that are harmful to population health, particularly in locations where ports are situated close to densely populated areas. SOx has been linked to asthma, pulmonary, cardiovascular and respiratory diseases and reducing premature deaths was a key consideration of the IMO when introducing this regulation. In 2016 a study undertaken in Finland submitted to the IMO's Marine Environmental Protection Committee (MEPC) found that if there were no restrictions on SOx levels from 2020, air pollution from ships would contribute to an estimated 570,000 additional premature deaths worldwide before the end of 2025.

This then poses the question as to what steps shipping companies need to take to comply with the new regulations. Ships must either simply reduce fuel SOx content to 0.5% through fuel blending or using alternative fuel sources such as LNG or biofuels, or they can continue to operate at a fuel SOx content level of up to 3.5% but must install an appropriate exhaust system, or scrubber, approved by the IMO.

Blending fuel oil has been a successful transitioning option for many shipping companies in order to comply with the new regulation. Refineries are able to blend oil with a high SOx content with alternative low SOx oil, in order to achieve a compliant fuel oil. Whilst this option has been estimated to cost an additional $300/mt to $500/mt, given the particularly low oil prices experienced in early 2020, the transition for shippers has been less disruptive than expected.

The installation of scrubbers has been effective as it allows shippers to continue to use heavy fuel and keep SOx levels within the required 0.5% threshold. By mid-2020, the IMO reported that 2,359 systems had been approved for this compliant alternative method.

Initially, a small percentage of ships operated on alternative fuel sources such as Liquified Natural Gas (LNG) but this has increased considerably as shipping companies purchase new ships that can run on LNG. The use of LNG reduces SOx and NOx emissions by 90% and 80% respectively and lowers carbon dioxide emissions by between 20 and 25% versus HFO. Whilst this is a good transitioning option for shippers to meet the IMO SOx regulations and at the same time reduce CO_2 levels, it is a fossil fuel, and therefore on its own, its impact in decarbonising the maritime industry will be limited.

The control of NOx emissions has been achieved by the IMO through the issue of an Engine International Air Pollution Prevention (EIAPP) Certificate with a validity of five years. The table below details the evolving regulation and amendments to the Initial Annex VI from January 2000 through the most recent regulation amendments for NOx in January 2016.

NOx limits under MARPOL

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	01-Jan-00	17	$45 \cdot n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	01-Jan-11	14.4	$44 \cdot n^{(-0.23)}$ e.g., 720 rpm – 9.7	7.7
III	01-Jan-16	3.4	$9 \cdot n^{(-0.2)}$ e.g., 720 rpm – 2.4	2

Source: IMO

GHG REGULATION

In addition to the IMO's decision to limit the SOx and NOx content of shipping fuel, the IMO has also recently adopted new policies to reduce greenhouse gas emissions (GHG) by 50 per cent by 2050. GHG resulting from the shipping industry has previously not been a government priority as shipping has been excluded from calculation of international greenhouse gas emissions under UN climate agreements and was therefore not an obligation for governments worldwide.

The IMO initial strategy on reduction of GHG emissions included the below:

- Reduction of CO_2 emissions per transport work (carbon intensity), as an average across international shipping, by at least 40% by 2030, with an aim of 70% by 2050, compared to 2008.

- For the first time a reduction of the total annual GHG emissions from international shipping by at least 50% by 2050 compared to 2008, whilst turning focus to fossil fuel free alternative energy sources to achieve CO_2 emissions reduction consistent with the Paris Agreement goals.

This strategy is set to be revised in 2023 and given a wider general trend to Paris goals we think this could see full decarbonisation targets put in place.

Giving this strategy some teeth, the IMO's Marine Environment Protection Committee (MEPC 76) has in June 2021 adopted amendments to the (MARPOL) Annex VI that will require ships to reduce their GHG emissions in line with the strategy.

These new measures will require ships to reduce carbon intensity through a mandatory ship rating system. All ships will be required to calculate their Energy Efficiency Existing Ship Index (EEXI) following technical means to improve their energy efficiency and to establish their annual operational carbon intensity indicator (CII) and CII rating. Carbon intensity links the GHG emissions to the amount of cargo carried over distance travelled. The dual approach aims to address both technical (how the ship is retrofitted and equipped) and operational measures (how the ship operates).

Attained and required Energy Efficiency Existing Ship Index (EEXI)

The attained Energy Efficiency Existing Ship Index (EEXI) is required to be calculated for every ship. This indicates the energy efficiency of the ship compared to a baseline. Ships are required to meet a specific required Energy Efficiency Existing Ship Index (EEXI), which is based on a required reduction factor (expressed as a percentage relative to the EEDI baseline).

Annual operational carbon intensity indicator (CII) and CII rating

The proposals are for ships of 5,000 gross tonnage and above to have determined their required annual operational carbon intensity indicator (CII). The CII determines the annual reduction factor needed to ensure continuous improvement of the ship's operational carbon intensity within a specific rating level.

The actual annual operational CII achieved (attained annual operational CII) will be required to be documented and verified against the required annual operational CII. This will enable the operational carbon intensity rating to be determined. The rating will be given on a scale - operational carbon intensity rating A, B, C, D or E - indicating a major superior, minor superior, moderate, minor inferior, or inferior performance level. The performance level would be recorded in the ship's Ship Energy Efficiency Management Plan (SEEMP).

A ship rated D for three consecutive years, or E, would have to submit a corrective action plan, to show how the required index (C or above) would be achieved. Administrations, port authorities and other stakeholders as appropriate, are encouraged to provide incentives to ships rated as A or B. The IMO has indicated that penalties will be levied on vessels with D and E ratings from 2025 although the actual penalties remain the subject of deliberation by the IMO.

IMO REGULATION IMPACT

The IMO is a specialised agency of the United Nations and therefore has no authority on its own and its role is to establish regulation to be adopted by governments who implement legislation into their own national law. Importantly, Flag Sates (the state of registry of a ship) and Port States have rights to enforce compliance through the adoption of the 2019 guidelines for port state control under MARPOL Annex VI. Major port regimes such as the United States Coast Guard (USCG), Tokyo MoU, Paris MoU and the Australian safety Maritime Authority (AMSA) have made it clear that enforcement of the IMO Sulphur 2020 rules will be vigorously enforced with penalties issued by heavy fines and ship detention. Whilst nations will enforce varying levels of fines as criminal actions, a survey by the Standard Club in 2019 provides some guidance for how certain countries intent to initiate fines.

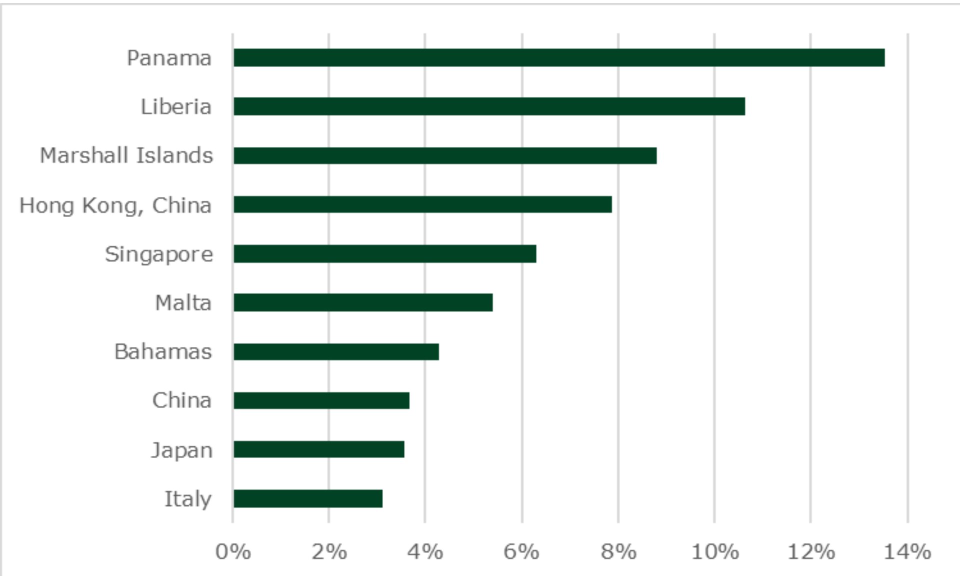
IMO Fines

Country	Low	High
Brazil	$1,200	$488,200
China	$1,400	$14,200
Norway	$8,900	$27,800
Denmark	$4,400	$44,400
Spain	$24,300	$664,300

Source: Standard Club

One of the main concerns is that many signatories of the IMO 2020 rules may not have required experience and resources to adequately enforce the rules. Whilst fines and uptake have in general being improving, large scale issues arise when ships are travelling in international waters as the responsibility falls to flag states where companies register. The challenge here is the flag states with the largest number of registered ships such as the Bahamas, Bermuda, Panama, and Malta have the largest responsibility to enforce IMO rules, yet these are the member states with the least resources and experience to do so. Panama however is tackling emissions with the announcement of Panama Canal charges based on emissions. We also think that the experience of SOx and NOx regulations suggests broad compliance and we especially see the behaviour of the major shipowners as helpful here.

Share of CO2 emissions by flag state (2019)



Source: UNCTAD

Panama Canal green corridor

The Panama Canal accounts for over 3% of global maritime trade and has recently unveiled a new GHG "Green Vessel Classification" system aimed to offer an incentive for low carbon shipping. The system penalises operators of higher emitting vessels with a financial fee (amounts not confirmed) and allows cleaner vessels to progress up the canal's customer rankings more quickly.

Under the new system, the Canal will classify all ships over 125 feet in length using an energy efficiency ranking that incorporates three factors:

1. The ship's EEDI score
2. Operational efficiency measures during transit, such as the use of bow thrusters
3. The use of zero-carbon or carbon-neutral fuels

According to the authority, these factors could reduce emissions during a canal transit by 20% to 100% and strengthen the waterway's position as a green corridor for global trade. This system is the first of its kind in the world and could play a role in influencing other canals such as the Seuz canal which handles over 12% of global maritime trade.

COP26

The biggest news to come out of COP26 for the maritime sector was in the form of the Clydebank Declaration for Green Shipping Corridors. The declaration was signed off by twenty-two countries including the US, UK, Australia and Canada, pledging support for the establishment of zero emission maritime routes between two or more ports to be known as "green shipping corridors". Under the declaration, two or more signatories will identify and take steps with relevant willing ports, operators and others along the value chain to decarbonise a specific maritime route. As such, the successful implementation of the declaration is largely dependent on the willingness of ship operators to work with signatory countries to achieve the objectives. The declaration aims to establish at least six such corridors by 2025 with additional corridors to be added before 2030.

Under the declaration, signatories have pledged to the following:

- Facilitate the establishment of partnerships, with participation from ports, operators, and others along the value chain, to accelerate the decarbonisation of the shipping sector and its fuel supply through green shipping corridor projects
- Identify and explore actions to address barriers to the formation of green corridors. This could cover, for example, regulatory frameworks, incentives, information sharing or infrastructure
- Consider the inclusion of provisions for green corridors in the development or review of National Action Plans
- Work to ensure that wider consideration is taken for environmental impacts and sustainability when pursuing green shipping corridors.

COP26 also saw governments agreeing to reduce non-carbon dioxide greenhouse gas emissions, including methane. This puts pressure on both LNG and ammonia which will need to address the risks of methane slip and N2O emissions.

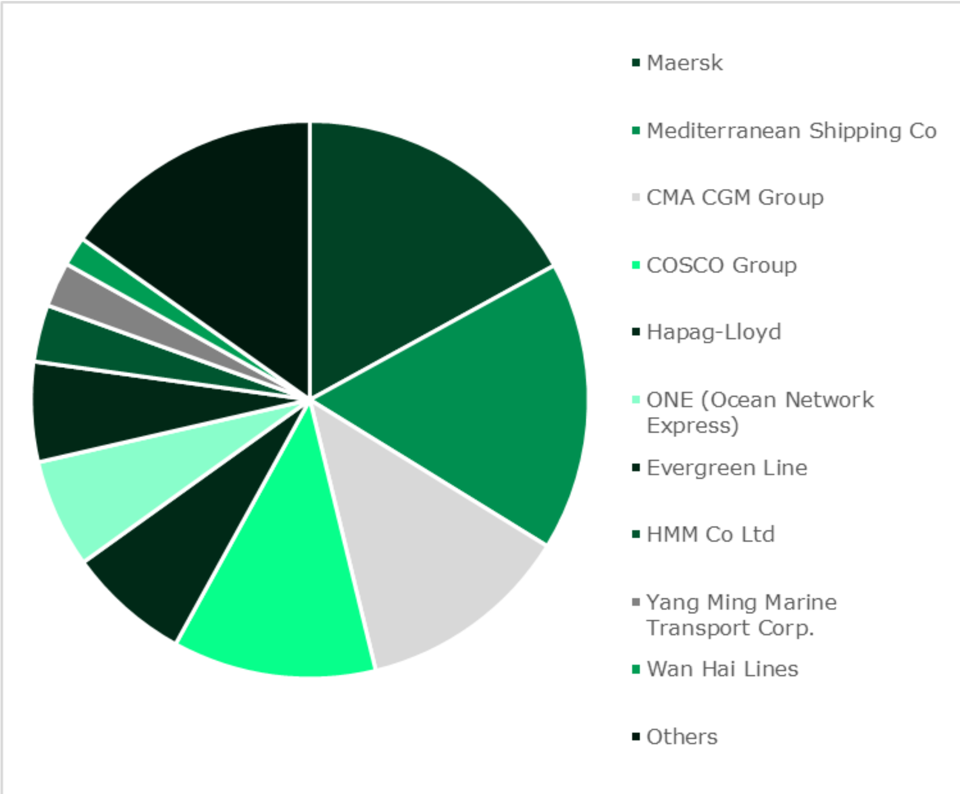
Maritime Research Fund

Of potentially more significance to the shipping industry is the post COP26 IMO MEPC meeting in London where 174 governments will meet to decide on the approval of the US$5 billion R&D Fund otherwise known as the IMO Maritime Research Fund (IMRF). They will be paid for solely by the maritime industry without any government assistance to accelerate the rapid increase of technology readiness levels to ensure zero carbon fuels can deployed for deep sea shipping. If agreed to, the fund will be expected to up and running by 2023..

SHIP OWNER BEHAVIOUR

Most deep-sea shipping segments are highly concentrated with the biggest segment, freight, showing the top 10 shipping companies making up 84.7 per cent of the market. Just the top four companies A.P Moller - Maersk Group, Mediterranean Shipping Company (MSC), CMA CGM group and China Ocean Shipping Company (COSCO) make up 58 per cent of total market share with 17, 16.8, 12.4 and 11.8 per cent respectively.

Freight ship owner market share



Source: Alphaliner

This concentrated market share is significant when it comes to fast tracking net zero emissions if this small portfolio of companies can align themselves with a net zero pathway, the maritime industry will not have to rely on regulation, government policy or public market investment as it can carry the maritime industry to net zero themselves. Evidence of this is already being seen with over 150 within the maritime, energy infrastructure, and finance sectors signing on to the Global Maritime Forum 'getting to zero' coalition. MSC and CMA have additionally pledged to reach net zero by 2050, going beyond the IMO ambition to reduce emissions by half by 2050. Maersk recently shortened their target date to reach net zero by 10 years to 2040. MSC data for 2020 shows a recorded 44.3 per cent reduction in CO_2 emissions compared to a 2008 baseline, however, the COVID 19 pandemic likely contributed to a significant percentage in our view. Perhaps less encouragingly, MSC has 60 ships in its order book and Alphaliner has indicated that the company has purchased over 100 ships or 400,00 TEU from the second-hand market in the last 12 months, likely to increase their emissions in 2021 and 2022.

In November 2021, Maersk successfully placed an inaugural 10- year EU 500m green bond to fund the delivery of the recent placed order for eight large container ships to run on e-methanol with delivery expected in 2023 and 2024. They increased this order to 12 methanol fuelled vessels in January 2022. Important to note is that the transaction was met with great positivity by investors and was seven times oversubscribed with a final order book value of EU 3.7 billion. Issuing green bonds are an important tool for channelling investment to projects delivering net zero outcomes.

Maersk, the world biggest shipping company has placed an order for eight container ships that will be the first to run on e-methanol due to be delivered in the first quarter of 2024. The ships will be built by Hyundai Heavy Industries and will cost $175m USD each, an estimated 10-15% increase on the prices of current ships used by the company run on fossil fuels. The engines will run on renewable methanol or e-methanol sourced from Danish start up REintegrate and is produced using renewable electricity to produce hydrogen through electrolysis and combining this with recycled CO2 from biogas plants through CCS, all of which are yet to be financed and then built. The syngas produced will be used to produce renewable methanol. Maersk's new ships will still have the ability to run on traditional heavy fuel if they are unable to source methanol.

Proman, one of the world's largest producers of methanol has teamed up with Stena, a privately owned shipping company operating 140 vessels, in a joint venture known as Proman Stena Bulk. Proman Stena Bulk has successfully completed the launching of the Stena Pro Patria, now afloat, the first of three 49,900 dwt methanol dual-fuel MR tankers that Proman and Stena Bulk are building together as part of their JV. Another five methanol-powered newbuilds are contracted to be delivered by 2023, of which two will be Proman Stena Bulk JV vessels and three will be Proman owned vessels operated by Stena. Additionally, an MoU to develop a retrofit and supply solution to enable Stena's ferry fleet as well as third party vessels the ability to use methanol as a fuel has been announced.

MSC CGM Group and energy solutions company ENGIE have partnered up as part of a long-term strategy to develop the large-scale production and distribution of synthetic methane and Bio-LNG. The CMA CGM group currently has twenty 'e-methane' ready ships with dual fuel engines running on LNG with plans to place to increase this number 44 by the end of 2024. The dual fuelled technology has the ability to run on bio-LNG and an initial project to produce bio-LNG has already been launched.

Large global shippers Hapag-Lloyd have ordered twelve new ultra large container ships from South Korean ship builder Daewoo with half scheduled for delivery in 2023 and half in 2024. The ships will be fitted with high-pressure dual-fuel engines, operating on cleaner burning LNG with the option to switch to conventional fuel when required. Further to this, Japan's Mitsui plans to launch 90 LNG ships by 2030 and earlier this year announced a strategic partnership with the world's leading methanol producer Methanex and its shipping subsidiary Waterfront Shipping to advance the commercialisation of methanol and renewable methanol as a viable marine fuel. Methanex have 30 vessels in operation.

PRESSURE FROM CUSTOMERS

In addition to initiatives from major shipping companies, pressure from customers for zero carbon shipping is likely to grow. The Cargo Owners Zero Emission Vessel Initiative now includes nine major shippers of consumer goods and will progressively ship all ocean freight to zero emission vessels. The signatories are shown below.

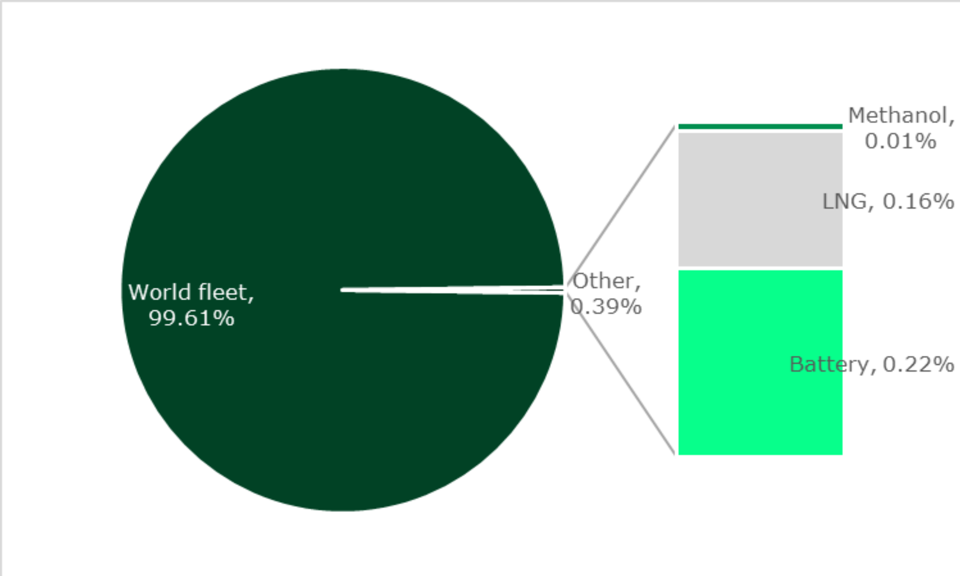
- Amazon
- Ikea
- Unilever
- Michelin
- Inditex (Zara)
- Patagonia
- Brooks Running
- Frog Bikes
- Tchibo

SOLUTIONS

There are a number of zero carbon shipping fuel alternatives being considered by the global maritime industry. When identifying the GHG emissions of alternative fuels it is important to implement a 'well-to-wake' approach to emissions, assessing the full supply chain rather than just the emissions of the fuel itself. This concept is something that the Methanol Institute (MI), a trade organisation representing the methanol industry has identified as imperative when introducing new industry policies on alternative fuels to support decarbonisation efforts.

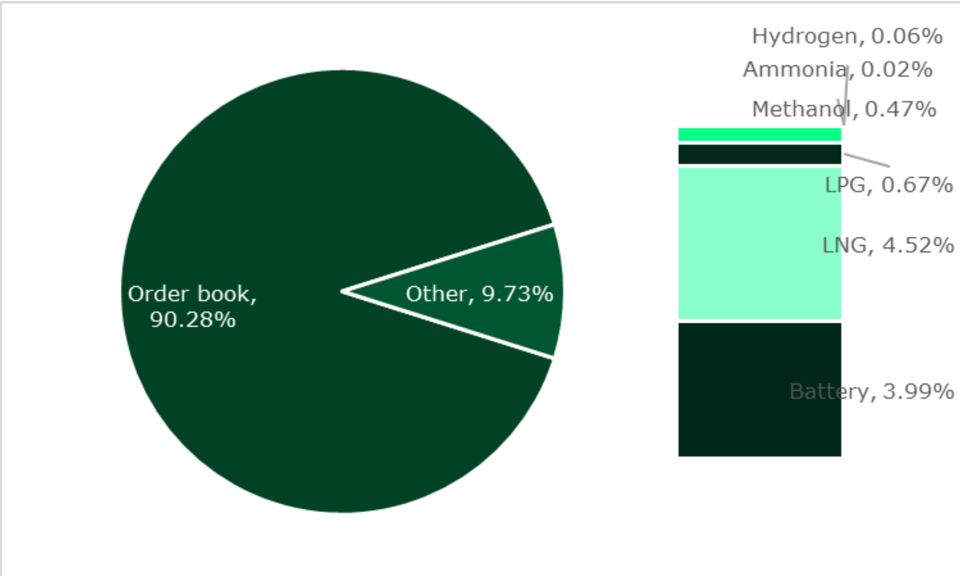
DNV-GL have summarised the alternative shipping fuel uptake using data from mid-2020. Across the world fleet of ships in operation 0.39% percent of ships are currently running on alternative shipping fuels and only 9.73% of the 2020 order book are made up of alternative shipping fuels.

Alternative fuel uptake – ships in operation



Source: DNV-GL

Alternative fuel uptake – ships on order



Source: DNV-GL

BATTERIES

All-electric marine vessels hold multiple advantages as they are quiet, environmentally friendly without any emissions or risks of oil spills and have reduced maintenance costs. However, using batteries on ships can also be a difficult market with multiple challenges such as:

- Limited range to the size of the battery bank, where the weight can add up quickly and beyond the maximum carrying weight of the vessel.
- Range can be improved by using a generator, however, speed is limited by the size of the battery charger and the generator may be a source of emissions.
- Batteries systems with electronic components on a boat are prone to corrosion and need to prove themselves to be safe and reliable in a hostile environment.
- Deep discharging of batteries can cause damage and failure that is not easily diagnosed.
- Lithium-ion batteries are particularly susceptible to thermal runaway where overcharge, over-discharge, over-temperature, short circuit, crush and nail penetration may all result in a catastrophic failure, including the pouch rupturing, the electrolyte leaking, and fire which is difficult to extinguish.
- Charging is affected by being at the "end of grid" and often in built up areas.

As it stands today with the current battery technology, all electric vessels are primarily used for shorter distances in harbours and coastal shipping and therefore account for a minor proportion of the global marine market.

HYBRID BATTERY SOLUTIONS

Presently, the majority of marine propulsion solutions are fuelled by diesel engines using residual fuel oil, that accounts for 78% of all marine propulsion systems. In a conventional marine propulsion system, a diesel engine delivers power through a gearbox to the propeller shaft. Because all ships also require a source of electricity to power heating, lighting and other systems, one or more additional diesel engines will drive generators to produce electricity. The auxiliary load can account for around 25% of the total power requirement.

Where vessel manoeuvrability is important, diesel electric systems are used with electric motors driven by diesel generators. Diesel engines convert the energy in the fuel into useful energy work at the propeller with an overall efficiency of around 24%. Diesel electric systems are slightly less efficient with overall efficiency of around 22%.

Propulsion System Efficiencies

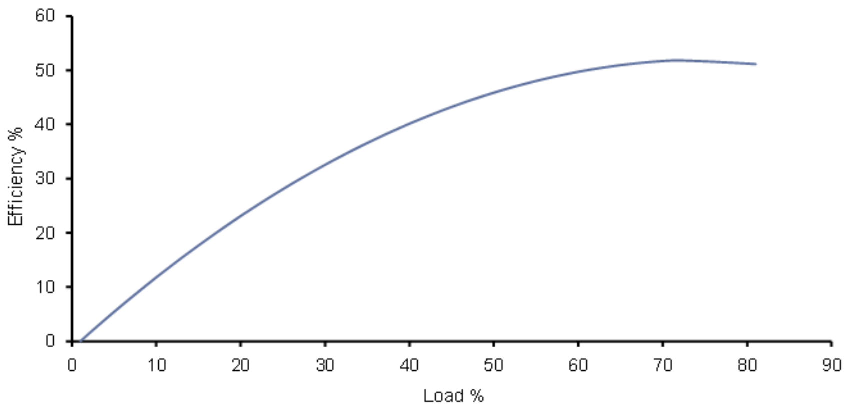
Diesel-Mechanical						
Diesel Fuel	4-S Medium-Speed Diesel Engine	Gearbox	Shaft	Propeller		Total efficiency
	0.35	0.98	0.99	0.72		0.24
Diesel-Electric						
Diesel Fuel	4-S Medium-Speed Diesel Engine	Generator	Variable Speed Drive	Propulsion Motor	Propeller	
	0.35	0.90	0.97	0.98	0.72	0.22
Battery Propulsion						
Grid power	Battery	Variable Speed Drive	Propulsion Motor	Propeller		
	0.99	0.97	0.98	0.72		0.68

Source: Longspur Research estimates based on Peng Wu, UCL

A battery propulsion solution is the most efficient at 68% if the power was provided by a zero-carbon source.

One of the reasons for lower efficiency of diesel or diesel electric systems is that the diesel engine does not run steadily at full power. Due to varying load the duty cycle can vary so that the average power output may be as low as 25% of the total capacity. This can reduce the overall efficiency of the engine itself by more than 20% from a typical 45% down to 35%.

Diesel Engine Efficiency at Part Load



Source: Longspur Research

By using a battery in the drive train and allowing the diesel engine to run steadily, significant savings are possible. The efficiency gains on its own can be as much as 30% resulting in fuel savings, reduction in costs and can free up space and weight on the vessel. This reduction in weight can also reduce maintenance requirements and the power required to manoeuvre the vessel.

This opportunity to improve efficiency with a hybrid battery solution can also be deployed where low carbon liquid fuels are used in reciprocating engines, creating a potential role for battery solutions beyond short range marine deployments.

WIND-ASSISTED SHIP PROPULSION (WASP) TECHNOLOGY AND EFFICIENCY APPLICATIONS

Alongside alternative fuels solutions, Wind-assisted ship propulsion (WASP) and efficiency technologies also has the potential to play an important role in the energy transition. WASP enables ships to reduce fuel consumption through the use of technologies that are able to utilize the wind to propel a ship forward. Unlike some alternative fuels, WASP technologies are not dependent on new infrastructure for storage, use a cost-free energy source and have technologies already developed that can be adopted at scale today. The ability for ship operators to flick between conventional or alternative fuels and WASP in times of high wind speed has the potential to be an attractive fuel cost saving method as well as having a positive effect on the IMO energy efficiency index EEDI. Modern WASP technologies that practical for deep sea shipping come in the form of wing sails, kite sails deployed in high altitude wind, Flettner rotors and Ventifoils.

The Flettner rotor is a rotor propulsion technology that uses vertical cylinders that can be retrofitted to existing large scale ships to spin and develop lift when the wind blows across the rotors. Unlike the Flettner rotor, which rotates on its axis, Ventifoils consist of a non-rotating wing with vents and an internal fan that uses boundary layer suction to generate forward movement.

Efficiency applications such as hull coatings reduce the frictional resistance of the ship's hull through water generally caused by corrosion or organism growth, reducing engine power and therefore fuel consumption. Whilst many hull coatings of the past have been banned due to their high toxicity, there have been big advances in environmentally friendly coatings in recent years. One of which is a graphene enhanced coating produced by battery anode and graphene company Talga Group. The graphene coating has been applied to the hull of a 33,000 tonne cargo ships before undergoing 15 months at sea with positive results.

LOW CARBON LIQUID FUELS

While batteries are only suitable for short range and sail is more about assistance then propulsion, the key long haul shipping solutions are liquid fuels of one form or another. The key contenders are hydrogen, ammonia, methanol and biomethane. Their key characteristics are shown below against those of the major fossil fuel alternatives.

Main liquid fuel options for shipping

Fuel type	LHV	Volumetric energy density	Storage pressure	Storage temperature	Tank volume*
	[MJ/kg]	[MJ/l]	[bar]	[°C]	
Liquefied Ammonia	19	12.7	1 or 10	-34 or 20	4.1
Liquefied Hydrogen	120	8.5	1	-253	7.6
Methanol	20	15.8	1	Ambient	2.14
Methane	50	23.4	1	-162	2.3
LPG	46	25.5	1	-42	2
MGO	43	36.6	1	Ambient	1
HFO	40	35	1	Ambient	1

Source: KR (2020), Vries (2019), MAN (2019)

Engines for liquid fuels

All these fuels can be used in reciprocating engines with greater or lesser degrees of modification, normally to the fuel delivery systems. The major manufacturers are working on methanol and ammonia ready engines with methanol units already in service. Ammonia engines remain in development and are only expected in 2025.

MAN's established two-stroke engine is used with a Liquid Gas Injection (LGI) methanol component as an added feature. The engine modification provides an additional benefit of not requiring selective catalytic reduction (SCR) technology to remove NOx from the exhaust by a process by which water is mixed into the methanol during the combustion process. This enables methanol to meet the NOx IMO Tier III regulation without the additional treatment required for fossil fuels.

MAN has also developed an additional dual fuel engine that can run on any type of methanol as well as mixing methanol with HFO. This gives ship owners the ability to transition to green methanol as prices for renewables become more competitive and gives potential investors the added security knowing there is fuel flexibility in case of a fuel shortage.

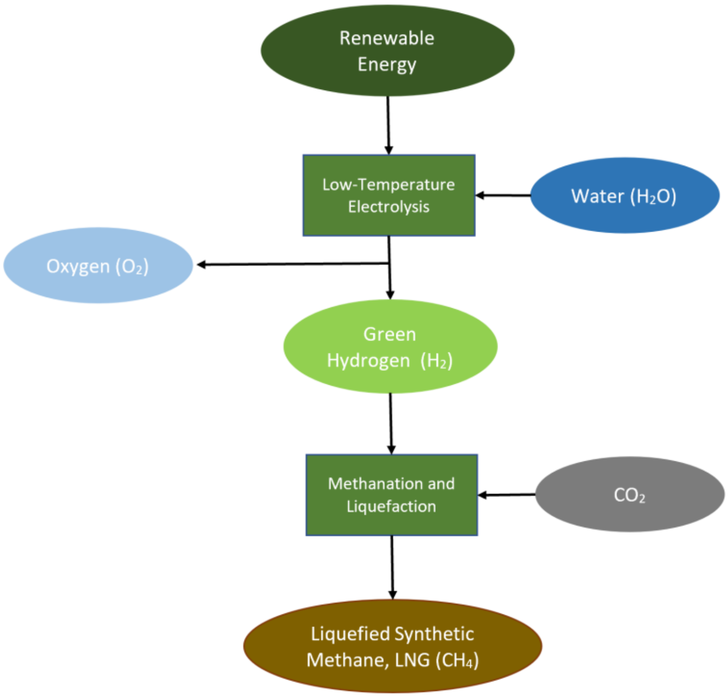
Wartsila has retrofitted four-stroke methanol engines using common rail fuel injection technology. These have been operating successfully since 2015 on the Stena Germanica operating between Kiel and Gothenburg. Rolls Royce is also developing a four-stroke methanol engine under its MTU brand.

Fuel cell solutions

These fuels can also be used in hydrogen fuel cells to create electricity for use in electric motor propulsion systems. These take pure hydrogen and convert it to electricity electrochemically without combustion. Some fuel cells have the ability to reform methane, ammonia or methanol to hydrogen so that these fuels can be used as well. The ability of a fuel cell to do this varies with high temperature PEM and solid oxide fuel cells most able, although the latter lack the flexibility that HT PEM cells can offer. This is really an option for new build only but may become a solution in time. Advent Technologies has already demonstrated its Serene marine fuel cell as part of the RiverCell demonstration project funded by Germany's Federal Ministry for Digital and Transport.

LIQUIFIED NATURAL GAS (LNG)

Bio-LNG (eLNG) process map



Source: Longspur Research

Liquified Natural Gas (LNG) is considered by many in the shipping industry as the ideal transitioning fuel for shipping decarbonisation. Whilst natural gas is a fossil fuel, it offers a lot of environmental benefits when compared to traditional shipping fuels and can be deployed today at a fraction of the cost of alternative low carbon green shipping fuels. Its growing popularity amongst shippers is largely due to its ability to minimise the long-term impact of GHG emissions and meet short term regulatory requirements implemented by the IMO. With the initial 40% GHG reduction target set by the IMO for 2030, a move to LNG gives the shipping industry an immediate carbon reduction of 23% on a well-to-wake basis according to an independent study commissioned by industry coalition, SEA-LNG, with minimal changes to infrastructure and engine technology needed to meet the 2030 IMO target. Additionally, moving to LNG reduces SOx emissions and particulate matter by 90% and NOx emissions by 80% when compared to HFO and will enable vessels to reduce their EEDI rating and Carbon Intensity Indicator by c.20%.

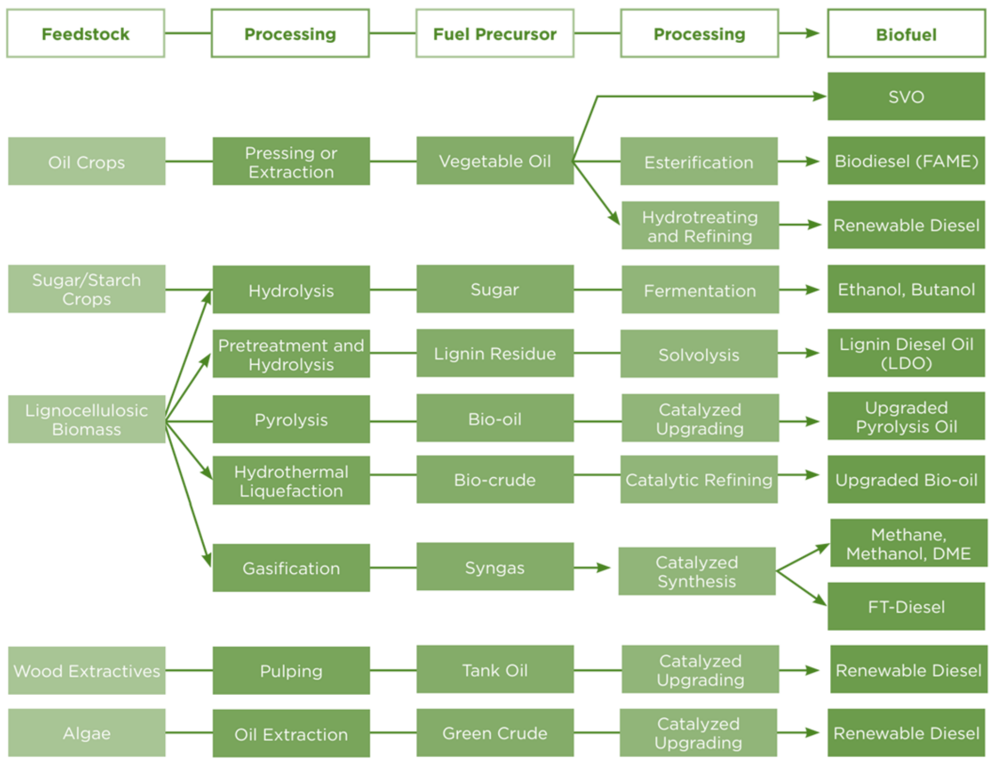
However, while LNG fuel has the effect of appearing to reduce CO2, engines using LNG can cause methane slip, where unburned fuel is expelled in the exhaust. This has a global warming potential of 21x that of CO2. In fact, in April 2021, the world bank released a report dismissing the long term role of LNG based on methane slip. Whilst engine manufacturers are making progress to reduce the release of methane through after treatment with methane oxidation catalysts, results are yet to be verified, high temperatures are required, and catalyst materials are expensive. On board, LNG must be pressurised and temperature controlled, and this is also required during bunkering.

The real reason LNG is seen as a transition fuel is the potential to move from natural gas to biofuel and synthetic LNG showing a pathway to net zero outcomes by 2050.

BIOFUELS AND BIO-LNG

Bio LNG is one of several biofuel options.

Biofuel process streams



Source: Longspur Research, ABS

Biofuels are primarily derived from biomass that is converted into liquid or gaseous fuels. A number of processes and technologies are used to produce biofuels, whether it be first generation biofuels derived from vegetable oil and animal fats, second generation biofuels derived from animals' waste and plant matter or third generation biofuels, derived from algae. The most suited form of biofuels for the shipping industry are hydrotreated vegetable oil (HVO), fatty acid methyl ester (FAME) otherwise known as biodiesel and bio-LNG. It is important to considered that each feedstock differs in its GHG emission reduction capabilities with Lifecycle GHG reductions in the range 20-90% are typically reported for different biofuels, making many of these poor low carbon solutions.

HVO as an alternative shipping is considered a 'drop in' fuel meaning it is a direct substitute for current HFO using existing petrol engines. Whilst untreated vegetable oils are not practical as a drop in fuel based on the fact, they reduce the engine lifespan due to build-up of carbon deposits and damage to engine lubricant, HVO is a much higher quality fuel having undergone the process of removing the oxygen using hydrogen. FAME or biodiesel is not considered a drop in fuel but instead can be blended with conventional fuel making it an ideal transitional fuel but long-term usability in deep sea shipping is unlikely.

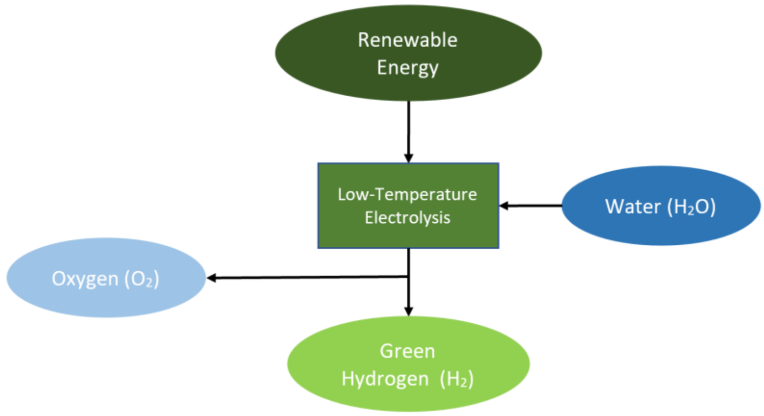
Bio-LNG is liquefied methane (CH_4) from biogas, which is produced by the anaerobic digestion of organic waste. Alternatively, hydrogen can be methanised using captured CO_2 to create eLNG. Provided methane slip can be avoided, burning LNG releases only carbon dioxide (CO_2) and water (H_2O) into the air. Since the bio-LNG is produced from biodegradable materials, the carbon dioxide is from sources that would anyway release CO_2 in a natural combustion process. Therefore bio-LNG is a sustainable and renewable product that does not add any new CO_2 into the atmosphere. Well-to-wake, the GHG emissions balance of bio-LNG can be even negative. This results in a fuel that is not just carbon neutral but has the potential to be carbon-negative in terms of lifecycle GHG emissions on a well-to-wake basis.

In addition to being carbon neutral, bio-LNG is also a high-energy biofuel that can be blended at any ratio with fossil LNG. Bio-LNG for ships can also be transported, stored and bunkered in ports utilising existing LNG infrastructure. The use of LNG emits close to zero NOx and SOx emissions and no particulate matter.

In November 2020, Total completed the world's largest LNG bunkering operation to date in Rotterdam, supplying 17,300 cubic meters of LNG to the CMA CGM Jacques Saade, 13 percent of which was bio-LNG. A month later, UECC bunkered the Auto Energy with drop-in bio-LNG, and in Finland, Gasum has bunkered ESL Shipping's dry bulk carrier Viikki with 100 percent renewable bio-LNG. The IEA estimates that biomethane (bio-LNG in gaseous form) production from sustainable feedstocks in Europe has the potential to grow from 18 bcm today to 125 bcm by 2050 – representing more than 25 percent of today's total EU gas consumption. The price of biogas remains a potential issue. Between March and June 2019 Maersk and the Dutch Sustainable Growth Coalition (DSGC) ran a successful pilot project where a large Triple-E vessel sailed 25,000 nautical miles from Rotterdam to Shanghai and back on biofuel blends alone, using up to 20% sustainable second–generation biofuels.

HYDROGEN

Green hydrogen process map



Source: Longspur Research

Hydrogen is currently produced by steam reformation of methane in natural gas. Steam methane reformation (SMR) is energy intense and a major emitter of CO2. While carbon capture and storage (CCS) is an option to reduce the CO2 emissions, creating 'blue' hydrogen, it is expensive and does not completely eliminate emissions. Green hydrogen is produced by a process called electrolysis where water is split into hydrogen and oxygen using renewable electricity. This process therefore does not produce any CO2 and, as long as the electricity used is generated by renewable sources such as wind, solar, hydroelectricity and geothermal energy, green hydrogen is emissions free 'well-to-wake'.

After hydrogen is produced it can be used in a number of ways to power a ship. The most desirable way to do this from purely an emission perspective is to use a reciprocating engine designed for hydrogen or a fuel cell electric motor propulsion.

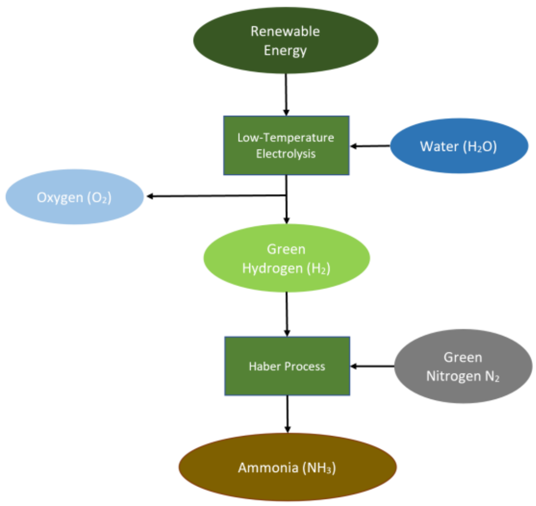
Some shipping is already diesel electric, so the electric motor component already exists potentially creating a retrofitting opportunity. Advanced fuel cells, such as Advent Technologies high temperature PEM cell, can reform methanol, LNG or ammonia instead of relying on pure hydrogen.

Alternatively, hydrogen can be burnt in an internal combustion engine but the downside of anything in air, consisting of mainly nitrogen is that NOx are produced. There is potential for an after-treatment device to be fitted to the engine to remove the NOx but this is still an unproven technology. The world's first hydrogen powered vessel is currently being tested in Belgium in the Hydroville project using a small sixteen passenger ferry operating between Kruibeke and Antwerp in Northern Belgium. The project has been going for three years using a hybrid engine and has been successful to date.

The biggest challenge for using hydrogen for long distance shipping is how difficult it is to store in comparison to not only the HFO but other potential fossil free fuels being considered. Hydrogen cannot simply replace current bunker fuel in the current system as in order to store it on a ship as a liquid, it will need to be frozen to temperatures of around minus 253°C requiring heavy cryogenic tanks that take up precious space.

AMMONIA

Green ammonia process map



Source: Longspur Research

Ammonia is liquid fuel that can be either combusted or used in a fuel cell and can still be produced using green hydrogen, alleviating some of the problems of hydrogen storage.

Ammonia is basically a hydrogen carrier but is arguable more suitable as a fuel source as it has a higher energy density. Ammonia (NH3) is produced by combining hydrogen and nitrogen. The nitrogen required is extracted from the air after liquefaction and the hydrogen produced through the process of water electrolysis, using either renewable or fossil fuel sources in the process. These hydrogen feedstocks are generally gasified to form synthesis gas (CO and H2), which can then be reacted with water and nitrogen to produce ammonia. The Haber Bosch process enables the nitrogen and hydrogen to be reacted to create ammonia.

One of the advantages ammonia has is it is already a traded commodity, used to produce fertilizer. This means that the infrastructure and procedures associated with transporting ammonia are already in place as ammonia is frequently loaded and unloaded from gas terminals onto ships and vice versa. Additionally, ammonia can be stored as a liquid at minus 33 degrees Celsius at ambient pressure on board the vessel and at port site facilities without the need for cryogenic tanks, Ammonia was therefore first considered a transport fuel for hydrogen or hydrogen carrier as once transported, the ammonia can be cracked back to hydrogen. However, ammonia has never been bunkered.

According to an Ammonia 2020 white paper by catalysis company Haldor Topsoe, if 30% of marine fuel consumption was replaced by green ammonia, 150m million tonnes of ammonia would need to be produced given its energy density. Using the process of electrolysis or synthesis technology, 1500TWh of renewable energy would be needed to produce this amount of green ammonia. To put this in perspective, the final power production could be achieved by installing 200 GW of wind power and 200 GW of solar photovoltaics (PV) in sites with good wind and solar resources.

Whilst ammonia is carbon free tank-to-wake and has the potential to be carbon free well-to-tank as well through the production of green ammonia, there is still uncertainty around N2O emissions and ammonia slip post combustion. N2O or nitrous oxide is a major greenhouse gas and is emitted when ammonia is combusted.

As with methanol, MAN's ME-LGIM engines combustion principle based on diesel cycle can be retrofitted to run of ammonia with slight modifications to the fuel delivery system. The high-pressure direct-injection systems used in DF engines, such as the MAN ME-LGIM and ME-LGIP, can inject fuel at optimum levels and timing to avoid ammonia slip. As with methanol, MAN's dual-fuel engines will not require selective catalytic reduction (SCR) technology to remove NOx from the exhaust. Ammonia engines are only expected to be available after 2025.

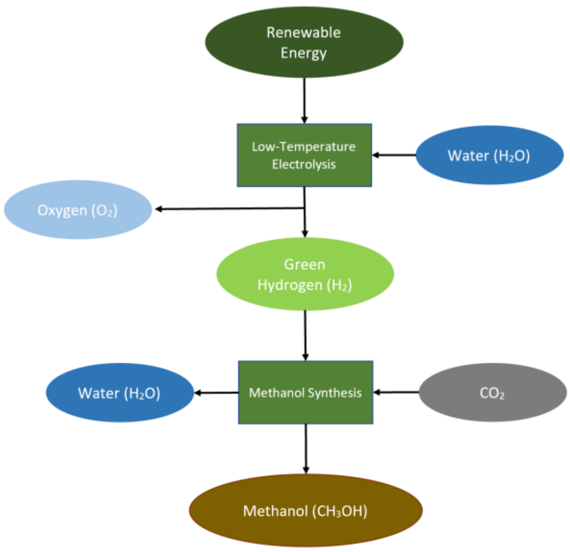
METHANOL

Methanol has been identified by the IMO as a fuel that delivers climate benefits today. Methanol is four parts hydrogen, one part carbon and one part oxygen and is typically produced from natural gas through reformation of the gas with steam to produce syngas and then converting and distilling the syngas to produce methanol. This is known as 'grey' methanol and today accounts for 95 per cent of total methanol used in the shipping industry. In saying this, grey methanol produces 80 per cent less NOx, 99 per cent less SOx, 95 per cent Particulate Matter (PM) and approximately 20 per cent less CO2 than HFO on a tank-to-wake basis according to MAN Energy Solutions, enabling compliance to the IMO's 2020 SOx emission regulations as well as the Tier III NOx emission regulations when combined with modern engine technology.

Whilst 'grey' methanol is considered a low carbon pathway fuel, the benefit of methanol is greatly enhanced through its ability to evolve into 'blue' and then 'green' methanol as these processes become more commonplace. 'Blue' methanol is produced through the utilisation of Carbon Capture and Storage (CCS) and natural gas. CCS is the process of capturing CO2 before it enters the earths atmosphere and storing it underground or reusing it. Additionally, 'green' methanol or renewable methanol in the form of bio-methanol derived from biomass or e-methanol derived from renewable energy has potential to produce a zero-carbon fuel.

RENEWABLE METHANOL

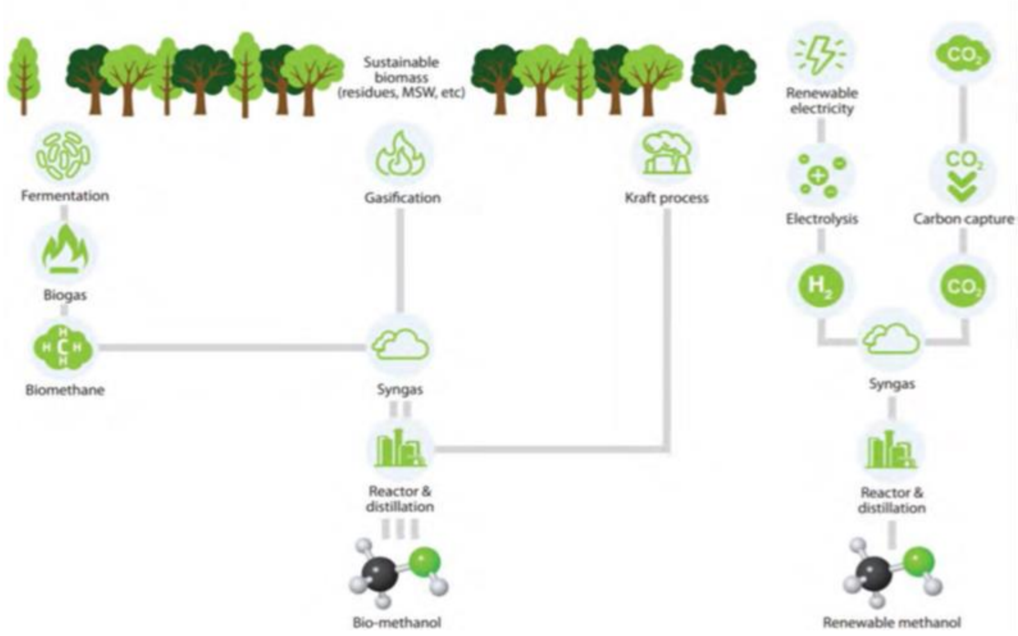
Renewable methanol process map



Source: Longspur Research

Renewable methanol can be produced using renewable feedstocks and renewable energy in the form of either Bio-methanol or Green e-methanol. Bio-methanol is produced from biomass from sustainable biomass feedstocks such as forestry and agricultural waste, biogas from landfill, sewage, municipal solid waste (MSW) and black liquor from the pulp and paper industry (IRENA 2020). Green e-methanol is produced by combining green hydrogen from renewable energy through electrolysis and CO2 from carbon capture.

Bio-methanol and renewable methanol compared



Source: Proman - Sea Commerce presentation 2021

Methanol is available in over 120 ports and is already being used by over 20 ships making it the fourth most used marine fuel globally. One of the reasons for this is the ability of methanol to be stored and transported using current infrastructure as it remains in liquid form at normal air temperature and pressure. Bunkering is already available on a vessel to vessel or shore to vessel basis.

Additionally, methanol is considered the safest alternative fuel with a long history of handling in both shipping and a number of other energy applications. In addition to being easily handled and transported, methanol is a clear and biodegradable liquid and when spilled in water quickly dilutes to non-toxic levels with no environmental effects or damage to marine ecosystems. The safety of methanol was confirmed in November 2020 with the IMO's approval of guidelines for methanol to be used as a safe ship fuel.

Engine Technology Capabilities

Considerable progress has been made in recent times to enable methanol to be used as a drop-in fuel or dual fuel using current engine technologies. Both Wartsila and MAN have developed methanol dual fuel engines built using the same technology as diesel fuel engines with nominal changes needed at little cost. One operator already has c.12,000 hours of safe operation of methanol dual fuel engines.

EMISSION SOLUTIONS COMPARED

We see four key issues when comparing marine fuels.

- Density
- Emissions
- Cost
- Useability

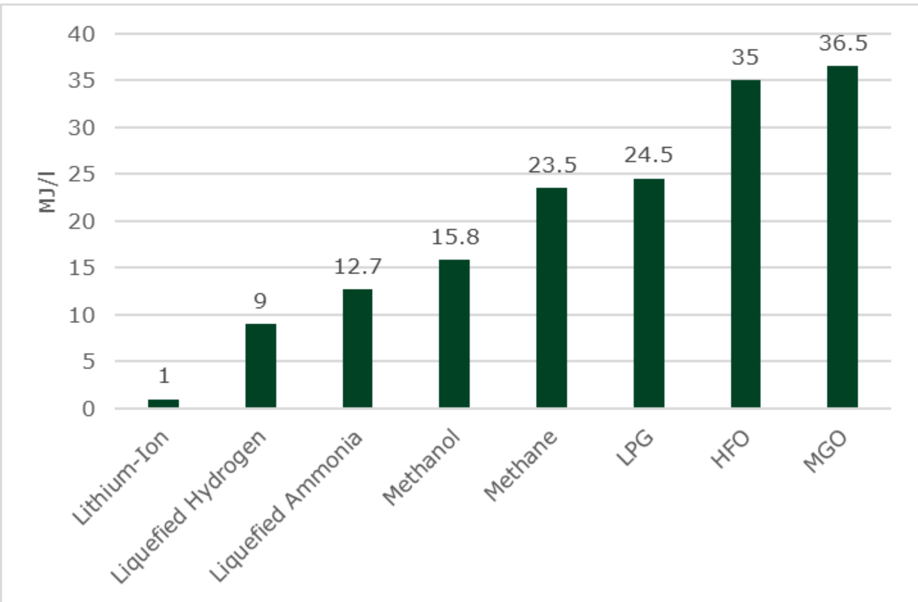
ENERGY DENSITY

The energy density of shipping fuels is important when assessing the storage solution required for fuels to be a realistic option for deep-sea long-distance “blue water” shipping. The higher the energy density of the fuel, the more energy may be stored or transported for the same amount of volume. Very Low Sulphur Fuel Oil (VLSFO) is the fuel being used by most shippers in the Emission Control Areas as it complies with the latest IMO regulations without use of a scrubber.

The volumetric energy density is high at 39.4 (MJ/I). LPG and LNG have a lower volumetric energy density at 24.5 (MJ/I) and 21.6 (MJ/I) with LNG providing the benefit of a 12% reduction in CO_2 emissions when compared to VLSFO, and LPG only providing a 2.7% CO_2 reduction. Of the potential low carbon fuels available biofuels have the highest energy density depending on the source at 20 MJ/I. Methanol whether produced from fossil fuels, recaptured CO_2, or renewable electricity has an volumetric energy density of 15.8 MJ/I. Ammonia has a higher energy density than hydrogen making it potentially more suitable than hydrogen as a fuel source but its low flammability characteristics as well as its low heating value require a pilot fuel injection to initiate the combustion process. Liquid ammonia has an energy density 11.5 MJ/I compared to 8.5 MJ/I for liquid hydrogen.

Battery technology has by far the lowest energy density amongst the alternative solutions, and this combined with range limitations makes employing battery technology for long-distance deep-sea shipping unfeasible.

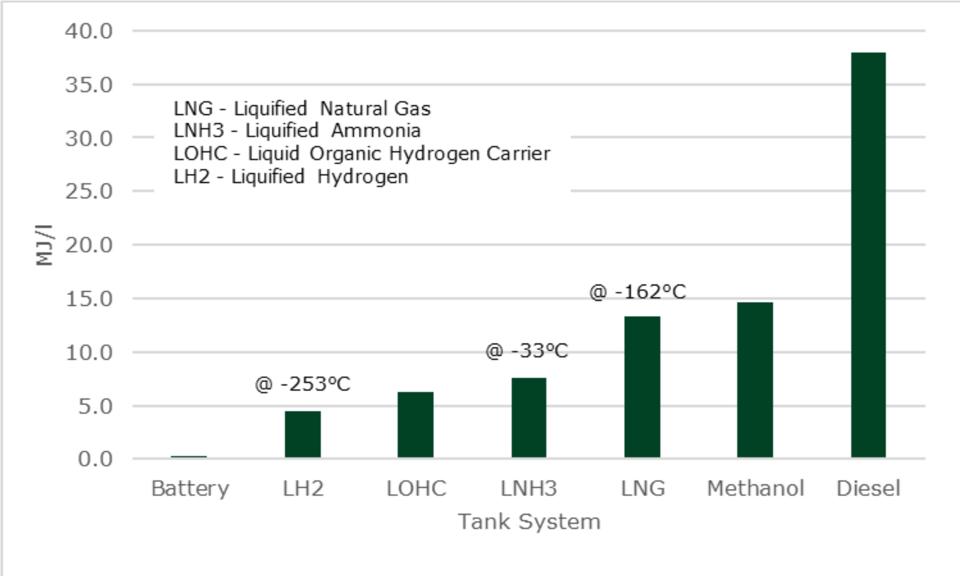
Volumetric energy density



Source: Longspur Research

Simple energy density is only part of the story. Where a fuel requires refrigeration or pressurisation, the space taken up by associated refrigeration equipment eats into the net carrying capacity of the vessel beyond that required to store the fuel. If we compare energy per volume of tank system, the positions of both LNG and ammonia worsen although methanol, as a liquid, remains unchanged.

Energy per volume of tank system

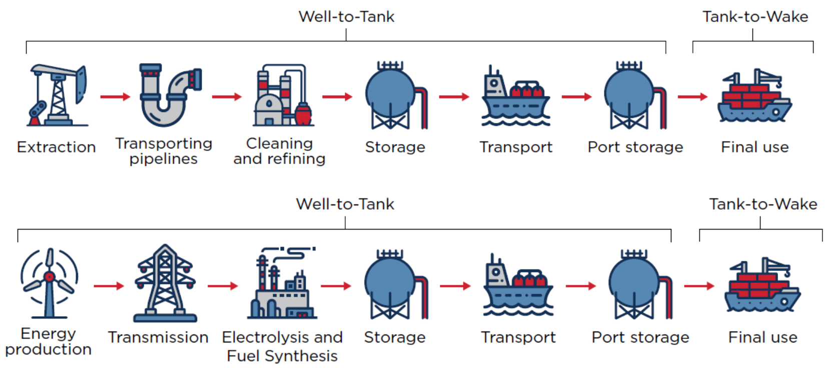


Source: Methanol Institute

LIFE CYCLE EMISSIONS OF SHIPPING FUELS

When analysing the emissions of shipping fuels, we use a well-to-wake analysis, including emissions from the whole life cycle from extraction and energy production to final use of the fuel in the ship. This is broken down into well-to-tank emissions and tank-to-wake emissions for fuels derived from fossil fuels and renewable sources as detailed below.

Well-to-wake



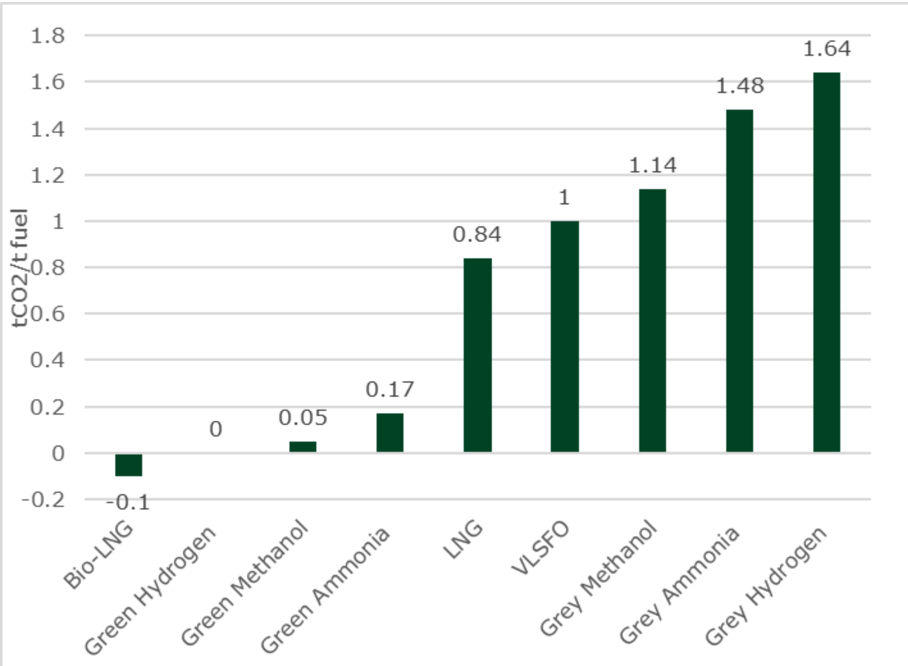
Source: Longspur Research

Using very low sulphur fuel oil (VLSFO) as a reference point, the International Convention for the Prevention of Pollution from Ships (MARPOL) calculates 3.114 tonnes of CO2 per tonne of fuel (tCO2/t fuel) tank-to-wake. Alternative fuels ammonia and hydrogen have similarly high emissions when produced using fossil fuels given the high amount of energy required in the production process. In fact, hydrogen and ammonia produces 64% and 48% more well-to-wake emissions when compared to VLSFO when using fossil fuels in the well-to-tank process. Hydrogen is emission free tank-to-wake given that water is the only biproduct of the process and burning ammonia will require pilot fuel for combustion given its low flammability as well as potential NOx emissions. Based on the need for a pilot light, CO2 emissions are calculated at 0.098tCO2/t fuel tank-to-wake assuming the ammonia is produced from green hydrogen which has zero co2 emissions.

LNG from fossil fuels reduced emissions by 12% at 2.750tCO2/t fuel when compared to VLSFO tank-to-wake according to MARPOL with the potential to reduce CO2 emissions by 100% well-to-wake when using bio-LNG and even result in negative emissions when CO2 is captured in the process. This is based on burning LNG in a dual fuelled diesel engine. However, a high level of energy is required for green Bio-LNG and CCS and will only be feasible when the price of renewable electricity becomes more competitive and CCS technology further develops.

Grey methanol actually has slightly higher CO2 emissions than VLSFO on a well-to-wake basis) and grey hydrogen and grey ammonia are even higher. Grey methanol does have reduced SOx, particulate matter and NOx emissions, something which VLSFO cannot provide Green methanol using hydrogen produced from electrolysis of water and CCS capturing CO2 can enable nearly 100% reduction in CO2 well-to-wake if all the CO2 is captured with only small emissions from the combustion of pilot light fuel.

Well-to-wake emissions



Source: Longspur Research, ABS

LEVELISED COSTS

Fuel pricing is likely to be based on its levelized cost of energy which is the marginal cost per unit of energy output plus the amortised value of the capital costs again in terms of cost pre unit of energy output.

$$LCOE = \frac{Sum\ of\ costs\ over\ lifetime}{Sum\ of\ electrical\ energy\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{n} \frac{It + Mt + Ft}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Et}{(1+r)^t}}$$

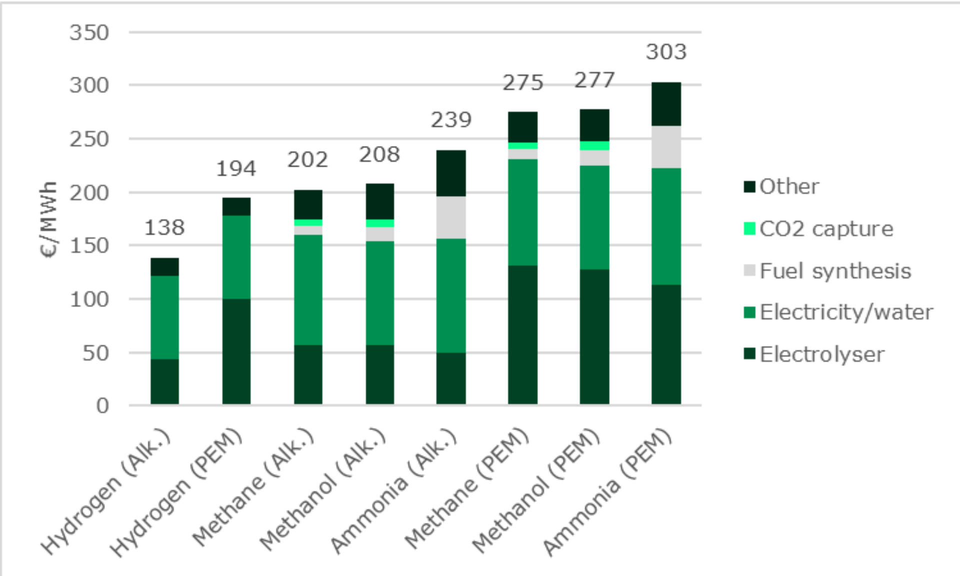
Clearly the method of production is key to determining the LCoE. These are discussed below.

LEVELISED COSTS COMPARED

We have used levelized cost calculations from Dias et al (Dias V, Pochet M, Contino F and Jeanmart H (2020) Energy and Economic Costs of Chemical Storage. Front. Mech. Eng. 6:21) these in turn are based on multiple references and in our view are well constructed.

The outcomes for the main shipping fuel alternatives are dependent on the exact method of production. Most use hydrogen as an input and this can be created using SMR plus CCS ("blue" hydrogen) or from electrolysis using either alkaline or PEM electrolysers. We show the cheapest options below.

Production costs for marine fuels suggest hydrogen lowest cost



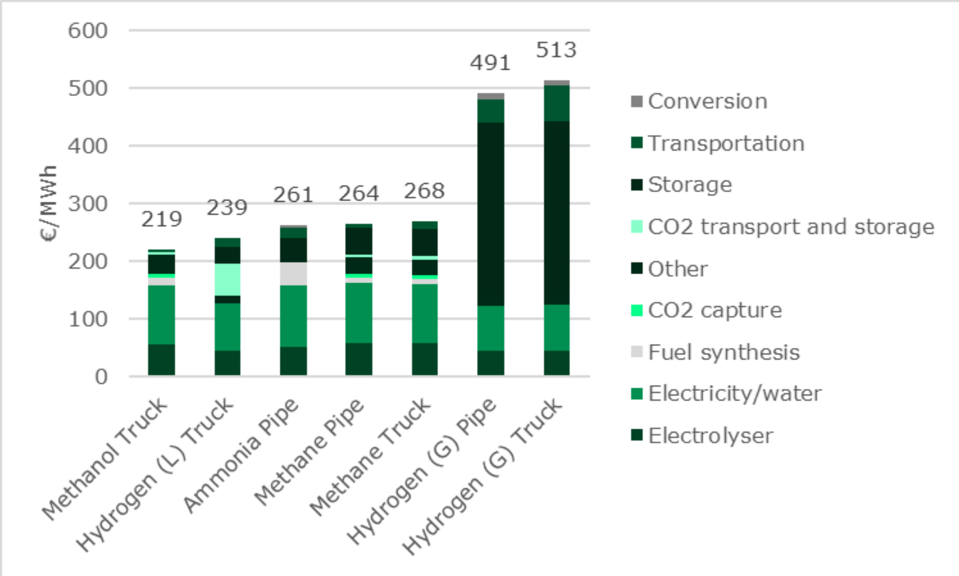
Source: Longspur Research, Dias et al

This suggests that hydrogen is the cheapest fuel to produce at the point of production. However, these calculations are only for the cost of fuel at the point of production and do not include delivery and storage costs.

Hydrogen can be stored in any state, as a compressed gas, or liquified or even as a solid using hydrides or sorbents. All these forms of storage consume energy reducing the final efficiency of the fuel and adding to its levelized cost. By comparison, methanol is a liquid and easily stored and transported at ambient temperatures. Ammonia requires some cooling to -33°C to liquify it.

Dias et al have also provided levelized costs at the point of use including assumptions on storage and transport.

Full delivered costs show methanol as lowest cost option



Source: Longspur Research, Dias et al

This shows the somewhat dramatic impact of cost and storage on the final levelized cost of hydrogen in a gaseous state. Liquid hydrogen is more reasonable and beats ammonia and methane but methanol, even trucked in, has the cheapest levelized cost at the point of delivery.

OTHER FACTORS

Flammability and explosion risks

The shipping industry takes safety extremely seriously given the seriousness of situations that ashore might be more easily contained. Fire is one of the key risks that concerns those regulating shipping.

According to the Royal Institution of Naval Architects, "fire remains one of the top three causes of loss for marine vessels in the World Fleet, and is a major risk for Ro-Ro ferries, due to their open decks, and Passenger Ships due to ever increasing passenger numbers. The risk of fire may never be eliminated, but its effects can be mitigated" (Fire at Sea, Royal Institution of Naval Architects 2014). In Europe, a study by the Marine Incident Response Group found that ship fires posed the greatest risk to maritime safety compared to other types of maritime incidents.

Lithium-ion batteries have had some well-publicised issues with thermal runaway which can in certain circumstances lead to fire. There have been a number of well-publicised incidents involving lithium-ion batteries catching fire including the Samsung Galaxy Note 7, the Boeing 767 Dreamliner and the Tesla Model S.

Lithium-ion flammability – potentially catastrophic at sea

Source: AJ Gill

Of course fuels, being energy carriers, tend to be flammable. Generally, for all the options considered here, this is an issue that can be managed by good fuel handling procedures and vessel design. Lower flashpoints on liquid fuel alternatives to diesel require management although this is true of gasoline where handling procedures are already well established.

Toxicity

The potential impact of fuels on the environment or on mankind is a key concern.

Lithium-ion is a potential environmental hazard on disposal although we feel that the marine industry is sufficiently regulated to minimise irresponsible disposal.

Methane is relatively non-toxic but is explosive in concentrations between 5% and 15%.

Ammonia is toxic and corrosive. It has a strong odour and is very irritating to the eyes, throat and respiratory tract - even in small concentrations in the air. It also has toxicity issues for fish and other marine life.

Data from the European Chemicals Agency shows that methanol is barely toxic for aquatic organisms (fish, invertebrates and algae). For humans it is toxic if swallowed.

As an extremely light gas, hydrogen tends to escape into the atmosphere if spilled, where it has minimal impact. It can explode although again the blast and heat tend to rise upwards rather than outwards making hydrogen fires more survivable and explaining why the majority of those on the Hindenburg airship survived its conflagration.

In terms of human toxicity, the following table shows the hazard statements required for marine fuels according to the Globally Harmonized System of Classification and Labelling of Chemicals (GHS).

GHS hazard statements required for main fuels

Hazard statements	Ammonia	H2	MeOH	LNG	LSHFO
H220 Extremely flammable gas		X		X	
H221 Flammable gas	X				
H225 Highly Flammable liquid			X		
H226 Flammable liquid and vapour					
H227 Combustible liquid					X
H280 Contains gas under pressure; may explode if heated	X	X			
H281 Contains refrigerated gas; may cause cryogenic burn or injury	X				
H304 Toxic if swallowed	X		X	X	X
H304 May be fatal if swallowed and enters airways					
H311 Toxic in contact with skin	X		X		
H314 Causes severe skin burns and eye damage	X		X		
H315 Causes skin irritation					X
H331 Toxic if inhaled	X		X		X
H332 Harmful if inhaled					X
H350 May cause cancer					X
H351 Suspected of causing cancer					
H361 Suspected of damaging fertility or the unborn child					X
H370 Causes damage to organs, optic nerve, central nervous system					
H373 May cause damage to organs through prolonged or repeated exposure					X
H410 Very toxic to aquatic life with long lasting effects	X				X
H411 Toxic to aquatic life with long lasting effects					
Number of statements	8	2	5	2	9

Source: Oko Institut eV, Proman AG

Infrastructure

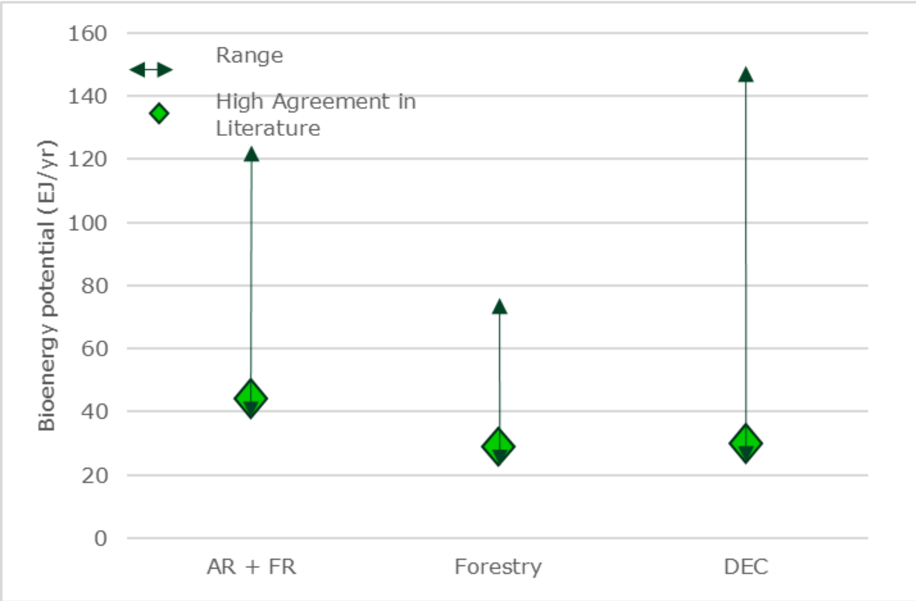
We have already touched on this in terms of the additional requirements of liquifying hydrogen, LNG and ammonia as well as the costs impact of these. But these requirements also require investment and deployment of liquefaction and other infrastructure which is not yet in place. Fuel handling within the vessel is also an important consideration. With a typical vessel operating life of between 20 and 30 years, vessel owners need to make decisions now about expected operating conditions in 2050. This gives methanol an advantage as it is already in use, can be retrofitted with minor engine modifications, and does not require the pressurised and cryogenic storage that ammonia and hydrogen require.

IS THERE ENOUGH FEEDSTOCK?

Both biofuels and e-methanol require CO2 and to be genuine low carbon solutions this CO2 must be removed from the air. That can be achieved by direct air capture which is inefficiently energy intensive or by photosynthesis in biomass. The biomass route combined with carbon capture is the key to producing CO2 for these processes. One of the main criticisms of using either fuel is based on concerns that there may be insufficient biomass that can be harvested in a sustainable fashion to make the process genuinely low carbon.

A great many assessments of sustainable global bioenergy potential have been published with a large range of outcomes. However, the availability figures with a high level of agreement in scientific literature point to a figure of about 100 EJ of sustainable biomass available annually.

Ranges/high literature agreement on sustainable bioenergy potential



Source: Grantham Institute

Using post combustion carbon capture we estimate that this would generate 6bn tonnes of CO2 per annum. That in turn would produce 4bn tonnes of methanol, equivalent to 2bn tonnes of HFO after adjusting for the lower energy density. We calculate the international shipping market demand after deducting 75% of oil and gas tanker demand (they won't be needed in a zero-carbon world) at 178mt or 9% of the available supply. There will be other calls on sustainable biomass including for sustainable aviation fuel and negative emission requirements, but we do not see 9% as especially onerous.

The calculation for eLNG is slightly more onerous as more CO2 is required per kg produced and we estimate a requirement of 11% of available supply if eLNG was the only solution.

Sustainable biomass share for marine use

	Methanol	eLNG	Units
Sustainable biomass available	100	100	EJ
BECCS capacity	1.0	1.0	TW
CO2 produced	6145	6145	mt CO2
Methanol/CH4 produced	4425	2458	mt methanol/CH4
Equivalent HFO	1997	1643	mt HFO
Total addressable marine market	178	178	mt HFO
Share of sustainable biomass	9%	11%	

Source: Longspur Research

Further comfort is given in the very recent (October 2021) study by Imperial College London Consultants on European biomass which concludes that "the potential availability of sustainable biomass, with no harm to biodiversity, could support an advanced and waste-based biofuel production of up to 175 Mtoe in 2050." In other words, European sustainable biomass alone could more or less support the global marine requirement of 178mt for biomass.

The study itself appears conservative as the following quotation shows.

"It is important to highlight that the biomass potential availability estimated in this study are based on very conservative assumptions. [ ] Therefore, it can be concluded that the biomass potentials in 2030 and 2050 would most probably be higher than those estimated by this study."

EMISSION SOLUTIONS SUMMARY

It can be seen that batteries are severely limited by density as far as long-haul shipping is concerned. Hydrogen in gas form is also limited but liquid hydrogen is acceptable as is ammonia. Biomethane and methanol are much closer to the high density seen in fossil fuel solutions.

Emission reductions are greatest for biomethane, green ammonia, green methanol and hydrogen. However, ammonia has a question mark over nitrous oxide emissions which can potentially increase its global warming potential as a fuel.

Ammonia also has useability concerns given its toxicity and associated handling requirements. Hydrogen scores well on these areas with the possible exception of flammability although we think concerns here tend to be overstated. Methanol also does well given its relative lack of ecotoxicity and although some care is required to avoid human consumption this is easily managed.

Finally, while hydrogen has a low levelized cost at the point of production it is the point of delivery that matters and here methanol is the lowest cost.

Sustainable fuel options summarised

Criterium	Hydrogen	Ammonia	Methanol	LNG	Li-ion	HFO
GHG reduction potential	5	4	5	5	5	1
Density	2	3	4	4	1	5
Cost	2	1	3	1	2	5
Useability	4	3	4	3	4	3
Average	3	3	4	3	3	4

Source: Longspur Research based on Oko Institut eV

METHANOL THE BEST SOLUTION AVAILABLE TODAY

Taking all these factors into account suggests methanol is the best solution available today. Firstly, it is available today and is technology proven so can be selected for new build or it can be retrofitted to existing fleets. It is dense enough to be useable without significantly displacing load capacity and it is useable without too many hazards. It can be bunkered vessel to vessel or shore to vessel. Finally, it is the lowest cost option at the point of delivery.

Other options should not be ruled out as individual use cases will work better with some solutions than others. Notably lithium-ion batteries will find markets in short haul shipping.

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