BEYOND FOSSIL FUELS

The case for the Arctic

October 2017

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1. Acronyms

BPS – battery-powered ships

FC – fuel cell

HT-PEMFC - High Temperature Proton Exchange Membrane Fuel Cell

ICE – internal combustion engine

LNG – Liquefied natural gas

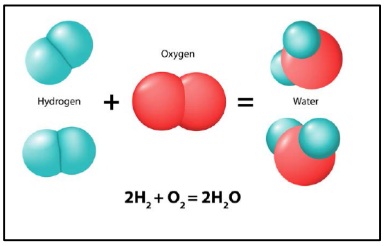
MCFC - Molten carbonate fuel cell

PEMFC - Proton Exchange Membrane Fuel Cell

SOFC - Solid oxide fuel cell

2. Fuel Cells

This technology converts energy stored in fuels directly to electricity via electro-chemical process, which in turn powers electric motors. Fuel cells can act as a replacement for currently used internal combustion engines - ICE (e.g. marine diesel engines).



2.1. On-board use

Depending on the fuel used and its main feedstock, on-board emissions vary. Fuel cell technologies can use liquid hydrogen (H2), methanol, LNG and diesel as fuel (or rather storage of energy). Generally, liquid H2 is used directly in the fuel cells, which produce electricity and water as a by-product. Hence, on tank-to-wake basis H2 fuelled fuel cells are climate neutral not causing any emissions apart from water.

Other fuels, notably, LNG, methanol, diesel, etc., need first to be converted in the on-board reformers to extract H2, which is then used in the fuel cells to produce electricity. As a result, total on-board emissions associated with the use of LNG, methanol and diesel are CO2 (from on-board converter) and water (from the fuel cells). Hence, unless sustainable biomass (manure, sewage sludge, etc.) is used as feedstock to produce LNG, methanol and diesel, the use of these fuels in fuel cell technology does not necessarily lead to climate neutrality on tank-to-wake basis. This is, however, an accounting issue, as the use of any carbon containing fuel (whether of biological or fossil origin) will generate emissions on board of a ship.

Table 1: Fuel cell technologies: types, efficiencies, emissions and fuels used.

Type	Temp	Fuel	Efficiency	Tech. maturity	Module Power levels (kW)	Emissions (with different fuels)
Alkaline Fuel Cell (AFC)		High purity hydrogen/direct ammonia (?)	50-60 % (electrical)	Mature (NASA)	< 500 kW	- water/ (nitrogen?)
Proton Exchange Membrane Fuel Cell (PEMFC)	Low	Hydrogen	50-60% (electrical)	Mature	< 120 kW	- water
High Temperature Proton Exchange Membrane Fuel Cell (HT-PEMFC)	High	Hydrogen, LNG, methanol, diesel (via internal reformers*)	50-60% (electrical)	Less-mature	< 30 kW	- water (H2); - CO2, low NOx (carbon fuels**)
Solid oxide fuel cell (SOFC)	High	Hydrogen, LNG/CNG, methanol, ethanol, diesel (via internal reformers), ammonia (directly)	60% (electrical); 85% (with heat recovery)	Less-mature	< 20-60 kW	- water (H2); - CO2, low NOx (carbon fuels); - water & NOx (ammonia)
Molten carbonate fuel cell (MCFC)	High	LNG, methanol, hydrogen	50% (electrical); 85 % (with heat recovery)	Less-mature	< 500 kW	- water (H2); - CO2, low NOx (carbon fuels)

Source: DNV GL, 2017

* *Internal reformers extract hydrogen from variety of different fuels (e.g. LNG, methanol, ethanol.), which is the source of CO2 emissions*
** *This refers to hydrocarbons (LNG and diesel), but also methanol.*

Benefits of fuel cell technologies

- Fuel cells have no moving parts and therefore, offer a quieter and non-vibrating power supply compared to ICE.
- Fuel cells usually require "clean fuels", thus, do not emit SOx, or PM.
- Fuel cells are low-temperature devices and produce no/little NOx. With H2 as the main fuel, fuel cells are also free of on-board CO2 emissions.

Current technological challenges

- Although hydrogen is an ideal fuel to use in fuel cells, it requires global infrastructure to be developed (for production, transportation and bunkering) for supplying ships. Transporting hydrogen is especially complicated.
- Hydrogen is not available naturally. It would need to be produced from other sources. The ideal option is to produce hydrogen through electrolysis from renewable energy. When made from electricity, H2 requires huge expended energy: on average 1.7 MJ of energy is required to achieve 1 MJ of final fuel.
- The use of LNG, methanol, diesel in fuel cells necessitate complex on board reformation with relevant expenses, a need for space and other complications. In addition, the use of carbon-based fuels does not eliminate on-board CO2 emissions.
    - Fuel cells have lower specific powers and power densities than diesel engines, thus, the space requirement for equivalent systems will be higher.

Production – H2 is the most optimal "fuel" for fuel cells and can different production pathways with different well-to-wake emissions:

- *Natural gas (conventional hydrogen)* – currently, most of global hydrogen is produced from natural gas via steam methane reforming. Since natural gas has carbon content, this pathway of H2 production involves emissions of CO2 during the production phase; hence, it is not climate neutral. In specific terms, steam reforming involves extracting hydrogen and carbon monoxide by reacting methane with steam at high temperature: $\boxed{CH_4 + H_2O \rightarrow CO + 3H_2.}$ Then using catalytic shift conversion, carbon monoxide is converted to carbon dioxide and more hydrogen contained in water is extracted: $\boxed{CO + H_2O \rightarrow CO_2 + H_2.}$
- *Heavy oil and coal (conventional hydrogen)* – the process involves first reacting coal with oxygen and steam under high pressure and temperature to form synthesis gas - a mixture consisting primarily of carbon monoxide and hydrogen. $\boxed{CH + O_2 + H_2O \rightarrow CO + CO_2 + H_2.}$ Similar to natural gas pathway above, carbon monoxide is then reacted with steam through the water-gas shift reaction to produce additional hydrogen and carbon dioxide.[1] $\boxed{CO + H_2O \rightarrow CO_2 + H_2.}$
- *Biomass (sustainable and non-sustainable)* - hydrogen can be further produced from biomass (e.g. food waste and crops), using catalytic (thermal) reforming. The well-to-tank carbon footprint of this pathway depends on the sustainability of biomass feedstock (e.g. manure, sewage sludge vs. palm oil).
- *Renewables (renewable power to liquid - PTL)* – hydrogen can also be produced via electrolysis process – electric current being passed through water splitting it into two atoms of hydrogen and one atom of oxygen – using renewable electricity. In general, this

[1] NH3 plants emit on average over 1.6 t CO2/t NH3 using natural gas, 2.5 t CO2/t NH3 using naphtha, 3 t CO2/t NH3 using heavy fuel oil, and 3.8 t CO2/t NH3 using coal. IEA, 2017. Ammonia producers

pathway is climate neutral. Generally, non-renewable electricity would not lead to well-to-wake climate neutrality in H2 production. However, electricity generation in almost all countries is covered under the intended nationally determined contributions (INDCs) to the Paris Agreement and are bound to decarbonise one way or another. In the EU, e.g. power sector is covered under the EU Emissions Trading Scheme (ETS), which sets an *absolute cap* for emissions. This means that there is only small or no margin for increasing emissions from the power sector due to additional demand for electricity from, e.g. H2 production (or battery powered vessels or methanol production); hence, additional demand for electricity will likely have to be met by renewables or other low-carbon means of power production.

H2 as the most optimal "fuel" for fuel cells can be produced from renewable electricity via electrolysis process with climate neutral well-to-wake emissions.

Other fuels, e.g. LNG, methanol, diesel, that can be used with fuel cells are conventionally produced from fossil sources and have considerable level of well-to-wake GHG emissions. Admittedly, they can also be produced from biomass, however, sustainable feedstock is very limited and cannot fuel all competing sectors, including shipping, road transportation, power sector and industrial and chemical sectors.

2.2. Fuel-cell ships/boats

Historically, marine fuel-cell has been limited to small-size submarines. More recently, some small ferries – e.g. a fuel-cell passenger ferry **Alsterwasser**, (100-persons) was developed for use on the Alster River in Hamburg. This ferry was powered by a pair of 48 kW PEM fuel cells using H2, 100kW electric motor and 20kW bow thruster. Currently it is out of service.

3. Battery-powered ships (BPSs)

This refers to ships propelled by electric motors, which are powered exclusively by electricity stored in batteries on board. Battery technology is likely to be the cornerstone of future hybrid and/or fully electric technologies. Regardless of the source of electricity, the tank-to-wake (battery-to-wake) GHG and other emissions of these ships are always zero. Well-to-wake (grid-to-battery) emissions on the other hand depend on the carbon footprint of the national/regional electricity grids that are used to charge the on board batteries.

Nevertheless, electricity generation is covered under the INDCs to the Paris Agreement. In the EU, e.g. power sector is covered under the EU Emissions Trading Scheme (ETS), which sets an *absolute cap* for emissions. This means that there is only limited margin for increasing emissions from the power sector due to additional demand for electricity from BPSs. Therefore, additional demand for electricity will likely have to be met by renewables or other low-carbon means of power production.

Benefits of BPSs

- BPSs are very quiet, thus, offer a relatively good solution against marine noise disturbances from ships at low-to-medium sailing speeds.[2]
- They lead to no air emissions.
- BPSs have no combustion related water discharges, such as washwater.
- Electric motors have high energy efficiency, usually 90-95% compared to 50% of marine diesel engines, hence, reducing energy demand required for propulsion.

Current technological challenges

- Current battery technologies have poor energy density (Wh/kg) vis-à-vis fossil-based marine fuels. Therefore, in order to store enough energy for long voyages, battery power ships would require huge and heavy on-board battery packs. For example, a typical 200,000+ dwt oil tanker sailing on Singapore-Rotterdam route (appx. 8,300 nm) would require a battery pack that weighs ~70,000 tonnes (34% of ship's DWT) with current 156Wh/kg energy density of current Tesla batteries. This compares to only ~1,780 tonnes of HFO (1% of ship's DWT) required to sail the same route on a marine diesel engine. However, with energy density of batteries expected to increase up to 500Wh/kg in the next 10-15 years, the weight of the battery pack required will go down to 22,000 tonnes (11% of ship's DWT).[3] Given that average global ship capacity utilisation rarely reach 100%, such a heavy battery pack would unlikely lead to capacity constrains in international shipping.
- On-shore charging systems pose another considerable challenge for the advent of battery-powered ships. For example, in the above example an oil tanker on Singapore-Rotterdam route would require about 11,000 MWh of electrical energy. This compares to an average of 13 MWh US and 6 MWh EU annual electricity consumption per capita.[4] To put differently, the amount of energy required for the ship in the above example equals on average to total electricity consumption of 850 US or 1800 EU citizens in one year. Such massive

[2] At higher speeds, it appears that noise from propeller and cavitation caused by it have a much bigger impact on ship-caused marine noise disturbance. Since battery electric ships would still (presumably) have propellers, they would not eliminate marine noise disturbance.

[3] In-house T&E estimations. The calculations take into account efficiency differences between diesel engines and electric motors; however, they exclude weight differences between diesel and electric propulsion systems. Hence, the weight of the required battery pack could be higher.

[4] World Bank

power requirements would necessitate the establishment of significant on-shore charging infrastructure, including possibly dedicated power plants and storage facilities to handle huge vessels.

3.1. Battery powered ships/boats

Ampere is the world's first fully battery-powered ferry with the capacity of 120 cars and 360 passengers and has been in service in Norway since 2015. It is powered by a 1000 kW battery and two electric motors, each with an output of 450 kW. The ferry makes 34 crossings in Norwegian fjord, each taking about 20 minutes. On-board batteries are charged both at night and during the day. On-shore batteries have been installed at each pier and 260 kWh units supply electricity to the ferry each time it docks on either side. Afterwards, the onshore batteries slowly recuperate from the grid until the ship comes back again to drop off passengers and recharge.

Karoline fishing cutter is another battery powered vessel in operation in Norway since 2016. It has two battery packs and a backup diesel power unit of 80 kW. The boat has battery autonomy of 12 hours for a typical 8 hours working day.

4. Hybrid Ships

This refers to technologies that offer multiple, including a combination of mechanical and electrical power generation and propulsion. Hybrid propulsion is an option where one or more modes of powering exists on board, such as, electrical, mechanical and a variety of power sources including diesel engines, fuel cells, batteries, gas turbines, etc.

A typical example of a hybrid ship is the existence of electric propulsion motors powered by diesel generators and/or gas turbines together with on-board battery packs. In this case, batteries can either be recharged from the on-board diesel generators and/or from the land-based grid when the vessel is moored in harbour. On low-load/low-speed sailings, hybrid ships can also be operated (for a limited range) solely by the on-board batteries feeding the electric motors. When batteries run out of charge on-board diesel generators kick in supplying both electric motors and re-charging the batteries (similar to plug-in hybrid passenger cars).

In many cases such as 'pod propulsion', the electric motor drives the propeller directly, while diesel engines use a gearbox. The gearbox reduces the efficiency of the engine.

Hybrid propulsion system also allows diesels generators to be operated at constant highest efficiency points even when ships are sailing at low speeds, hence, reducing overall fuel consumption per unit of work performed.

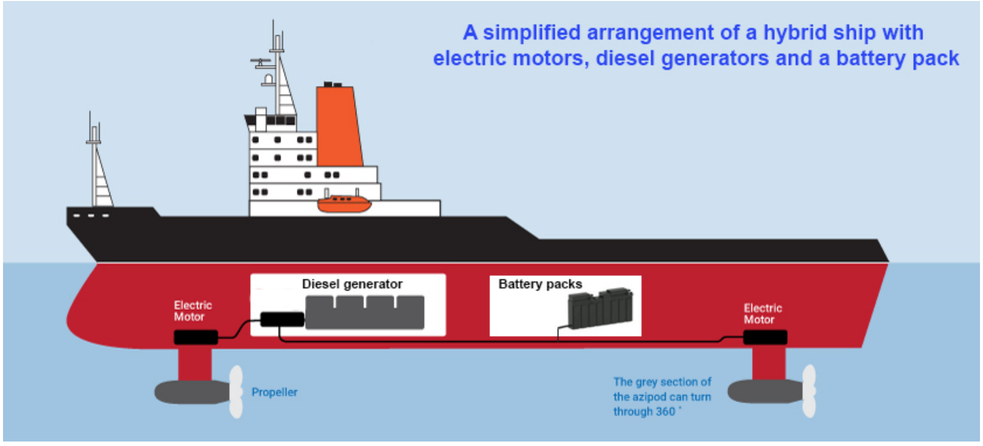
4.1. Hybrid ships/boats

Viking Lady, Norwegian offshore supply vessel is a prime example of a hybrid ship. 90m long with a deadweight of 6200 tonnes, the vessel is propelled with 2 Rolls Royce electric motors. Electricity for the propulsion, on the other hand, is generated by molten carbonate fuel cells and 4 diesel/LNG generators. Fuel cells generate 320 kW of power and operate at 650°C. Because of high operating temperatures, MCFC can work with H2, methanol, LNG and biofuels.

Vision of the Fjords, a passenger sightseeing boat is another example of a hybrid design. In operation in Norway since 2016, the vessel has 2 MAN 749kW diesel engines (*unclear whether they are only electricity generators or also linked to the main shaft for propulsion*) and 2 Oswald PM 150kW electrical motors, in addition to a 600 kWh battery pack.

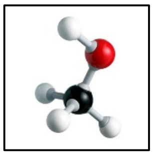
Currently, the largest fleet of battery electric hybrid ships is owned by Scandlines. Six ferries (up to 169m, 22500 DWT, with a capacity of 1,300 passengers, 460 cars or 96 trucks) are equipped with 2.7 MWh batteries. The batteries are charged by the main engine when there is excess energy and provide the electric drive with extra electricity for acceleration. The main engine can run on constant revolutions per minute (rpm) and can be smaller. This saves fuel and maintenance costs and increases the lifetime of the engine. The hybrid ferries reportedly save 24% fuel and thus reduce CO_2 emissions by around 24% in comparison to their sister ships.

KOTUG towing company operates three hybrid tugboats (eKOTUG) equipped with batteries. When not towing, the tugs use the electric drive for transit. When more power is needed, diesel generators are started. The batteries are charged by the diesel engine.


A simplified arrangement of a hybrid ship with electric motors, diesel generators and a battery pack
Diesel generator
Battery packs
Electric Motor
Electric Motor
Propeller
The grey section of the azipod can turn through 360 °

5. Methanol as an alternative marine fuel

Methanol (a.k.a. methyl alcohol/ wood alcohol) is a chemical with the formula **CH3OH**. Most methanol produced today is used to produce other chemicals. It is also one the most cited potential alternative fuels for the maritime sector.



Production - Currently, there are 3 main ways/pathways/feedstocks for producing methanol with varying well-to-tank emissions:

- *Natural gas (conventional methanol)* – production entails a combination of steam reforming and partial oxidation (burning of natural gas). The main emissions occurring during the production process are the emissions from the combustion of natural gas. However, emissions also occur during the natural gas extraction and transportation to the methanol plants, which can vary depending on the source and mode of transportation (pipeline vs. LNG). In addition, methane leak should also be factored in from natural gas production/transportation.
- *Biomass (bio-methanol)* - Methanol can be produced using electricity and biomass such as residues from forestry. In such a process, emissions from methanol production will come from the emissions generated elsewhere to create the electricity needed. The source of electricity is an important factor as emissions from electricity generation can vary according to the energy source (renewable vs. coal vs. natural gas).[5]
- *Renewable electricity, water and sourced CO2 (renewable methanol)* - this pathway creates methanol from CO2 and water. CO2 can potentially be sourced directly from atmosphere, as well as from flue streams. Using renewable electricity, water is then split into hydrogen and oxygen through electrolysis process. Renewable methanol is then synthesised from the hydrogen and sourced CO2. In this pathway, GHG emissions during the production phase of methanol is equal to zero. If transportation and bunker is also decarbonised, then well-to-wake emissions of renewable methanol equals zero, too. The use of non-renewable electricity would reduce the climate benefit drastically as the efficiency losses in production would multiply any associated CO2 emissions in non-renewable electricity production. However, these conversion steps come at significant efficiency losses.

5.1. On-board use

Methanol (as fuel) is used in conventional internal combustion engines – ICE, (e.g. diesel engines), which undergo small adjustments to burn this particular fuel. On average methanol combustion emits 69 gCO2 per MJ methanol combusted (75 gCO2 per MJ HFO). Unlike natural gas-based methanol, CO2 from the combustion of (sustainable) bio-methanol is *climate neutral*, as this CO2 is assumed to be removed from the atmosphere once new bio-feedstock grows to replace the biomass used to produce the fuel. Carbon neutrality of CO2 from the combustion of renewable methanol, lastly, depends on the source of CO2 used for methanol production. CO2 sourced

[5] However, electricity generation in almost all countries is covered under the intended nationally determined contributions (INDCs) to the Paris Agreement and are bound to decarbonise one way or another. In the EU, e.g. power sector is covered under the EU Emissions Trading Scheme which sets an absolute cap for emissions. This means that there is only small or no margin for increasing emissions from the power sector due to additional demand for electricity from methanol production (or battery powered vessels); hence, additional demand for electricity will likely have to be met by renewables or other low-carbon means of power production.

directly from atmosphere is climate neutral. However, flue streams of CO_2 sourced from industrial processes cannot be assumed to be climate neutral.

Regardless of the origin of the methanol, there will be associated combustion emissions (mostly CO_2) on board of ships, but if they are considered climate neural or not, depends if they are renewable or not.

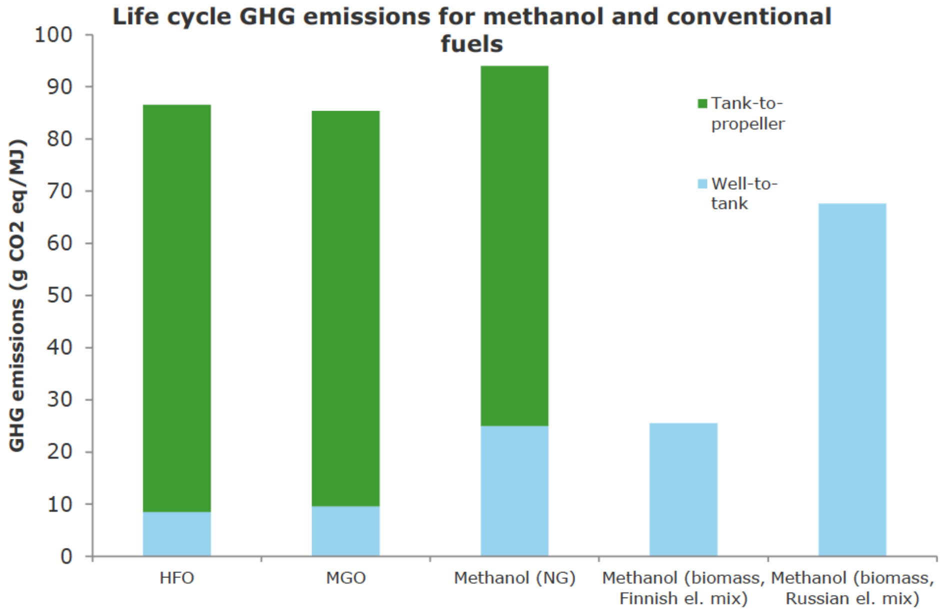


Figure 2: Life cycle emissions for methanol produced using natural gas and biomass, compared to conventional fuels *(source: DNV GL, 2016)*

As the figure 2 illustrates, carbon footprint of natural gas-based methanol is bigger than those of conventional fossil fuels and does not provide any climate benefit.

Climate impact of bio and renewable methanol, on the other hand, depends on the sustainability of biomass feedstock, type of CO_2 sourced and electricity used to produce it.

5.2. Air pollution/spill risks/toxicity

Methanol has a relatively low flashpoint, is toxic when it comes into contact with the skin or when inhaled or ingested and its vapour is denser than air (DNV GL, 2014). Methanol normally does not contain sulphur, hence, there are no SOx emissions from the on-board use. NOx emissions, on the other hand, depend on the engine type used. On average, a 60% reduction compared to HFO and a 30% reduction compared to diesel have been reported (DNV GL, 2016).

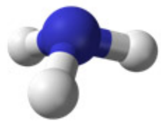
Methanol is a water-soluble chemical; hence, in the event of a spill, it quickly evaporates. Methanol represents a marine C1 substrate derived from phytoplankton (13) and the atmosphere which may be actively metabolized by marine methylotrophs, however the rate at which methanol can be metabolized is temperature dependent. Methanol is used for hydrostatic testing of soils before laying pipelines and has been spilt in Arctic environments. Methanol, which is poisonous to plants and animals, is used to clear ice from the insides of the Arctic-based pipelines. In 2007, nearly 2,000 gallons of mostly methanol, mixed with some crude oil and water, spilled onto a frozen tundra pond At BP Plc site of Prudhoe bay from a pipeline. Further analysis is required for Arctic spill risks as the necessary marine bacteria facilitating the solution process might be low or inactive in Arctic waters depending on season. An accidental release of methanol in the environment would, however, cause much less damage than a comparable gasoline or crude oil spill.

5.3. Methanol ships

Stena Germanica (Stena Line) is the world's first methanol powered ferry launched in 2015 on the Kiel–Gothenburg route. It uses dual fuel engine, with methanol as the main fuel and MGO as a backup. It is economically viable project as methanol is readily available in Sweden and ship has to comply with SECA requirements.

6. Ammonia as alternative marine fuel

Similar to methane, ammonia is a gas at normal temperature and atmospheric pressure. But it becomes liquid under ~ 10 bars atmospheric pressure at 24 degrees C temperature. Similar to methane, since liquid ammonia has more energy density than in its gaseous form, it can be stored in liquid form and re-gasified when in use.



In general, an ammonia molecule consists of one atom of nitrogen and three atoms of hydrogen (NH3). It is commonly found in nature with big majority coming from natural decomposition of biomass (manure, decaying plants, and animals). Because it does not contain any carbon molecule, during combustion ammonia produces only nitrogen and water vapour.

Production – Ammonia can be synthesized through the catalytic reaction of hydrogen and nitrogen. $\boxed{3H_2 + N_2 \rightarrow 2NH_3.}$ Nitrogen can be sourced directly from the atmosphere as dinitrogen (N2) is the most abundant gas on Earth. Sourcing of hydrogen, however, can have different pathways with different well-to-tank emissions:

- *Natural gas (conventional hydrogen)* – currently, most of global hydrogen is produced from natural gas via steam methane reforming. Since natural gas has carbon content, this pathway of H2 production involves emissions of CO2 during the production phase; hence, it is not climate neutral. In specific terms, steam reforming involves extracting hydrogen and carbon monoxide by reacting methane with steam at high temperature: $\boxed{CH4 + H2O \rightarrow CO + 3H2.}$ Then using catalytic shift conversion, carbon monoxide is converted to carbon dioxide and more hydrogen contained in water is extracted: $\boxed{CO + H2O \rightarrow CO2 + H2.}$
- *Heavy oil and coal (conventional hydrogen)* – coal is the second biggest source of hydrogen in ammonia production. The process involves first reacting coal with oxygen and steam under high pressure and temperature to form synthesis gas - a mixture consisting primarily of carbon monoxide and hydrogen. $\boxed{CH + O2 + H2O \rightarrow CO + CO2 + H2.}$ Similar to natural gas pathway above, carbon monoxide is then reacted with steam through the water-gas shift reaction to produce additional hydrogen and carbon dioxide.[6] $\boxed{CO + H2O \rightarrow CO2 + H2.}$
- *Biomass (sustainable and non-sustainable)* - hydrogen can be further produced from biomass (e.g. food waste and crops), using catalytic (thermal) reforming. The well-to-tank carbon footprint of this pathway depends on the sustainability of biomass feedstock (e.g. manure, sewage sludge vs. palm oil).
- *Renewables (renewable power to liquid - PTL)* – hydrogen can also be produced via electrolysis process – electric current being passed through water splitting it into two atoms of hydrogen and one atom of oxygen – using renewable electricity. Indeed, up to 1960s, most fertilizers sold in Europe came from hydropower-based electrolysis and ammonia production at Vemork & Rjukan in Norway. Currently, this pathway makes up only ~5% of global ammonia production; this is largely due to cheaper natural gas prices around the world and higher efficiency of steam methane reforming process.[7] In general, this pathway is climate neutral.

Globally almost all manufactured ammonia is used as fertilizer in agricultural sector. It is commonly sold in liquid forms (dissolved in water or in pressurised tanks).

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[6] NH3 plants emit on average over 1.6 t CO2/t NH3 using natural gas, 2.5 t CO2/t NH3 using naphtha, 3 t CO2/t NH3 using heavy fuel oil, and 3.8 t CO2/t NH3 using coal. IEA, 2017.

[7] *Producing ammonia and fertilizers: new opportunities from renewables* (2017), IEA.

6.1. On-board use

Ammonia can be used in current ICEs with some modifications and since the fuel does not contain carbon molecules, on-board emissions are free of CO2 and other greenhouse gases.

$$\boxed{4NH_3 + 3O_2 = 2N_2 + 6H_2O}$$

However, ammonia has very high resistance to auto-ignition (651°C - ammonia vs. 210/225°C diesel vs. 440°C gasoline) and narrow flammability limits (16-25% by volume in air). Therefore, ammonia does not compression ignite requiring blending with a certain amount of other (high-cetane) fuel – e.g. MDO.

This would mean that on-board CO2/GHG, SOx and PM emissions would still take place in proportion to the amount of "other" fuels blended with ammonia. Combustion of ammonia blends can lead to considerable NOx and soot emissions depending on engine load.[8] These could however be controlled using after-treatment technologies, such as SCR and DPF.

With regard to spark-ignition engines, on the other hand, narrow flammability limits and low flame speed causes incomplete combustion of ammonia. To overcome this, ammonia can be blended with hydrogen or gasoline. In the latter case ammonia-gasoline blend will lead to GHG and other, notably, NOx emissions.[9]

Ammonia-fueled combustion turbines and oxidation turbines that produce low or zero GHG and minimal conventional emissions are also under development, with significant R&D initiatives in Japan, Netherlands, and elsewhere.[10]

In addition, ammonia can be used as hydrogen storage (hydrogen carrier) for fuel cells. Ammonia has higher volumetric hydrogen density (10.7 kg H2 /100L11) than liquid hydrogen; therefore, e.g. a litre of liquid ammonia contains ~50% more hydrogen than the same volume of liquid hydrogen. Similar to other hydrogen carriers, ammonia has to be split via on-board reformers before released hydrogen is supplied to fuel cells. However, currently there are several technological challenges for on-board reforming of ammonia.

Notably, decomposition (splitting) of ammonia into hydrogen and nitrogen is energy intensive process and involves high temperatures (up to 1000 °C). At these high temperatures it becomes more difficult for the reactor materials, including the catalyst to sustain exposure to this environment.12 Additionally, current fuel cells (except alkaline fuel cells) have very low tolerance threshold (< 0.1 ppm) for ammonia; therefore, extensive hydrogen purification is required if fuel cells use hydrogen produced from ammonia. This appears to remain a techno/economic challenge to this date. However, Commonwealth Scientific and Industrial Research Organisation (CSIRO) in

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8 Kong S.C., (2008): *Ammonia combustion in diesel engines for reducing greenhouse gas emissions*, Technical Report, Iowa State University, USA.

9 Kong et al., *Characteristics of an SI Engine Using Direct Ammonia Injection*, Presentation, University of Iowa.

10 E.g., Michinari Hamaguchi, Japan Science and Technology Agency, Development of Carbon-Free Hydrogen Value Change (2016); Hideaki Kobayashi, Ammonia Direct Combustion: Thermal Power Generation Using Carbon-Free Fuel (2017); Holland Renewable Energy Techologies BV, *From Waste Gas to Sustainable Energy: Oxidation of NH3 Without Formation of NOx*, Presentation (2017).

11 *Potential Roles of Ammonia in a Hydrogen Economy* (2006), U.S. Department of Energy.

12 *ibid*.

Australia has made recent strides into membrane-based hydrogen separation from ammonia, which if commercialised, could fill the required technology gap in this area.

It should also be noted that, some research point to the possibility of ammonia being used directly on alkaline FC without the necessity of prior cracking of ammonia into hydrogen and nitrogen.13 Ostensibly, this would solve the efficiency and fuel cell contamination problems associated with PEMFCs.

6.2. Safety and spill risks

In general ammonia is toxic gas and can cause blindness, lung damage, burns and even death. US EPA specifies that, *"when ammonia is present in water at high enough levels, it is difficult for aquatic organisms to sufficiently excrete the toxicant, leading to toxic buildup in internal tissues and blood, and potentially death. Environmental factors, such as pH and temperature, can affect ammonia toxicity to aquatic animals"*. In addition, EU Directive 2006/11/EC on pollution caused by certain dangerous substances discharged into the aquatic environment requires reduction of pollution of in the EU water by the dangerous substances which, inter alia, *"have an adverse effect on the oxygen balance, particularly: ammonia and nitrites"*.

Benefits of ammonia

- Ammonia does not contain carbon molecules; therefore, its combustion in ICEs or (full) decomposition for use in FCs does not release GHGs or other environmentally damaging substances.
- To increase its energy and hydrogen density, ammonia can be liquefied under mild conditions (10 bars and normal temperatures/or normal atmospheric pressure and -33 °C). This means that ammonia can be stored and transported in simple and relatively inexpensive pressure vessels.
- Liquid ammonia has highest hydrogen density per volume of all liquid fuels, including liquid hydrogen. Hence, ammonia is a good hydrogen carrier.
- Ammonia can be, in fact is being produced from renewable electricity. This makes it a zero emission fuel/hydrogen carrier in its entire life-cycle if transportation, storage and distribution also take place using renewable energy sources.

Challenges associated with ammonia

- There are currently no safety procedures and standards for ammonia as marine fuel. However, given that shipping has considerable experience in storing and transporting ammonia as cargo, bunkering standards for ammonia could always be development if needed.
- On-board reforming of ammonia to release hydrogen is energy intensive and technologically challenging process. It requires excessive purification of released hydrogen as non-alkaline FCs cannot function in the presence of even trace levels of ammonia (> 0.1ppm).
- Use of ammonia in ICEs often requires blending with other fuels (e.g. gasoline and diesel); in these instances, the use of ammonia as fuel would not eliminate tank-to-wake

13 Rong Lan and Shanwen Tao (2010), *Direct Ammonia Alkaline Anion-Exchange Membrane Fuel Cells*, Electrochemical and Solid-State Letters, 13 8, B83-B86

emissions. Methods for combusting pure ammonia in ICEs are being pursued by researchers in Japan, South Korea, and elsewhere.[14]

- Ammonia is a toxic substance and it is considered dangerous for aquatic animals in case of spill or release into water.

6.3. Use by means of transport

There are currently no known commercial ships that run on ammonia or its blends. The most cited example of ammonia in ICE is passenger busses running on ammonia/coal gas blend in 1940s after invading German army requisitioned all the available diesel for war.

14 Hamaguchi at 11 (referencing ("successful power generation with ... single-fuel (NH3 only) turbines"); Donggeun Lee et al. 2017. Development of New Combustion Strategy for Internal Combustion Engine Fueled by Pure Ammonia (Abstract).

7. Wind Propulsion Technologies

There are a variety of wind propulsion technologies (WPT), both commercially available or on drawing boards, which can be used by ships to reduce their fuel consumption; hence the emissions.

Four technologies especially stand out in terms of their potential: flettner rotors, wingsails, towing kites, and wind power turbines. Most of these technologies are used in combination with other propulsion (diesel, electric etc), so in fact wind-powered ships are essentially hybrid-powered ships.

Examples of wind technologies - The majority of the propulsion technologies have been developed for bulkers, tankers and general cargo vessels due to availability of deck space. For container vessels few options seem to be available, with the most obvious one being towing kites. The below list of WPTs reflect the groupings (as opposed to individual) of technologies, which function more or less based on the same principles.

- **Fletter rotor** – are rotating cylinder towers that are vertically installed on a ship's deck and turn cross-winds into forward thrust. Cylinder rotation (powered by electric motors) together with the wind creates a pressure difference on the cylinder at the right angle to the wind direction (a.k.a. Magnus effect). This in turn gives a propulsive force to the ship.
- **Rigidsail/Wingsail** – Traditional sails were soft. Conversely, rigid sails/wingsails are wing-shaped foils with different geometry and configurations. The operating principle is the same as for plane wings: when moved through a fluid it produces an aerodynamic force consisting of lift and drag. By rotating to the optimum angle of attack, the lift can be maximised. Aerodynamic lift, in turn, lifts ship up reducing its wetted surface area under the hull, hence lowering the frictional resistance of water (drag) acting on the hull.
- **Hullsail** - The hull of a vessel can be shaped like a symmetrical aerofoil going in the relative wind; in this case, hull itself can generate an aerodynamic lift, giving a pull in the ships direction.
- **Soft sails** (incl., pinta-rig, dynarig, delta wing sail, fastrigs) **–** Are flexible sails similar to traditional sails with historically proven potential. However, modern soft sails feature many innovative features, including, freestanding square rigs, duplex rigs, rotating masts/spars most of which are/can be automated to a great extent.
- **Towing Kites** – can be installed at the bow of a ship and tow it in the direction of the wind.
- **Wind turbines** – can, similar to onshore wind turbines, be installed on ships to generate electricity. Some systems allow the power generated to be used for electric propulsion. Furthermore, forces generated by the blades of wind turbines could also be used to propel ships forward.[15]

[15] *Study on the analysis of market potentials and market barriers for wind propulsion technologies for ships*, CE Delft, 2016, p.26, p33.

The benefits of WPTs depend on a few parametres associatied with ship type, size, speed, operational conditions including sailing routes, wind speed and direction. Unfortunately, there doesn't seem to be a standardised method to estimate fuel and emissions savings associated with the deployment of WPTs. However, a recent study by CE Delft carried out simulations of savings from four types of WPTs for different vessels, and under slow and fast sailing conditions. The modelling was based on actual ship movements data and relevant for global trade shipping lanes.

The results, based on standardised methodology, provided in Tables 2 and 3 point to potential savings in low and high speed profiles. One of the most important finding of the study is that that there is a barrier (for uptake of WPTs) that has been overestimated so far: ships do not necessarily need to slow down for, at least some, wind propulsion systems to become cost efficient

Table 2: Relative energy average savings across the AIS-recorded voyage profiles – higher speed

	Rotor	Wingsail	Towing kite	Wind turbine
Large bulk carrier (90,000 dwt)	17%	18%	5%	2%
Small bulk carrier (7,200 dwt)	5%	5%	9%	1%
Large tanker (90,000 dwt)	9%	9%	3%	1%
Small tanker (5,400 dwt)	5%	5%	9%	1%
Large container vessel (5,000 TEU)			1%	
Small container vessel (1,000 TEU)			2%	

Source: CE Delft, 2016.

Table 3: Relative energy average savings across the AIS-recorded voyage profiles – lower speed

	Rotor	Wingsail	Towing kite	Wind turbine
Large bulk carrier (90,000 dwt)	23%	24%	9%	4%
Small bulk carrier (7,200 dwt)	7%	7%	14%	2%
Large tanker (90,000 dwt)	13%	13%	4%	2%
Small tanker (5,400 dwt)	7%	8%	15%	2%
Large container vessel (5,000 TEU)			2%	
Small container vessel (1,000 TEU)			4%	

Source: CE Delft, 2016.

The results indicate that Rotor and Wingsail technologies promise the highest savings for 2 out of 3 modelled ships, namely, bulk carriers and tankers. Normally, these are assumed not to be suitable for container vessels due to deck space constraints.

For these ships towing kites are assumed to be the only options. Among all technologies considered wind turbines appear to provide the least amount of energy savings.

7.1. Current ships with WTP technologies

WPT	Ship type	Size	Name & company	Reported savings	Current use	Comments/details
Rotor Sail	RoRo	~10,000 (dwt)	M/V Estraden (Norsepower)	20%		
Flettner rotors	RoLo	~10,000 (dwt)	E-Ship-1 (Enercon)	15%		
Turbosail	Research vessel	114 (GT)	Alcyone (Cousteau Society)			
Dynarig	Yacht	~150 (dwt)	Maltese Falcon (Tom Perkins)			
Soft sails	Schooner	65 (GT)	Opal	86%	In use	A hybrid sail vessel operating in the Arctic which combines sail with regenerative plugin hybrid-electric propulsion (RPHP) and battery technology. The large improvement in the energy efficiency is partly due to the high efficiency of the electric drive system and partly due to the high efficiency of the large diameter propeller, which has a much slower rotation speed than the previous propeller.
Towing kite	General Cargo	~ 10,000 (dwt)	MV 'BBC Skysails' (Briese Schiffahrts GmbH & Co. KG)			
	General cargo	3666 (dwt)	MV Theseus (MV Theseus)			
	Bulk carrier	~28,500	Aghia Marina	35%		

Further Notes

In order to identify climate benefits of alternative fuels for the maritime sector, it is important to analyse their total life cycle emissions and compare them to conventional fuels. Life-cycle emissions are usually divided into: (1) well-to-tank and (2) tank-to-wake emissions. The former refers to the emissions of GHG and other pollutants during the extraction/production, transportation and bunkering phases of the fuel/energy source. The latter refers to the emissions of GHG and other pollutants during the on-board use of fuel/energy in ships.

Further information
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Endnotes

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