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WAYS TO DECARBONIZE SHIPPING

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1. Executive summary

Changes in the marine industry are today faster and more visible than ever before. A business that has faced almost no environmental regulations before this century and utilised cheap fuels, which were considered as waste in most other industries, has had few incentives to pursue any developments by itself. Today this is very different. Stricter regulations encourage the ship industry to find new, clean and energy efficient solutions to meet the ever-increasing emission requirements.

The big trends in energy use is electrification, the gas age, and increased use of renewable energy sources. Many projections show that a bigger share of primary energy sources will be used more extensively for electricity production, which then will be used as power source for other consumers. The amount of CO_2-emissions in the electrical grid will largely define how sustainable the shore connection and shore-charged battery packs may therefore be in marine applications.

Use of natural gas is increasing, replacing oil and coal in many segments. While the price impact of this development is still unknown, it will offer a good fundament for a worldwide availability of natural gas and consequently, also LNG, which infrastructure in the marine sector is also developing at a fast pace. While LNG does not offer any significant greenhouse gas (GHG) emission reductions on a well-to-wake basis compared to diesel oil, it is still an effective way to reduce other harmful emissions, such as almost 100% lower SO_x emissions and particulate matter, and about 90% lower NO_x emissions. However, LNG or any other fossil-derived fuel for that matter, are not solutions to meet the set emission reduction targets.

Therefore, shipping will have to introduce alternative, fossil-free fuels derived from sustainable sources to meet the set climate goals. Fortunately, there is potential to introduce sustainable fuels in shipping, but it will require joint efforts from ship owners, fuel suppliers, engine makers and port authorities, with the support of strong policies to materialize.

Building a new infrastructure for introducing a new sustainable fuel is not an attractive solution. The challenges involved, let alone the time and costs required before worldwide availability of a new fuel has been achieved should not be underestimated – the ongoing expansion of the LNG infrastructure is a good reference, which still requires significant investments to become readily available worldwide. Another aspect to consider is the end-users: the ships. The energy density of a fuel will partly determine how applicable the fuel is for certain ship types and operations, and particularly for retrofits. Majority of ships designed and built today are optimized to operate on fuel oils with a relatively high energy density – and these ships will still be sailing in 2050. Retrofitting an alternative fuel with lower energy density can therefore significantly compromise on the travel range, or alternatively, if tank capacities must be increased can have a negative effect on the ship's income generating spaces or ship performance.

The future availability of clean and cheap energy will largely dictate to what extent the expansion of renewable hydrogen will realize. While projections show that a major share of the world's energy production will come from renewable energy sources in 2050, it is, however, unrealistic to believe that a large share will be allocated for hydrogen production, which is a very energy-intense process. In addition, the virtually non-existing hydrogen infrastructure today, would require massive investments to realize. Storing large amounts of hydrogen needed for marine use has also proved to be an overwhelming challenge. Renewable hydrogen as fuel will therefore not likely play a major role in shipping before 2050. And even then, the poor energy density of hydrogen, even as a liquid, will most likely limit its use to only niche applications in shipping.

While renewable hydrogen as fuel likely will have a limited role in shipping in near term, it can, and will play an important role for the production of various synthetic fuels also relevant for shipping, e.g. synthetic methane and synthetic diesel. The advantages will also outweigh these fuels' poor conversion efficiency, as the synthetic fuels are characteristically similar to their fossil fuel counterparts, meaning existing fuel infrastructure and ship technologies could utilize these fuels with minor modifications.

The commercial production of high biofuel volumes required for shipping is not yet established. However, biofuels are a promising alternative to decarbonize shipping. If the biofuels would be produced to be functionally equivalent to petroleum fuels, i.e. so-called drop-in biofuels (or if gaseous biofuel: biomethane to replace LNG), they could also use the existing bunkering infrastructure with minor modifications, and therefore show a strong potential to replace part of the fuel mix. Another advantage of producing biofuels for the marine sector is that the fuel can be of lower quality than for e.g. aviation or road transport. Thus, eliminating the need for intensive upgrading and refining, resulting in potentially lower production costs. Still, a global standard and guideline for marine biofuel quality will be needed to ensure the bunkered biofuel does not cause any incompatibility issues, regardless where it is bunkered and from what feedstock it is produced.

Biofuels' sustainability depends to a large degree on the type of feedstock that is used. Biofuels produced from waste have a significantly lower GHG impact than traditional biofuels, while simultaneously not compromising food production or increasing land use. Today, the only pathway that produces significant volumes of a suitable drop-in biofuel is based on lipid feedstocks, such as vegetable oils or other bio-derived fats such as animal fats, used cooking oils and tall oil. The disadvantage, however, are the arguably limited lipid feedstock volumes available, particularly from waste. Feedstocks derived from vegetable oils can offer greater volumes, but sustainability and direct land use is a concern. If biofuels shall replace a larger part of the fuel mix in shipping, other production pathways than from lipid feedstocks must be introduced. From a strategic point of view, biofuels derived from lignocellulosic biomass show good potential to produce significant volumes of drop-in biofuels in the future. It is estimated that current agriculture and forestry residues are (in theory!) sufficient to produce biofuel volumes to cover the shipping industry's needs. However, the assessment of biofuel feedstock is not a straightforward process, as they are part of a highly complex and integrated systems with a number of interconnected markets and mechanisms. Further work is needed to recognize the potential market and availability of various feedstocks for production of biofuels.

Producing biofuels from lignocellulosic biomass, however, also poses some challenges. Generally, it is a more complex production pathway than producing biofuels from lipid feedstocks, and will also require different technologies to convert the feedstock into fuel. While there is potential for larger biofuel volumes, more research is still needed in the conversion technologies and upgrade methods. As of today, no commercial biofuel refineries using lignocellulosic biomass as feedstock exist.

All the proposed fossil-free fuels have, however, one major disadvantage - regardless if they are derived from biomass or produced from cheap renewable energy sources: their production costs are much higher compared to fossil fuels, and they will most likely remain so for the foreseeable future. Policy support will be needed to enable these fuels to mature, and a substantial carbon cost applied to fossil fuels is likely unavoidable if the fossil-free fuels shall have any potential to replace part of the fuel mix in shipping. However, as the availability and production of sustainable fuels are still limited, and it is very likely that shipping will have to rely, at least partially, on fossil fuels in the foreseeable future. As a short-term strategy, different methods – both technological and operational measures to improve the energy efficiency of ships are available already today, and these should be implemented, as far as practicable, to cut emissions from shipping.

2. Regulations in shipping

According to the third IMO GHG study (released in 2014), estimated that shipping emitted approximately 938 million tonnes of CO_2 in 2012, accounting for 2.6% of the global anthropogenic CO_2 emissions that year. This is a reduction compared to the 1100 Mt CO_2 emitted in 2007 (3.5% of global emissions), however, increase in vessel size and lower operational speeds are the main reasons to this reduction (Bouman, et al., 2017).

Ship emissions are expected to increase in this growing industry. Depending on future economic and energy developments, shipping emissions may increase by 50% to 250% in the period to 2050. The continued growth of the industry is a concern if no significant gains in energy efficiency are achieved and alternative low-carbon fuels are introduced.

In maritime shipping, few policies that are directly promoting the use of renewable energy sources exist. The resolution MEPC.304(72), adopted on 13 April 2018, indirectly points out measures how to reduce the GHG emission from shipping:

1. **carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships**
   to review with the aim to strengthen the energy efficiency design requirements for ships with the percentage improvement for each phase to be determined for each ship type, as appropriate;
2. **carbon intensity of international shipping to decline**
   to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008; and
3. **GHG emissions from international shipping to peak and decline**
   to peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 whilst pursuing efforts towards phasing them out as called for in the Vision as a point on a pathway of CO_2 emissions reduction consistent with the Paris Agreement temperature goals (IMO, 2020)."

Local regulations are also emerging. The Port of Rotterdam Authority announced an incentive to support vessel owners that use low-carbon or zero-carbon fuels, as well as commitment to reduce emissions from the port, starting in 2030 (REN21 Renewables Now, 2019). The Norwegian parliament have taken even more stringent emission measures, announcing that only zero emission cruise ships and ferries may enter the UNESCO-protected fjords no later than 2026 (Hermundsgård, 2019).

3. Global trends in renewables

Renewable energy has established itself on a global scale with 2378 GW installed in 2018, accounting for more than one third of the world's installed power generating capacity, and more than 25% of total power generation (REN21 Renewables Now, 2019). As the pressure to tackle climate crisis and reduce carbon emissions grow, renewable energy is predicted to increase. Renewable power capacity is expected to expand by 50% between 2019 and 2024 (IEA, 2019). Most projections also foresee an almost complete decarbonization of up to 95% by 2050 compared to today (Figure 1). However, the increase in power generation from renewables will pose serious challenges to the stability of the energy system, due to supply and demand of power are intermittent and variable.

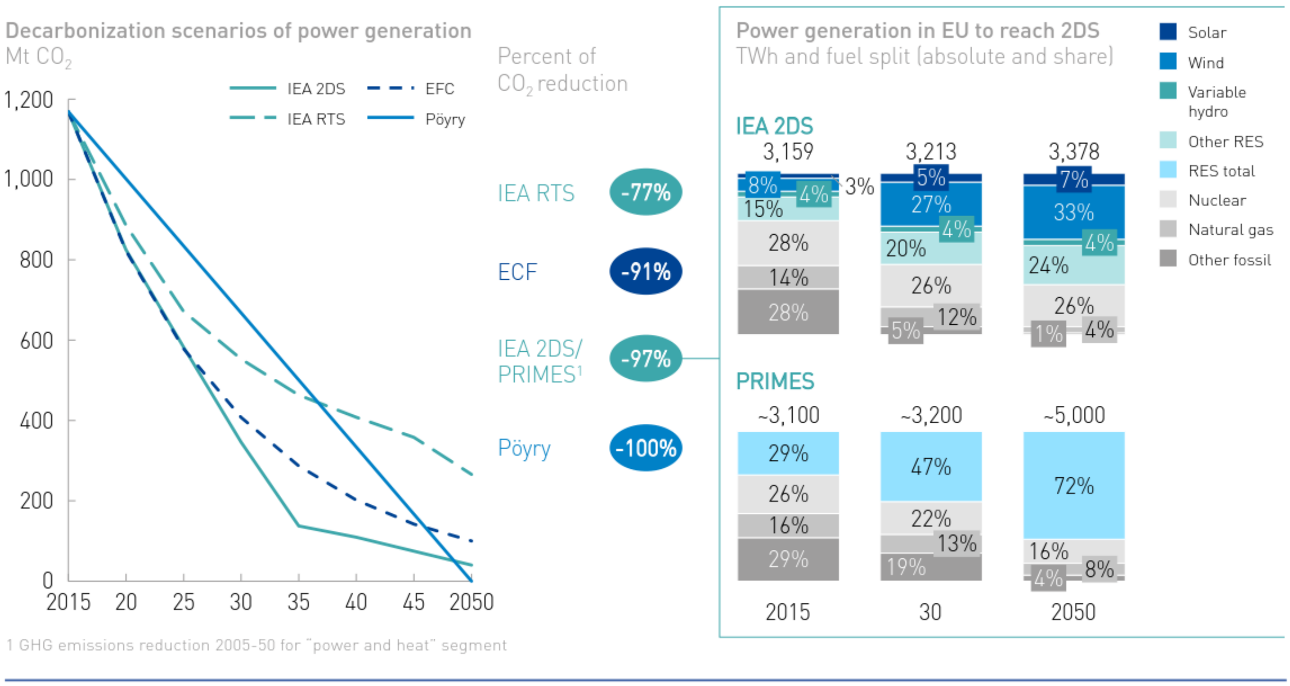


Figure 1 Decarbonization scenarios and power mix – today to 2050 (Fuel Cells and Hydrogen Joint Undertaking, 2019).

3.1. Solar and wind are taking the lead

Due to decrease in costs, solar PVs and wind power are considered the most promising renewable power sources for decarbonizing the power generation in the world. The international Energy Agency, in its World Energy Outlook 2019, predicts that global wind capacity will reach 1000 GW around 2025, and 1856 GW by 2040 (today's capacity is approx. 500 GW). In terms of energy generation, a similar development for solar PVs is expected. However, as solar PV has a lower capacity factor than wind, its installed capacity will be higher. The IEA expect solar PV to overtake wind in terms of installed capacity in 2020 (currently it is around 500 GW), and then grow to 3100 GW by 2040. Most authorities expect the contributions from solar and wind to be similar, generating around 5000 TWh each to global electricity by 2040 (Milborrow, 2020).

3.2. Power sector is decarbonizing – other sectors, not so much

The transport and building sector has seen much slower development compared to the power sector for introducing renewable energy. The transport sector accounts for about one third of the total final energy consumption share. Road transport continues to account for the bulk of the energy demand (75%), followed by aviation (11%), marine transport (9.6%), pipeline transport (2.3%), rail (1.8%), and other forms of transport. Only a small share of the transport energy is supplied from renewable energy (3.3%), mostly in the form of biofuels and electricity (Figure 2). Reducing the fossil use in this sector is therefore critical to reach international emissions reduction goals. However, the progress remains constrained, mostly due to lack of strong policy support and slow developments in new technologies, such as the production of advanced biofuels.

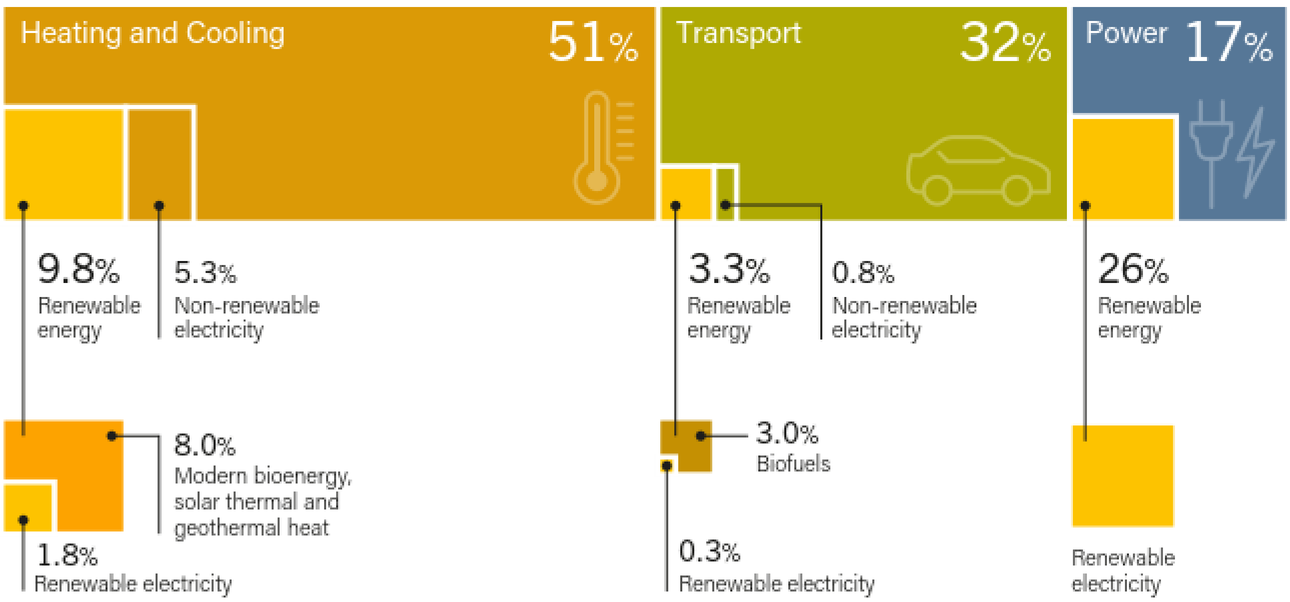


Figure 2 Total final energy consumption share by sector in 2016 (REN21 Renewables Now, 2019).

3.3. Global biofuel production is increasing – slowly

Global biofuel production reached almost 100 Million ton oil equivalent in 2019. Bioethanol accounted for 63% of global biofuel production, first generation biodiesel (FAME) for 31%, and renewable diesel (HVO) 6%. Biomethane and other advanced biofuels represent still small shares, though biomethane is growing rapidly in some countries. A 3% annual production growth is expected over the next five years. To be on track with the Sustainable Development Scenario (SDS), transport biofuel needs to almost triple the production by 2030 (i.e. 298 Mtoe), which corresponds to a needed production growth of 10% annually, starting today – and that considers only sustainably produced biofuels. In international shipping, low-carbon biofuel demand should reach a total fuel share of 7% (15 Mtoe) by 2030 to meet the SDS, however, current consumption is virtually non-existent (IEA, 2019).

3.4. Policy and carbon taxes are critical

Carbon pricing policies are slowly expanding, but are still covering only 13% of global greenhouse gas emissions (REN21 Renewables Now, 2019). Majority of the renewable energy technologies are strongly dependent on government policies to stimulate growth - either by direct or indirect support. Majority of the carbon-related policies, however, are found within the power sector. Policies outside the power sector are not only less numerous, but are also far less ambitious. Overall, renewable energy policy frameworks greatly vary in scope and comprehensiveness, and most remain far from the ambition level to reach international climate goals. A carbon market will be needed to stimulate growth of renewable sources, where the emitting companies will pay, and carbon sequestrating companies will get an income to finance for carbon removing/production of sustainable fuel investments, such as one proposal visualized in Figure 3.

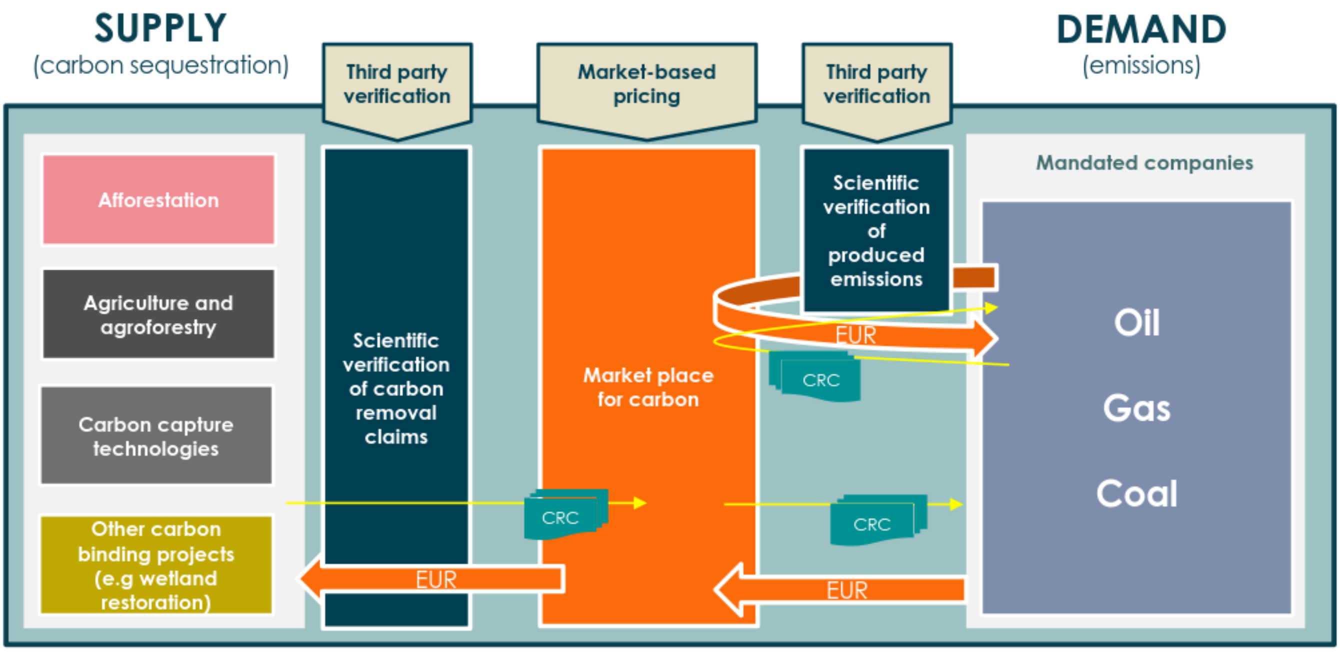


Figure 3 A similar carbon market is likely needed to increase the share of renewables - even in shipping. CRC = Carbon Removal Credit (Anttonen, 2019).

4. Maritime fuels – now and future

Today, majority of the fuels utilized in the maritime industries are produced from fossil-based feedstock, mostly crude oil and natural gas. To reach the targets set by IMO, these fossil fuels must gradually be replaced by fuels that are both renewable and GHG-neutral on a well-to-wake basis. Without any emission reduction methods implemented, CO_2 emissions from shipping is projected to be in the range of 1000 to 1750 million tonnes in 2050. With the set GHG emission targets and using the baseline emissions of 810 million tonnes in 2008, means the targeted CO_2 emissions from international shipping in 2050 would be 405 million tonnes. Assuming diesel fuel would still remain as the predominant fuel (carbon factor 3.206), it is expected the need of fossil-free diesel equivalent fuel in 2050 would be in the range of 185 to 419 million tonnes (IMO MEPC 73, 2018).

When speaking about emission-free or zero-emission ships, it is a term that can be interpreted in different ways. It depends widely on what type of energy carrier the ship is using, which in (IMO MEPC 73, 2018) is defined as follows:

- **Zero-carbon fuel:** Ships utilizing an energy carrier that does not release CO_2 emissions when used (e.g. hydrogen, ammonia, or batteries), but the fuel can originate from a fossil feedstock, or batteries are recharged with fossil-based electricity while in port.
- **Fossil free fuel:** Fuels such as biofuels, hydrogen and other synthetic fuels produced from a non-fossil feedstock utilizing renewable energy sources for the production processes.
- **Low carbon fuel:** fuels that originate from industrial processes, utilizing fossil-based CO_2 as feed-stock to create a less GHG intense synthetic fuels than that of the conventional maritime fuels.

4.1. LNG's potential GHG savings

Thus far, Europe has spent about half a billion USD on LNG fuelling and infrastructure for shipping, almost half of the budget being from taxpayers. An additional $22 billion may be needed up to 2050 in a scenario where the LNG consumption is further incentivised (Transport & Environment, 2018).

Many studies have demonstrated LNG's GHG impact in shipping – with varying results. At one end of the spectrum, LNG is claimed to offer 7 to 21% lower well-to-wake GHG emissions compared with HFO (Thinkstep, 2019). Another study claims on the other hand that LNG does not reduce GHG emissions compared to MGO or HFO at all (Lindstad, 2019). Regardless what the LNG's actual well-to-wake GHG reductions may be, it is still obvious that the potential abatements would still not contribute significantly to the set emission reduction goals. However, switching to LNG is still an effective way to reduce other harmful emissions; almost 100% reduction in SO_x and PM emissions, and about 90% in NO_x emissions compared to other marine fuel oils can be achieved (Aakko-Saksa & Lehtoranta, 2020).

5. Potential alternative fuels

To meet climate targets in shipping, the marine sector shall pursue for deployment of fuels that are non-fossil based, and have a lower GHG impact than currently used fuels. Fuels like hydrogen, ammonia, methanol, and various synthetic- and biofuels are often considered as suitable fuels for shipping. However, none of the fuels are without limitation. The fuel's energy density and required storage system will determine how applicable the fuel is for certain ship types and operations (Figure 4). There is no magic bullet, and future shipping is likely to be dependent on various fuel alternatives to meet the ever tightening emission regulations.

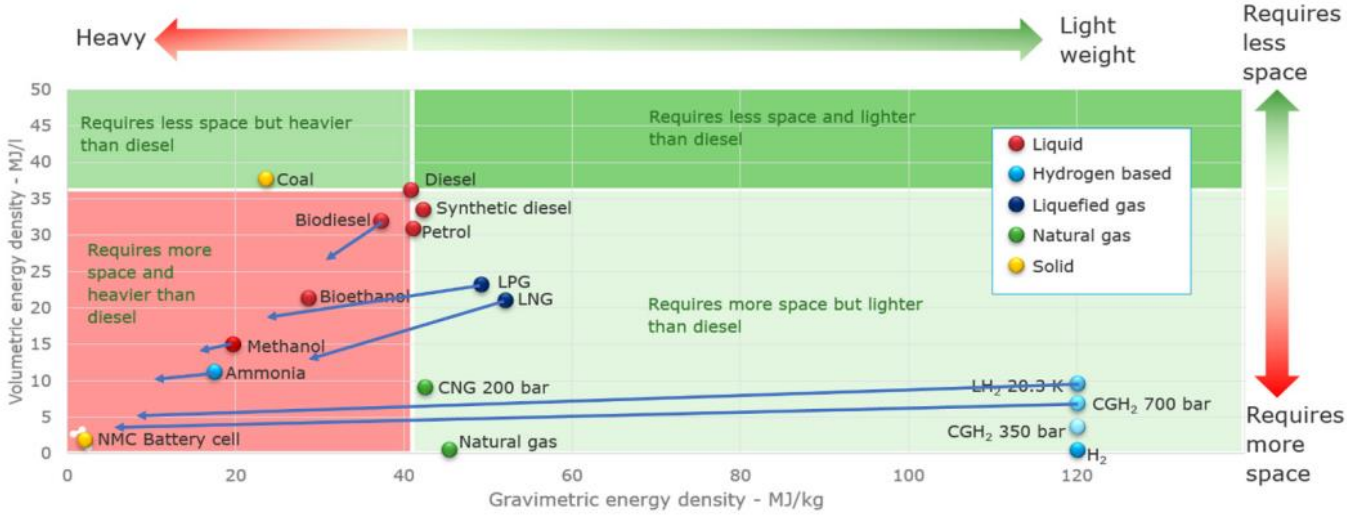


Figure 4 Energy densities of various fuels. Blue arrow indicates the energy density when the storage system is also taken into account (indicative value) (DNV-GL, 2019).

5.1. Hydrogen

Hydrogen has many times before been hyped as the future fuel for a decarbonized economy, but thus far, the hype has not fully been realized. However, with a growing number of countries getting serious about decarbonization, this could change in near future.

Hydrogen might be the most abundant element on earth, but is rarely found in its pure form. Characteristically, hydrogen can be produced or extracted from virtually any primary source of energy, be it fossil or renewable (Figure 5). But unlike natural gas, coal and oil that only requires extraction, hydrogen is still a fuel that must be manufactured, which requires energy. Therefore, even at low production costs, hydrogen is still likely to need carbon taxes and policies to be able to compete with cheap fossil fuels in hard-to-abate sectors, such as aviation and shipping.

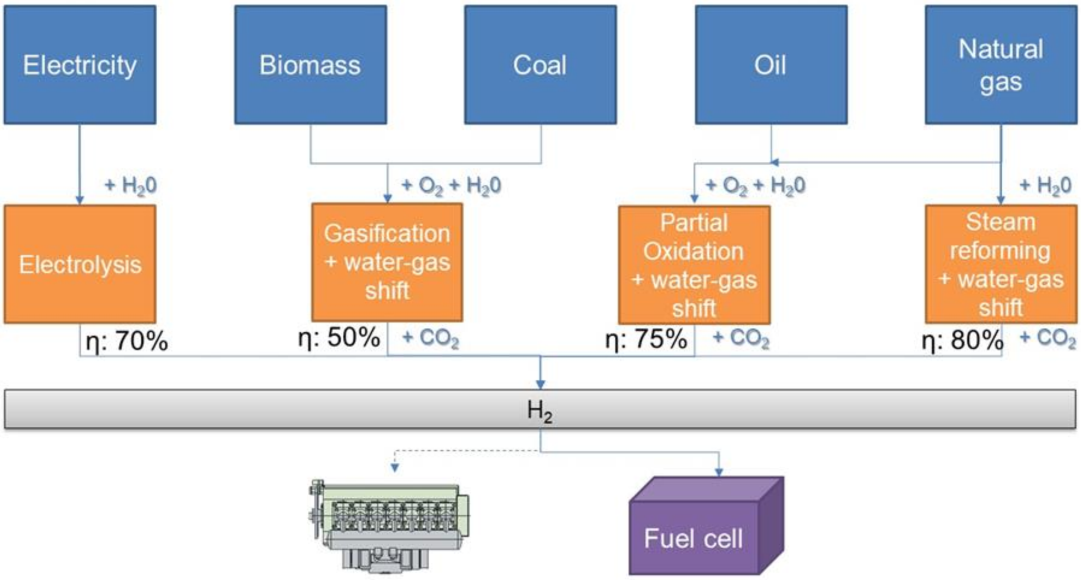


Figure 5 Hydrogen production pathways and conversion efficiencies.

5.1.1. Hydrogen characteristics & storage

Hydrogen in its natural state is an unscented, non-toxic and colourless gas. It is also a gas that catches fire very easily, and readily forms an explosive mixture with air. The specific energy of hydrogen is one of the highest, which makes it attractive as fuel. However, the energy density is just a fraction of other fuels, and storing large masses of hydrogen has therefore proved to be an overwhelming challenge.

Compressed hydrogen in tanks or bottles of very high pressures (between 200 and 700 bar) is the most common way of storing hydrogen in fairly small quantities. Pressurizing hydrogen is a costly process, consuming around 3 – 5 kWh/kgH_2 compressed, which equals to 9 to 15% of the energy content of the fuel. The storage efficiency is also poor at around 40 g H_2/kg system for a 700 bar storage tank. Storing large amounts of compressed hydrogen is therefore not only large, but also heavy.

Alternatively, hydrogen can be stored as liquid to further increase its volumetric density. The liquid hydrogen is stored in vacuum insulated cryogenic tanks at atmospheric pressure and -253°C. Considerable energy is also required to liquify hydrogen. Reported specific power to liquify hydrogen ranges from around 6 to 13.6 kWh/kgH_2 (Berstad, et al., 2010). Due to more sophisticated technology required, some suggest the capital cost increase for liquid hydrogen could be 4 to 5 times higher than compressed hydrogen storage (McKinlay, et al., 2020).

Alternative storage methods of hydrogen are metal hydrides and liquid organic hydrogen carriers (shortened LOHC). Metal hydrides are interesting for their potentially very high storage density. Hydrogen are absorbed to the metals using chemical bonding, and the absorption is performed above atmospheric pressure. Discharge of hydrogen is endothermic and e.g. hot water or waste heat is needed to start the hydrogen desorption. The working principle can figuratively be described as a hydrogen “sponge”. LOHC works in a similar way, where gaseous hydrogen reacts with the LOHC together with a catalyst to form a liquid organic hydride. The organic liquid is a stable liquid in room temperature and thus allow easy storage and transportation, the LOHC is considered a promising technology as it can utilize the existing gasoline infra-structure for long-distance hydrogen transportation. Main drawback, however, is the high temperature (300 – 400°C) and pressure that must be applied for the hydrogen release to occur (He, et al., 2015).

5.1.2. Hydrogen production today

Today, around 80 million tonnes of hydrogen is produced worldwide, of which 96% is produced from a fossil-based feedstock, mostly from natural gas. Hydrogen production accounts for 6% of global natural gas and 2% of global coal use. The global demand for hydrogen has grown more than threefold since 1975, and still continues to rise (IEA, 2019).

Current hydrogen production is well-established and a relative energy efficient process, but the lifecycle emissions are still significant. Production of hydrogen is responsible for around 830 million tonnes CO_2 emissions per year, which corresponds to around 2.5% of the world's global emissions. The industrially produced hydrogen is currently not used as an energy carrier for energy production, but rather almost entirely as feedstock for converting raw material into chemical or refinery products in industrial applications (Figure 6). Therefore, the production and distribution of hydrogen would have to increase significantly, should either hydrogen or ammonia become a globally used fuel.

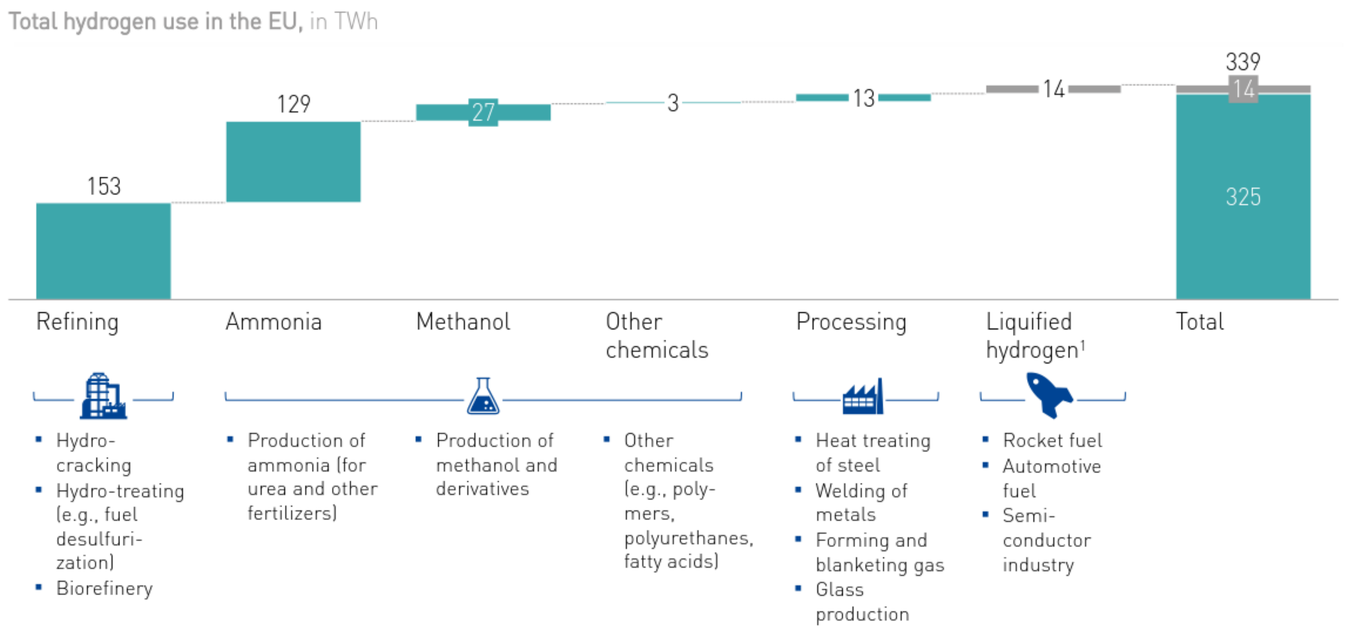
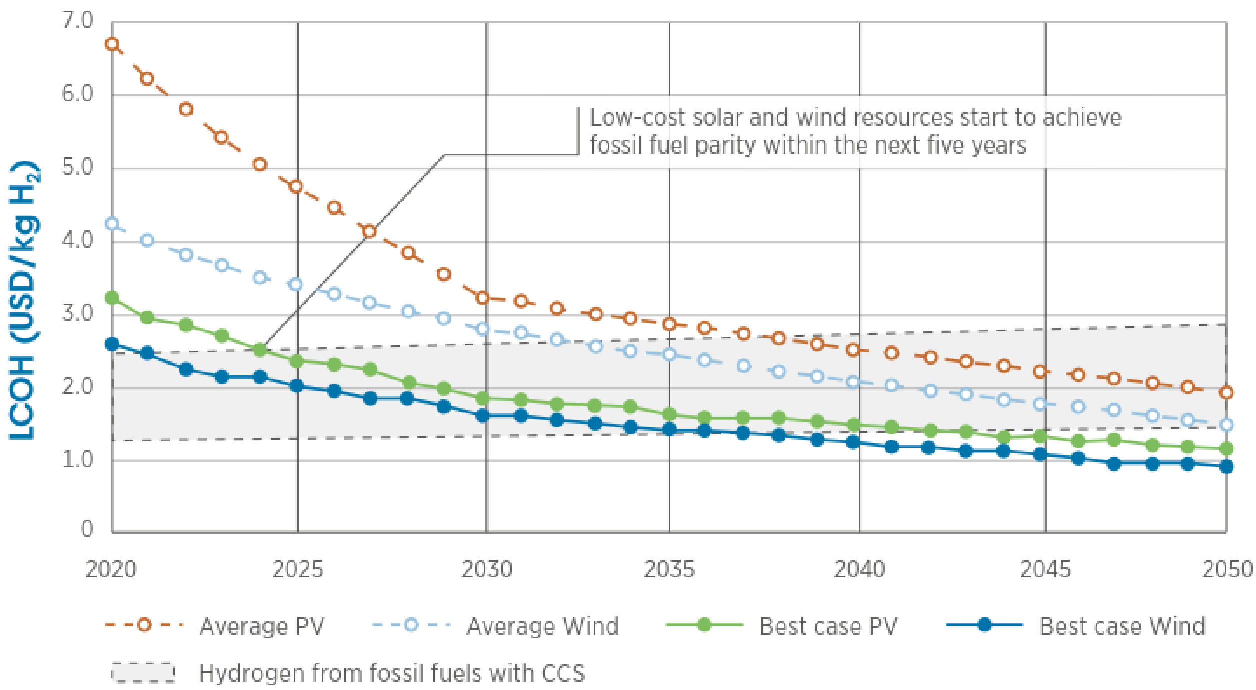


Figure 6 Hydrogen use in the EU (Fuel Cells and Hydrogen Joint Undertaking, 2019).

5.1.3. Sustainable hydrogen

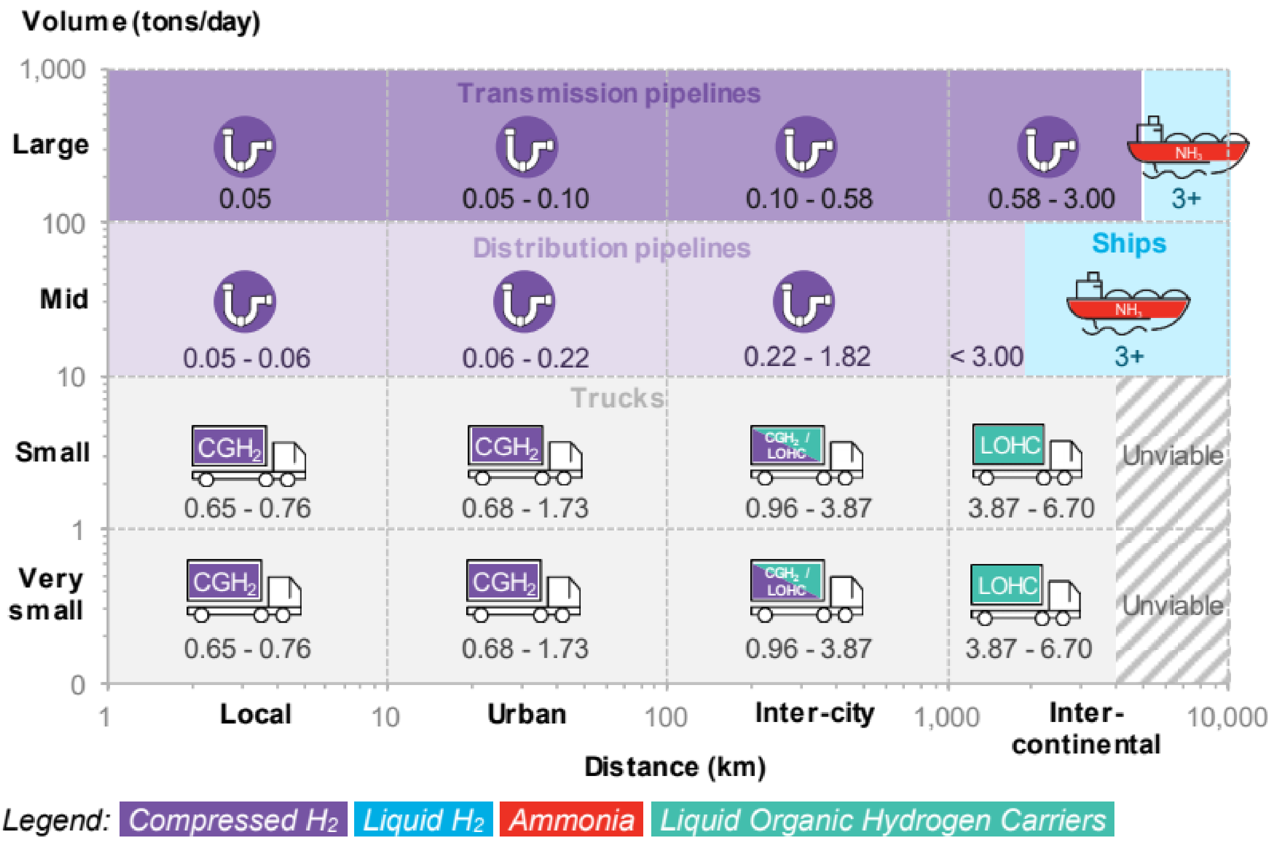
Renewable hydrogen holds large potential for a future carbon-free power generation. However, significant work is needed to decrease the cost of electrolysed hydrogen to increase its market share, which is less than 0.1% of the global hydrogen production today (IEA, 2019). However, with declining costs for renewable electricity, particularly from solar PV and wind, there is a growing interest in electrolytic hydrogen. Future electricity prices are difficult to predict accurately, but forecasts estimate hydrogen produced from low-cost wind and solar PV is expected to achieve fossil-based hydrogen price levels within the next five years in the best-case scenarios (Figure 7). However, significant improvements in electrolyser efficiency will still be needed to reduce hydrogen production costs. For instance, if the expected fossil-free diesel needed in 2050 by shipping (i.e. 185 to 419 million tonnes diesel-equivalent fossil-free fuel) would be replaced by hydrogen, about 66 to 149 million tonnes is needed. If all that hydrogen is to be produced from water electrolysis, then with today's electrolysers the total electricity demand would be in range from 3135 to 7100 TWh. For comparison, the total gross electricity production in Europe in 2017 was almost 3300 TWh.



Note: Remaining CO_2 emissions are from fossil fuel hydrogen production with CCS.
Electrolyser costs: 770 USD/kW (2020), 540 USD/kW (2030), 435 USD/kW (2040) and 370 USD/kW (2050).
CO_2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050).

Figure 7 Hydrogen production cost estimations from solar PV and wind versus fossil fuels (IRENA, 2019).

The cost of electrolysers are also coming down. According to Bloomberg, the cost of alkaline electrolysers in North America and Europe fell by 40% from 2014 to 2019, and Chinese made systems are already up to 80% cheaper than those made in the west. If the manufacturing of electrolysers can scale up, and costs continue to fall, then renewable hydrogen could be produced for \$0.8 to \$1.6/kg in most parts of the world before 2050 (BloombergNEF, 2020). The low density of hydrogen is still problematic, and transporting hydrogen via road or ship is expensive. Transporting hydrogen via pipes is considered the most cost-efficient option for large-scale transport (Figure 8).



Source: BloombergNEF. Note: figures include the cost of movement, compression and associated storage (20% assumed for pipelines in a salt cavern). Ammonia assumed unsuitable at small scale due to its toxicity. While LOHC is cheaper than LH_2 for long distance trucking, it is less likely to be used than the more commercially developed LH_2.

Figure 8 Hydrogen transport cost based on distance and volume in \$/kg (BloombergNEF, 2020).

5.2. Ammonia

Ammonia (NH_3) remains in liquid phase at a temperature of -42°C and ambient pressure, alternatively at 10 bar and ambient temperature. Ammonia is not a low flash point fuel but the vapours, that are lighter than air and invisible, are extremely hazardous and exposure to a high concentration of ammonia vapor may be fatal within minutes.

In liquid phase, ammonia requires approximately 3 times more storage space, tanks excluded, than HFO for the same amount of energy. Another concern may be ammonia's relatively low gravitational energy density. A study shows that powering a tanker from only ammonia would increase the total mass of a vessel by over 2.74% compared to LNG when refuelling (McKinlay, et al., 2020).

Ammonia is together with hydrogen a fuel that has no carbon emission during combustion. While ammonia do not contain any carbon or sulphur, the nitrogen molecule is heavily present, and will cause higher NO_x emissions during combustion compared to any other alternative fuels in shipping (LNG, methanol and hydrogen). Today, no ship operating on ammonia exist.

5.2.1. Ammonia production today

A major drawback of current commercial ammonia is its energy intense production processes. Current annual production worldwide is exceeding 150 million tonnes, of which a majority is used for the fertilizer industry. The ammonia production accounts for 2% of global energy consumption, and approximately 1% of the global CO_2 emissions. Part of the reason is ammonia requires hydrogen as feedstock, which is produced mostly from steam reformed natural gas.

5.2.2. Sustainable ammonia

A sustainable ammonia process would rely on a combination of two already well-established and proven technologies: Electrolysis and Haber-Bosch (E-HB). While both being mature, there are some limitations that might create some obstacles for a modern ammonia plant to rely on this combination, mostly due to ammonia produced from fossil feedstock being cheaper. However, there have been ammonia plants of smaller scale in the world relying on E-HB, all strategically located beside hydroelectric dams where a constant and (relatively cheap) supply of electricity was available. E.g. Norsk Hydro scaled-up the E-HB technology in the 1920s to produce hydroelectric ammonia until 1991. The company later split into Yara – now the biggest ammonia producer in the world, and Nel, which still makes electrolysers (Brown, 2017).

There are two technological limitations for a modern E-HB plant relying on renewable power. First, the intermittent power supply from renewable energy sources such as wind and solar power conflicts with Haber-Bosch, which requires constant operation. Second, Haber-Bosch benefits from economies of scale (e.g. capacity of 800 000 tonnes/year), that don't match the scale of renewable power plants (e.g. 200 000 tonnes/year) (Brown, 2017).

Although not yet commercially available, the solid state ammonia synthesis (SSAS) is another promising alternative technology for future renewable ammonia production. Here, ammonia is synthesized directly from water and nitrogen without going through the intermediate steps of creating hydrogen through electrolysis and Haber-Bosch. The claimed efficiency is also in the range of commercial electrolysers (65 –

75%), meaning ammonia could be produced as efficiently as hydrogen. The technology can, however, not yet be considered a viable solution, as it is still in its early development stage.

5.3. Methanol

Methanol is often considered as the dark horse in the alternative fuel race. As it is a liquid at ambient conditions, it is easier to store than most other alternative marine fuels such as LNG, ammonia and hydrogen. Consequently, investment costs into infrastructure and storage tanks should be lower. Methanol is therefore considered as one of the most promising fuels for retrofits.

Methanol as fuel in the maritime industry is also already well-known, and operational experience and test results have shown that methanol could comply with the most stringent emission reduction legislations. During combustion methanol produces no sulfur emissions, and very low NO_x and particulate emissions.

Methanol's disadvantages, however, are that it is a low flash point fuel, and due to its lower energy content, means that to reach the same operability range as with diesel oil, methanol requires approximately 2.5 times larger fuel tanks. From a safety point of view methanol also has some undesirable properties that must be taken into account. Methanol is highly flammable and burns with colourless flame. In addition, it is highly toxic, has no taste and mixes easily with water-based fluids. Despite its toxicity, it is not carcinogenic and has none of the nasty mutagenic properties of some other fuels. For the environment it is also less harmful as it bio-degrades quickly. In case of a maritime spill, even in large volumes the damage may be minor compared to other oil fuels.

5.3.1. Methanol production pathways

Methanol is a worldwide produced chemical with annual production around 100 million tonnes. The main feedstock, which also is methanol's major downside today, is that it is predominantly produced from fossil fuels, mostly from natural gas, but coal and residual fractions from refineries are also common production sources.

On the upside, however, methanol can also be produced from virtually any renewable sources, such as various biomasses, municipal waste, landfill gas, biogas, and even synthetically from renewable hydrogen and CO_2. Therefore, production of renewable methanol is also directly competing of the same feedstocks used for production of other renewable fuels.

5.4. Power-to-X / E-fuels

While hydrogen is not considered a feasible option for long-range shipping due to its poor energy density – even as a liquid it would require more than 5 times the space compared to HFO (tanks excluded). Renewable hydrogen, however, can still be a valuable feedstock for producing synthetic gases or liquids by adding CO_2 (or nitrogen if ammonia) from either the atmosphere, or CO_2 that would otherwise be put to the atmosphere, creating a so-called Power-to-X fuel, or electro-fuel/E-fuel. While this fuel type does not reduce the local CO_2 emissions, however, with a climate-neutral source of CO_2, such as from combustion of biomass or direct air capture of CO_2, PtX-fuels can be considered a viable alternative for decarbonizing shipping.

Ammonia production, as previously discussed, is predominantly produced by the Haber-Bosch process from nitrogen (extracted from air) and hydrogen with an iron catalyst at high temperatures and pressures (400 – 500°C and 15 – 20 MPa). Ammonia yield increases with pressures, at the expense of higher energy costs. Therefore, the choice of pressure is a compromise between ammonia yield and cost.

Synthetic liquids can be obtained through the Fischer-Tropsch process. The Fischer-Tropsch process is a combination of chemical reactions that converts a fuel gas mixture – a synthesis gas, consisting primarily of carbon monoxide and hydrogen into liquid hydrocarbons. The technology is proven, and synthetic liquids are produced on a commercial scale, not from renewable but from coal in e.g. South Africa (IRENA, 2019). Chemically the synthetic fuels are very similar to existing fuels, and can even be of better quality than their fossil-based equivalent due to the absence of sulphur and aromatics. Another advantage is that current infrastructure, and powerplants and storage tanks in shipping can be directly used, or easily modified to utilize the synthetic fuels.

Methanation is a chemical reaction that converts carbon monoxide and/or carbon dioxide with hydrogen to methane. Methanation can undergo two different paths: catalytic and biological methanation. The efficiency of both methanation processes are limited by the Sabatier reaction to a maximum of 80%. Each of the techniques can, besides pure CO_2 also be fed with biogas and can then serve as an upgrading technique (Banjaminsson, et al., 2013).

Methanol synthesis is a CO hydrogenation catalytic reaction and is very exothermic. The synthesis occurs under high pressure (3.5 – 10 MPa) and temperatures 200 – 300°C. The conversion per pass is poor at around 25%, so to achieve higher conversion efficiency, several methods can be applied: 1) recirculate unconverted synthesis gas, 2) Lower the temperature by increasing cooling, but the trade-off is a reduced catalyst activity, and 3) Quickly remove the methanol as it is produced to improve the conversion efficiency (Yang & Ge, 2016).

The biggest challenge, however, for all the Power-to-X fuels are their low conversion efficiency (Figure 9).

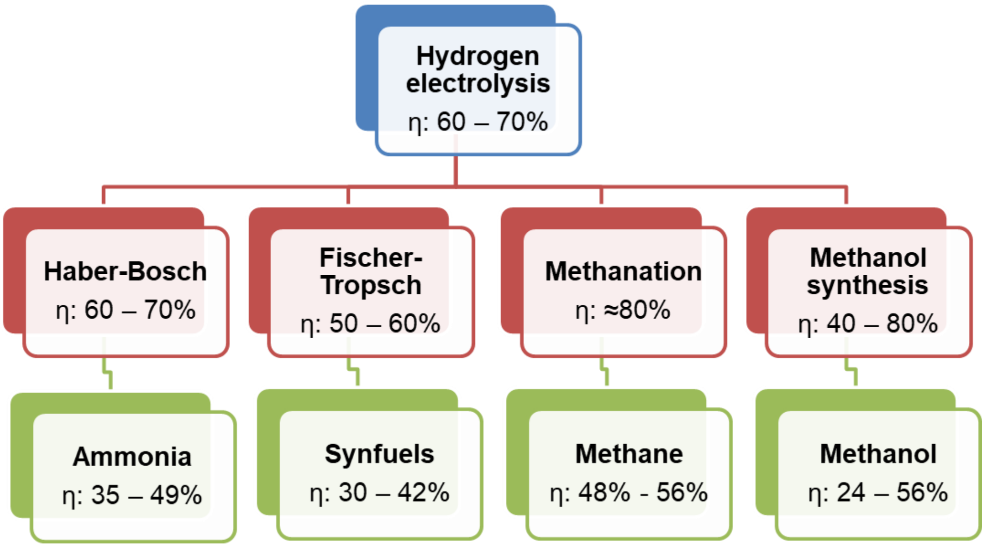


Figure 9 Conversion efficiency of electrolytic hydrogen to other fuels.

5.5. Biofuels

Biofuels consist of a group of liquid fuels derived from biomass. Having similar characteristics as their fossil-fuel based counterparts, biofuels could relatively easy replace existing fuels in shipping with limited modifications to the existing fuel infrastructure. Another advantage of producing biofuels for the marine sector is that the fuel can be of lower quality than e.g. for aviation or road transport. Thus, eliminating the need for secondary refining, resulting in lower processing costs (IEA Bioenergy, 2017). Biofuels are not (yet) abundantly used in the maritime sector, but with strong policies in place, that could change.

Biofuels are typically categorized into three main groups, which are the follows:

Traditional biofuels are a group of biofuels produced from agricultural crops and the only group that have reached technological maturity and are commercially available. The two main types of biofuels are ethanol and biodiesel. Ethanol is produced by fermenting sugar or starch from products such as sugarcane, maize or wheat. It is predominantly used for blending with petrol. First generation biodiesel (also known as Fatty Acid Methyl Ester, or FAME) is produced by esterifying vegetable and/or animal oils, fats or greases. The feedstocks used for producing FAME are generally costly, and availability are also limited due to competition from food, pharmaceutical and cosmetics industries. Due to the high demand from other sectors, it would be economically unrealistic to produce large volumes of biodiesel as a low-quality marine fuel (IEA Bioenergy, 2017). New technologies and processes are therefore being developed to produce so-called second-generation biofuels, or also called

Advanced biofuels, which are pre-commercial technologies using non-food crops, agricultural and forest residues as their feedstock. Hydrotreated vegetable oil, or HVO, also commonly referred to as renewable diesel is one of the first commercial advanced biofuel. Many other advanced biofuels are also under development, including cellulosic ethanol, biomethanol, DMF, Bio-DME, F-T diesel, mixed alcohols and wood diesel (IEA Bioenergy, 2016).

Synthetic biofuels, consist of a groups of synthetically produced liquid fuels originating from gases, made by thermal gasification of biomass and Fischer-Tropsch (i.e. Biomass to Liquids, often shortened BtL).

5.5.1. Biomethane

Global biomethane production still represents a very small share of the total biofuel market (less than 1%). However, production and refining of biogas to produce biomethane, which is injected into gas pipelines and used as a heating or transport fuel is rapidly growing, mainly in Europe and North America.

Like liquid biofuels, biomethane can be made from different types of feedstocks by means of different conversion technologies, and the feedstock used will largely define how sustainable the produced biomethane will be. As shown in Figure 10, there are two main conversion routes for production of biomethane: anaerobic digestion and gasification. Independent of the conversion route, biomethane has to be liquefied to obtain liquid biomethane (LBM). Ships that are already utilizing LNG as fuel could easily switch to using LBM without major changes to the vessel. Like liquid biofuels, production of biomethane are facing similar challenges, i.e. costly production and availability of sustainable feedstock.

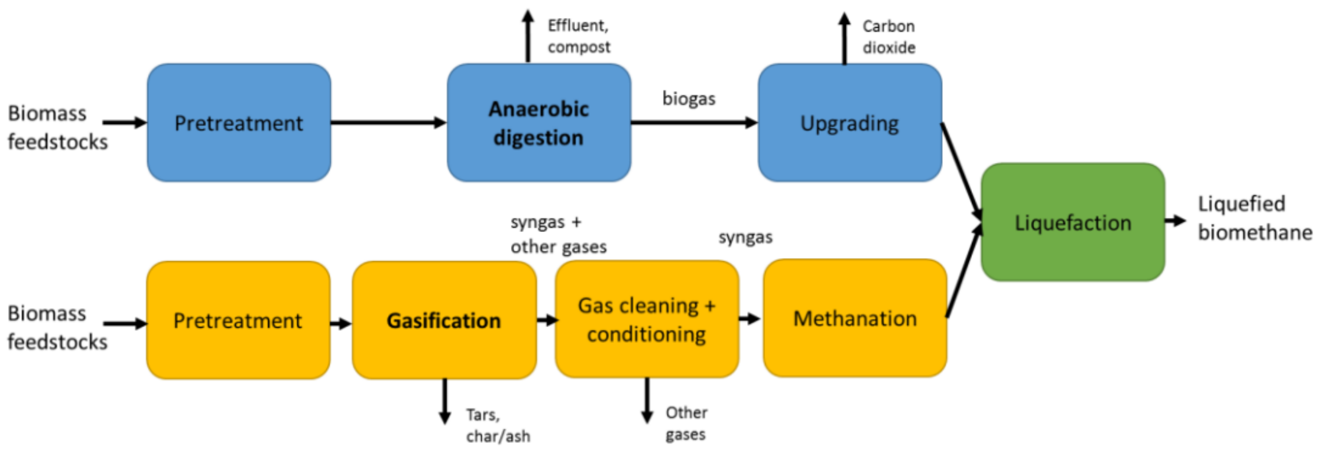


Figure 10 The two main conversion routes for production of liquid biomethane (Nelissen, et al., 2020).

5.5.2. Drop-in biofuels

Customizing a marine engine for a new fuel is generally an expensive conversion, but also switching to a different fuel represents a risk for the shipowner if the fuel supply is not guaranteed for the lifetime of the ship. If a new fuel could be made to have similar characteristics to those already in place, the need for extensive investments in both ship conversions and infrastructure modifications could be avoided.

A drop-in biofuel is by definition, a liquid hydrocarbon that must fulfil the same bulk property requirements as their fossil fuel counterparts to be fully compatible with the existing infrastructure. Chemically, they should also have similar characteristics, meaning a high carbon and hydrogen content by mass, and a very low oxygen content. Especially oxygen and its functional groups are highly undesired in drop-in biofuels. Not only because they are detriment of storability/stability, but oxygen also reduces the fuel's energy density. For ships particularly, where space is limited, this can be a deal-breaker if the tank capacity must be significantly increased to reach the same travel range as with fossil fuels at the expense of reduction in other valuable areas, such as cargo space, passenger cabins, etc.

Deoxygenation, i.e. removing the undesired oxygen from biofuel feedstock can be done in two ways: 1) sacrificing feedstock by oxidizing the carbon or 2) saturating the compound by adding hydrogen. The second option is usually the preferred choice not to lose yield. Consequently, the origins of hydrogen will play an important role in any future expansion of drop-in biofuel production, whether fossil or renewable derived will have a big impact on the lifecycle emissions of the finished fuels. The requirement of deoxygenation also varies depending on the feedstock used, where sugars and lignocellulosic biomass generally are highly oxygenated and have a poor H:C-ratio compared to e.g. lipids (van Dyk, et al., 2019).

Drop-in marine biofuels are yet quite scarce in the shipping fuel market, and of the commercially available biofuels, i.e. bioethanol, biodiesel (FAME) and renewable diesel (HVO), only HVO can be considered as a true drop-in biofuel. Other drop-in biofuels are also emerging, e.g. a drop-in HFO-equivalent marine biofuel from GoodFuels Marine (Goodfuels, 2018).

5.5.3. Biofuel feedstock & production processes

Biofuels have the advantage that they can be produced from a wide range of feedstocks (Figure 11). However, assessment of biofuel feedstocks is not as straightforward, as they are part of a highly complex and integrated system of forestry and agriculture with a number of interconnected markets and mechanisms.

Studies estimate an upper limit of 45 Mt 1st generation biodiesel can be derived from plant oils and animal fats, i.e. based on current crops and agricultural land. Adding the contributions from used cooking oil and tall-oil derived diesel lifts the potential production capacity up to 54 Mt, which is almost double the capacity currently produced (IEA Bioenergy, 2017). To date, the only commercial pathway producing drop-in biofuels are from lipid feedstocks. The reason this pathway has pioneered is that fats are relatively easy to convert to a finished fuel, due to the feedstock's already low oxygen content and relatively high hydrogen-to-carbon ratio.

From a strategic point of view, biofuels (including both liquid and gas) derived from lignocellulosic feedstocks show most potential to increase the biofuel production volumes significantly. It is estimated that current residues from agriculture and forestry is between 3.3 – 6 Gt. Assuming 50% could be used for biofuel production, and a yield of 250 kg fuel/ton of biomass, the existing feedstock could provide 400 – 750 Mt of biofuel. However, the existing lignocellulosic biomass is currently not used as feedstock for biofuel production, but rather entirely used for heat and power production. However, in the medium to long-term, the use of biomass is expected to decrease due to growth of other renewable energy sources (IEA Bioenergy, 2017). Another feedstock found in literature for biofuel production is aquatic biomass, such as algae. While they have a theoretical very high yield, they are not on a technological level to enable long-term projections of supply potential. Table 1 summarize the potential biofuel production, including existing bioethanol production volumes.

While lignocellulosic biomass show good potential to increase biofuel production volumes, the feedstock is generally more complex to convert to biofuels than e.g. from lipids. Converting lignocellulosic biomass to biofuel follows the thermochemical pathway, where the biomass is reacted at elevated temperatures (>500°C) to form carbonaceous liquids and gases, as well as solid chars. The two main routes are gasification and liquefaction, where the former converts biomass to a gaseous intermediate, known as syngas, and the latter maximizes the production of liquid intermediates, also known as pyrolysis oils, bio-oil or biocrudes. The gaseous and liquid intermediates require further processing and upgrades to produce a final fuel or blendstocks. However, the commercialization of these technologies has been slow. Ongoing attempts to commercialise the technologies has proven problematic due to several reasons such as high initial investment costs, syngas clean-up, and catalyst challenges when upgrading biocrudes/bio-oils into finished fuels (van Dyk, et al., 2019).

Table 1 Comparison of fuel consumption in the maritime sector with current and potential biofuel production based on current crops and feedstocks (IEA Bioenergy, 2017).

Consumption / potentials	Mt oil equivalent
Maritime fuel consumption	330
Biodiesel production 2019	30
Biodiesel potential from existing feedstocks	50 - 55
Bioethanol production 2019	60
Lignocellulosic potential from existing feedstocks	455 - 805

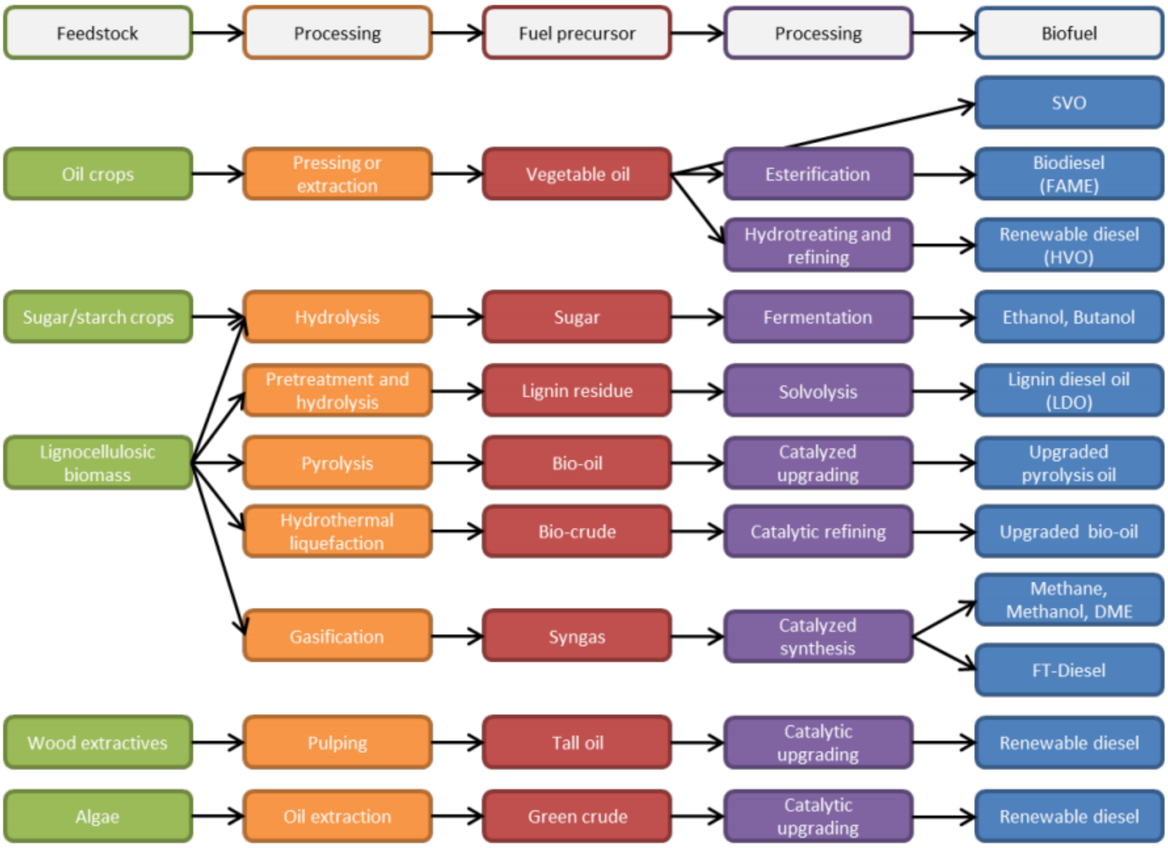


Figure 11 Overview of different feedstock conversion routes to biofuel, including both conventional and advanced biofuels (IEA Bioenergy, 2017).

5.5.4. Biofuel GHG impact

Biofuels present as a good option for reducing the overall GHG emissions in shipping. Highest emission reduction can be achieved when waste and residues are used as feedstocks for biofuel production. Traditional biofuels, such as biodiesel derived from crops grown explicitly for biofuel production on the other hand result in higher GHG emission due to direct and indirect land use change during the feedstock production process. The lifecycle GHG emissions, i.e. well-to-propeller for fossil fuels, and field-to-propeller for commercial biofuels, are listed in Table 2.

Table 2 GHG impact of various biofuels compared to fossil fuels (IEA Bioenergy, 2017).

Fuel	Carbon content (%)	CO_2 emission on combustion (g/MJ)	Life cycle GHG equivalent (g/MJ)
HFO	86	69-76	77-87
MDO	86	71-74	74
Diesel	86	72-74	87
Gasoline	87	67-73	81
Propane	82	60-65	
Natural gas	75	50	63
Bioethanol (1st gen)	52	72-81	34
Bioethanol (2nd gen)	52	72-81	24
FAME	77	75	75-111
HVO	77	75	8-25

6. The problematic fuel infrastructure

The well-established shipping operational procedures make customizing the marine sector a costly process. Many of the proposed alternative fuels currently does not have an existing fuelling infrastructure in place. Some fuels could benefit for an easier up-scaling where there is already a well-developed distribution of the chemical for bulk transportation existing. Such fuels are e.g. methanol and ammonia. Biofuels, and particularly drop-in biofuels could on the other hand take advantage of the existing infrastructure, while also avoiding expensive investments in modifying the marine engines to utilize the fuels. The developing LNG infrastructure also offer a good foundation for switching to or mixing with liquid bio or synthetic methane in the future.

Gaseous fuels generally are more complicated to store and transport in large volumes, which consequently is noticed in the fuel price for the end-user. In Scandinavia for instance, up to three quarters of the price of LNG delivered to a ship is made up of supply chain costs, i.e. in relation to the Central European gas market price. As supply volumes increase, however, the supply chain costs will also slowly decline.

Hydrogen would need a purpose-built infrastructure as fuel, which currently is virtually non-existing. Blending hydrogen to the existing natural gas grid is possible, however, a switch to 100% hydrogen later would still require upgrading appliances and piping. A hydrogen fuelling infrastructure is the most expensive as well, and will require “substantial but achievable investment” according FCH JU. During the scale-up towards 2030, an annual investment of 8 billion euro is estimated in the ambitious scenario (Fuel Cells and Hydrogen Joint Undertaking, 2019). With such ambitious investments, the projections for a hydrogen-based fuel infrastructure for shipping could be available before 2040, or in a “business as usual” scenario by 2050 (Figure 12). Still, hydrogen is likely to depend on substantial carbon taxes to be cost competitive with cheap fossil fuels. Even at a hydrogen price as low as $1/kg, a carbon price of approx. $145/tCO2 in shipping would be needed in 2050 according to BloombergNEF (Figure 13).

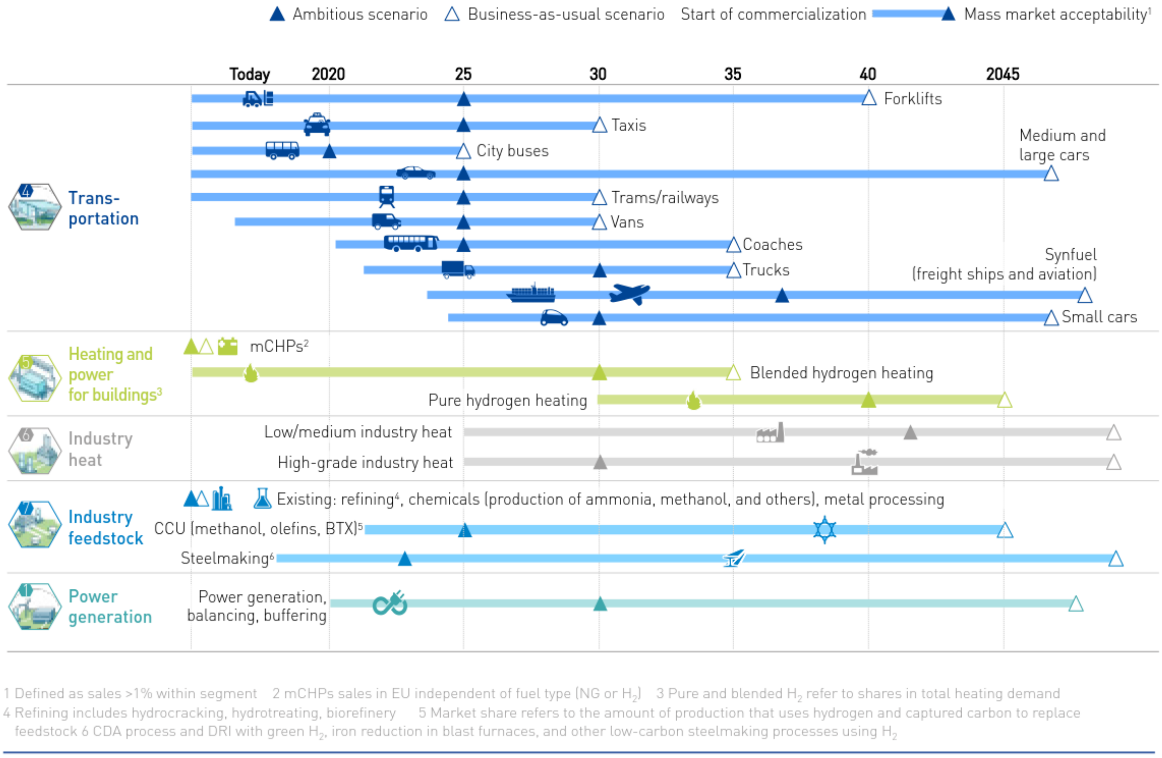
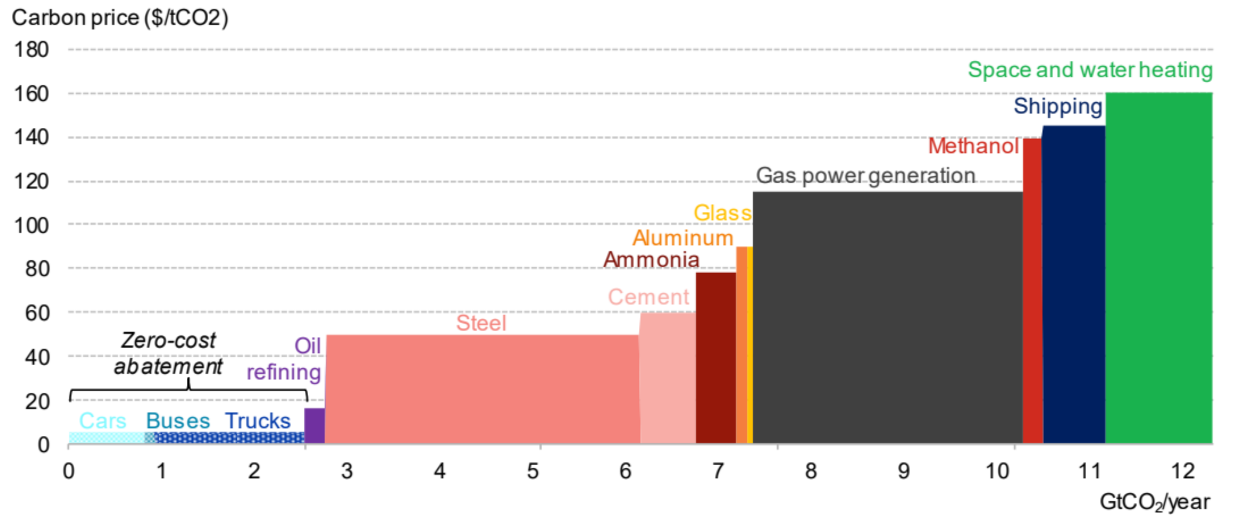


Figure 12 Roadmap for deployment of hydrogen technology (Fuel Cells and Hydrogen Joint Undertaking, 2019).



Source: BloombergNEF. Note: sectoral emissions based on 2018 figures, abatement costs for renewable hydrogen delivered at $1/kg to large users, $4/kg to road vehicles. Aluminum emissions for alumina production and aluminum recycling only. Cement emissions for process heat only. Refinery emissions from hydrogen production only. Road transport and heating demand emissions are for the segment that is unlikely to be met by electrification only, assumed to be 50% of space and water heating, 25% of light-duty vehicles, 50% of medium-duty trucks, 30% of buses and 75% of heavy-duty trucks.

Figure 13 A carbon price is needed to make hydrogen even at $1/kg competitive with cheap fossil fuels (BloombergNEF, 2020).

7. Other emission reduction methods

The average lifetime of a ship is 30 years, and it is well known that current world fleet is relatively old. A large dominance of ships older than 15 years are found in the small category (71.8%), for medium-sized ships the spread is more even (55.6% over 15 years old). For the large and very large ship categories, the trend is reversed; 79.5% and 81% respectively, are less than 15 years old (Figure 14).

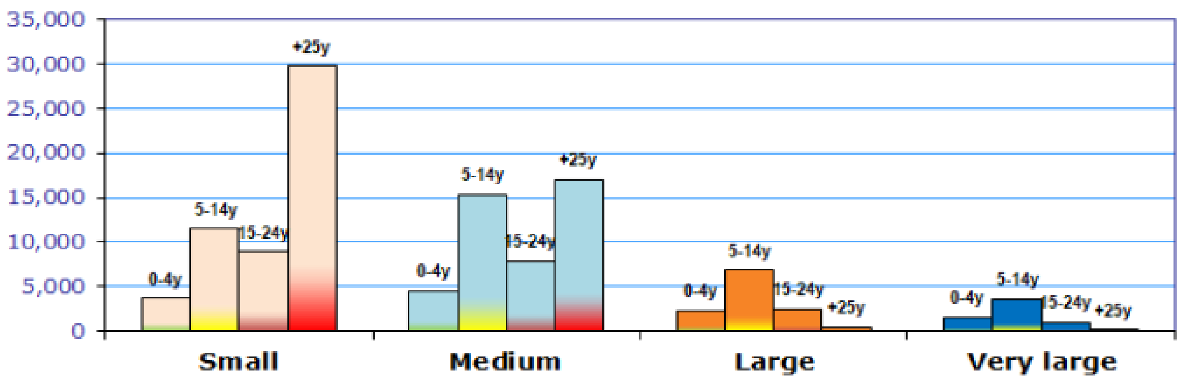


Figure 14 Total number of ships, by age and size in 2018. (Small: GT<500, Medium: 500 ≤GT<25 000, Large: 25 000 ≤GT<60 000, Very Large: GT≥ 60 000) (Equasis, 2019).

Reducing the emissions will therefore also naturally occur by replacing the aging fleet with new energy efficient vessels, but over a very long period of time. Retrofit solutions could aid to improve the existing vessels' energy efficiency, but there are some constraints. Typically, the payback periods of retrofit investments tend to be considerably long, which make it difficult to get the shipowners and ship operators interested. Several studies have tried to quantify the cumulative emission reduction potential of different technical and operational measures, but the results often tend to be too optimistic due to generalisation. Indicative emission reduction potential of different technical and operational measures are shown in Figure 15. Due to variations in ship size, type and operations means the given numbers can not necessarily be considered cumulative due to technical incompatibilities.

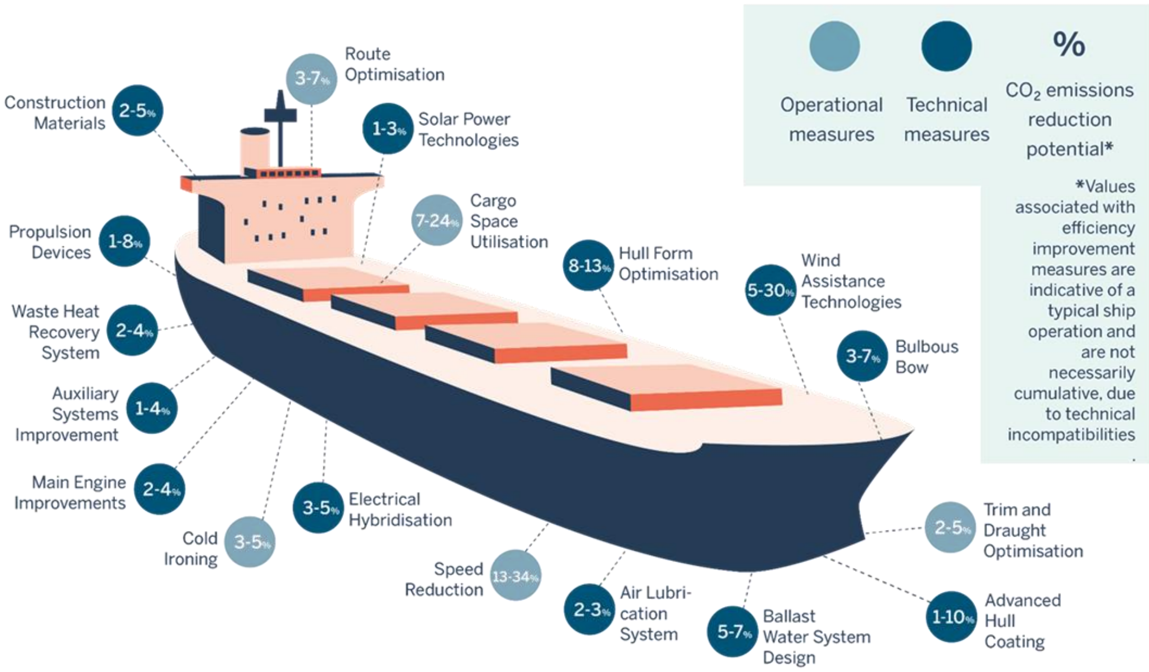


Figure 15 Indicative emission reduction potential of various operational, and technical measures (photo courtesy: UMAS: www.u-mas.co.uk).

7.1. Wind propulsion

Text written by: Ville Paakkari, Norsepower

Wind propulsion and sailing have a long history in shipping and recent years have shown increasing interest towards utilizing wind also in modern commercial shipping. In contrast to other fossil-free technologies described before, wind propulsion technologies utilize the renewable energy of wind directly. This results in some distinct features of wind propulsion. First, the energy source is free and hence the only running costs come from maintenance. This reduces the dependence on market price of fuel so wind propulsion may increase profitability, if alternative fuels (which are typically more expensive) are adopted. Secondly, as the energy is not stored anywhere, wind propulsion must be coupled with other means of propulsion to maintain schedules and ensure smooth operation also when there is no wind. Finally, the overall "well-to-wake" efficiency of direct wind propulsion is typically much higher than in case of using the wind in electricity production, which is used to produce the fuel, which is again used to propel the ship (Figure 16).

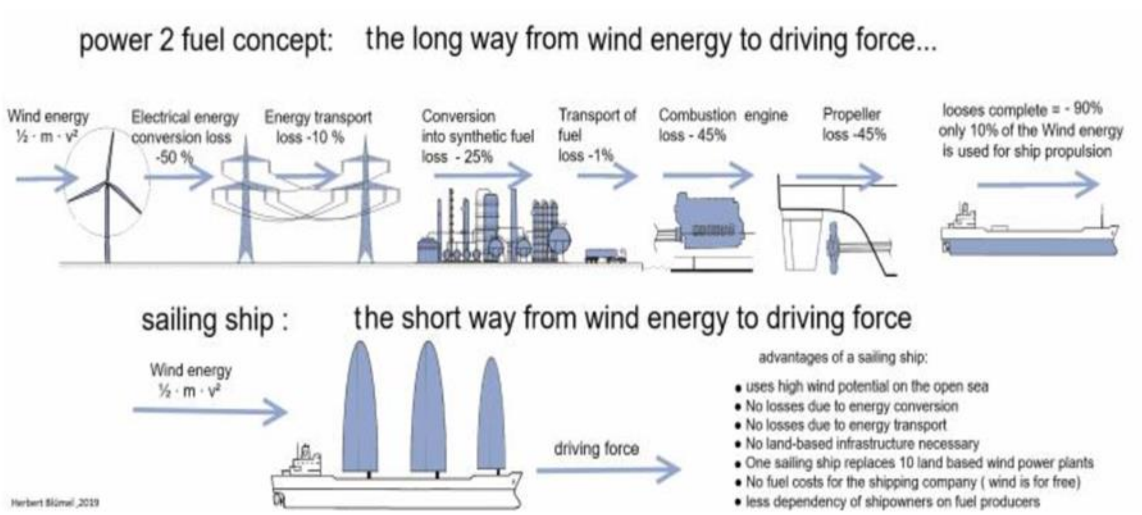


Figure 16 Comparison of wind energy use (IMO MEPC 75/INF.26, 2020).

Today's sail technologies are Flettner rotors, kites and different types of wing sails. To date, various projects (mainly retrofits) with sails have been completed, with the most utilization of Flettner rotors. Publicly available reports of these projects indicate savings such as 6.1% fuel saving on a roro with two small Flettner rotors, 8.2% annual average savings on LR2 tanker with two large Flettner rotors and approximately 20% savings with a relatively large Flettner rotor on a small general cargo vessel (IMO MEPC 75/INF.26, 2020).

7.2. Batteries & shore connection

Batteries and hybrid solutions in shipping are emerging. While still being expensive, battery cost is expected to fall. Bloomberg New Energy Finance estimated lithium-ion battery cost to fall below $100/kWh by 2024 (BloombergNEF, 2019). Regardless of the price, batteries' energy density and weight are still a concern, and are therefore unlikely to be suitable for applications with long autonomy requirements. Short distance applications (e.g. ferries) and hybrid solutions for dynamic operations (e.g. offshore vessels) may, however, provide sufficient fuel savings to make the investment worthwhile.

Shore connection, or recharging of the batteries while in port may offer GHG emission reduction. However, using land based energy may not always be the most ecological alternative (Figure 17).

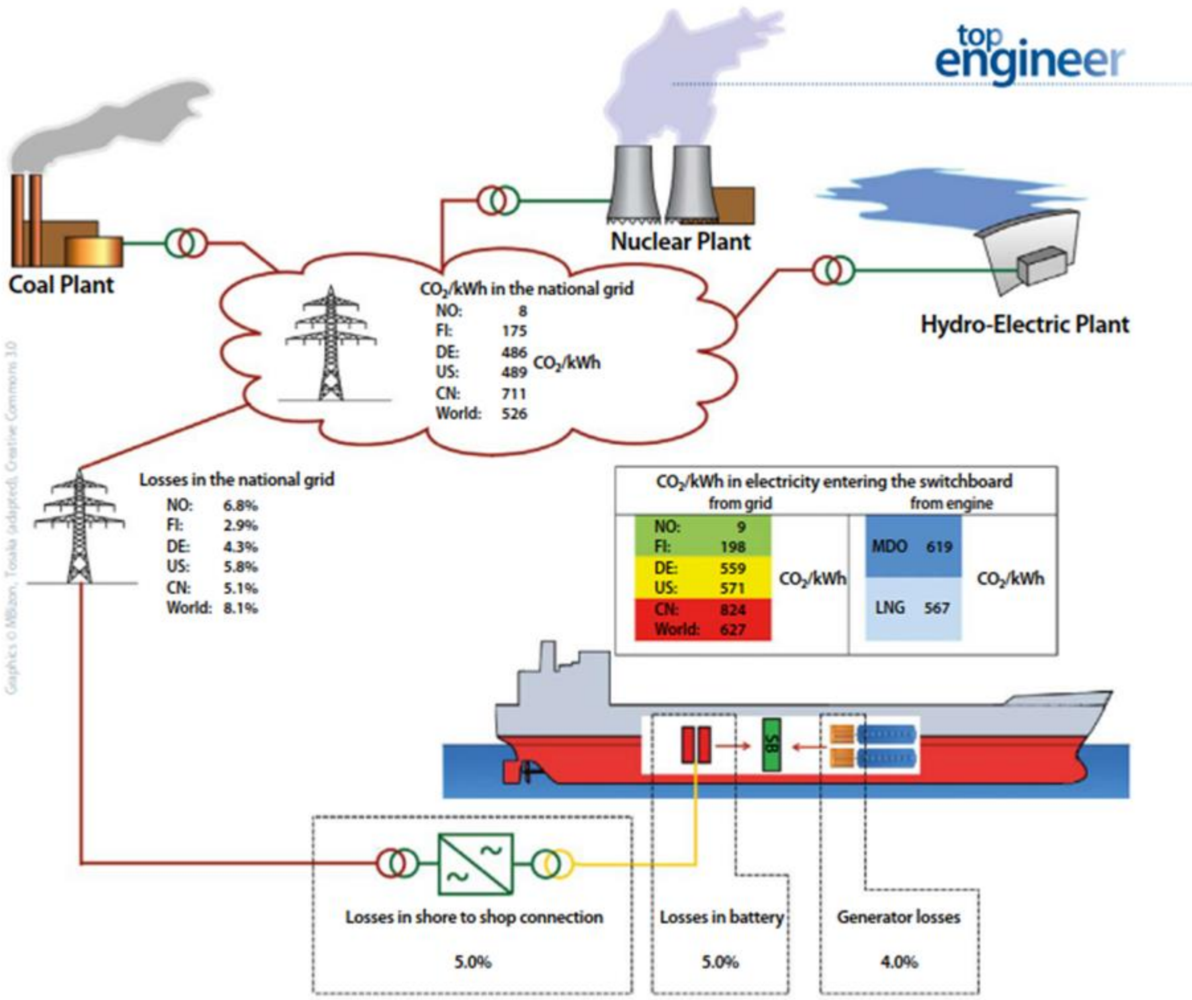


Figure 17 Shore connection may not always offer environmental benefits.

7.3. Fuel cells

Fuel cells have, similar to hydrogen experienced a hype cycle before, but commercialization has thus far remained low. However, with increasing pressure on emissions from road transport, and evidence that pollution in cities killing many more people than previously thought, this might change soon. The growth in interest in hydrogen continues worldwide, which can also help the fuel cell industry to gain momentum. Fuel cells in maritime sector is also advancing, with smaller fuel cell vessels already proven and other maritime projects emerging. Still, fuel cells are facing a chicken-and-egg dilemma – the non-existing infrastructure of suitable fuels. Other issues, more specifically for the maritime industry are also the short expected lifetime of the fuel cells, low power density of certain fuel cell technologies, and fuel cell costs that needs to be solved before fuel cells can become a competitive alternative to the currently used internal combustion engine.

The FCH JU (Fuel Cell and Hydrogen Joint Undertaking) a public private partnership supporting research, technological development and demonstration activities in fuel cell and hydrogen energy technologies in Europe, called for 24 new project proposals in 2020 for a total budget of 93 M€. Among the new project proposals is a demonstration project to develop a maritime power system operating on liquid hydrogen

(FCH 2 JU, 2020). According to Bloomberg, the fuel cell industry is also the most expensive sector to scale up and would require about $105 billion in subsidies to 2030 (BloombergNEF, 2020).

8. Conclusions and recommendations

- **Maritime fuelling infrastructure and operational procedures are already well-established.** However, this also poses some challenges for deployment of alternative fuels as few of them are directly compatible with the existing infrastructure. Building an additional infrastructure for alternative fuels is neither an attractive option, as the time and investments required would be enormous. The marine sector should strive for finding solutions to avoid major investments in both existing infrastructure and thus avoid expensive conversions of marine diesel engines.
- **Short to mid-term focus should be on deployment of advanced biofuels.** Particularly advanced biofuels derived from lignocellulosic biomass, as the existing feedstock volumes are estimated to be sufficient to produce biofuel to fully replace fossil fuels in shipping in long-term. Yet so far, their production is only at a limited scale, and more research is still needed in the conversion technologies and upgrade methods before commercialization is possible. Another aspect is the competition for the feedstocks with other sectors, especially the heat and power sector, which however is expected to decrease its use of biomass in near- to medium-term as the growth of renewable sources increase. For deployment of a large-scale introduction of biofuels requires joint forces between engine manufacturers, biofuel suppliers, ship owners and infrastructure (i.e. port) operators.
- **Involvement of other sectors to increase biofuel production.** As commercial biofuel production takes off, it is possible that the feedstocks for marine biofuel production will compete with other liquid transportation fuels, especially for aviation. It would therefore be advantageous to produce both aviation and marine fuels simultaneously, as aviation could use the higher quality fractions, and the potentially “cheaper” residues could be used for bunker fuel.
- **Policies and carbon taxes are unavoidable.** All alternative fossil-free fuels, regardless if they are derived from biomass or produced from cheap renewable energy sources, have a significant cost disadvantage compared to fossil fuels, and will most likely remain so for the foreseeable future. Policy support will therefore be needed to enable these fuels to mature, and a substantial carbon cost applied to fossil fuels is likely unavoidable.
- **Renewable hydrogen and power-to-x fuels can offer feasible solutions in long-term.** Hydrogen’s role will be modest in the coming decades, and further cost reductions and efficiency increase in electrolysers are still required, let alone one the enormous investments needed to build a hydrogen infrastructure. Sustainably-produced hydrogen in the future will also be highly dependent on the availability of cheap renewable energy. Regardless, hydrogen’s poor energy density will still limits its use to niche applications. For deep-sea shipping the conversion of renewable hydrogen to a synthetic hydrocarbon fuel is a more viable option. While, the conversion efficiency is poor, and a sustainable source of CO_2 is vital, introducing a synthetically produced fuel with similar characteristics as the current used fossil fuels is a much more straightforward process.
- **Different methods to improve the energy efficiency of ships are available already today, and these methods can, and should be further improved**. It is very likely that sustainable bunker fuels will be scarce in the coming years that shipping will have to rely on fossil fuels for a while, even partially in the foreseeable future. Therefore, focus should be on encouraging shipowners to invest in technologies and solutions to improve the ships’ energy efficiency. Deployment of energy efficient solutions to cut emissions and meet the future regulations in newbuild projects are generally “easier” to implement, but by no means self-evident. Retrofit solutions are more tricky, and how to overcome the often long payback periods of the investments to get shipowners and ship operators interested needs to be solved.

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