Study on methods and considerations for the determination of greenhouse gas emission reduction targets for international shipping

Final report

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Study on methods and considerations for the determination of greenhouse gas emission reduction targets for international shipping

Final Report: Technology Pathways

CE Delft
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Content

Executive summary

The Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) has adopted the Initial IMO Strategy on reduction of greenhouse gas (GHG) emissions from ships which envisages to 'reduc[e] GHG emissions from international shipping and (…) phase them out as soon as possible in this century'. It also expresses the ambition to:

- reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030 compared to 2008; and
- 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.

The Initial Strategy recognises that in order to meet the 2050 Level of Ambition, the global introduction of alternative fuels and/or energy sources will be required.

Within the context of the Initial Strategy, this report explores technology pathways to meet the 2050 Level of Ambition and the Strategy's vision and identified associated research and development needs.

Pathways to phase-out greenhouse gas emissions from shipping

In order to meet the 2050 level of ambition of the Initial IMO GHG Strategy and fulfil its vision, the shipping sector has to transform swiftly from relying on fossil fuels to using sustainable low- and zero carbon fuels.

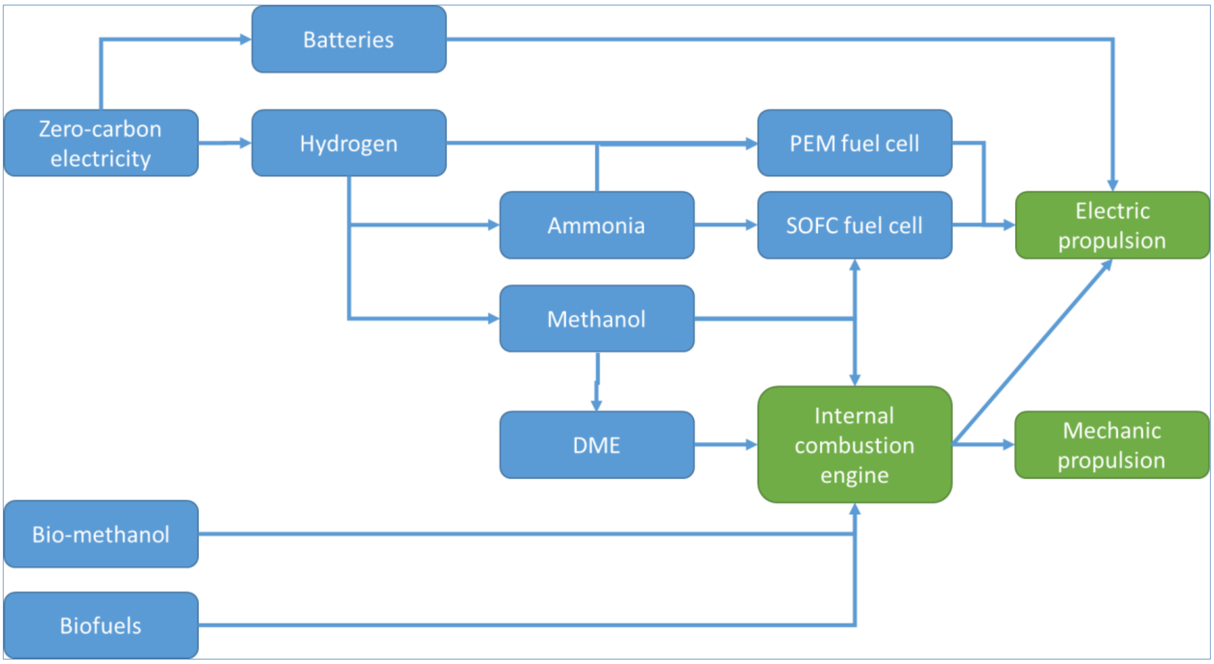
There are essentially three ways in which these fuels can be produced (Figure 1). One is by using renewable electricity either directly or in a electrochemical process to generate fuel; another by having plants convert solar energy into a biological fuel precursor; and a third one to produce hydrogen by reforming methane or other hydrocarbons and store the CO_2 underground.

Renewable electricity can be either stored in a battery on-board or converted into chemical energy, in particular by electrolysing water to produce hydrogen. This hydrogen can be stored on board or converted into ammonia, methanol or other fuels. Of these, we consider ammonia and methanol to be the most plausible because they are the most advanced technically. The sustainable biofuels with the largest potential for scaling up to the extent needed to fuel a sizeable portion of the world fleet are biomethanol and algae-based fuels.

The fuels can either be used in an internal combustion engine or in a fuel cell. The internal combustion engine is most suitable for methanol (of biological origin or not) and liquid biofuels, but in principle ammonia and hydrogen can also be used in internal combustion engines. For fuel cells, the reverse is true: they are best suited – and most advanced from a technical perspective – for hydrogen and to a lesser extent for ammonia, but could in principle also be used to generate electricity from methanol and other fuels.

As shown in Figure 1, an internal combustion engine could either drive the shaft directly, or generate power which is used in a diesel-electric system. The electricity for such a system can also be generated in fuel cells.

Figure 1 - Stylised overview of fuel-technology pathways



Note: PEM - proton exchange membrane; SOFC – solid oxide fuel cell; DME – dimethyl ether.

The global technical production capacity will probably not be a constraint for any of these fuels, with the exception of hydrogen produced by steam-reforming fossil hydrocarbons in combination with carbon capture and storage. For these fuels carbon storage capacity may be a constraint. Most of these fuels have a similar level of technical development, i.e. the technical feasibility has been proven, but often not at a scale that is relevant for the maritime sector nor in a maritime environment. Moreover, the integration of the technologies is only starting to occur in some pilot projects.

So whilst it is clear that the shipping sector in, say, 2050 will be very different from the shipping sector today, there is uncertainty about the route that will be taken as there are many fuel/technology combinations that could become important over time, and given the uncertainty about which will prove to be most competitive in this timescale.

With a few exceptions, the sector currently relies on internal combustion engines running on petroleum-derived fuels. This propulsion technology could continue to be the case in the future if biofuels, e-methanol or ammonia will be used as fuels. Biofuels and methanol can be used without or with relatively modest changes to the fuel systems and engines, even for existing ships. One technological pathway could then be that these fuels are used in internal combustion engines of both new and retrofitted ships, potentially in a dual-fuel setup while the global production and bunkering industry is expanding. Using ammonia in internal combustion engines requires more modifications as well as modifications of fuel tanks and systems, as well as technologies to limit the emissions of NO_x and ammonia.

In order to support this pathway, research should focus on the production of sustainable biofuels, e-methanol and ammonia, as well as on the integration of fuel systems for ammonia.

Another pathway would be a switch from internal combustion engines to fuel cells as the primary way to convert energy on-board ships. This would be compatible with the use of hydrogen, ammonia and methanol as fuels, although biofuels can also be used in certain types of fuel cells.

In order to support this pathway, research should focus on the production of sustainable hydrogen and ammonia, on the further development of fuel cells, on the fuel systems that can handle either compressed or liquefied hydrogen, as well as on the integration of fuel systems for ammonia and possibly other fuels.

Neither of the two pathways described above is clearly preferable. The former has the advantage that it is closer to the current technology, but it may rely considerably on biofuels of which the production potential appears to be smaller than for electrofuels and which may have a higher risk of being unsustainable. The latter can use electrofuels which appear to be able to produce in abundant quantities, however they require more technical development.

With a view to the limited amount of time available to transform the industry, the best policy could be to support the development of technologies for both pathways.

1. Introduction

Policy background

The Paris Agreement of the UNFCCC aims to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C. To that end, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible and to undertake rapid reductions thereafter. In the second half of the century, the net emissions of greenhouse gases should become zero.

The Paris Agreement does not set specific targets for countries or sectors, but relies on 'nationally determined contributions' (NDCs). International shipping emissions are generally not covered by NDCs (and neither are the emissions of international aviation) but given their share in the total emissions and their projected increase, they risk increasing the costs of reaching the Paris Agreement goals if unabated or even put reaching the temperature goal at risk.

In April 2018, the MEPC adopted the Initial IMO Strategy on reduction of GHG emissions from ships (Resolution MEPC.304(72)). It aims to 'reduc[e] GHG emissions from international shipping and (…) phase them out as soon as possible in this century'. It also sets three Levels of Ambition:

- 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;
- 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
- 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.

The Initial Strategy also includes a list of candidate short-, mid- and long-term measures, defined respectively as measures that will be agreed by the MEPC before 2023, between 2023 and 2030, and after 2030. Given these timelines, the level of ambition for 2030 will have to be achieved by short- and possibly also mid-term measures.

Climate scientists have developed the concept of a carbon budget, which indicates the amount of anthropogenic CO_2 emissions that will result in a certain global average temperature increase. The most recent estimate indicates that the budget to limit the global average temperature increase to 1.5°C is about 420–570 Gt of CO_2 which can be emitted from 2018[1]; if an additional 50% of that amount of CO_2 is emitted, the global average temperature increase will reach 2°C.

[1] These estimates result in a 66% probability of keeping the temperature increase to 1.5°C; the first estimate relates to the global mean surface *air* temperature, the second to the global mean surface temperature. IPCC 2018, summary for policymakers C1.3.

There is no scientific way to divide the remaining carbon budget over countries or sectors. One way to do so is to start from the current share in annual emissions and allocate proportional shares of the carbon budget to sectors or countries.

In order for the shipping emissions to be reduced in a way that is consistent with the Paris Agreement temperature goals, as called for in the Initial Strategy, it is necessary to estimate how the emissions will develop, and what the impact of short-term measures will be on emissions up to 2030.

1.1. Aims and scope of the study

This report aims to support informed decision making related to the implementation of the initial IMO GHG strategy on GHG emissions from ships. Against the policy background described in the preceding chapter, this report aims to calculate the carbon budget for shipping as well as the share that will remain after implementation of the short-term measures. It also lays out technological pathways towards decarbonisation and identify areas in which further research would be needed in order to phase out emissions completely.

An accompanying report identifies and designs short-term measures that can reduce emissions in the short-term. It estimates their impact on 2030 emissions and the 2030 level of ambition in the Initial Strategy.

Specifically, the research questions of this report are:

- What is a proportionate climate budget for international shipping; and
- Which share of the budget will be left in 2030, taking into account the possible implementation of short-term measures?
- Which technological pathways can result in staying within the carbon budget as well as meeting the 2050 level of ambition?

The associated report answers the following questions:

- Which short-term measures have the ability to reduce GHG emissions from international shipping in the short term?
- What will their impact be on:
  - 2030 emissions; and
  - The 2030 level of ambition included in the initial strategy?

Following from the context provided in Section 1.1, this report focusses on measures included in the Initial IMO Strategy. Its scope is limited to CO_2 emissions, which account for over 98% of the GHG emissions of shipping, expressed in CO_2 equivalents (IMO, 2015).

1.2. Methodology

This study employs a diverse suite of methods and models. Chapter 3 is based on an extensive literature review. Chapter 4 has developed technology pathways on the basis of a combination of a literature review and stakeholder consultation.

1.3. Outline of the report

Chapter 3 presents estimates of the carbon budget for shipping. Chapter 4 develops technology pathways for decarbonisation of shipping. Chapter 5 summarises and concludes.

2. Shipping Carbon Budget

A range of shipping emissions to 2050 have been calculated according to the methodology described by Faber et al. (CE Delft , 2018). These assume a range of GDP assumptions taken from the so-called 'Shared Socioeconomic Pathways' (SSPs) (Riahi, et al., 2017) and GDP assumptions from the OECD (C.O'Neill, et al., 2017).

The projection of Faber et al. (CE Delft, 2017 and 2018) methodology is an update of that used for the IMO in the latest Greenhouse Gas Report (IMO, 2015) and uses historical transport activity data from Clarksons for 7 different ship types and regresses the ratio of transport work divided GDP as an economic predictor, or fossil fuel energy consumption for transport of oil, coal and gas over time with a non-linear growth model. The modelled ratio is then used to predict transport work for the various ship types against projections of GDP and energy usage. It was viewed that the SSP projections of GDP may be too optimistic (especially SSP1), so that a more recent view of GDP from OECD was used in addition.

From the transport work projections, emissions were then projected under a range of technology development assumptions, e.g. on the future development of ship sizes, fleet productivity, the impact of the EEDI and SEEMP and the impact of the Marpol Annex VI sulphur regulations.

The emission projections to 2050 under these assumptions are shown in Figure 2.

Figure 2 – Projections of shipping emissions to 2050

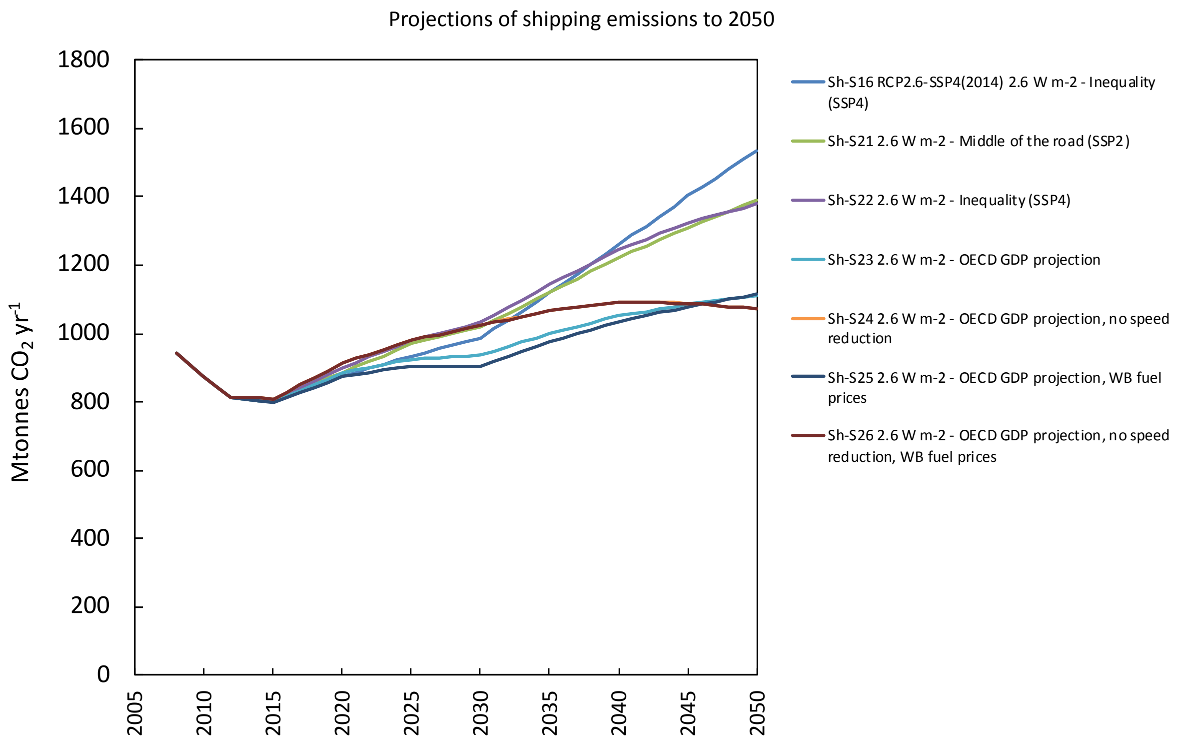


Figure 2 Projections of CO_2 emissions from shipping, 2008 – 2050. The nomenclature indicates the shipping scenario reference number (Sh-S*n*) and then the details of the scenario are given (the underlying RCP scenario W m^{-2} and the SSP scenario or OECD variant).

The cumulative emissions are given in Table 1. Two sets of global emissions scenarios are used for reference; the RCP 2.6 W m^{-2} scenarios that equate to a global mean surface temperature increase of less than 2°C by 2,100, and the more recently IPCC (2018) scenarios described by reference (2018) of 1.9 W m^{-2} that that equate to a global mean surface temperature increase of less than 1.5°C by 2,100. In each case, many emission scenarios have been formulated, but reference 'marker' scenarios as recommended by the originators have been used. The RCP 2.6 W m^{-2} scenarios are shown in Figure 2, and the 'SSPx 1.9 W m^{-2}' scenarios shown in Figure 3.

Table 1 – Cumulative emissions

Shipping scenario	Cumulative emissions 2010-2050 Gtonnes CO_2	Shipping scenario (1.5°C)	Cumulative emissions 2010 to zero emission date Gtonnes CO_2	Cumulative emissions remaining after 2030 to zero emission date Gtonnes CO_2	Shipping scenario (2°C)	Cumulative emissions 2010 to zero emission date Gtonnes CO_2	Cumulative emissions remaining after 2030 to zero emission date Gtonnes CO_2
Sh-S16	44.0	Sh-S30 P1	18.7	3.7	Sh-S35 SSP1	32.2	15.5
Sh-S21	43.4	Sh-S31 P2	18.3	3.7	Sh-S36 SSP2	31.7	14.0
Sh-S22	43.8	Sh-S32 P3	21.9	5.3	Sh-S34 SSP4	25.8	9.9
Sh-S23	39.3	Sh-S33 P4	26.3	8.6	Sh-S37 SSP5	37.3	19.0
Sh-S24	40.6						
Sh-S25	38.7						
Sh-S26	40.6						

Figure 2. RCP 2.6 W m^{-2} scenarios (all) of global CO_2 emissions from fossil fuel and land-use change shown in light blue, with the four marker scenarios for SSP1, SSP2, SSP4 and SSP5 shown in orange, green, blue and red lines (source Riahi, et al., 2017). Also shown are historical emissions of CO_2 from the same sources to 2016.

Figure 3 – Global emission pathways to limit warming to less than 2 degrees

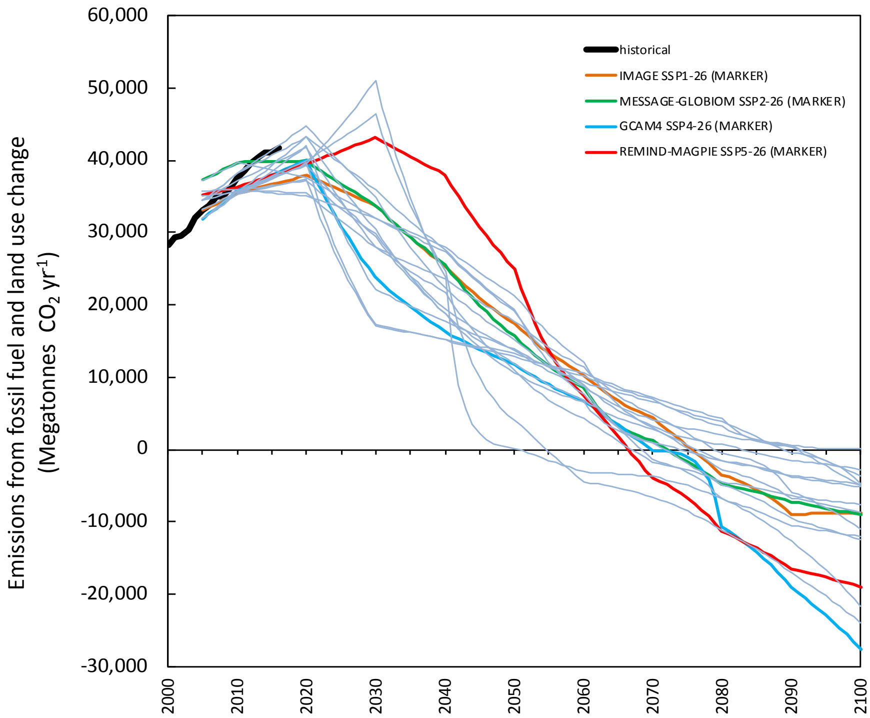
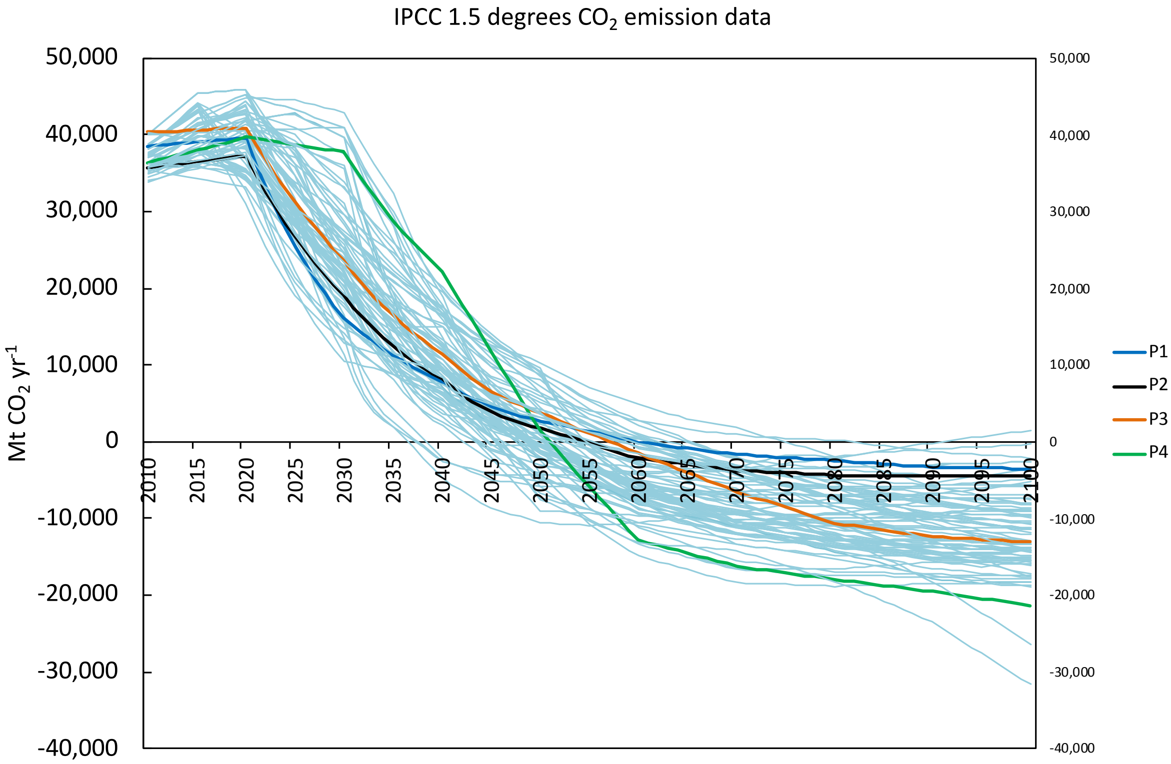


Figure 3. SSPx 1.9 W m^{-2} scenarios (all) of global CO_2 emissions from fossil fuel and land-use change shown in light blue, with four illustrative model pathways for P1, P2, P3 and P4 shown in blue, black, orange and green lines that limit global mean surface warming to 1.5°C by 2,100 over preindustrial temperatures. Data replotted from IIASA and originally shown as Figure SPM.3a in IPCC (2018).

Figure 4 - Global emission pathways to limit warming to 1.5 degrees

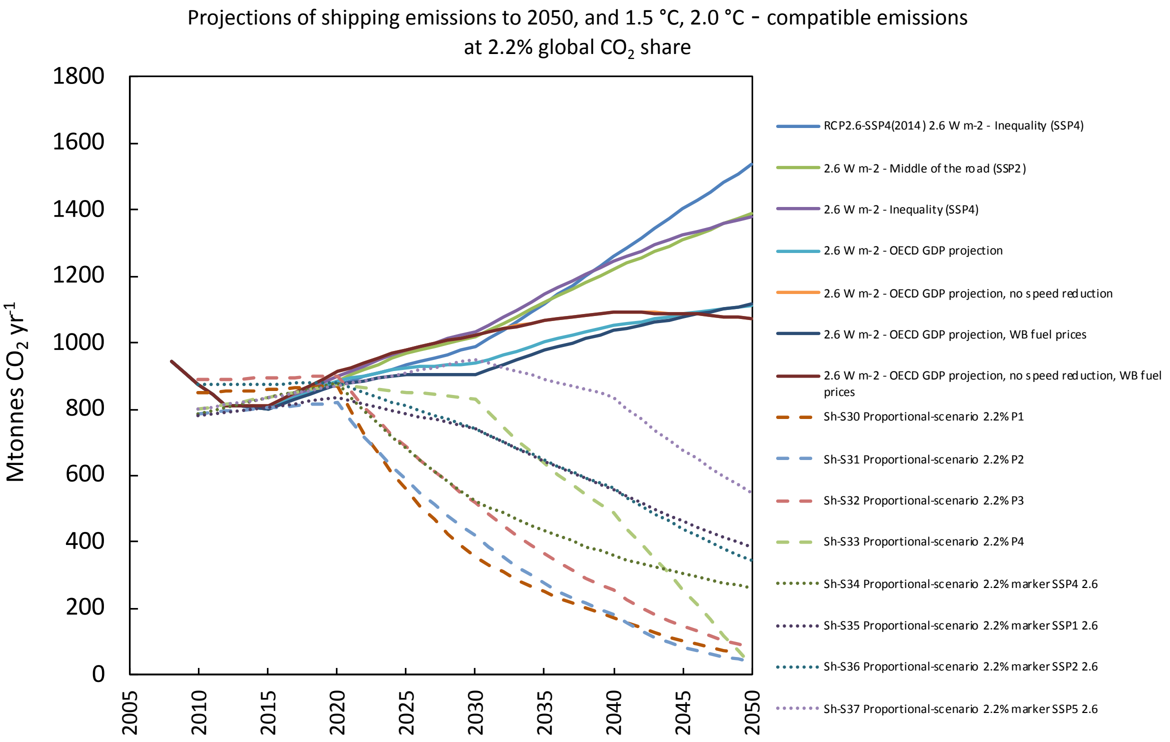


From Figure 2, in order to limit temperature increases to less than 2°C under the 2.6 W m^{-2} scenarios, it is clear that CO_2 emissions need to go to zero, and then negative by sometime in the second half of the 21st Century. However, to limit warming to around 1.5°C, shown in Figure 3, emissions reductions of CO_2 need to be made earlier, and reach zero around the middle of the 21st Century.

The shipping emissions shown in Figure 1 are incompatible with these global scenarios; in the case of the RCP 2.6 W m^{-2} scenarios (< 2°C), shipping CO_2 emissions are still increasing by 2050 when global emissions are required to fall sharply; in the case of the 1.9 W m^{-2} scenarios (~1.5°C), global emissions of CO_2 need to be around zero by 2050 as a median date (IPCC, 2018). If we make a simplistic top-down assumption that shipping, as a sector, can be the same percentage of global CO_2 emissions as they are today (i.e. ~2.2%), the prescribed shipping emission pathways with the RCP 2.6 W m^{-2} and SSPx 1.9 W m^{-2} scenarios can be defined. These are illustrated in Figure 4 as the dashed and dotted lines (2°C; 1.5°C compatible). The cumulative emissions required to meet these pathways are given in Table 1, from 2010 to the individual pathway's date at which emissions become zero or negative.

Figure 5 Shipping emission scenarios of CO_2 from Faber et al. (CE Delft , 2018) and further scenarios based on a 2.2% portion of total global CO_2 emissions available under RCP 2.6 W m^{-2} (dashed lines) and SSPx 1.9 W m^{-2} scenarios (dotted lines) to 2050.

Figure 5 – Projections of shipping emissions and shipping emission pathways



The analysis shows that a proportionate contribution of the shipping sector to reaching the temperature goal of the Paris Agreement requires immediate action to start reducing emissions. For a 2 degrees temperature increase, i.e. an increase that signatories to the Paris Agreement aim to stay well below, emissions need to peak before 2030 and be reduced to zero around 2070. For a 1.5 degrees temperature increase, i.e. an increase that signatories to the Paris Agreement aim to pursue efforts to reach, emissions need to start declining immediately and be zero by 2050. If shipping emissions peak later or decrease at a slower pace, other sectors need to reduce their emissions more in order to meet the temperature targets.

3. Technology Pathways to Decarbonize Shipping

3.1. Introduction

This chapter presents technology pathways to decarbonize shipping.

In order to meet the 2050 level of ambition of the Initial IMO GHG Strategy and fulfil its vision, the shipping sector has to transform swiftly towards zero GHG emissions. Because ships need energy to move, this implies that they should sail on energy forms that do not create greenhouse gas emissions.

The transition from the current fossil fuels to zero carbon has many different aspects. For example, zero carbon fuels are likely to be more expensive than fossil fuels, so regulation may be needed to ensure that ships sailing on zero carbon fuels can compete. Also, many of the zero carbon fuels require different engine types, and in turn, ships sailing on these fuels may not be able to switch to other fuels, which necessitates the build-up of a global supply infrastructure. Also, many of the technologies required to sail on low-carbon fuels have not been applied in the shipping sector or are only used sparsely, so there is a need for further technical development.

This chapter focusses on technology pathways to decarbonise shipping with an emphasis on the technical obstacles. It starts with an overview of the different fuel-technology combinations that have a chance of becoming important in the shipping sector in the next decades (Section 4.2). Section 4.3 analyses the availability of the different fuels, while Section 4.4 analyses the technical obstacles related to the storage, bunkering, and application on-board of ships of the different fuels and technologies. Conclusions are drawn in Section 4.5.

3.2. Overview of fuel-technology pathways

There are numerous different combinations of fuels, production processes for these fuels, and energy conversion methods on-board. This section aims to structure them in a meaningful way with an emphasis on the options that have the highest chance of becoming widely-used options in the shipping industry.

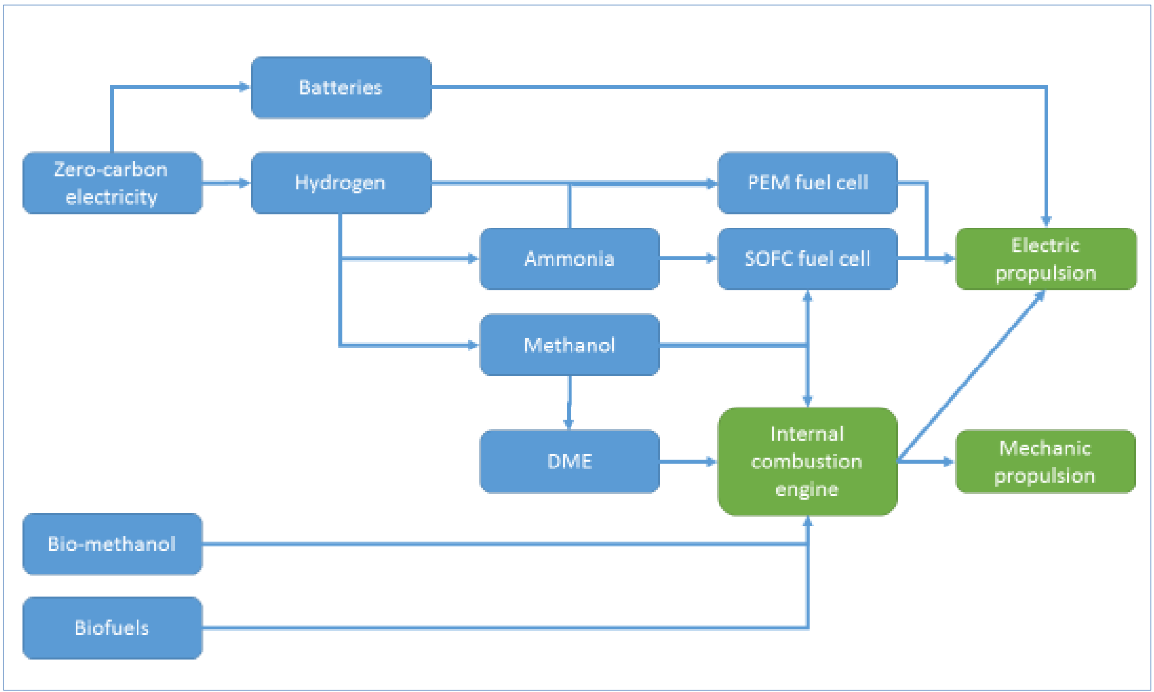
There are essentially three ways in which zero emission fuels can be produced (Figure 3). One is by using renewable electricity either directly or in a electrochemical process to generate fuel; another by having plants convert solar energy into a biological fuel precursor; and a third one to produce hydrogen by reforming methane or other hydrocarbons and store the CO_2 underground. Note that the production capacity of the latter is constrained by the capacity of underground storage.

Renewable electricity can be either stored in a battery on-board or converted into chemical energy, in particular by electrolysing water to produce hydrogen. This hydrogen can be stored on board or converted into ammonia, methanol or other fuels. Of these, we consider ammonia and methanol to be the most plausible because they are the most advanced technically (see Section 4.4). The sustainable biofuels with the largest potential for scaling up to the extent needed to fuel a sizeable portion of the world fleet are biomethanol and algae-based fuels (see Sections 4.3 and 4.4).

The fuels can either be used in an internal combustion engine or in a fuel cell.
The internal combustion engine is most suitable for methanol (of biological origin or not) and liquid biofuels, but in principle ammonia and hydrogen can also be used in internal combustion engines (see Section 4.4). For fuel cells, the reverse is true: they are best suited – and most advanced from a technical perspective – for hydrogen and to a lesser extent for ammonia, but could in principle also be used to generate electricity from methanol and other fuels.

As shown in Figure 6, an internal combustion engine could either drive the shaft directly, or generate power which is used in a diesel-electric system. The electricity for such a system can also be generated in fuel cells.

Figure 6 - Stylised overview of fuel-technology pathways



3.3. Availability of fuels

3.3.1. Introduction

This section focusses on the availability of sustainable fuels for maritime transport. In line with Section 4.2, the section focusses on power to fuels (Section 4.3.2) and on biofuels (4.3.3), as these are the most promising options. Each of the two subsections starts with a short introduction of the technology options. Afterwards, the technical potentials are discussed. The respective sub-chapter ends with considerations on possible barriers. The barriers focus on the production process of the considered fuels whereas supply and end-use is not discussed in detail. E.g. new infrastructure is required in ports and on the ship at least modifications of the combustion engine are necessary. Section 4.3.4 points out which fields research should focus on.

3.3.2. E-fuels (PtX)

Power to Hydrogen

Hydrogen is produced from water by electrolysis using electricity. This process requires fresh water, thus, **desalination** is required if only sea water is available at the production site (otherwise chlorine (Cl_2) is created as an undesirable by-product).

Electrolysis can be distinguished in low-temperature and high-temperature electrolysis. **Low-temperature electrolysis** is the more established technology. The two general technological options are AEL (Alkaline electrolysis) and PEMEL (Polymer electrolyte membrane electrolysis). **High-temperature electrolysis** (SOEL – Solid oxide electrolysis) requires an external heat source. It is therefore limited to locations that offer a waste heat supply. This technology has not been implemented at industrial scale.

For storage and refueling, the hydrogen needs to be **liquefied** (LH_2) and/or compressed. On board of the vessel, hydrogen can be used either in a combustion engine or in a fuel cell. **Fuel cells** are currently being applied as a propulsion technology at an initial design or trial stage in smaller passenger ships or ferries (Adolf, et al., 2017). In September 2019, the first hydrogen fuel cell vessel shall be delivered by the California-based Bay Ship & Yacht Co. (Safety4Sea , 2018). According to Tronstad et al. (2017), the fuel cell types which are considered most promising fuel cell types for nautical applications are Proton Exchange Membrane Fuel Cells (PEMFC, low-temperature) and the Solid Oxide Fuel Cell (SOFC, high temperature). The use of hydrogen in combustion engines shows less efficiency than fuel cells. In comparison to diesel engines, the fuel cell power train (currently >200,000 €/MW_{net}) is still expensive, but a steep cost reduction through learning and upscaling is expected with technology uptake: approximately 80,000 $/$MW_{net}$ can be achieved in 2025 if an annual fuel cell system production of 16,000 MW/a is reached (James 2018). Also, hydrogen supply is still much more expensive than marine bunker fuels: today, retail prices for hydrogen (14 $/kg) in California are seven times higher than distillate fuels (ICCT, 2018).

Power to methanol

To obtain a liquid synthetic fuel, the hydrogen from electrolysis can be further processed via methanol synthesis into methanol (MeOH). The methanol from the synthesis plant can be used directly or after a conditioning and refining process as a liquid fuel. Methanol enables a broader range of applications than hydrogen because it is easier to handle and to store than hydrogen and provides a higher energy density.

Methanol synthesis can be performed **by a two-step process using synthesis gas.** This is a well-established large-scale industrial process, in which first the synthesis gas (a mixture of CO and H_2) is produced from CO_2 and H_2 via the reverse water-gas shift (RWGS) reaction. Secondly, the synthesis gas is converted into methanol by hydrogenation (Brynolf, et al., 2017). Methanol production from synthesis gas is associated with comparatively high energy consumption.

Another synthesis option is the one-step process or **direct methanol synthesis** that converts CO_2 and H_2 directly into methanol and water. Subsequently, the methanol-water-mixture needs to be distilled in order to yield pure methanol (Brynolf, et al., 2017).

Both processes require a **CO_2 source**.

Examples of concentrated CO_2 sources are industrial processes such as cement production, which would not lead to carbon-neutral e-fuels, or geogenic sources and biogenic process emissions, which can provide highly concentrated CO_2 streams.
The total volumes of these sources are limited and upscaling of the plant would not be possible.

In addition to CO_2 from concentrated sources, CO_2 from ambient air can also be used.

This process is called Direct Air Capture (DAC) and requires additional energy (electricity and heat) and has a high land consumption.

Power to ammonia

The use of liquid ammonia (NH_3) as a fuel for conventional internal combustion engines in shipping has also been discussed recently (Brohi, 2014; Cames, et al., unpublished). The synthesis of ammonia via the **Haber-Bosch process** is a well-established industrial process. It is applied today at a large technical scale in the chemical industry, for example, in fertilizer production. Compared to today's process, fossil hydrogen (produced from natural gas by steam reforming) must be replaced by hydrogen from renewable sources.

Besides hydrogen, **atmospheric nitrogen (N_2)** is required for the ammonia synthesis. Compared to CO_2, which is required for MeOH synthesis, N_2 with the Hampson-Linde cycle is easy to grasp from the air, which means that less energy is required in this process step (ISPT, et al., 2017).

Direct **solid-state ammonia synthesis** (SSAS) is currently being investigated. It promises to reduce the energy consumption of NH_3 synthesis. There are no commercially available SSAS systems today (ISPT, et al., 2017).

Finally, the ammonia needs to be **liquefied** in order to be used as a fuel in maritime shipping. Ammonia can be stored in liquid form (LNH_3) at a low pressure of 10 bar or temperatures of -33.6°C (240 K). Thus, the boil-off and the potential additional energy losses are small compared to those of liquid hydrogen and liquid methane (Cames, et al., unpublished).

The specific energy consumption for the Power-to-Ammonia systems is estimated at between 7.1 and 11 kWh per kg NH_3. Taking into account the heating value of ammonia (18.6 MJ/kg), the energy demand for Power to Ammonia is between 1.4 and 2.1 kWh per kWh ammonia (ISPT, et al., 2017).

Technical and economic potentials and likely production sites

From a **physical and technical** point of view, there is a huge global potential for e-fuel production. Fasihi und Breyer (2017) have evaluated the **economic** potential of methanol production by generating industrial cost curves (annual MeOH generation potential vs. MeOH production cost) for the year 2030. These cost curves show that roughly 300 million tonnes of methanol could be produced at production costs of up to 500 €/t_{MeOH} (equal to 7.9 ct/kWh_{MeOH} or 40 ct/l_{MeOH}). This amount of methanol is equivalent to 6.9 EJ and, thus, represents more than half of the global energy demand for shipping which is projected to reach 12.5 EJ in 2020 (CE Delft, et al., 2016). When the production cost limit is raised to 600 €/t_{MeOH} (9.4 ct/kWh_{MeOH}), the global MeOH generation potential increases 20-fold to 6,000 mio. tonnes of methanol. About 20,000 mio. tonnes could be produced in 2030 at costs below 800 €/t_{MeOH} (12.6 ct/kWh_{MeOH}).

Fasihi und Breyer (2017) also indicate for each continent a so-called "optimal annual generation potential" for methanol as shown in the figure below. This optimal annual generation potential is based on the assumption that maximum 10% of the land area with the globally lowest electricity generation cost can be used for PV and wind installations. Under this assumption, the MeOH production potential amounts to 27,000 mio. tonnes worldwide out of which approx. 1,000 mio. tonnes can be produced in Europe.

Figure 7 – Optimal annual generation potential of DME and Methanol synthesis plants

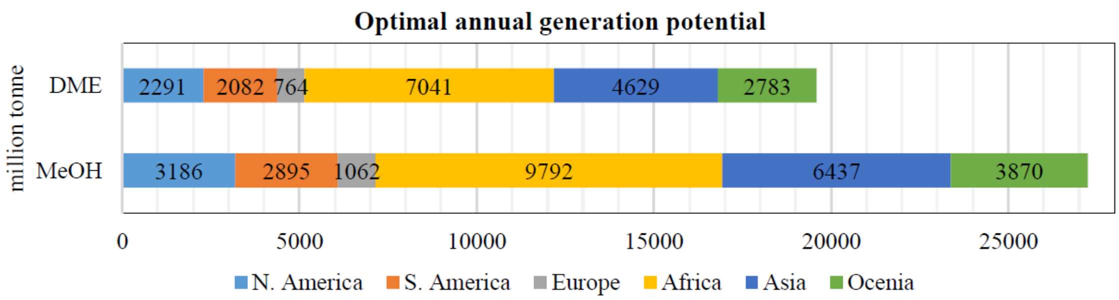


Figure 12. Optimal annual generation potential of methanol and DME synthesis plants.

The global optimal annual generation potentials are much **larger** than the global energy **demand in the maritime shipping and aviation** sectors taken together. Also, the EU long term strategy claims that there is enough potential within Europe to cover EU demands – based on the assumption that also larger amounts of biofuels are used.

However, there are also much lower estimates for the PtL production potential. For instance, according to Christensen und Petrenko (2017), only around 400 million litres (0.3 million tonnes, or 1,000 times less than the lowest production potential mentioned above) of PtL could be produced in 2030 in the most favourable policy scenarios for the economics of power-to-liquids production with 1.50 € per litre subsidies (roughly equivalent to 500 € per tonne CO_2 e reduction). This amount represents only 0.15% of total EU road transport fuel demand in 2030.

Generally, there are a number of geographical and societal constraints that lower the economic potential for generating PtX-fuels. Production plants require high capital cost.

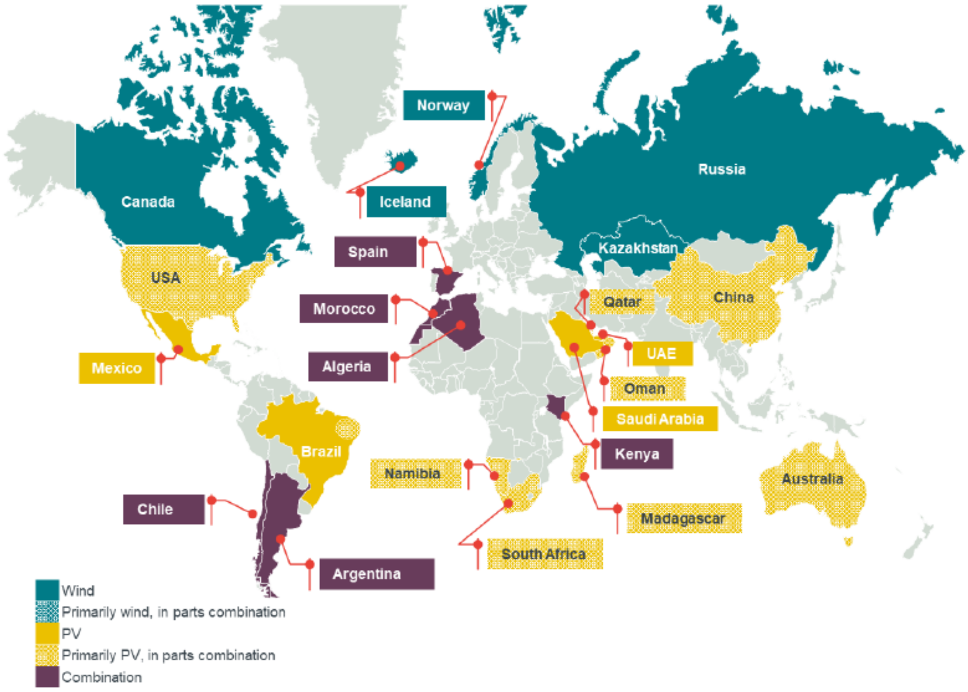
Therefore, to minimize production cost, **low electricity prices** and **high capacity utilisation** are necessary – still even in the optimal case the cost will be higher than the fossil alternative. Hard factors such as generation costs of electricity from renewable sources (driven by full load hours) and additional **area-specific resource potentials** such as surface area and water demand define the potential PtX production locations worldwide.

In comparison to biofuels, space and water demand for PtX production is lower, but still these factors play the key role. In case of methanol, additional land space is required for CO_2 capture from the air.

The availability of sites for generating electricity from renewable energy sources is **limited in many European countries**, e.g. due to landscape and maritime protection. Frontier Economics (2018), who only roughly applied sustainability criteria in their analysis, found that only 1 EU member state out of 23 countries worldwide demonstrate strong potential for PtX production:

Figure 8 – Strongest potential PtX producers worldwide

Figure 17 Strongest potential PtX producer worldwide



Source: Frontier Economics

Note: Illustrative presentation of the strongest RES potentials only; not an extensive list of all countries.

Hence, in contrast to the EU long term strategy, it is likely that production will mostly happen outside of the EU. Similarly to fossil fuels, there will be a global and not an EU-only market. Production cost and land-use constraints are potentially significantly lower outside the EU – eventhough "soft" factors such as political stability, development status and embedded energy framework also play their role (Frontier Economics, 2018).

It is very likely that in the short term, all e-fuels options will have higher costs than advanced biofuel options (Kreyenberg et al. 2015).

Possible barriers

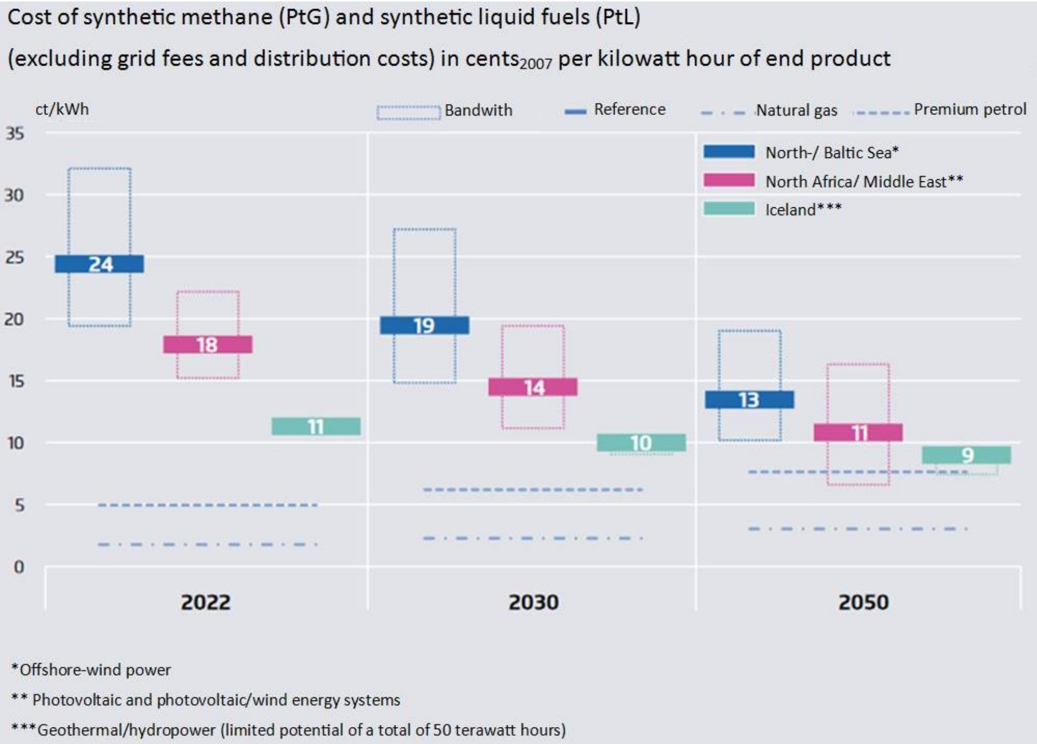
Barrier: Costs

The major cost factor in synfuel production is the cost of electricity generation. According to Agora Verkehrswende (2018), the levelised cost of electricity accounts for slightly more than 50% of the overall PtL production costs and essentially depends on the specific investment costs of the renewable energy plants and their respective full load hours. In case of methanol, the electrolyser costs and the costs of CO_2 capture from the air (DAC) are equally important cost factors in 2030 and account for nearly 3 ct/kWh$_{PtL}$ each whereas the costs for the methanol synthesis plant is below 1 ct/kWh$_{PtL}$.

In case of ammonia, the electricity generation and electrolyser costs are even more prominent since the cost of N_2 capture from the air only plays a minor role. Liquefaction is an important cost factor for hydrogen: the cost of H_2 liquefaction is specified in Pfennig et al. (2017) as 1,47 €/kgH_2 (equaling 4,4 ct/kWhH_2).

According to Agora Verkehrswende (2018) synthetic fuels (methane, PtL) will even in 2050 be more expensive than liquid fossil fuels and significantly more expensive than natural gas as shown in the following figure.

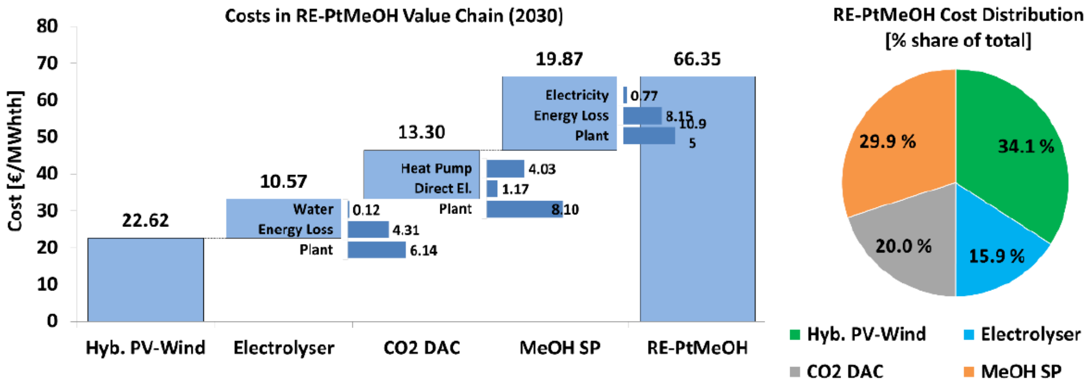
Figure 9 – Cost of synthetic fuels



Source figure: Agora Verkehrswende (2018).

On the other hand, Fasihi und Breyer (2017) present considerably lower costs of only 6.6 ct/kWh$_{MeOH}$ for the production of methanol from renewable electricity (RE-PtMeOH) in 2030 at an overall electricity-to-fuel efficiency of 52,5% (see section 4.3.2.4 for the correlation between production cost and production potential of methanol). The cost structure as shown in the figure below also appears different. However, the different cost distribution is due to a methodical difference: in Fasihi und Breyer (2017) the conversion losses ("Energy Loss") are assigned to the costs of the conversion plants (electrolyser, CO_2 DAC, methanol synthesis plant) whereas in Agora Verkehrswende (2018) these conversion losses are 'replaced' by additional renewable electricity generation (and, to a lower extent, by additional electrolyser and DAC capacity), thus increasing the share of the electricity costs.

Figure 10 – Cost structure of Power-to-Methanol



While the details may differ, there is one common theme that runs through all the results: synthetic fuels are expensive to produce given current and projected grid prices and will likely not be produced unless there is an unprecedented level of policy support. Even when including technology improvements and other cost reductions, the economics of these plants remain challenging (Christensen & Petrenko, 2017).

Barrier: Land Use

For the impact of the land requirement two factors are highly relevant: the possibility to use the required land for other purposes and the requirements regarding the land type. In the case of wind power, up to 95% of the land can still be used for other purposes (e.g. agriculture). In contrast to biofuel production, requirements regarding the type of land are also relatively low, as no arable land is needed. Wind and PV installations can also be located in areas where other uses such as agriculture are not possible (e.g. in deserts). Therefore the danger of competition between food and energy production is far lower in the case of synthetic fuels than for biofuel production.

The land requirement for solar or wind farms to supply renewable electricity for a large electrofuels industry could still be considerable though (supplemented by area demand for direct air capture of CO_2). Assuming that electrofuel production using EU solar electricity can deliver at least 500 GJ per hectare per year (Bracker & Timpe, 2017; Schmidt, et al., 2016), for the case of delivering 330 TWh PtL energy in 2050, this is equivalent to the entire area of the Czech Republic devoted to wind farms or solar PV installations (Malins, 2017).

Barrier: Competition and overlap with demand from other sectors

There could be a competition for the use of renewable electricity in regions with suitable locations for the generation of renewable electricity, such as in North Africa. Preferred areas for local RE generation could be occupied by PtX plants. The lower the energy efficiency of the chosen path (MeOH, NH_3; H_2) and the higher the primary energy demand, the stronger this competition will be.

On the other hand, synergies could be the economic prosperity as a co-benefit in production countries. Fresh water from desalination plants and excess power plants could also be used for the local population.

Barrier: Water

The production of synthetic fuels requires water for electrolysis. At 0.04 -0.08 m^3/GJ, the water demand is significantly lower than the water demand for the production of biofuels from cultivated biomass and from algae (41-574 m^3/GJ and 14-53 m^3/GJ respectively). Water consumption for the production of biofuels from residues should be even lower than for the production of synthetic fuels. The water demand should nevertheless be met in a sustainable manner (Schmidt, et al., 2016).

In many of the potential regions of future synthetic fuel production water availability is already critical, and it cannot be assumed that the required water demand can easily be satisfied by the existing regional water supply. However, DAC can contribute to the coverage of the water demand as in that process it condensates from the air. The Middle East and North Africa (MENA region) are already today among the world's driest regions, and climate change will lead to a further increase in aridity in many regions of the world. For example, in the MENA region, a 20% reduction in rainfall and higher rates of evaporation will further increase water scarcity ((WBG, 2014). At the same time, water consumption is constantly increasing in this region due to population growth and growing per capita water consumption (Bracker & Timpe, 2017). If no sufficient fresh water supply is available, desalination of sea water is the only feasible option, but is an energy intensive process with no great further efficiency gains expected (Bracker & Timpe, 2017).

Barrier: Insufficient availability CO_2 sources (methanol)

The overall availability of biomass is very limited compared to the carbon volumes required for large scale synthetic fuel production.

Direct capture of carbon from ambient air is the only feasible and environmentally sensible option for a large scale production of synthetic fuels. From a technical perspective, it is available in sufficient amounts and at every potential production site. But this pathway has a low overall efficiency.

Table 2 - Synthetic fuel production efficiencies (fuel output vs.electricity input)

Table 3-1: Synthetic fuel production efficiencies (fuel output vs. electricity input)

Pathway*	Production efficiency today		
	Air	Exhaust gas (e.g. wood burner)	Fermentation (e.g. biogas upgrading)
Low-temperature electrolysis	38%	47%	48%
High-temperature electrolysis	45%	60%	62%

*Differences between the Fischer-Tropsch and the methanol pathway are negligible

Source: German Environment Agency 2016

Source figure: Bracker & Timpe (2017).

If CO_2 from industrial point sources is used, it is important t from a sustainability point of view that this does not slow down the necessary emission reduction in the industrial sector.

Barrier: Lack of sustainability criteria

So far, the potentials have mainly been generated by technical-economic considerations. The discussion on sustainability criteria that are necessary for PtX has not yet taken place. From today's perspective, no assessment can be made of what is a sustainable global and European PtX potential.

In order to ensure an ecological advantage in the long term, it is necessary to develop sustainability criteria at an early stage in order to avoid negative impacts similar to the introduction of crop-based biofuels. The process for the development of such criteria and the establishment of a respective certification scheme should be initiated in the near future, before a large market for post fossil fuels develops.

The development of these sustainability criteria and a certification scheme are important to the widespread **acceptance of e-fuels**. The criteria must be understandable and comprehensible so that the additional costs arising from the sustainability requirements are also accepted.

Sustainability criteria should address the **overall greenhouse gas balances** of hydrogen and e-fuels, based on lifecycle assessments that take into account the upstream emissions of electricity production required for all production processes, including CO_2 and N_2 capture and water desalination and treatment, where required.

To achieve significant CO_2 emission savings through the use of LH_2 and e-fuels in shipping compared to conventional fuels, their production must be based on **additional renewable energy** generation and in order to ensure long-term sustainability, only atmospheric carbon sources (CO_2 from air and geothermal wells) should be used (Bracker und Timpe 2017).

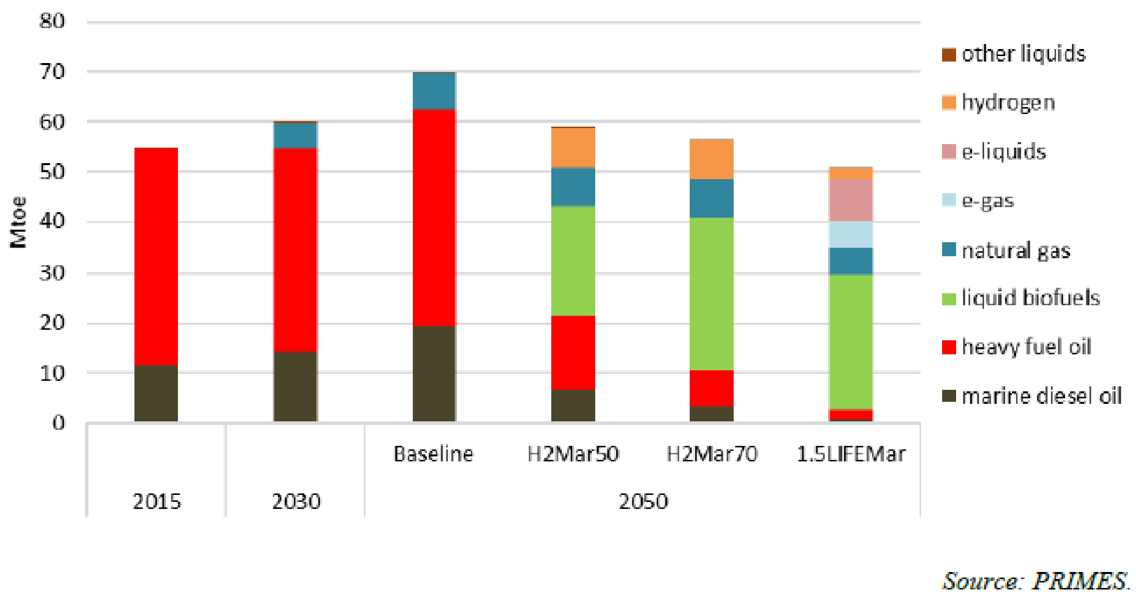
Further sustainability criteria should be developed with a special focus on sustainable land use and competition with food production and forest land. Especially in arid climatic zones such as North Africa and the Middle East, e-fuel production will increase the already high seawater desalination capacities in the region. Both criteria should also include social criteria to avoid negative impact on availability of food and drinking water in regions of PtX fuel production as well as criteria on competition for electricity in regions with energy poverty.

3.3.3. Biofuels

Technical potentials

In global maritime transport as well as intra-EU and inland waterway shipping, projections state that liquid fuels will by far be predominant; and the more ambitious the CO_2 reduction goal for 2050 (-80 % GHG emissions or net zero (GHG emissions)) the higher the share of biofuels, according to European Commission (EC, 2018a). In a net-zero GHG emissions world in 2050, approximately half of the liquid fuels demand from **inland shipping** will be met by using biofuels. In maritime transport, more than half of the final energy demand will come from liquid biofuels if GHG emissions are reduced by 70 % (scenario "H_2Mar70") or 88 % ("1.5LIFEMar").

Figure 12 – Current and future energy sources for shipping



In: EC, 2018a.

Bouman et.al.(2017), identify the use of biofuels as the (by far) most powerful single measure to reduce CO_2 emissions.

Other literature identified **smaller potentials** for advanced biofuels to fulfil future transport sector demands than stated in the long-term strategic vision of the EC. E. g., Schmied et al. (2014) found that in 2050 some 10% (between < 5% and approximately 13%, depending on development of the transport demand) of the global final energy demand could be delivered by 2nd generation biofuels such as ethanol (methanol is not regarded); biomass from algae could add up to this potential significantly, but at high cost and limited GHG emission reduction potential. Generally, the potential of algae-based fuels to contribute to the potential is highly uncertain from today's perspective.

The question on what role Methanol will play in a possible future advanced biofuels "mix" is also highly uncertain as today's technology readiness level of bio-methanol is on the technology demonstration level (Uslu et al. 2018). The commission long-term vision does not determine which biofuels will be predominant in the shipping sector. whereas the PRIMES Biomass model used in European Commission (EC, 2018b) considers only Biodiesel, Kerosene, and Ethanol for the entire transport sector.

International Transport Forum (ITF) and Organisation for Economic Co-operation and Development (OECD) (ITF; OECD, 2018) put strong emphasis on hydrogen and ammonia in the medium-term perspective (2035).

Possible barriers

Barrier: Lack of sustainability in the feedstock supply

Conventional biofuels give rise to sustainability concerns. In Europe, the share of biofuels from agricultural sources for use in the transport sector has therefore been limited through the ILUC and RED directives. The concerns apply to a lesser extent to advanced biofuels, but a lack of comprehensive sustainability coverage and deficiencies of sustainability verifications may affect public confidence (Uslu, et al., 2018).

When it comes to biofuels from macroalgae, the currently predominant wild harvesting causes strong detrimental effects on marine ecosystems (EC, 2017) while relevant improvements in energy efficiency and land use demand would be necessary to make microalgae a more sustainable option.

The EC long-term strategy summarizes that, "land constraints imply that advanced biofuels should be deployed only in those transport modes or means where they are necessary".

Barrier: Insecurities in feedstock supply

The high relevance of transport cost for feedstock supply (e.g. in comparison to e-fuels production which can use CO_2 captured on-site as the carbon source) makes availability and costs of advanced biofuels more insecure.

Under insecurities in the biofuels market, potential agricultural producers might decide not to switch to energy crops due to social aspects and also as a result of risk minimisation (especially in case of perennials such as switchgrass).

A barrier that obstructs biofuel production especially for the marine shipping sector is the fact that fuel supply takes place globally. Therefore sustainability and quality standards make much more sense on the global level; but setting standards is more difficult on the global level (Uslu, et al., 2018).

Barrier: Lack of efficiency and insecurities in the conversion process

In the global competition and market for biofuel production many different types of feedstocks are / will be used. For operators of conversion plants this causes several problems: Conversion plants have to offer a high degree of flexibility – with the result of costly additional technical requirements. This barrier applies especially if low-quality material is used. And, the more renewable sources (residuals etc.) are often of a lower quality. The current situation does not offer the necessary security for investments in new facilities.

One reason for the relatively low efficiency of the production chain of biofuels from lignocellulosic sources comes from the fact that as only cellulose part used. Improved supply processes that also use the lignin part could improve the efficiency (Uslu, et al., 2018).

Barrier: competing uses

There are several competing applications which inhibit mobilisation of potential feedstocks for biofuel production:

- agricultural producers already use residuals such as manure, e.g. to improve soil quality;
- for forestry residuals, there are also existing utilisation chains in several countries;
- bio-energy consumption for production of textiles, plastics etc. is expected to grow by 80 % by 2050;
- bio-methanol is a well-suited feedstock for industrial processes: bio-ethanol and bio-methanol are regarded as the most efficient ways to use bio-energy in chemical industry;
- forests and other ecosystems fulfil the function as a carbon sink – this is the benchmark when considering natural resources as possible biofuel feedstocks.

Competing uses lead to higher prices and due to the limited feedstock the price of biofuels will tend to rise in future. In the shipping sector, the cost differential to the current technology is particularly high as today's low-quality shipping fuels are the benchmark.

In other sectors such as aviation and road transport the willingness to pay is higher, so that an uptake of any alternative fuel technology is more likely if no policy measures are taken to manage the allocation. Additionally, in comparison to aviation, the relevance of the power-to-weight ratio is even higher than in shipping. Therefore, the aviation sector will make a claim on the available renewable liquid energy carriers.

Potentially, there is a synergy effect with e-fuels production, when CO_2 from biomass combustion is used as a carbon source. But this effect cannot be exploited when biomass is used in a mobile application (EC, 2017; Uslu, et al., 2018; Bazzanella & Ausfelder, 2018; EC, 2018a).

Barrier: general aspects

In expert interviews conducted by Uslu et al. (2018), general aspects such as:

- low oil prices;
- lack of dedicated and long-term policy support; and
- lack of long-term experience of the end-users.

were seen as some of the most important barriers – of courses these obstacles apply to most low-carbon technologies.

3.3.4. What should research and development focus on?

In the field of e-fuels, there is firstly a need for more basic research into technologies:

- Electrolysis is the central element for which there is still considerable cost reduction potential and which must be exploited to the fullest.

Ammonia production processes, including solid-state ammonia synthesis, could enable cost reductions:

- Further research is needed on the direct methanol synthesis which could improve efficiency of e-methanol production (direct conversion of CO_2 and H_2 to methanol in a one-step process). There is ongoing research on the direct conversion of CO_2 and H_2 into methanol with the aim to make the one-step process more efficient and, thus, increase the attractiveness of methanol as a fuel, according to (Fasihi & Breyer, 2017).
- The methanol synthesis is exothermic and its high-temperature waste-heat could be reused as heat input for high-temperature electrolysis.
- The Direct Air Capture (DAC) process is a crucial technology which needs further research in order to bring energy consumption and costs down.
- In the field of advanced biofuels, more efficient microalgae production in closed reactors is a promising field of research. Additionally, improved exploitation of manure as a source for methanol production is also a subject which needs more research.
- Secondly, most technologies with need for research have been demonstrated and tested on a small scale so that the focus of the research should be upscaling and efficiency improvements in order to bring energy consumption and costs down. This is crucial for advanced biofuels production, especially from microalgae, as well.
- Thirdly, the development of sustainability standards is crucial for future e-fuel policies. There are currently no studies that indicate quantitative sustainable potentials for e-fuels. It is also not known that there are studies that consider the need for renewable energies electricity across sectors and thus analyse competing uses for electricity and land use. Substantial development and communication of sustainability criteria will also improve acceptance of e-fuels. In the field of advanced biofuels, a better quantification of potentials of afforestation of

degraded forest lands and other degraded ecosystems (and their use as a feedstock for methanol production) is needed.

Support the large-scale market uptake of both e-fuels and advanced biofuels.

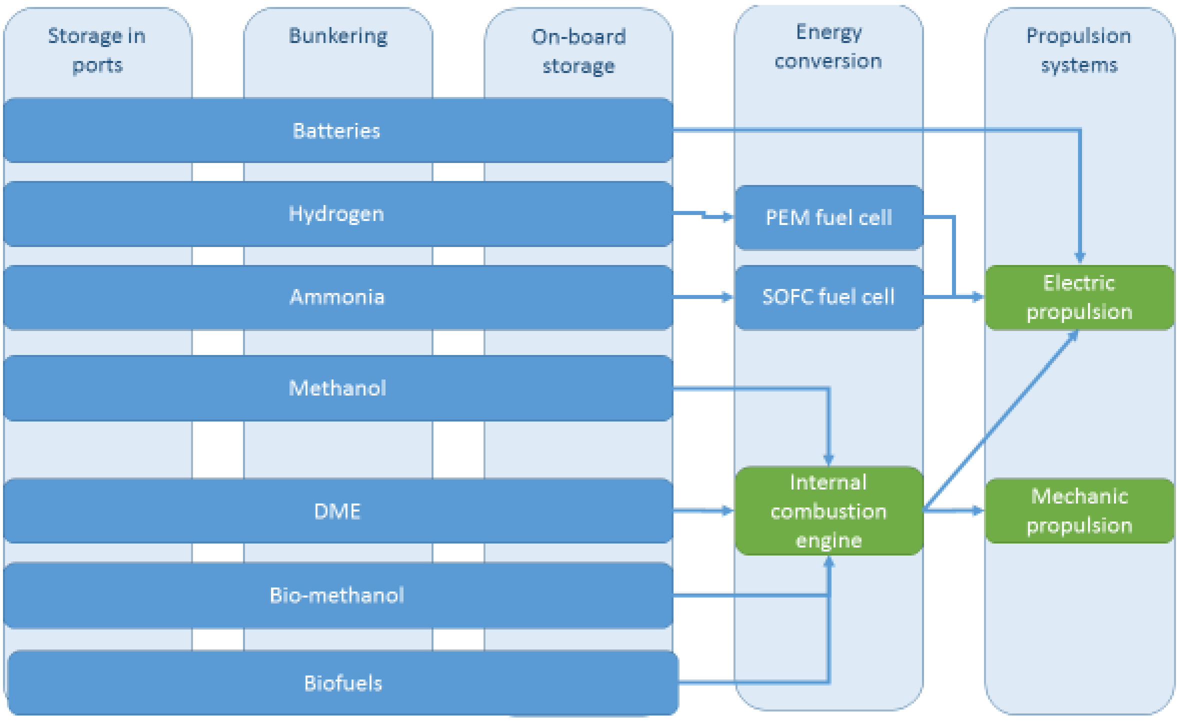
3.4. Technology assessment

This section assesses the technology for applying the different fuels on board of ships, and specifically on:

- propulsion systems;
- fuel cells;
- storage of fuels or energy on board;
- bunkering; and
- transport and storage of fuels in ports.

These areas are compatible to the fuel-technology pathways presented in Section 4.2 (see Figure 4).

Figure 13 - Technology assessment framework



The focus of the assessment is on the following questions:

- Is the technology currently available on the market and if not, when could it become available?
- Has technology been scaled up to sizes required for ships?
- Has technology been applied on ships?

The section is based on a detailed technology assessment in Annex A.

3.4.1. Propulsion systems

There are two main propulsion systems that are used in most existing and new ships: direct mechanical propulsion, in which the engine drives a shaft that is connected to the propeller, and electric propulsion, in which one or more generators generate electrical power that is used to drive an electric engine to which the propeller shaft is connected. As shown in Figure 4, both can be used in set-ups with zero carbon fuels. Hence, propulsion systems do not constitute a barrier to the transition to zero carbon fuels.

3.4.2. Internal combustion engines

Internal combustion engines are installed on virtually all self-propelled ships. Most of these ships use petroleum-derived fuels and the technology to do so has been well established for decades. Internal combustion engines can also use ammonia, methanol, DME and other substances as fuels, in which case further development may be needed.

In order to use ammonia as a fuel in internal combustion engines, it has to be mixed with a combustion promotor. This can be a petroleum-derived fuel or hydrogen, which can be produced on-site by partially reforming the ammonia. While this technology has been proved to be feasible on scale on land, it has not yet been applied in a maritime environment. The NO_x that is formed in the combustion process can be sufficiently reduced by reducing it with ammonia.

The use of methanol and biofuels has been applied in marine internal combustion engines. In some cases, engine modifications are needed, but these have been tested on board ships.

3.4.3. Fuel cells

Fuel cells are relevant for hydrogen and possibly for ammonia, methanol and other fuels. Hydrogen can be converted into electricity in proton exchange membrane fuel cells (PEM) and other fuels (as well as hydrogen) in solid oxide fuel cells (SOFC) or molten carbonate fuel cells (MCFC). The former has a much higher level of technical maturity: on-land PEM fuel cell systems have been built in the MW range and these fuel cells have also been applied in a maritime environment, namely in a submarine with a relatively modest power of 300 kW.

There are several developments that have to take place before fuel cell technology will be market-ready. First of all, fuel cells need to be scaled-up and tested in a marine environment. This is currently being done on a small scale. For example, the public-private partnership Golden Gate Zero Emission Marine is building a 600 kW fuel-cell powered ferry for the San Francisco Bay Area[2]. For most ships, engines would need to be at least an order of magnitude larger: many bulk carriers and oil tankers have main engines ranging from 5 to 15 MW, while the largest container ships and cruise ships have an installed power of 70 MW or more (IMO, 2015).

In addition, safety aspects of fuel cells need to be better understood and legal obstacles need to be removed, for example with regards to ventilation and integration of fuel cells in a ship (DNVGL, 2017).

3.4.4. Storage of fuels or energy on board

Fuels need to be stored on board and transported from the tank to either the engine or the fuel cell. Currently, some ships store enough fuel on board for several weeks or months. They have tanks and piping systems designed to handle heavy fuel oil or lighter fuels at ambient temperatures or heated up to 150–180°C. many of the fuels discussed in this chapter have different requirements. The barriers to the storage of fuels or energy

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[2] Golden Gate Zero Emission Marine : Water-Go-Round Project

on board depend on the type of fuel and will therefore be discussed separately for the different fuels.

Methanol

The storage of methanol in fuel tanks and the delivery of the fuel to an internal combustion engine is a proven technology, there are currently 8 ships operating on methanol worldwide (one ferry and seven methanol tankers). The storage on board and the fuel systems are not fundamentally different when methanol is used in a fuel cell. If other ships would also use methanol, they would either have to bunker more often or be designed with larger tanks because of the lower energy density of methanol compared to HFO and MGO.

Biofuels

Biofuels for ships are currently predominantly liquid biofuels that can be used in ships designed to sail on HFO or MGO (CE Delft; Technopolis, 2018).Trials have been conducted with FAME and HVO biodiesels. The former can suffer from biodegradation and tanks and pipings may need to be retrofitted to accommodate sailing on these fuel types. HVO fuels do not appear to suffer from these problems, as they are not as susceptible to degradation.

In any case, the use of biofuels in internal combustion engines has been applied to ships without reported major obstacles and can therefore be considered to be technically feasible without further technological development.

Ammonia

Ammonia is currently not used as a fuel, but it is transported in tankers so there is experience with storing it onboard ships and transporting it from ship to shore. On-land storage is well established, as are cooling and compressing techniques.

Hydrogen

Hydrogen can be either stored as a compressed gas or in liquid form. Both require substantially more space per unit of energy than conventional fuels: at 700 bar, compressed hydrogen has an energy density of one sixth of HFO, while liquefied hydrogen needs to be stored in well insulated tanks in order to keep the temperature below -253°C. There is an emerging small-scale experience with compressed-hydrogen storage on board ships, while storage on-land is an established market. In comparison, the experience with storing liquid hydrogen is smaller on-land (primarily in spacecraft) and just starting to emerge in the marine sector for smaller craft (e.g. ferries). Hence, further technological development of tanks and fuel systems would be required to improve the potential for hydrogen as a marine fuel.

Batteries

Batteries also have a much lover volumetric and gravimetric energy density than petroleum-derived fuels and therefore require more space and weight than conventional fuel systems. There are a few pilot projects with batteries on ships, either in a hybrid set-up with diesel generators and with or without the possibility to charge the battery with shore power, or in a full electric set-up. The latter is currently only possible for ships that sail short distances and spend a relatively large share of their time near a power supply point, such as ferries.

There are a few pilot projects of ships sailing on batteries either on inland waterways or in fjords or bays. The technology has been proven but unless the battery technology improves considerably and the energy density is greatly improved, the prospects of this technology beyond the current uses is limited.

3.4.5. Transport and storage of fuels in ports and bunkering

Fuels need to be provided to the ship. In the case of methanol, biofuels and batteries this is unproblematic and already common practice: there are methanol ships and in addition there is much experience with handling methanol as cargo; biofuels are similar to petroleum-derived fuels in their physical properties, and batteries can be powered with onshore power supply installations.

There is much experience with handling ammonia as cargo, which is similar to bunkering liquefied ammonia.

All the above products are currently stored and transported in ports as cargoes.

In case of hydrogen, bunkering technology and procedures need to be developed. There is some experience with storage of liquid hydrogen on land, but only in a few countries. Moreover, the largest existing storage systems are too small for bunkering even a few ships. Hence, the technology and safety regulations on storage of liquid hydrogen needs to be developed before hydrogen can be used as a marine fuel.

3.4.6. Safety

Compared to conventional marine fuels, the introduction of zero carbon fuels and technologies brings with it new safety risks which need to be mitigated or managed. This is mainly due to the properties of these fuels. Ensuring safety to handle hydrogen and ammonia for marine applications, would require a robust risk assessment, whereas, safety for biofuels have already been addressed in a certain extent. Safety around new technologies such as fuel cells and batteries would also be important to consider.

The accidental release of cryogenic liquid hydrogen, for example, could crack unprotected steel, expand to hundreds of times of its original volume and become flammable as it turns back to gas. This would be a serious problem if it occurred below deck. Hydrogen is also far easier to ignite and specialist equipment is required to detect its flames. Moreover, the high flame velocity means in confined spaces this can result in detonation.

Although ammonia is a colourless, flammable, highly toxic and corrosive gas with a suffocating odour, it could be handled with appropriate management. Ammonia has a low flammability but measures need to be taken to control ignition sources and avoid contact and inhalation as exposure can result in burns and asphyxiation. It has a very strong odour however, it is much lower than dangerous levels, so potential small releases will not cause injury but can result in discomfort.

It is important, therefore, that for both hydrogen and ammonia, prevention, ventilation and detection principles need to apply.

Safety of bio-based fuels on board have already been addressed and proven. However, biofuels can have varying types of safety concerns, in some cases acid degradation can cause damage to fuel pumps, injectors and piston rings, also degradation over time can happen in combination with microbial growth. Some biofuels such as straight vegetable oils (SVOs) can have a high viscosity and boiling point which can reduce the engine lifespan due to carbon deposit build up. Fatty acid methyl ester (FAME) has a lower boiling point and viscosity but higher flash point which degrades quickly in water and has a high cloud point which can result in filter clogging & poor fuel flow at low temperatures. To mitigate these risks fuel standard can be applied and continuous fuel testing to biofuels used in bunkering should be carried out.

Batteries and fuel cells technologies could be used in combination with some of the fuel options. They would also require risk assessments for marine applications. For example, there is a wide variation of battery requiring specific regulations and testing requirements to mitigate against specific failure modes (e.g. performance and health degradation at adverse temperature operations, thermal runaway). Fuel cells undergo a chemical process to convert chemical-based fuels into electricity, their lifespan is highly dependent on the quality of the fuel used, and the main hazards with such a technology result from uncontrolled reactions, loss of containment of fuels and side reactions.

3.4.7. What should research and development focus on?

Based on the assessment presented in this section, most of the technology components for the use of zero carbon fuels on board ships have been validated and are available with the notable exception of SOFC or other fuel cells. However, in many cases existing technologies need to be scaled-up, applied in a maritime environment, and different components need to be integrated in a maritime propulsion system.

It is therefore recommended that R&D should be focussed on:

Fuel cells that can use other fuels than hydrogen, especially ammonia and methanol:

- scaling up, cost reduction and marinisation (development specific for marine uses and environments) of fuel cells to a scale that is relevant for maritime applications: 5–50 MWe;
- technologies for low cost onboard storage of hydrogen and ammonia in particular.

These topics are not tightly linked to the use of zero carbon fuels in the marine industry because they are relevant for the use of hydrogen and ammonia in energy systems in general.

For the shipping sector, the most important barrier that has to be overcome is that technologies have to be integrated in marine propulsion systems and tested on-board of ships. It is recommended that the R&D activity focusses on the systems integration. In doing so, regulatory and infrastructural hurdles can be identified and addressed.

3.5. Conclusion

In order to meet the 2050 level of ambition of the Initial IMO GHG Strategy and fulfil its vision, the shipping sector has to transform swiftly from relying on fossil fuels to using zero carbon fuels. The global technical production capacity will probably not be a constraint for any of these fuels, and most of these fuels have a similar level of technical development, i.e. the technical feasibility has been proven, but often not at a scale that is relevant for the maritime sector nor in a maritime environment. Moreover, the integration of the technologies is only starting to occur in some pilot projects.

So whilst it is clear that the shipping sector in, say, 2050 will be very different from the shipping sector today, there is uncertainty about the route that will be taken as there are many fuel/technology combinations that could become important over time, and given the uncertainty about which will prove to be most competitive in this timescale.

With a few exceptions, the sector currently relies on internal combustion engines running on petroleum-derived fuels. This propulsion technology could continue to be the case in the future if biofuels, e-methanol or ammonia will be used as fuels. Biofuels and methanol can be used without or with relatively modest changes to the fuel systems and engines, even for existing ships. One technological pathway could then be that these fuels are used in internal combustion engines of both new and retrofitted ships, potentially in a dual-fuel setup while the global production and bunkering industry is expanding. Using ammonia in internal combustion engines requires more modifications as well as modifications of fuel tanks and systems, as well as technologies to limit the emissions of NO_X and ammonia.

In order to support this pathway, research should focus on the production of sustainable biofuels, e-methanol and ammonia, as well as on the integration of fuel systems for ammonia.

Another pathway would be a switch from internal combustion engines to fuel cells as the primary way to convert energy on-board ships. This would be compatible with the use of hydrogen, ammonia and methanol as fuels, although biofuels can also be used in certain types of fuel cells.

In order to support this pathway, research should focus on the production of sustainable hydrogen and ammonia, on the further development of fuel cells, on the fuel systems that can handle either compressed or liquefied hydrogen, as well as on the integration of fuel systems for ammonia and possibly other fuels.

Neither of the two pathways described above is clearly preferable. The former has the advantage that it is closer to the current technology, but it may rely considerably on biofuels of which the production potential appears to be smaller than for electrofuels and which may have a higher risk of being unsustainable. The latter can use electrofuels which appear to be able to produce in abundant quantities, however they require more technical development.

With a view to the limited amount of time available to transform the industry, the best policy could be to support the development of technologies for both pathways.

4. Conclusions

The Initial IMO GHG Strategy envisages to phase out GHG emissions from shipping as soon as possible in this century. This report has laid out several promising fuel/technology combinations and pathways for transformation of the sector, which would be able to fulfil the vision of the Strategy.

In some of these pathways, ships would continue to be powered by internal combustion engines which would no longer run on fossil fuels but instead on biofuels or fuels produced with renewable electricity or – in a transitional period – with carbonless fuels that are produced by sequestering the carbon and storing it indefinitely. Apart from biofuels, viable fuels include ammonia and methanol.

In other pathways, ships would be powered by fuel cells, which would run on hydrogen, ammonia, methanol or other fuels that are either generated with renewable electricity or in combination with carbon capture and sequestration.

None of these technologies are currently available on the market at a scale that enables a transformation of the industry. Most technologies are already used on land, or separately, but much development is needed to scale up the technologies to the requirements of the maritime sector, to integrate components into systems and test them in maritime environments.

The technology needs to be developed urgently. This report shows that, if shipping is allocated a share in the global carbon budget that is proportionate to its current share in annual emissions, after 2030, it would have 4-9 Gt CO_2 left to emit if it wants to constrain the temperature increase to 1.5°C, or 10–20 Gt if 2°C would be the limit. The emissions from the shipping sector currently amount to approximately 1 Gt CO_2 per annum. So the transition to zero carbon shipping needs to take place rapidly.

The time available for a transition to zero carbon shipping can be prolonged somewhat by implementing short-term measures to reduce GHG emissions from shipping.

Apart from meeting the levels of ambition of the strategy, there are other advantages of improving the energy-efficiency of shipping in the short term. New fuels are projected to be substantially more expensive than fossil fuels, partly because the damage that fossil fuels do to the climate and the environment is not reflected in their price. If ships improve their efficiency, and lower the amount of energy they require to perform a unit of work, the price increase of using zero carbon fuels will be smaller.

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A Technology assessment of fuels

In order to phase-out greenhouse gas emissions of shipping, the sector has to shift away from fossil fuels towards zero carbon fuels. At present, there are several candidate fuels that all have been portrayed as potential future fuels but none of them is widely considered to be the fuel of the future. Instead, several publications have indicated that the future may have more different fuels and that their properties may be more diverse than the fuels that are currently predominantly used in ship propulsion.

This Annex provides an overview of the fuels that can be produced without emitting greenhouse gases and that also do not emit them when used onboard ships. For each fuel, it describes the production method or methods and the technical and environmental constraints and barriers to their production, as well as to their use in both existing and new ships. It identifies research and development needs and non-technical barriers to the use of fuels.

The Annex identifies the technical readiness level (TRL) for the production of the fuels as well as for their use.

The reference period of this study is 2018 to 2030. All the assumptions and predictions made in the study focus on the zero carbon production capability, scalability, technical availability, feasibility and market readiness of the alternative fuels and the energy efficiency technologies are assessed for this specified time period under the assumption that these fuels are ready for the maritime industry to take it up from 2030 onwards that would support the goal of staying within the

Every fuel has to fulfil two criteria's to attain the zero carbon fuel status:

1. Zero emission during the production (Well to tank, in terms of emission analyses).
2. Zero emission during the combustion (Well to wheel or Well to propeller, in the case of shipping).

With the above two criteria playing a vital role in the decision making process, we see that currently there are only two pathways that could potentially help us this status. The two pathways are:

1. Electrofuels.
2. Biomass.

Below we shall explain briefly explain the production process and the potential capability of the process to help us achieve a zero carbon fuel.

Electrofuels: Electrofuels is an umbrella term for carbon based fuels e.g. methane or methanol (Maria Taljegard, 2016) which are produced using electricity as the primary source of energy. Electrofuels could play an important role for the decarbonisation of the transport sector but also could contribute in balancing the energy system (can be used to store oversupply of renewable energy production). The pursuit for renewable fuels of non-biological origin was the basis for the production of electrofuels also known as power to liquid (PTL) or gas (PTG).

Production (Power to liquid or gaseous fuels): Electrofuels are fuels produced from two basic ingredients: carbon dioxide and water (T&E, 2017) making it possible to attain both liquid and gaseous fuels. The fundamental building block of electrofuel production is electrolysis where the water is broken down into hydrogen and oxygen with the use of electrical energy. The hydrogen along with CO_2 (The source of CO_2 should be from non-fossil source i.e. captured from various industrial processes such as exhaust gases, the sea or the air to attain the low or zero GHG intense status) is fed into a synthesis reactor to form different types of energy carriers. High purity oxygen and heat are the residues from the above mentioned production process. The term electrofuels can cover a range of energy carriers. We have taken into consideration four energy carriers based on the recent interest and research that is taking place in the shipping industry to move away from fossil fuels. Each of their production process will be discussed under their respective sections briefly to highlight the importance of the life cycle emissions.

The above mentioned criteria would help us to narrow down an electro fuel for further technical analysis. Electro fuels taken into account for analysis are:

- power to Methanol (CH_3OH);
- methanol to drop-in synthetic fuels such as Di-methyl ether (DME);
- power to Hydrogen (H_2);
- power to Ammonia (NH_3).

All the above production methodologies will be discussed under separate particular section in depth. None of these fuels are currently produced at an industrial scale. There are barriers related to the specific fuels, and also barriers that are common to all electrofuels. These are discussed below.

Barriers for electro fuels:

- **Cost:** High current cost of electrofuel synthesis is a primary barrier which reduces its competitive advantage with fossil fuels. A 2017 study by (T&E, 2017) estimated the cost to be 3,000 €/tonne compared to 454 € for a tonne of IFO 380 and 705 for a tonne of MGO during the time of writing this report.
- **Renewable electricity and time frame:** Lack of available renewable electricity in the EU grid mix reduces the possibility of rapid expansion within 2030 for the production of renewable electrofuels. According to the EU roadmaps, the amount of installed renewable energy sources in the EU will rise from 20% in 2020 to 30% in 2030 and will reach 50% in 2050. This raises the primary question on how does this surplus renewable energy that is required to produce electrofuels is going to be generated.
- **Land use:** Renewable electricity generation is the most land intensive part of the electrofuel production since large hectares of land is required. More data is needed to assess its feasibility for shipping with respect to land use.
- **Electrolysers:** Currently electrolyzes are usually designed to run at steady state with a constant load but for electrofuel to be power balancing (able to follow the non-dispatchable renewable power sources, the production process needs to be flexible. E.g. short ramp-up times and low start-up cost for the electrolyser. (Maria Taljegard, 2016) This can be fulfilled only either by PEM and SOEC, if heat sources are available (SOEC haven't entered the market during the time of the study).
- **CO_2 Source:** It would require 2-4 times more energy (5.4–9.0 MJ/kg CO_2) to extract the CO_2 from air compared to flue gases (Maria Taljegard, 2016). More energy efficient methodologies of extracting CO_2 from air is in its development phase and more pilot plants are needed to optimise the technology before 2030.
- **GHG Intensity:** Drop-in electrofuels produced with current grid average EU electricity would have a greenhouse gas intensity approximately three times higher than liquid fossil fuels (Cerulogy, 2017).
- **Technological status:** Production of electrofuels is still in its very early stage and significant amount of barriers need to be overcome both from technical (Sustainable mass production with high efficiency) and policy level (Expand

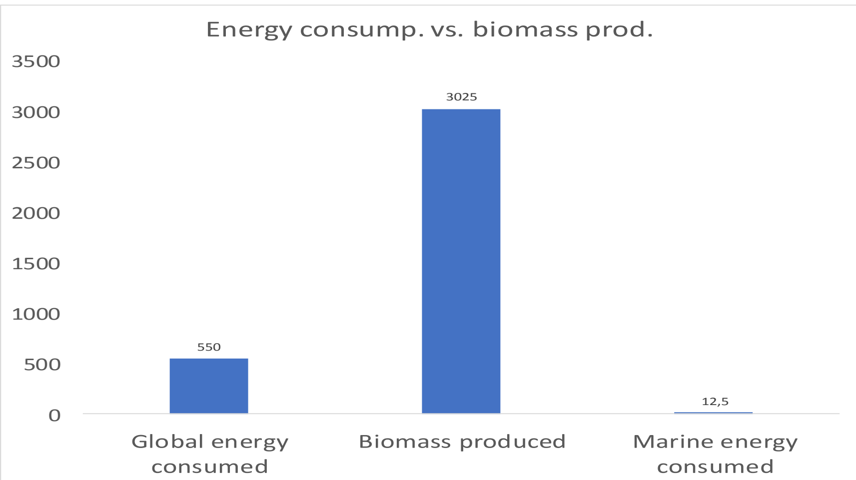
renewable electricity production on top of the needed electricity to produce electrofuels) before these products are brought to market on a large scale to support the shipping industry's need.

- **Lack of large scale plants**: During the time of the study, we were also not able to identify commercial large scale production of e-methanol other than the plant situated in Iceland producing only 5 million litters per year. Major scaling needs to take place to fuel an industry that consumes approximately 300 million tonnes of fuel per year.

Biomass: Biomass would be the second source available that could potentially help us achieve a near zero carbon fuel. Biomass residues from forestry could be used to produce alternative fuel production such as methanol and the use of lignocellulosic feedstock's to produce ethanol. The environmental benefits of fuels produced through biomass solely depends on the nature of the electricity used in their production. Zero emission status will not be applicable, if the electricity used in their production is not from renewable resources.

Future of bio mass availability: We have considered biomass sources that potentially does not compete with agricultural land as a selection criteria for the chosen alternative fuels which use biomass as a source. These biomass sources which does not compete with agricultural land is referred to as second generation feedstock. While some of the biomass sources are available in significant quantities not all the production route is technically mature, economically and environmentally viable for conversion. Estimates of US biomass indicate that it could be sufficient to supply around 80-100 billion gallons of gasoline equivalent of biofuels per year and depending upon vehicle efficiency and projections of the future travel demand this could be around 1/3 of transportation fuel demand in 2050 in business as usual scenario (Institute of transporation studies, 2011). It is fair to point out that this study did not separate biomass between the first generation and second generation (based on waste and residues). Limiting the use of specific biomass resources because of sustainability concerns will reduce their availability even further. The limitations on biomass is dependent on the specific feedstock, regional availability and conversion pathway to produce the needed biofuel. But in a global scale, the below graph taken from (University of Copenhagen, 2018) shows the availability of the biomass in comparison to global energy consumed and marine energy consumed. The future regulations, certification and sustainability criteria's are ongoing and that will dictate its role in the future but in terms of availability. it is one of the largest renewable energy source available (Felby, 2018). The energy consumption is measured in EJ.

Figure 14 – Energy consumption and biomass production



Carbon foot print: CO_2 from combusted fuels produced using biomass is considered climate neutral since it is assumed that CO_2 emitted biomass based fuel is removed from the atmosphere once new biomass grows to replace the biomass used to produce the fuel (DNV GL , 2016).

Please note that, usage of biomass could produce other pollutants such as NO_x, PM and black carbon especially when they are produced in large quantities and the production is concentrated in a single location. These emissions could have harmful effect on humans.

Barriers: Both of these sources has their own disadvantages and barriers. Below, we shall discuss the barriers possessed by these two production pathways. These barriers apply for all the six different types of alternative fuels (Not applicable for batteries) discussed below. Under the each section of the fuel would only focus on the barriers that are fuel specific.

Barriers for biomass:

- **Biomass demand:** Syngas produced from gasification process is suitable for bio-methanol production but it requires large amounts of bio-mass for large scale bio-methanol production.
- **Optimal use of bio-mass:** Bio mass feedstock to produce bio-methanol may compete with the use of biomass for other products and commodities such as biofuels, electricity, chemicals and plastics.
- **Regional restrictions on biomass:** If the bio mass supply is limited in a certain country this would lead to the use of fuel oil to supply heat and this would contribute to a significant increase in CO_2. This can act as a barrier during scaling up in certain countries with limited supply.

A.1 Methanol

Description:

Methanol is the simplest alcohol that is light, volatile, colourless, flammable liquid with a distinctive odour and high toxicity. Methanol is used as an antifreeze, solvent, fuel, denaturant for ethanol and also for producing biodiesel via transesterification reaction. Methanol can also be produced from coal (high GHG emissions), biomass, waste, or hydrogen and carbon dioxide (electrofuels) or using biomass.

Methanol found its relevancy within maritime transport as an alternative fuel for smaller vessels mainly in response to air quality regulation. Even though the NO_x emissions are slightly higher than with LNG, the storage is easier and the entire installation can be smaller in size while reducing the modifications and simpler than LNG (TU Delft , 2017).

Production (Sources used):

Interest in methanol as a marine fuel began when it was discovered it was possible to produce methanol with renewable feedstock such as municipal waste, industrial waste, and biomass. Currently the two commonly used feedstock are glycerol from bio diesel production and black liquor from the pulp and paper industry. We will discuss in short both production process.

Glycerol production pathway:

The core ingredient here is Glycerol which is one of the by-products of transesterification of fatty acids to produce bio-diesel (DCMR, 2013). Glycerol is gasified in water with supercritical conditions of 600°C and 300 bar which forms syngas (a gas mixture of carbon monoxide and hydrogen). The syngas is then converted into methanol at a low temperature and high pressure.

Biomass production pathway (Black liquor):

Bio mass residues from forestry are used to make black liquor in pulp and paper mills, where it is normally combusted to generate energy. If black liquor is gasified in an oxygen rich atmosphere and is used for methanol synthesis from the resulting syngas.

Black liquor is available in large quantities and about 400 million tonnes of pulp and paper products are produced every year (TU Delft , 2017). For manufacturing every tonne of pulp approximately seven tonnes of black liquor is produced. The cost of methanol production from CO_2 is 500-600 euros/tonne compared to production from bio-mass is approximately around 300-400 euros/tonne which minimises the barriers for scaling up (N.S. Shamsul, 2014).

Bio-methanol produced from biomass using gasification process has showed a conversion efficiency of 54%. Methanol exhibits more efficient energy storage with a higher volumetric energy density(99gL-1) than liquid hydrogen (71gL-1) and eliminates the requirement of cryogenic tanks.

The environmental benefits of methanol are highly dependent on the raw materials that is being used since the lifecycle emissions of bio methanol are similar to those of fossil fuels if it is produced with electricity from fossil fuels. Production with renewable electricity will be the determining factor.

CO_2 from combusted bio-methanol is considered climate neutral since it is assumed that CO_2 emitted biomass based fuel is removed from the atmosphere once new biomass grows to replace the biomass used to produce the fuel. (DNV GL , 2016).

Bio MCN in the Netherlands operates commercial scale plant producing bio methanol from glycerine. At present, about 200,000 tonnes of bio methanol is produced every year (TU Delft , 2017).

The above brief analysis portrays that bio-methanol has the potential to reduce GHG emissions significantly and its level of reduction is directly dependent on the electricity mix that is used for production. Bio methanol produced through renewable electricity will be the scope for further technical evaluation below.

Electrofuel production pathway (Power to CH3OH):

Methanol synthesis process can be used for liquid production of e-methanol based on the conversion of CO_2 And hydrogen generated by renewable sources. Small molecules like methanol seems more preferable since larger molecules like ethanol requires additional steps that adds up to the efficiency losses and additional need of energy.

In Europe, during the last decade several demonstration facilities of electrofuels have been developed but most of them focus on hydrogen production while some facilities focus on capturing CO_2 and the production of hydrocarbons, mainly methane or methanol (Maria Taljegard, 2016). One examples of these facility is Carbon recycling international (CRI), which produces 5 million litres of methanol per year (Carbon recycling international, 2018).

Three types of sources of CO_2 that can be potentially used as input to withheld the status as a sustainable alternative are:

1. CO_2 from biogenic origin.
2. CO_2 from the atmosphere.
3. CO_2 emitted from fossil fuel production or power stations.

The total amount of CO_2 demand is 1.46 t/t methanol, if captured from the atmosphere (Mar perez fortes, 2016).

Based on the above finding on the possible renewable production process and the availability of an established production unit have fulfilled our criteria and allowed us to consider e-methanol for further technical analysis.

With further chemical processing, e-methanol can be synthesised into Di-methyl ether (DME). Methanol to drop-in synthetic fuels DME has not been taken into account for further study as an energy carrier even though DME has shown clear signs of its potential to play a role in the future marine alternative fuels. This is due to the fact that it requires further chemical processing which in turn makes it more energy intensive to synthesise (Power To Liquid) methanol or e-methanol into drop-in DME. This energy intensive process will face the similar barriers that NH_3 and H_2 faces.

Outcome (Production):

Power-to-methanol is still limited due to lack of surplus renewable electricity. Currently glycerine (by-product from bio diesel) and black liquor are used as a feedstock for bio methanol production in large scale. As DNV GL stated in their study in 2016 thatthis eventual transition to bio-methanol will act as the ultimate environmental motivation for using methanol on ships (DNV GL , 2016).

Carbon foot print (Well to tank – Total emissions of extracting raw materials, producing and transporting the fuel) and tank to propeller (the emissions from combustion and potential leakage):

The CO_2 emissions depend on where and how the project is implemented e.g. in Finland by using average emission factor from IEA, the production footprint would be 25.5 kg CO_2/GJ where as in Russia with the same production conditions but varying electricity mix, it would be 67.6 kg CO_2/GJ compared to a total of 92.8 kg CO_2/GJ for methanol produced using fossil fuels. This contradiction and its dependency on the electricity mix, in itself, could act as a major barrier. Please note that these are based on the current emission factors, if the electricity is from renewable sources emission factors will be lower. So far Finland, Sweden, Portugal and Spain can produce methanol with the lowest CO_2 footprint (DNV GL, 2015).

From the combustion point of view, bio-methanol proves to be climate neutral and not considered as a GHG gas, this gives us the basis to conclude that bio-methanol using renewable electricity has the potential to reduce GHG taking into account both well to tank and tank to propeller emissions to a very low level but not in itself act as a **zero emission fuel.**

Barriers:

An holistic approach by taking into consideration the entire life cycle of Bio methanol is studied to identify and formulate the below mentioned barriers which also indicates the problems that exist in scaling up towards the mass implementation of bio methanol for shipping:

- **Cost:** Production cost of bio-methanol is between 1.5 to 4 times higher than the cost of natural gas-based methanol (IRENA, 2013).
- **GHG (CH_4 & N_2O):** They are not emitted in large quantities during the combustion process but should be taken into account since they are emitted during the production process which has significant global warming potential of 25 and 298 for 100 year time horizon.
- **Energy efficiency (Biomass):** The energy efficiency of methanol production via biomass is estimated to be lower (50 to 60%) compared to production from natural gas (60 to 70%) (IRENA, 2013)**.**
- **Gasification - Environmental impact:** Gasification can affect the environment negatively by the emission of pollutants such as ash, tar, particulates and CO_2 (N.S. Shamsul, 2014).

Outcome (Barriers): Most of barriers with respect to successful demonstration of the production of bio methanol with black liquor and glycerine have crossed the demonstration stages. The barriers that is standing in the way for mass production of bio-methanol are **bio mass availability and inexpensive availability of renewable electricity.**

Technical feasibility:

- **Applicable to fleet families:**
  - Bio-methanol is applicable as a fuel to all ship types especially with compatible business cases for chemical tankers but no engines are commercially available for the smaller marine engine segment (Up to 1,200 kW range) and the requirements for larger space for fuel storage may limits its applicability for existing vessels. Currently research is taking place to develop methanol engines for smaller ships under the "SUMMETH" project.
  - Engines needs to be retrofitted to accept e-methanol as a fuel achieving the same efficiency with lower emissions compared to current petroleum-based fuels.

- **Technical requirements for installations (E.g. Modifications, required space, state of the engine, mass production of engines, yards, bunkering, storage, handling, combustion, engines reaction with Methanol):**
  - Methanol can be used as a marine fuel in diesel engines with minor modifications, although dedicated methanol engines would probably be more fuel efficient with dedicated tanks and piping systems (Karin andersson, 2015).
  - Wartsila tests indicate that the fuel efficiency is the same or better when running on methanol on methanol fuelled dual fuel engines. Stena's experience indicated that they have better fuel efficiency in the order of 1-2% (This efficiency gain has not been documented as it is based on the ship owners reporting).
  - Both two stroke and four stroke methanol engines have been developed for new builds.
  - Energy density is about half of fossil fuels which increases the space requirements for fuel storage which might pose a problem for mass implementation in existing vessels.
  - Several engine models can be retrofitted but this does not apply to older marine diesel engines (Methanol institute, 2015).
  - Specific locations for fuel tanks are recommended when carrying methanol (DNV GL , 2016).
  - Double walled high pressure fuel pipes should be installed for safety purposes as a requirement for low flashpoint fuels.

- **Installation:** Apart from "Stena lines" retrofitted ro-ro passenger vessel, currently there are three chemical tankers which ran successfully for an year and four ships waiting to be delivered by waterfront shipping under construction which will ship methanol and run on their cargo.

Technological readiness:

- Production: TRL 6 (Technology demonstrated in relevant environment).
- Technical feasibility (On board): TRL 7 (Technology validated in relevant environment).

The technology readiness level of 7 for on-board feasibility is given after an complete assessment of successful sailing of a retrofitted dual fuel methanol engine in a 24 MW Ro Pax ferry. This along with the summary of technology readiness performed by (DNV GL , 2016) which indicated that all the technologies expect four systems namely:

1. Fire detection - IR CCTV, additional LFL engine monitoring system.
2. Additional methanol fuel injection system.
3. Purge return system.
4. Fire detection to engine room – IR CCTV.

These are relatively new in the maritime industry but other than these four all the systems in the entire life cycle (bunkering, storage, handling and combustion) of methanol as a marine fuel has reached the level of maturity. The assessment also added that the methanol fuel system consist mostly of well-known components and that the individual components are of a mature technology and have been used in the maritime industry (DNV GL , 2016). The above arguments convinced us to designate the above mentioned TRL status.

Non-technological maturity: (Legal, financial, knowledge, market, culture, others):

- Regulations to support the retrofit or for new builds vessels are in place (The IGF code which introduces safety regulations for gas fuelled ships with low flash point came into force on 1st Jan 2017).
- There is a mandatory class notation called LFL FUELLED prepared by DNV GL for ships using methanol as a marine fuel which covers aspects such as materials, arrangements, fire safety, electrical systems, control and monitoring, machinery components and some ship segment specific considerations.
- There is a certain level of acceptance and willingness to explore methanol as a fuel for marine applications from ship owners but lack of incentives and reliable global supply infrastructure has stopped them from installations. This statement is an assumption made from the concerns raised by methanol engine manufacturers.
- Its toxicity could pose a problem for the crew on board which requires investment in knowledge building in creating the acceptance and safety culture on-board.
- Research work done by methanol institute has well documented the barriers and challenges with a methanol engine which provides sufficient knowledge for ship owners and other stakeholders involved in decision making.
- Enough knowledge has been gained with respect to modifications of engines have been derived mainly from three projects SPIRETH, and EFFship.

Market ready by 2030?: The possibility of bio-methanol to fuel the marine industry to keep the CO_2 level within post 2030 carbon budget is possible but not in the business as usual scenario due to lack of incentives and policies to address the two main key issues:

1. Sufficient investment in renewable electricity infrastructure on top of the electricity produced to produce bio methanol.
2. Sufficient incentives to segregate between methanol produced via LNG and bio-methanol which can foster the R&D in optimized production techniques and ultimately making it competitive with LNG based methanol.

Conclusion:

In 2016, a report by the European commission's joint research centre on alternative fuels for marine and inland waterways concluded that methanol and LNG are currently the most promising fuels for shipping. This is evident from the amount of research and demonstration that has taken place both in terms of renewable production and technical feasibility for maritime transport. But it is fair to point out that the EU report, did not distinguish between methanol and bio-methanol. Policies should be adopted that would foster the growth of large scale bio-methanol production sustainably and optimally by crediting the environmental advantages across the entire life cycle from feedstock to end-use which could possibly include eco-labelling, incentives, carbon tax, information campaigns. Since the technical feasibility has reached an acceptable stage of maturity, the scaling up of production of bio-methanol and the infrastructure needed to store and handle bio methanol will provide the necessary confidence needed by ship-owners to take the leap.

A.2 Ethanol

Description:

Ethanol also known as ethyl alcohol, pure alcohol, grain alcohol or drinking alcohol which is often abbreviated as EtOH. (European biofuels technology platform, 2011). It is a colourless flammable liquid. Ethanol is the most widely used as biofuel in land based transportation and can be found at most large chemical storage hubs in Europe. Bio ethanol is produced by two different types of feedstock, we shall discuss both of them briefly below to understand the process but to stay within the scope of this paper, we shall look into bio ethanol produced from second generation feedstock's due to its low carbon intensity. Ethanol along with methanol gained its relevancy as an alternative fuel for maritime transport to reduce both sulphur emissions and carbon footprint in the wake of European commission sulphur directive.

Production (Sources used):

Feedstock based production pathways:

Bio ethanol is mainly produced from biomass with the majority on the world produced from feedstock's such as corn and sugarcane. Production of bioethanol involves the microbial fermentation of sucrose, starch or cellulose (glucose based feedstock's) to ethanol (IEA Bio energy, 2017). Carbohydrates from feedstock such as sugarcane, corn and sugar beets are extracted and hydrolysed to glucose before fermentation to ethanol. Even though using feedstock's proves advantageous since the production methodology, infrastructure and the know-how is already in place, this is expected to be unsustainable in the long run to meet the energy demands of shipping especially since sugarcane or corn are consumable food stocks that have low yields per hectare and the legislation from the EU parliament which limits the crop based bio fuels to only 7%. These two factors currently limits bio ethanol from feedstock's entering the shipping market.

The above rationality naturally inclines the attention towards the use of second generation feedstock based bioethanol production which uses lignocellulosic feedstocks (woody biomass, agricultural residues such as corn stover, wheat straw and grasses). Bio ethanol from second generation feedstock will be the scope of our further technical evaluation along with assessing its potential and barriers to fuel the shipping industry. But this process comes with its own disadvantages especially being energy intensive and requiring more steps than the first generation feedstock method but offsets with advantages such as cheaper feedstock and more yield per hectare are evident.

Outcome (Production):

Bio ethanol production through second generation feedstock exists but very low at present. The production process is mature with a relatively high number of research and development initiatives with first demonstration plant already in place. The study conducted by (Ecofys, 2012) identifies a list of total 87 pilot and demonstration plants based on lingo-cellulosic biomass as of Jan 2012 in Europe, USA and Brazil.
The demonstration projects is expected to streamline the technology to scale up their capacity.

This indicates that bio ethanol from second generation feedstock is commercially available as a marine fuel since the commercial production of bioethanol is almost twice as much as bio diesel and widely used in the road transportation sector along with this, they also possess the high supply potential capable of replacing all fossil fuels in the shipping sector (IEA Bio energy, 2017). Scaling up the production could reduce the cost and make it more competitive not only with fossil fuels but also among other alcohol based fuel such as methanol which can increase the trust and attractiveness among ship-owners especially for new builds.

Carbon foot print:
The greenhouse gas equivalents as an indicator of global warming potential varies according to the feedstock used. Well to tank emissions from ethanol are lower than fossil fuels but the amount varies with different production methods and feedstock's. But bio ethanol from second generation feedstock proves to be more favourable compared to the former. The below table taken from (IEA Bio energy, 2017) indicates the difference with respect to life cycle GHG emissions.

Table 3 – Production process

Production process	CO_2 emission on combustion (g/MJ)	Life cycle GHG equivalent (g/MJ)
Bio ethanol (1st gen)	72-81	34
Bio ethanol (2nd gen)	72-81	24

Source: (IEA Bio energy, 2017).

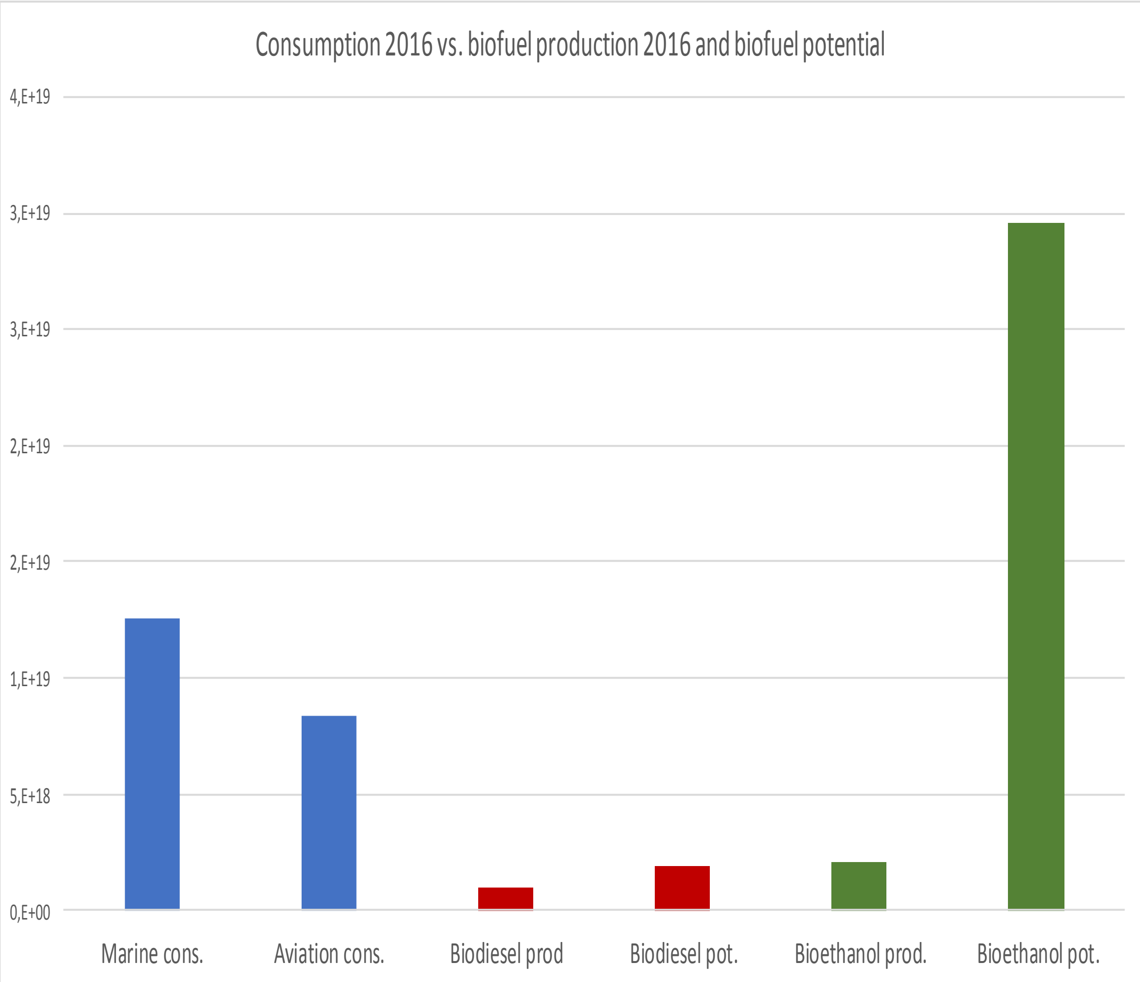
Barriers:
An holistic approach by taking into consideration the entire life cycle of Bio ethanol is studied to identify and formulate the below mentioned barriers which also indicates the problems that exist in scaling up towards the mass implementation of bio-ethanol for shipping:

- **Availability of feedstock:** To increase the production volumes at a scale suitable for marine shipping, the industry would have to introduce lignocellulosic feedstock into the production mix to create the transition from first to second generation but the availability of this needed supply to keep the production and cost sustainable is questionable.
- **Second generation feedstock:** Currently there are only two refineries in EU that produce bio ethanol for fuel in large scale where as there are 71 refineries which produce bioethanol with first generation feedstock. 2018 annual production of bio ethanol is projected to be only 60 million litres out of the total 5,380 million litres (USDA Foreigh agricultural service, 2017) This data gives us an overview on the current percentage share of second generation bio ethanol.
- **Low EU production share:** With 84.5 billion litres of bio ethanol produced in 2011 of which EU share is only 5% but this production is still grain based from countries like France. Even though we do not possess the share of EU in 2018, based on the above data from (USDA Foreigh agricultural service, 2017) the share has not increased in the past 6 years. A major shift to second generation feedstock based bio ethanol is needed to open the pathway to stay within the post 2030 carbon budget.
- **Limited knowledge/experience:** Along with lack of installations on board, there is also a lack of studies (other than then the study by EMSA) that provides the sufficient technical assurance and knowledge to increase the trust among ship owners.
- **Additional processing for drop in quality:** Bio ethanol is usually blended with gasoline for use in petrol engines and cannot be used as drop in fuel for marine diesel engines. It has to go through the additional processing steps such as deoxygenation to obtain a high H:C ratio.

Outcome (Barriers):
Above mentioned barriers indicates that even though fuelling the shipping industry with second generation bio ethanol is possible and bio ethanol is the only renewable alcohol that is available in commercial quantities (University of Copenhagen, 2018). The infrastructure needed to supply the quantity needed by the shipping industry is not available yet. With several project aimed to tackle this, we hope to see the interest

among ship owners (new builds) to use it as an alternative fuel in a dual fuel or multi fuel engines in diesel cycle. The below graph indicates the bio ethanol potential vs production from the second generation feedstock which clearly states the gap in scalability that needs to be filled.

Figure 15 - Bio ethanol potential vs production



Source: (University of Copenhagen, 2018).

Technical feasibility:

- Applicable to fleet families:
  - Technical compatibility for medium speed for both auxiliary/main engine and for low speed main engine seems to be incompatible technically (Ecofys, 2012). This limits the possibility for installation for a large group of fleet families. For shipping, it is recommended to be applied only for high speed main and auxiliary engines.
  - Most current marine engines can operate successfully on ethanol blended fuels only up to 10% (Renewable fuels association, 2014) and most of the dual fuel engines of low flash point nature can use ethanol as a fuel in a diesel cycle so ship engines have to be modified for old vessels (which is highly unlikely to happen due to lack of incentives) for mass implementation.

- Technical requirements for installations (E.g. Modifications, required space, state of the engine, mass production of engines, yards, tanks and pipe, engines reaction with Ethanol):
  - Energy density is about half of HFO which increases the space requirements for fuel storage which might pose a problem for mass implementation in existing vessels.
  - Out of all the bio fuels, Bio ethanol has the highest mass with mass needed is 213% compared to fossil fuel and volume needed is 200% for a mono ethanol fuel engine. This makes the current fuel tank structure and capacity redundant while separate tanks with minor modifications (e.g. Right paint and correct fuel lines are needed) (Ecofys, 2012).
  - Corrosive in nature so material selection for tank coatings, piping, seals and other components restricts compatibility for existing vessels.
  - Flash point is below the minimum flash point for marine fuels which means additional risk assessment or evaluation must be carried out.
  - It has low vapour pressure (Ecofys, 2012) which means it possess problems to start engines at low ambient temperature. Without aids, mono fuel bio ethanol engine cannot be started at temperature below 20ºC.
  - It attracts water which means that extra measures must be taken in handling, transportation and storage.
  - It is possible to use bioethanol in multi fuel engines (engines which are designed to accept low flash point fuels such as MAN ME -LGI engines but the share of multi fuel engines for both old and new vessels is speculated to be limited in the short to medium term which may pose a problem.
  - It is considered to have very poor lubricating property. This may pose warranty issues for old vessels with dual fuel engines that is compatible with bio ethanol.
  - With the experience of Scania (Bus) engines running on ethanol, the possibility of applying bio ethanol in diesel engines as a clean fuel exists with the help of glow plug ignition and an ignition improver (SCANIA, 2017) but there is no technical evaluation available so far on the possibility of this in marine engines.

- Installation:
  - 1.No projects have been identified for ethanol on ships, we assume that it could be due to the consistently high price of ethanol as compared to methanol and the lack of suitable mono fuel engines for retrofit and new installation, making it unattractive as a primary candidate for a ship fuel even though Ethanol has been used in diesel engines in road transport for many years (Joanne Ellis, 2015).

Technological readiness:

Production: TRL 8 (System complete and qualified)

Technical feasibility (On board): TRL 5 (System prototype demonstration in relevant environment).

The TRL 5 has been given based on the availability of marine engines for selected fleet family. This is based on the assumption that these engines have been demonstrated in a relevant environment. Without being overly optimistic and also based on the evidences found from various studies we find that the current landscape indicated that there are more installations for testing and operation of methanol as a marine fuel compared to ethanol this has not helped this fuel to surpass its technology readiness to a level beyond 6.

The limitations to surpass the technology readiness of this fuel is evident both in production thru second generation feedstock (at present) and technical feasibility on board (mainly for old vessels or vessels intending to use mono fuel).

Non-technological maturity: (Legal, financial, knowledge, market, culture, others):

- Regulations to support the retrofit or for new builds vessels for bio ethanol are in not place (The IGF code which introduces safety regulations for gas fuelled ships with low flash point came into force on 1st Jan 2017 has only focussed on LNG, and methanol is under development during the time of the study).
- There are no mandatory class notations for Bio ethanol.
- The "Summeth" project aims to test and evaluate different methanol combustion concepts in a laboratory and this project included the testing of additive treated ethanol (ED95) in a Scania engine. This is the closest we have come in terms of testing.

Market ready by 2030? With the BAU scenario, the fuel will be available by 2030 especially with significant amount of demonstration projects with 2nd generation feed stock identified but we assume that it will not be market ready as there has been no indication of additional refineries other than the two identified ones. Below are some of the recommendations that could turn the tables around for this fuel:

- Sufficient investment in R&D is needed since during the time of the study, we found only two detailed studies that explains the possibility of bio ethanol in marine diesel engines.
- Incentives or subsidies should be in place to explore the technical possibilities that will enable to use this fuel for all types of engines along with retrofit options especially for smaller engine segment is needed.
- Majority of studies performed so far with respect to use of ethanol as a marine fuel has not clearly distinguished between the importance 1st generation feed stock and 2nd generation feed stock based bio ethanol. Any realistic opportunity for bio ethanol to play a part in keeping the shipping within the post 2030 carbon budget needs mass production from 2nd generation feedstock in Europe which clearly lacks at present.
- More ethanol testing on marine engines (under sailing conditions) should be conducted since during the time of the study no information on ethanol testing on marine engines has been found.

Conclusion:

Based on the above evidences on both the production and technical feasibility, it is highly unlikely that this fuel will be able to achieve the transition that is required with in the available time frame of eight years to meet the post 2030 carbon budget for shipping.

A.3 Di-methyl ether(DME)

Description:

Dimethylther (DME) also known as methoxymethane, wood ether, dimethyl oxide or methyl ether is the simplest ether (European biofuels technology platform, 2011). It was only used as an propellant gas for deodorant so far but now the possibility to use it as marine alternative fuel is being explored. DME can be produced by Methanol which in turn can be produced by methane. The molecule of DME is polar which means it can be mixed with water and other alcohols like ethanol and methanol (TNO et al., 2013). The cetane number of DME is between 55-60 which gives an idea about the will of the fuel to ignite compared to MGO having an cetane number of 45. The cetane ranking is an indication of the combustion quality of the fuel during compression ignition. This makes DME superior in terms of its ignition properties and a potential candidate among alternative fuels in terms of combustion properties for maritime transport when compared to HFO.

Keeping in mind, the aim of the report, the goal should be to produce DME via the organic route of methanol through the sustainable use of feedstock such as renewable biomass with renewable electricity and this will be the scope for our further technical analysis. We shall use the term Bio DME further in this study to indicate the production of DME thru above chosen pathway.

Production (Sources used):

DME can be produced both via electrofuels and biomass route, we shall discuss the production methodology briefly below.

Electrofuel production pathway:

With further chemical processing, e-methanol can be synthesised into Di-methyl ether (DME). Methanol to drop-in synthetic fuels DME has not been taken into account for further study as an energy carrier. This is due to the fact that it requires further chemical processing which in turn makes it more energy intensive to synthesise (Power To Liquid) e-methanol into drop-in DME. This energy intensive process will face the similar barriers that all the electrofuels faces only with an added requirement of energy.

Biomass production pathway:

DME is directly produced from syngas. Syngas can be generated either via fossil based fuels such as coal or renewable sources as biomass or renewable electricity. The chosen pathway is to produce bio methanol thru renewable means and the production of bio methanol by using both glycerine and black liquor has been discussed in detail in the section 1. From the produced bio methanol, DME (CH3OCH3) is a gas which can be produced by the dehydration of methanol (TNO et al., 2013). By the loss of water, one methanol loses its OH group and the other methanol connects to it, this forms the desired Dimethylether. The chemical processes involved in the synthetization of renewable bio mass feedstock are well established with reasonable efficiency.

Using DME as a fuel has not reached the commercial stage yet, mainly due to lack of large scale supply and distribution system for DME as a transport fuel (IEA-AMF, 2018) but demonstration projects are ongoing in road transportation sectors in both China and Japan and in maritime via the project "SPIRETH" in Sweden.

Currently for shipping, storage and loading of methanol as a fuel on board and converting the methanol into a DME fuel mix (DME (60% by weight, methanol and water) through the well-established OBATE process has been identified as a favourable option. OBATE is a fuel solution process where crude or regular methanol is feed through a catalytic process and transformed into OBATE methanol fuel, which is basically a mix of DME, methanol and water. The process is a catalytic reaction where two molecules of methanol can be processed into one molecule of DME and one molecule of water. This procedure was demonstrated and tested through the "SPIRETH" project on a Ro-pax ferry's auxiliary engine. The project has chosen this path due to the following benefits:

- excellent diesel fuel characteristics;
- better combustion properties than methanol;
- minimizing the requirement for modifications especially since DME is a gaseous fuel which needs new infrastructure or expansion of to load, store and supply the fuel on board.

Based on the benefits of the on board conversion of methanol into DME mix (DME, methanol and water) which requires less modification and infrastructure for bunkering along with the results of the project "SPIRETH" we have chosen this as our preferable path for our further technical analysis below. This pathway in no means changes the course of our research since we will still be focussing on the technical feasibility of burning DME on marine engines for both old and new vessels. The only advantage would be that the chosen pathway could reduce the bunkering modification and infrastructure costs and time that is needed to store, supply and load. With this technology, it is possible to achieve our goal within the specified time frame of twelve years (2018 – 2030). The lack of bunkering infrastructure along with low production capacity of Bio DME has been the primary barriers that prevents DME from entering the marine fuel market even after possessing the benefit as a drop in fuel.

Outcome (Production):

The production of DME through the organic route is matured and established with reasonable achievable efficiency. By producing Bio methanol, we can produce Bio DME.

Barriers:

An holistic approach by taking into consideration the entire life cycle of Bio ethanol is studied to identify and formulate the below mentioned barriers which also indicates the problems that exist in scaling up towards the mass implementation of DME (produced from bio methanol) for shipping:

- **Lack of data:** There is no clear data on the availability of DME through organic route of methanol. We have identified through our research that bio methanol production capacity is significantly low at present so this indicates that DME production through renewable means is either low or non-existent.
- **Lack of recognition:** DME has not still achieved any recognition as an alternative marine fuel and the production of it is very local and limited. During the time of the study, No policy nor initiatives exist in an European level to support ship owners who would be interested in testing this fuel.
- **Low Production (Europe):** ChemRec and Akzonobel are two European companies which produce DME in large scale and as a transport fuel most of the production and research is done in China at this moment (TNO et al., 2013). Nevertheless, the global production quantity of bio DME is very low.
- **Lack of Infrastructure:** Large scale maritime bunkering infrastructure is unavailable at this moment for DME.

Outcome (Barriers):

Currently, based on the above evaluation of the barriers. We see a clear lack of policies and incentives to support the already in place demonstrated technology both in terms of applicability in marine engine and the infrastructure needed to allow DME to enter the shipping market. Even though, it is evident from the "SPIRETH" project that DME marine fuel can surpass the need of bunkering infrastructure through the use of OBATE process on board, it has not reached the stage of technical feasibility to gain the trust from the industries stakeholders. Without addressing the lack of demonstration of DME marine fuel under sailing conditions, DME could stagnate in its current position.

Technical feasibility:

Along with the results of the project "SPIRETH", we have also looked into the lab testing results of the DME engine (1.25MW) built by Dahitsu and JFE engineering. We will share the technical issues and requirements faced by these two case studies below in the section (technical requirements for installation) which will bring to our attention the need for any further R&D, testing and demonstration of this technology to our reader. We believe that this will allow the shipping industry to become aware of the technical hurdles facing with respect to this fuel technology for all fleet families of both old and new builds.

- **Applicable to fleet families:** The project “SPIRETH” has proven to us that is feasible to convert ships (auxiliary engines) to operate on DME mix fuels. From technical perspective, this can be performed to main engines. Below we have looked into some pro and cons which could support our feasibility argument.
  - DME has better drop in properties compared to it alcohol counterparts and such as methanol and ethanol. DME can be used as a drop in fuel for marine engines for both old and new vessels with minor modification to the engine itself.
  - The project “SPIRETH” identified that the cost for conversion/adaption for using DME/methanol on board is a fraction of the cost of converting to LNG.
  - DME can be quickly liquidized at the pressure of 5-6 bars and does not require intense cooling like LNG or LPG which negates the need for complex storage and supply systems.
  - Methanol port infrastructure (store and fuel supply) can be used to support DME’s uptake as fuel with the possibility to convert methanol into dimethyl ether (DME) with the help of a catalyst on board conversion process called OBATE.
  - The high cetane number of DME contributes to cleaner air (Less NO_x and PM) and less noise.

Technical requirements for installations (E.g. Modifications, required space, state of the engine, mass production of engines, yards, Tanks and pipes, Engines behaviour with DME):

- The behaviour of DME in a diesel engine was recorded by means of an experiment by Dahitsu diesel and JFE engineering’s four stroke engine with a power output of 1.25 MW. The engine was running on MGO and DME and the results of the two different fuels have been compared. This is the only available evidence of DME’s reaction on an existing diesel main engine. This power output testing is too low for assessing its technical feasibility with large vessels since according to (IMO, 2014) 3rd GHG study, this is the average installed power of a bulk carrier of size category of 0 – 9,999 dwt. This proves that the technical feasibility of DME marine main engines has not crossed this threshold of lab testing.
- MAN diesel and turbo has developed DME engines that is applicable to all low speed engines categories which can be ordered either as an original unit or thru retrofitting. During the time of the study, there has been no evidence of this engines being used on board with DME as a fuel.
  Lack of experience (Main engines/Dual fuel), even though it is true that DME can be used to run diesel engines along with MGO. This has been proven thru an experiment under lab conditions by Dahitsu diesel and JFE engineering. No real life testing of DME as a fuel with main engines under sailing conditions has been done. During the time of the study, no proven installation of a DME engine on a vessel for main engines under sailing condition for commercial cargo ships of the three major categories (Tanker, Container and Bulk) exists. This decreases the trust and the willingness among the ship owners to explore DME as an viable option. Two Scania DI13 075M diesel engines with a power output of 323 kW and averageMGO fuel consumption of 215 g/kWh were modified to operate on a mixture ofdimethyl ether (DME), methanol and water (denoted OBATETM – On Board Alcohol To Ether) (Norden Energy and transport, 2014) This indicates the ability to retrofit auxiliary engines without a major issue.

- Lack of incentives or subsidies, there are no incentives or subsidies available for the early movers with respect to DME engine. We do recognise this is a barrier applicable to all alternative fuels but we have bought this up here especially due to its low capital cost with respect to ship modifications compared to its alcohol counterparts.
- DME can be used in compression engines with no need for after treatment for NO_x and PM. This is not applicable for spark ignition engines.
- The low density of DME results in poor lubrication and this acts as a major disadvantage since feed pumps, high pressure fuel pumps and injectors will experience more wear due to the absence of lubrication.
- According to (DCMR, 2013), lubricity additives were added to compensate but the results were unsatisfying and pumps still had premature wearing. This requires to explore the option of building a separate lubrication system which has the purpose to lubricate the moving parts of the pumps and injector. We again run into space restrictions with this new need.
- The compression energy required for compressing DME is greater compared to oil. This contributes to energy loss (DCMR, 2013) and ultimately to fuel penalty.
- Back pressure is experienced, when DME is injected into the chamber. This is due to the fact that DME must be pressurized to 5-6 bars. This backpressure affects the needle motion in the injector resulting in a negative influence on the efficiency of the engine (DCMR, 2013)
- The lower energy density of DME increases the requirements for larger space for fuel storage which may limits its applicability for existing vessels. DME has a lower energy density which means more DME should be injected per cycle to derive to the same output. This also increases the size of fuel tanks creating restrictions with retrofitting old vessels where space constraints exist.
- DME has a lower ignition delay since the spray angle of DME is wider than gasoil creating a better homogeneous mix of fuel and air.

Installation:

- An on board conversion of methanol into a mixture of DME, methanol and water has been considered and successfully tested using the Haldor – Topsoe's OBATE (On board alcohol to ether concept) since this would enable an easy on board storage of alcohol and the use of ether on a diesel engine. This has been successfully demonstrated and tested on board using an adapted diesel auxiliary engine on board the Stena Scanrail, a Ro-pax ferry that sailed between Gothenburg and Frederikshavn with the support from the "SPIRETH" project.
- During the time of the study, there has been no installation of marine (main) engines using DME directly as a fuel.

Technological readiness:

Production: Due to lack of information, we are not able to assess the technological readiness level for organic DME production route.

Technical feasibility (On board): TRL 5 system (Technology validated in relevant environment).

The production process of bio DME through bio methanol is well established but the lack of data prevents us from making any assumptions on the TRL levels.

The above technical feasibility (On board) analysis portrays that the knowledge of DME with internal combustion is high compared to ethanol but it faces the same problem as ethanol due to lack of installation. Without being overly optimistic and based on the evidence from the above mentioned case studies along with the indication from the study by the Royal naval engineers of Netherlands (Royal academy of engineering, 2013), DME propulsion could not be achieved in the short term (2018–2030). This led us to come to a conclusion that the DME engines have been validated in a lab along with the fact that for low speed engines DME engines are available. Even though the "SPIRETH" project has proved its applicability, it has been only used in auxiliary engines and this refrains us from giving a higher technological readiness level. Other than the "SPIRETH" project, there has been no proven evidence that DME engines have been used by any ship owner especially the ones that comprise the biggest market share in the commercial shipping such as tanker, container and bulk.

Non-technological maturity: (Legal, financial, knowledge, market, culture, others):

- The knowhow on the storage and supply of DME is already in place as its similar to the storage, supply and transportation of propane (LPG). Extension of LPG infrastructure could pave the way for DME fuel to enter the market.
- During the time of the study, there is no available legal instrumentation available from IMO to address the provision for arrangement, installation, control and monitoring of machinery, equipment and systems using DME. (The IGF code does not address DME).
- The risk and safety analysis in SPIRETH has contributed to the development of ship classification society rules (Lloyds register) for using DME mix as a ship fuel. (TU Delft , 2017).

Market ready by 2030? In the BAU scenario, we do not see the uptake of DME as an alternative fuel anytime soon especially due to its infrastructure and technical barrier. This raised the lack of mistrust among ship owners due to no real life sailing conditions data on some the major commercial cargo vessel categories (tanker, bulk and container). Existing market conditions does not support the uptake as well since LNG with its higher energy content (54 MJ/kg) is much cheaper than DME (31 MJ/kg) but much higher than methanol (19 MJ/kg). This eradicates any near term possibility on the uptake without supporting policies and carbon based levy.

Regardless of the achievements made with respect to DME engines (on board conversion of methanol into DME and DME based auxiliary engines). We are still far away to materialise the potential benefits of this fuel in the shipping industry due to lack of policy instruments, knowledge centre and awareness aiming to get the attention of the ship owners. This statement is also true with respect to LPG or chemical carriers for whom, the business case could be more interesting. Along with this we also clearly lack testing of this fuel under sailing conditions, we have succeeded in using it in a marine auxiliary engine but not on a main engine yet. For new built, even though MAN diesel has developed DME engines but it address only the slow speed segments which limits its application for the vast majority of fleet families.

Conclusion:
The study conducted (Chalmers university of technology, 2014) by department of shipping and marine technology, Chalmers university of technology which analysed the environmental performance of various fuels, DME and methanol have been selected as the possible future marine fuels especially Methanol and DME produced from 2nd generation biomass (willow or forest residues) have the lowest life cycle global warming potential (GWP) of all fuels compared in this study and could contribute to reduction of the greenhouse gases emissions from shipping significantly. But within the available time frame (2018 -2030), its highly doubtful, if it can be market ready to help the shipping to stay within the post 2030 carbon budget.

A.4 Biofuels

Description:
Bio fuels are basically any fuel that has been derived from biologically renewable resources (IEA Bio energy, 2017). They can be derived from three primary sources such as edible corps, non-edible crops (waste, or crops harvested on marginal land) and algae (DNV GL, 2014).

Biofuels production methodology is usually split into three categories:

1. **First generation:** Produced from animal fats and vegetable oils such as coconut, palm, rape seed, soybean and tallow. There are also commonly known as Fatty acid methyl esters (FAME). Bio diesel and bio ethanol were first generation bio fuels that was widely used.
2. **Second generation:** Second generation are produced from non-food corps and organic waste such as wood, organic waste, food crop waste and specific bio mass corps.
3. **Third generation or advanced**: It uses specially engineered energy corps such as algae as its energy source. The algae act as a low cost, high energy renewable feedstock.

Currently the industry has reached the initial stages of third generation based feedstock (Algae) bio fuel which possess the highest sustainability criteria while holding a very low GHG intensity. Third generation bio fuels will be the scope for our further technical analysis and we will justify this statement in the analysis below.

As per the study conducted by (DNV GL, 2014), the land required for production of 300 Million tonnes of oil equivalent (TOE) biodiesel based on today's (first and second generation biofuels) technology is slightly larger than 5% of the current agricultural land in the world. This may be a too large increase of land use. Therefore, this Annex focuses on he third generation or advanced biofuels as the possible alternative since it does not compete with food nor the use of agricultural lands nor compete with food production. Biofuels derived from algae has many benefits but nonetheless to make sure the volume needed to power the shipping industry is a challenge that have not been overcome yet.

Photosynthetic algae and/or cyanobacteria can be grown using saline and waste water (non-arable land or marine environment) creating a fuel with a high flash point. Even though algae feedstock's show a potential to be turned into fuels because the strains may have very high growth rates which ultimately translates to high biomass yield per hectares but unfortunately this was not evident in any of the demonstration nor the handful of commercial scale units at this point (IEA Bio energy, 2017). Currently three categories have been identified for future commercial development of algal biomass:

1. Conversion into lipid, protein, and carbohydrate fractions.
2. Thermochemical hydrothermal liquefaction.
3. Bio gas production from whole algal biomass.

Any advancements in the development of biofuels derived from algae will also depend on the price of the oil and gas. This raises two questions in the two key areas of this process, the technological maturity and the production capacity of this feedstock. There has been no data available that could provide us with some indication on the time span on when we could expect this fuel would enter the market in a commercial scale. But with the available knowledge on the technological maturity of this process, we can roughly assess the stage in which we are in. In June 2018, Exxon mobile along with its partners announced that they solved a key challenge by tweaking a particular gene in certain species of algae which could push them to produce 10,000 barrels of this fuel type a day in few years (Peters, 2018). This indicates we are still in the (technological) development phase and could possibly reach the stage of **demonstration in the next coming years**. So far it has been proven that the process of third generation bio fuels has the highest efficiency (conversion) over the long term due to its high photosynthetic efficiency and assuming the use of commercially mature process called transesterification. Exact conversion efficiency percentage is still debateable due to the ongoing research on this field. Normally algae have 20-80% oil contents that could be converted into different types of fuels such as kerosene oil and biodiesel (Suliman Khan et al., 2017). With respect to marine, the goal is to use this feedstock to arrive at a drop in nature bio diesel.

Outcome (Production):
Taking into account the current technological immaturity of producing third generation bio fuels in large scale, it is highly unlikely that this fuel can feed the shipping industry in the short term (2018-2030). As concluded by the report (IEA, 2017) which reviewed the technology of algae based bio energy concluded that to produce bio energy products like liquid or gaseous fuels is not foreseen to be economically viable in the near to intermediate future even though it has not clearly mentioned the definition of intermediate future. Based on current status, it seems we have significant barriers (especially in identifying suitable alga strains) to follow through before supplying an industry like shipping by 2030 can reach reality.

Barriers:
An holistic approach by taking into consideration the entire life cycle of third generation bio fuel is studied to identify and formulate the below mentioned barriers which mainly focusses on the problems that exist in scaling up towards the mass implementation of this fuel for shipping:

- **Cost:** The processing (cultivating and harvesting) cost of third generation bio fuel is very high and the single biggest barrier faced by the industry now. This reduces its chances to compete with other fuels including alternative fuels.
- **Operational cost:** Extra voyage cost was the only projected operational cost contribution concluded by the study (Lloyds register and UMAS, 2017) for using bio fuel in comparison with the 2017 oil prices.
- **Processing cost:** After harvesting the algae, the biomass needs to be processed in a series of steps which includes the lipid extraction process where the cost of extraction is often higher than the desired products.
- **Demonstration stage:** Has mentioned in the above "production" section about the challenges facing for the technology to move from demonstration stage to deployment stage.
- **Commercialization issue:** Some of the difficulties in the commercialization process stem from finding the right algal stains of high lipid content. Exxon technology case study have not shared any proven results such as fast growth rate, easy to harvest and suitability for growth in a cost effective cultivation system yet. This leaves the industry in dark with respect to information on time lane for commercialization.
- **Shift of focus:** Many companies involved in this field have shifted their focus from bio fuel production to other areas such as algae production for cosmetic industries since it has not yet created a fast growing, high oil content algae to make mass production commercially viable and this resulted in further restriction on investments.
- **Stagnation in research process:** As a result of lower crude prices since Aug 2014, the challenge to produce cost competitive algae based bio fuels has been difficult and this has resulted in companies that were leading commercial developments focussing on production of higher value food, feed and speciality products. This has stalled the progress for the last number of years.
- **Water and nutrients:** For sustainable cultivation of algae for commercial production to supply commodity-scale markets is to mitigate the enormous amounts of water nutrients required to grow and process algal feedstock's with the current technology (Niemiec, 2013). According to the NRC, at least 123bn litres of water would be needed to produce 39 bn litres of algal biofuels while the estimated requirement for nitrogen and phosphorus needed to produce the above amount ranges between 15 million tonnes of nitrogen and 1-2 million tonnes of phosphorus.
- **Consistent fuel supply:** Till date, there has not been any commercial algal fuel based bio fuel on a consistent basis to secure the fuel supply for any potential ship-owner.

Outcome (Barriers):

The study conducted by (Llyods register and UMAS, 2017) assessing the comparative profitability of the seven different fuel combination with an internal combustion engine option for five different ship types concludes that biofuel is said to be the most profitable for a zero emission solution for ship owners. This is predominantly due to the lack of capital costs needed for both on the shore (Storage and supply) and on board (Handling and combustion) side of shipping sector. To fully benefit from the result of the above mentioned study, it seems we have many more barriers to overcome.

Technical feasibility:

Within the context of its feasibility with marine engines, bio fuel (third generation) seems to be applicable with minor modifications. The study (Lloyds register and UMAS, 2017) concluded that bio fuel is the most profitable zero emission vessel (ZEV) option compared with five different ship types, three regulatory/economic scenarios and six different ZEV options (Electric, Hydrogen, Fuel cells, Hydrogen + ICE, Ammonia fuel cell, Ammonia + ICE). This is mainly due to its technical feasibility with ICE along with the possibility to use the existing infrastructure for storage with near zero capital costs:

- **Applicable to fleet families:** Although no practical experiences of using algae based biofuels in ships have taken place, technical compatibility of biofuels with marine engines seems high and integration manageable (Ecofys, 2012).
- **Technical requirements for installations (E.g. required space, state of the engine, mass production of engines, yards, Tanks and pipes (Few words about the engine):** Based on the above finding from the (Lloyds register and UMAS, 2017), we assume that there is no real extra requirement needed with respect to modification or new equipment installation to use third generation bio fuel on board a marine application. We cannot support this statement with any technical information at this point due to lack of data.

  Internal combustion engine: Even though the goal is to derive a bio diesel**,** there is a lack of knowledge on the characteristics on this bio diesel and its feasibility and on the drop in nature of the algae based bio fuels on an internal combustion engine especially for the engines in existing vessels.

  Energy density: Biofuels in general have a lower energy density than marine fuels, Unfortunately there is no data on the energy density of the third generation bio fuels as this determines the inevitable cause of loss of revenue due to reduced cargo space.
- **Installation:** There has been no installation during the time of the study that uses the third generation biofuel on a marine application.

Technological readiness:

Production: TRL 3 (Experimental proof of concept).

Technical feasibility (On board): TRL 3 (Experimental proof of concept).

The research performed in the past years have bought to light the promising aspects of algae based bio fuels. Applying a holistic approach on the report formulated by the (IEA, 2017) which focussed solely on the technological status on production along with reviewing the recent technological developments that has taken place in 2018 such as Exxon's project has directed us towards an reasonable conclusion with respect to the entire life cycle of this fuel's technological readiness.

The report by (IEA, 2017) does not explicitly address the technological readiness levels of algae based bio fuels as they do vary widely across various approaches since some technologies as open pond based production of higher value products are already commercialised and possess a higher TRL (not yet for bio fuels) while others such as closed photo bio reactor (one exists in Netherlands) or hydrothermal liquefaction (HTL) processing are at much earlier stages of development. If we can grow the right kind of algae in sufficient quantities with an integrated process approach (by the use of CO_2 which forms as an emission from industrial process) while reducing the costs of cultivating and harvesting. By achieving these milestones, we will be able to move towards the next step i.e. demonstrating the technology in a relevant environment.

Non-technological maturity: (Legal, financial, knowledge, market, culture, others):

- During the course of this research, we also found that there is little or no information on topics such as combustion properties, feasibility of this fuel for both old and new vessels, what kind of modifications does it require on existing vessels, the drop in nature. The lack of knowledge on these subjects does not allow us to make a concrete decision on its capability by enter the market by 2030.
- Various ongoing research projects to produce bio fuel from algae based feedstock have been identified in Europe along with other countries such as USA, China, South Korea, Taiwan, India and Brazil. This supports our technological readiness conclusion.
- Biofuels in general, do need special attention, if used in 100% or higher blends (mainly due to the higher water content which needs frequent monitoring). This will need the training and familiarization of this fuel within the stringent HSSE management on board of ships.

Market ready by 2030?

In business as usual scenario, it is highly unlikely that this technology will take up the challenge of fuelling the shipping industry in such a short time span (2030 onwards). The barriers facing this fuel are mainly within the scope of technological readiness to demonstrate the validity of the fuel production in an operational environment. While, in terms of compatibility with marine internal combustion engine, the knowledge is absent for us to make any concentrate conclusion. The market survey conducted by (Lloyds register and UMAS, 2017) shows a desire of no more than a 10% increase in ship capital costs among the industry stakeholders for the uptake of any alternative fuels and bio fuels (3rd generation) seems to satisfy that criteria with nearly zero capital investment cost. By holding this potential against other alternative fuel candidates, it seems we need to wait more before this fuel shows positive signs of technological maturation.

Conclusion:

The U.S. Department of Energy’s projected cost target for 2022 for algal biomass production is $0.54/kg ($491/tonne), a cost which may enable cost-effective biofuel production from algal biomass (IEA, 2017) Along with this, the slow recovery of oil prices in 2018 has regained the cost competitiveness of this fuel. Regardless of the fact, that developments that are taking place are in favour of this fuel’s technology with ambitious plans for the future such as the Exxon mobile project. Assessing the technology maturity through the “Gartner hype cycle” the algae based bio fuels has passed the stage of “Trough of disillusionment” because they failed to meet the expectations and presented with more challenges. We now see that it has reached the stage “Slope of enlighten” where some researcher continue to understand and foresee the benefits while working towards the practical application of the technology. Based on the maturity analysis, we assume that it’s highly unlikely that this fuel will be market ready to by 2030 for the shipping industry. This assessment made is purely based on the technological readiness level of this production methodology This conclusion is based on the current status on the technology of this fuel in terms of production and lack of available knowledge on the feasibility and combustion properties of this fuel on an internal combustion engine.

Regardless, algae still remains a promising biological feedstock to research and address the future energy and sustainability challenges for shipping.

A.5 Ammonia

Description:

A fuel in the natural nitrogen cycle instead of the carbon cycle makes ammonia an interesting carbon free candidate. Its existence as a fuel dates back to 1942. Ammonia combustion only emits water and nitrogen while the storage, supply and handling could be done with the similar infrastructural knowledge as propane. The global industrial production of ammonia in 2017 was 170 metric tonnes (Szymanski, 2017). With respect to both energy use and GHG emissions, ammonia is ranked #1 among the eighteen other large volume chemical, this has been mainly due to the Hydrogen (H_2) reformation step from steam methane reforming (SMR). If ammonia could be produced sustainably with carbon free emissions then ammonia could play a significant role in this transition.

(Green) Ammonia found its relevancy as a maritime alternative fuel when it was found that renewable energy sources like wind and solar power often provide more energy during certain periods. This energy surplus can be utilized to produce and therefore be stored in a renewable fuel such as ammonia also known as NH_3.This along with the existing experience in working with ammonia in the fertilizer industry which already laid the foundation for storing, supplying and transporting ammonia gave ammonia its potential candidacy among other alternative fuels.

Production (Sources used):

Ammonia is currently produced as a base chemical and feedstock for fertilizers in very large quantities from natural gas (70%) or coal (30%) based on the data derived in 2014. We shall discuss the three production pathways based on the sources and choose the least or (if possible) zero GHG intensity pathway for the production of bio ammonia for our further technical analysis.

- **Ammonia from fossil fuels:** In this pathway, ammonia is produced by the haber-bosch process where hydrogen and nitrogen are combined over an iron oxide catalyst. Water and natural gas is mixed to form water vapour and there by hydrogen. In this process natural gas acts as both fuel and a hydrogen source. An approximate 30 GJ of natural gas is needed for this methodology to produce one ton of ammonia (Brohi, 2014). CO_2 intensity amounts up to 1.87 tonnes per ton of ammonia. This production pathway is therefore associated with higher emissions than natural gas (Royal academy of engineering, 2013),thus making it more energy efficient to use natural gas a main fuel source than ammonia derived from natural gas. This naturally negates this process from its climate appropriateness for fuelling the shipping industry.
- **Bio mass to ammonia (Bio ammonia):** The process involves a pressurized oxygen blown biomass gasifier operating in an expanding bed fluidized mode. The system gasifies biomass into a mixture of hydrogen and carbon monoxide and is optimized in a way to minimise the formation of methane. After the gas stream is cleaned, the carbon mono oxide portion is shifted to maximize hydrogen. Then the hydrogen is purified and catalytically reacted with nitrogen to make ammonia. The plant situated in Iowa (USA) operates in the methodology explained above to convert 150,000 tons of corncobs into 50,000 tons of anhydrous ammonia. This process again faces the same problem as bio fuels ethical question of food vs fuel even though a study conducted by (Brohi, 2014) concluded that using biomass (corn cob) for ammonia production only requires half of the mass compared to bio fuel. Due to the large scalability to accommodate both agriculture and maritime shipping along with the land mass needed to support this process pushed us to not include this this process for further technical analysis.
- **Power to ammonia:** Ammonia can be produced using nitrogen and hydrogen through the below mentioned steps:
  - nitrogen is gained through an air separation process;

- hydrogen is gained through electrolysis of water;
- finally, one can produce ammonia using the components nitrogen and hydrogen applying the Haber-Bosch way of processing.

An electrolyser requires about 53 kWh electricity to generate 1 kg of hydrogen corresponding to an average efficiency of 74.5% based on the higher heating value of hydrogen and 63% based on the lower heating value of hydrogen (Yusuf bicer, 2017). Renewable electricity such as solar, wind and hydropower are most commonly used renewable electricity sources that is used in the production of green ammonia today contributing to the net zero CO_2 ambition. Power (renewable sources) to ammonia, will be the chosen production methodology for further analysis below.

In the past, ammonia has been produced using this approach in Norway and Zimbabwe, however, no such plants are currently operational (ECN, 2017).

Future (Power to ammonia):

Ammonia can also be produced using algae and using the solid state ammonia synthesis (SSAS). Production of Ammonia from aquatic cyanobacteria is still in the early research stages and it has been proved to be more efficient compared to the ammonia produced via the haber bosch process, savings of about 1.0 x 105 MJ of non-renewable energy and 3,100 kg CO_2 equivalent of global warming potential per 1,000 kg of liquid ammonia might be possible (Ammonia industry, 2017). Solid state ammonia synthesis (SSAS), a concept where ammonia is produced using a solid state electrochemical process was initiated. It is suitable for use with renewable sources and uses around 7,000-8,000 kwh per produced ton of NH_3 (Brohi, 2014). Currently there are no commercially available SSAS systems (ISPT, 2017).

With ambitious plans ahead to explore the suitable ammonia synthesis which will help them to surpass the early developmental stages of (power to ammonia) production, questions still exist on the scalability of the production process so that it could enter the market in a commercial scale before 2030. This led us to not to include them in our technical analysis even though the renewable energy source is involved.

Outcome (Production):

A study conducted by institute for sustainable process technology (Institute for sustainable process technology, 2017) concluded that production of ammonia through renewable electricity cannot compete with ammonia produced from natural gas unless a carbon price is introduced, and the production cost of electrolysers are lowered significantly. In addition, an excess supply of renewable energy is needed. The two largest electrolyser plants situated in Norway has an capacity of 30,000 $Nm_{3/}h$ each with an energy consumption of 135 MW for each electrolyser which is supplied by renewable hydro power based on data from 2017. Most of the green ammonia produced now are focused towards the production of sustainable fertilizers so it is highly doubtful whether green ammonia production capacity is achievable within the limited time span (2018–2030) to secure a trustworthy fuel supply for the entire life cycle of the ship even though distribution networks are already in place.

Basically, from the technological readiness perspective, power to ammonia process is matured but the production amount of bio ammonia is in its developmental stage with no significant quantities produced so far since no large scale plants are available at this point as stated by ECN in their study (ECN, 2017). Various projects announced in countries like Australia, Netherlands, USA etc. Currently, the supply of renewable electricity and low cost electrolysers are the major two barriers towards commercialization of bio ammonia production.

Barriers:
An holistic approach by taking into consideration the entire life cycle of bio ammonia is studied to identify and formulate the below mentioned barriers which mainly focusses on the problems that exist in scaling up towards the mass implementation of this fuel for shipping:

- **Cost:** Electrolytic plants suffers from the price of (renewable) electricity consumed and the high cost of electrolysers. This does not allow ammonia to compete with fossil fuels.
- **High temperature electrolyser:** Lower electrical energy input is required when producing hydrogen through a high temperature electrolyser (Electrical input required at 800°C is 25% lower than at 100°C (ISPT, 2017) but currently there are no high temperature electrolyser commercially available.
- **Production transformation:** It is evident that NH_3 as an energy source is clearly not a barrier to fuel to the current fleet but the questions remains in the need for transformation from fossil based ammonia to green ammonia (renewable electricity) which will ultimately help the shipping industry to achieve its goal.
- **Energy density:** Compared to HFO, the energy density is low which results in it requires 2.5 times more space than HFO and adds weight 1.9 times more. (MVO Nederland, 2017) This will result in added capital cost in installation of larger fuel tanks for existing vessels.
- **Infrastructure:** Even though the know-how is already available, new bunkering facilities or extension of existing ammonia as a cargo based infrastructure Fertilizer industry carries ammonia in bulk loads up to 60,000dwt (Wendy Laursen, 2018) should take place to support the 300 million tonne consuming fossil fuel powered marine industry. We do witness the enthusiasm among the engine developers to integrate ammonia in their strategy but we do not see same enthusiasm nor relevant future strategies in place by governments and port authorities to extend or re-modify the existing ammonia as a cargo infrastructure to bunkering facilities.

Outcome (Barriers): There are significant barriers spans from production technology maturity to lack of demonstration projects in the pipeline to move the technology maturation process further which cast doubts on the scalability of this fuel in the short term (2018–2030). But unlike other alternative fuels, ammonia has the least barriers when it comes to port infrastructure for bunkering, storing and supplying the ships in the future.

Technical feasibility: Currently there are two options to use ammonia in the marine propulsion system. We shall discuss this below:

- **Ammonia Internal combustion engine (ICE):** Burning of pure ammonia is difficult due to its chemical properties under certain load. Equipment called "reformer" should be installed between the fuel tank and the engine. Reformer will crack enough of the ammonia into hydrogen and nitrogen and this provides a small amount of hydrogen which acts as a combustion promoter, allowing the ammonia to combust more easily and completely. In this set up, an emergency HFO tank is installed and the propulsion is produced through a dual fuel combustion engine (Ammonia energy, 2016).
- **Ammonia Fuel cells:** In this process, ammonia will be either separated into nitrogen and hydrogen or used purely to generate electricity via fuel cells. These cells enable high efficiency conversion of ammonia to electric power (TNO , 2017).

There are no engine architectures currently at present that supports ammonia as a fuel (Brohi, 2014). The conclusion made by (Brohi, 2014) is still valid during the time of the study since we noticed there has been research in laying out different options for an optimal combustion technology but no concentrate answers on how we can burn ammonia on board reaching the thermal efficiency in comparison with fossil fuels and the question of efficiently converting that into electrical/mechanical power for propulsion is still under research. The above-mentioned methodologies needs further research and few engine manufacturers are already working on the NH_3 (main fuel) + H_2 (Combustion promoter) technology to use ammonia in an internal combustion engine. If succeeded, this would significantly reduce the technological barrier for ammonia to enter the shipping industry.

- Applicable to fleet families:
  - **Ammonia (ICE):** Ammonia (ICE) is applicable as a fuel probably only for new builds and some old vessels which can bare the necessary modifications in terms of installation of large (ammonia energy density) or dual fuel tanks space (HFO or ammonia), the needed tank connection space (Vaporisers, valves and fuel gas supply system.
  - **Ammonia (fuel cell):** Ammonia (Fuel cell) is only applicable to new builds since this needs an entire new approach to the design of the ship considering the stability changes this retrofit could bring.
- **Technical requirements for installations (E.g. Modifications (If so what), required space, state of the engine, mass production of engines, Yards, Tanks and pipes, Engines/fuel cells reaction and experience with Ammonia).**

We have distinguished below the requirements based on the ammonia propulsion technology.

Ammonia (ICE):

- The internal combustion engines (including dual fuel engines) requires a combustion promoter fuels such as gasoline, hydrogen or diesel etc. (Ammonia energy, 2016).This is mainly due to the low combustion rate of ammonia (inconsistent combustion at low loads and high speeds).
- To avoid the subsequent approach of having a dual fuel storage systems/delivery systems and injection systems an introduction of on-board reformer which can crack enough of the ammonia into nitrogen and hydrogen. Hydrogen will combust as a result ultimately supporting the combustion of ammonia as well. Industrial research has shown that it can be gained using 3% hydrogen and 97% ammonia (MVO Nederland, 2017). But this process has been never been validated nor demonstrated on a vessels under sailing conditions during the time of the study.
- The toxicity of ammonia should be one of the primary risk factor that must be reflected in engineering design and operational best practices keeping in mind the crew safety on board.
- Ammonia based internal combustion engine will cause NO_x emissions which should be supressed by proper design and operating combustion temperature.
- For ammonia burning engines, the requirement for the combustion promoter fuel fluctuates with varying engine loads and engine speed which can cause control issues. This bears the challenge that cracking a fixed proportion of the ammonia or a proportion that varies simply with the rate of fuel flow is unlikely to produce good combustion. More research need to be done in this area to identify the necessary modifications needed.

Ammonia fuel cells:

- No ammonia based fuel cell maritime application has been demonstrated during the time of the study. This statement has been based on the (DNV GL, 2017) study which listed a total 23 fuel cell projects with no ammonia fuelled projects so far. This in itself acts as barrier providing the industry with limited knowledge to proceed further.

Both ammonia (ICE) and ammonia (Fuel cells):

- Corrosion sensitivity of copper alloys to ammonia is evident and should be addressed in the design. This again poses restrictions for old vessels. To control, the corrosion sensitivity of copper alloys by adding a small amount of water (0.2%) to ammonia. This requires modifications in the fuel supply lines (Royal academy of engineering, 2013)
- The fuel tanks would store liquid ammonia either at refrigerated (at ambient pressure and -33.4°C) or (compressed at 10 bar and room temperature) depending on the combustion methodology. This results in change in fuel tank infrastructure on board causing space restrictions in existing vessels which may not able to accommodate new fuel tanks or otherwise lose their cargo capacity but currently there is no information on which storage methodology will be the most suitable for marine bunker fuel.

Installation: Currently there are no new built planned or in operation that uses ammonia as a fuel either to power fuel cells or a conventional internal combustion engine.

Technological readiness:

Production: TRL 7 (System prototype demonstration in operational environment).

Technical feasibility (On board):

- Ammonia (ICE): TRL 5 (Technology validated in relevant environment).
- Ammonia (Fuel cells): TRL 4 (Technology validated in Lab).

Based on the above analysis, taking into account both the technological readiness of large scale production capacity of bio ammonia and using ammonia as a marine fuel (Both ICE and fuel cells) has not surpassed the demonstration stages (TRL 7 was given for production based on the operational plants in Norway and Zimbabwe). Various projects that are being set up in the production of bio ammonia in larger quantities in Australia, Netherlands and USA are set to open between 2018 and 2023. Along with this, there is a complete lack of experience in using ammonia (ICE + Fuel cells) in vessels of any type and category under sailing conditions. Based on these findings, we have assigned the technological readiness of this fuel for the shipping industry.

Non-technological maturity: (Legal, financial, knowledge, market, culture, others):

- Ammonia is a globally traded commodity, there is significant port loading infrastructure, handling experience and safety knowledge. Further study and expansion of the existing knowledge is required to create a maritime specific bunkering, storage and handling operational manual. During the time of the study, we found out that bureau Veritas is in discussion with a naval architect firm in developing a risk analysis and system design guidelines (Wendy Laursen, 2018).
- Ammonia is toxic but as a chemical we have around 100 years' experience in handling. But this does not down play any requirement for further development of safety culture within the management and on board through training and familiarization for the crews on how to handle ammonia as a fuel. Transfer of know-how from chemical tanker industry could be advantageous. Health profile risk is higher than fire risk profile (Wendy Laursen, 2018).
- A consortium (C-job naval architects, Proton Ventures and Enivu) in the Netherlands announced its intention this year to research and demonstrate "the technical feasibility and cost effectiveness of an ammonia tanker fuelled by its own cargo". This results of this project will be available by 2020 which could provide the needed knowledge and increase the trust among ship-owners towards an ammonia fuelled shipping.

Market ready by 2030? The possibility of Bio ammonia to fuel the marine industry to keep the CO_2 level within the post 2030 carbon budget is possible but not in the business as usual scenario due to significant amount of progress needed in both the production and the technical feasibility side which needs to be addressed and this can be only addressed with investments in further research both in the economics (governments) and technical (engine manufacturers and ammonia energy providers) to push the TRL level beyond 5. With demonstration plants aiming to be active around 2020, we foresee the market readiness of bio ammonia by 2030. It is fair to note that surpassing these barriers not only push ammonia towards a market ready fuel but also support the hydrogen business case in some scenarios.

Conclusion:
The study conducted by (Lloyds register and UMAS, 2017) concluded that ammonia is the second most profitable zero emission solution compared with five different ship types, three regulatory/economic scenarios and six different ZEV options (Electric, Hydrogen, Fuel cells, Hydrogen + ICE, Ammonia fuel cell, Ammonia + ICE). This is mainly due to its possible technical feasibility with ICE while using the existing infrastructure for storage resulting in low capital costs compared to options like batteries and fuel cells. The scalability of the bio ammonia in the coming years and especially developments in the ammonia based ICE will decide its market readiness by 2030.

A.6 Renewable Hydrogen

Description:
Hydrogen (H_2) is odourless, colourless and tasteless. It could potentially be an alternative fuel for ship propulsion but its ability to achieve zero emission depends on its source of energy used in the production process.

Production (Sources used):
Hydrogen with the formula H_2 is the lightest of all gas molecules offering the best energy to weight storage ratio of all fuels. Based on the sources, renewable hydrogen can be produced through two sources namely electricity and natural gas. We shall discuss the two production pathways and choose the production pathway with the least or zero GHG intense production pathway per unit of hydrogen for our further technical analysis:

- **Reforming of natural gas:** Natural gas contains methane (CH_4) that can be used to produce hydrogen with thermal processes such as methane reformation. In the steam methane reformation process, methane reacts with steam under pressure in the presence of catalyst to produce hydrogen, carbon mono oxide and carbon dioxide. The release of CO_2 during production means that this production pathway cannot be considered to be zero emission. Carbon Capture and Storage (CCS) can be used to reduce the GHG intensity but not eliminate it. This is due to the fact that there are currently four CO_2 capture options could be deployed and based on the study conducted by IEA (IEA , 2017), concluded that the capture rate is in the range of 56 to 90% while integrating CCS also increased the natural gas consumption by 0.46 to 1.41 MJ/Nm^3 H_2 which ultimately reduced the surplus electricity that could be exported to the grid. These findings raised the possibility of the real GHG reduction by incorporating CCS in the long term for an enormous industry like shipping.
- **Electrolysis of water:** Emissions associated with the source are related only to power generation. If renewable power is available, hydrogen can be produced emission-free but for a typical electricity grid mix, emissions are quite significant resulting in equivalent or higher than those of fossil based fuels (TNO, 2016) especially since the energy efficiency of the electrolysis process is approximately 66% in comparison with the energy contained in the produced hydrogen. Biomass, solar, hydro, wind and geothermal are some of the renewable energies that could be used to supply the electrolyser with energy.

One of the biggest benefits of hydrogen production through electrolysers is its scalability, a two megawatt hydrogen electrolyser is roughly the size of shipping container and can be easily installed next to a field of wind turbines, for example. A study conducted by (Sandia national laboratories, 2014) shows that resources availability for production of renewable hydrogen by eight developed countries to meet their domestic demands and targets will not be a problem at all.

Direct solar water splitting or photolytic processes use light energy to split water into hydrogen and oxygen. This process is currently in the very early stages of research (United states office of energy efficieny and renewable energy, 2018). Similar to ammonia, microbes such as bacteria and microalgae can produce hydrogen through biological reactions, using sunlight or organic matter. Since both of this process is currently in the early research stages and highly unlikely to enter the market in the commercial scale before 2030, led us to not to include them in our analysis even though the renewable energy source is involved.

Outcome (Production):
The process of hydrogen through renewable electricity is matured even though more research is underway with respect to increasing the efficiency of the electrolysers. Resource (renewable electricity and biomass) availability is not a problem for hydrogen but resource utilization is a barrier that we have to overcome to achieve have to move towards the scalability of hydrogen production to supply the shipping industry to achieve the goal of making hydrogen a zero emission fuel taking into account the entire life cycle.

Barriers:
An holistic approach by taking into consideration in the entire life cycle of electrofuels is studied to identify and formulate the below mentioned barriers.

- **Cost:** A study conducted by US department of energy (Sandia national laboratories, 2014) concluded that it is difficult for other resource options to compete on cost with natural gas unless the cost of natural gas is doubled or a 100$/ton CO_2 tax by 2025.
- **Catalyst:** Costs of material used in fuel cell (e.g. platinum catalyst) is high at this point.
- **Lack of supply chain infrastructure:** Hydrogen fuel supply chain infrastructure is not available yet to support the maritime industry. An extension of its existing infrastructure should be developed to support the hydrogen based shipping economics.
- **Lack of experience and knowledge:** Largely untried in the merchant shipping industry for propulsion purposes. The durability of fuel cells under harsh marine conditions is largely unknown and this reduces the trust among ship-owners for further testing and demonstration especially in the merchant shipping.
- **Lack of regulations:** Further development of IGF code needed which could addresses the bunkering of gaseous or liquid hydrogen, storage of compresses or liquid hydrogen and safe handling of liquid or gaseous hydrogen and safe handling of hydrogen and fuel cells on board.
- **Lifetime:** One of the biggest challenge is to increase the lifetime of the fuel cells to suit the lifetime of the ships. SOFC has higher lifetime (Up to 40,000 hours is reachable with latest developments and heading towards a target of 60,000 hours) (IEA, 2007). This is basically 1666 operational days of a ship (4,5 years). This would result in changing the entire fuel cell system every dry dock and at least 5 times during the lifetime of the ship. Even though, this lifetime is higher compared to its counterpart its technological maturity has not yet reached the stage to power large scale merchant ships. SOFC is considered due to be used in large energy demanding systems with capacities up to 10 MW. Other fuel cell technologies was not considered for the lifetime analysis and we have explained the reason why under the section "technical feasibility".
- **Hydrogen storage:** Compressed hydrogen has a very low energy density by volume requiring six to seven times more storage space than HFO. If stored at 700 bar pressure the storage tanks would be at least six times bigger than

conventional fuels (Royal academy of engineering, 2013). While liquefied hydrogen on the other hand requires cryogenic storage at very low temperatures (-253°C) associated with large energy losses and in need of a very well insulated fuel tanks which requires the need for new tank structures that can hold a fuel which has lower temperature than LNG . This not only has implications on the loss of cargo space but also on the tank space connections, fuel pipe line systems and can alter their operational profile such as trading routes. These negative effects can lead to shortening the range between bunkering which reduces the possibility of using it as a fuel for sea going vessels (Lloyd's register, 2017). With this being said, this technology could disrupt the industry and clearly limits its technical application for only new vessels. Safe storage and handling of hydrogen will be a key concern and if converted into monetary terms, this will increase the cost of storage and handling with the current available technology.

Outcome (Barriers): Although hydrogen can be used mostly for new builds as a fuel.

Due to the above mentioned barriers, we foresee that the first vessels using hydrogen as a fuel will be installed with fuel cells being part of a hybrid engine. This is mainly due to the current high costs of fuel cells (Greater than 1,000$/kW, while low temperature PEMFC has reached a price range of 280$/kW). A 50$/kW would put most fuel cell technology in competing with diesel generators although lifetime issues would be a barrier when compared to fossil fuels. To reach a successful market penetration, three aspects are often mentioned as deciding factors: performance, lifetime and costs. During the time of the study, all the three aspects proves to be disadvantageous.

It has been clear from our study that fuel cells is the preferred methodology for propulsion for shipping with respect to hydrogen as a fuel. We shall briefly discuss the technical aspect of fuel cells before we conduct technical feasibility.

Fuel cells: There are in total 7 fuel cell technologies that has been identified. But to stay within the scope of the study, we will look into only three technologies that has the potential to be used in the maritime. The three technologies has been chosen based on the study conducted by (DNV GL, 2017) based on 11 parameters that resulted in technology/attributes scoring. Even though the molten carbonate fuel cell has been installed in two projects, it has not been considered since it did not use hydrogen as a source of fuel (uses LNG) and scores low in the technology/attributes in the (DNV GL, 2017) and its large size which may pose a problem especially old vessels with space restrictions led us to not include it in the below analysis.

The chosen three technologies have been assessed against the following technological readiness parameters:

- technological maturity;
- efficiency;
- sensitivities;
- potential emissions;
- lifetime;
- highest energy output installed (during the time of the study).

- **Proton exchange membrane fuel cell (PEMFC):** In terms of, technological maturity PEMFC has reached the highest stage reducing its cost. Lower temperature provides high cycling operation with a moderate efficiency of 50–60%. The physical size is small which makes it compatible for installation for marine applications without the need for larger machinery space while the energy capacity heading up to 120 kW for each module. The study by (DNV GL, 2017) has given this technology the highest scoring in the ranking. The drawback is its sensitivity to impurities in the hydrogen especially with CO and its moderate life time. It has been used in submarines and allows obtaining an air-independent propulsion (Jingang Han, 2015). High power density and quick start up makes it more attractive for maritime. Highest energy output installed is 306 kW for submarines.
- **High temperature PEMFC:** In terms of, technological maturity, its less matured than low temperature PEM. The higher temperature offers advantages such as less sensitivity to fuel impurities which helps in using a broad range of fuels such as bio methanol, simplifies the water management system and removes the need for clean-up reactor after the reformer. Clean up reactor lowers the system efficiency, expensive and space demanding (DNV GL, 2017) while the excess heat can be used for other purposes such as ship internal heat system. Highest energy output installed is 250 kW (in the "Felicitas" project).
- **Solid oxide fuel cell (SOFC):** In terms of technological maturity, it has reached a moderate stage especially due to its use in the Schibz project. It is highly efficient, moderately sized and highly efficient due to its high operating temperature which can allow it to reach an efficiency of 85% (including heat recovery). The fuel cell is flexible with different fuels. The promising approach for the SOFC is its use in hybrid systems (SOFC + Heat recovery + batteries). This combination could allow it for a more flexible operation to the system, with less cycling of the SOFC, the problems associated with short cycle life are reduced (DNV GL, 2017).Potential long life expectancy of 80,000 hours. Highest energy output installed is 250 kW in "Rivercell" project.

Currently both PEM (both high and low temperature) and SOFC are considered to be more promising for maritime applications and the 23 projects identified by (DNV GL, 2017) study mostly comprises of these three technologies. PEM (low temperature) is attractive from a gravimetric power density perspective and is technologically mature.

Technical reasons behind the chosen fuel cells:

- **PEM (Low temperature):** PEM (Low temperature) was also discounted as, when matched to the BOP required for marine diesel fuels, PEM fails to offer any significant efficiency, density or performance advantages over current marine diesel systems. (Livia Cohen, 2012).
- **PEM (High temperature):** PEM (High temperature) offers the best mix of characteristics in the sub 250°C temperature technologies.
- **SOFC:** Of the high temperatures fuel cell technologies (600-1.000°C), SOFC offers the highest power density and potential efficiency as well as more rapid starting times when compared to the MCFC. Highest operating temperatures have the potential to provide the highest efficiency if suitable shipboard uses for their waste heat can be identified. (Livia Cohen, 2012).

The average efficiency of piston turbine is 35-40% and gas turbine is 25-40% while slow speed diesel engines are reaching efficiency up to 50%. With this comparison, currently these three technologies are the ones that could achieve an efficiency above 30-55% which is similar to the current marine propulsion infrastructure in terms of efficiency. The below table gives you an insight on some of the determining values which gives these two technologies the edge when compared to its colleague MOFC which faces its drawbacks in terms of the need for internal reforming and limited temperature range.

This table has been formulated based on information from two sources namely (L.van biert, 2016) and (US Department of energy, 2016).

Table 4 – Fuel cell types

Fuel cell type	Temperature	Fuel	Poisonous substances	Internal reforming	Efficiency (%)	Typical stack size
LT –PEMFC	65-85	H_2	S, CO > 10 ppm	No	30-40	< 1 kW – 100 kW
HT-PEMFC	140-200	H_2	S,CO >3%	No	30-40	< 1 kW – 100 kW
MCFC	650-700	H_2, CO	S	Yes	29-54	300 kW - 3 MW, 300 kW module
SOFC	600-1,000	H_2,CO	S	Yes	45-55	1 kW-2 MW

Future of fuel cells within maritime applications: There has been a development in the fuel cells power output by leveraging the existing kilowatt scale fuel cell technologies and optimize them to create a mega-watt scale fuel cell for powering large ships with electrical generating capacity up to 3MW by making sure this system could possibly fit within a module that is not bigger than a traditional marine engine running on fossil fuels.

Technical feasibility:

In principle, internal combustion engines and turbines can also be used for combustion of hydrogen. This has been demonstrated in various small engines suitable for automotive applications, but fuel cells have superior efficiency (DNV GL, 2017).We will focus only on fuel cells as an energy conversion methodology for propulsion in our technological readiness level analysis. Let's look into the storage criteria that needs to be met for hydrogen storage.

Hydrogen storage possibilities for maritime:

Liquefied hydrogen:

To store hydrogen in liquid state the following conditions should be met:

- cryogenic (boiling point -253°C);
- cryo compressed (-240°C and at 13 bar).

Compressed hydrogen:

To store hydrogen in gaseous state the following conditions should be met - Compressed gas (300-700 bar).

- Applicable to fleet families:
  - Hydrogen is applicable as a fuel to all ship types but with its disadvantages in terms of energy density, need for large storage capacities to supply required energy output along with increased above water structures to support these storage capacities limits its application mostly to new builds with short cruise times. Retrofitting might be possible but mostly for small Ro-ro, ferries and cruises which can afford the deck space and the design and stability implications.
- Technical requirements for installations (E.g. Modifications, if any, required space, state of the engine, mass production of engines, yards, Tanks and pipes Fuel cells reaction with Hydrogen: We shall take into account only the technical requirements for installing fuel cells using hydrogen as a fuel, Even though, In principle, internal combustion engines (ICE) and turbines can also be used for combustion of hydrogen but fuel cells possess the superior efficiency which suits the maritime industry (DNV GL, 2015). Even though hydrogen ICE seems

interesting both technically and economically allowing retrofits to take part in the transition, we were not able to identify any commercially available hydrogen internal combustion engine. The use of conventional fuels (Diesel/LNG) to power fuel cells has also not been taken into account due to the scope of the report:

- When installed with a fuel reformer, hydrogen along with other zero emission fuels such as green ammonia and bio methanol can be used to power a fuel cell.
- Even though fuel cells can be stacked to supply the required energy output, the problem lies in powering those fuel cells with hydrogen which has to be carried for several days (up to 70 days for supertankers).
- Fuel cells have no moving parts but do require additional support plants such as pumps, fans and humidifiers (Royal academy of engineering, 2013).
- A refrigeration unit is also required, if the hydrogen is stored in a cryogenic gaseous state (Motor ship, 2017).
- New ship designs would require increased above water structures to accommodate this storage capacity which will have stability implications that is largely unknown for the large merchant vessels. It is estimated that depending on the pressure, the tank size must be 10-15 times larger than required for heavy fuel oil.
- EMSA performed a complete analysis on the safety and the risks associated with using fuel cells. It has been concluded that tolerable risk levels could be reached with respect to operational and human safety but some of the identified safety risks such as strong exothermic, reaction of reformer material, Internal leakage in FC module, High energy collision penetrating liquefied hydrogen tank, Rupture of compressed hydrogen tank containment system and leakage of hydrogen rich gases during bunkering of hydrogen. This presents a new design vision to be adopted by naval architects.
- Fuel cells produce a DC electrical output so suited only to ships with electrical transmissions not mechanical transmissions.
- Need an energy storage device to cover peak load in this case batteries or other thermal energy storage devices need to be installed, creating the necessity for a hybrid energy system. Technologically, batteries seems to be more feasible and matured which increases the cost and loss of revenue due to reduced cargo carrying capacity.
- Power requirements can also be an issue as fuel cell systems with at least 500 kW of ocean required for larger ships. This is not available currently after reviewing the list of projects mentioned in the DNV GL study (DNV GL, 2017) fuel cell study.
- Due to the increase in the storage size, new ship designs would require increased above water structures to accommodate this storage capacity and to retrofit ships with new tanks, tank connection space (Valves, vaporizers and fuel supply system etc.) and inverters to convert the AC current produced by fuel cells to DC to supply power for propulsion. Therefore, this may create difficulties and in most cases (sea going vessels) eradicate the possibility of retrofitting ships to use liquid hydrogen fuel. The study conducted by (Royal academy of engineering, 2013) did recognise the potential possibility of retrofits but it would depend on various characteristics of the existing ship. Based on our research, we assess that the applicability is feasible to ships that want to make the cruise time leap from battery power to hydrogen which in this case would be fleet of smaller size families.

- Installation:
  - In 2008, the FCS alsterwasser was the first commercial inland passenger ship to use hydrogen fuel cell propulsion. It combines tow fuel cell systems (48 kW) with a 560 V lead gel battery pack and 50 kg of hydrogen stored at 350 bar.
  - As part of the fellow ship programme, a 330 kW fuel cell was successfully tested on board the offshore supply vessel "Viking lady" which successfully operated for more than 7,000 hours. This was first fuel cell merchant ship operation ever.
  - CMBs 1,900 teu ice class feeder which will be equipped with a hydrogen auxiliary engine (Hydroville, 2018).
  - There are ongoing projects that use liquid hydrogen as a marine fuel where fuel cell converts hydrogen into electricity for propulsion such as the new cruise orders placed by Royal Caribbean (icon classes planned to be delivered in 2022 and 2024) and Viking cruises.
  - Demonstrations have been conducted by the hydrogen energy supply chain technology association (Hystra) and a road map has been for operational stages that need to be addressed to deliver a viable LH_2 carrier. The first LH_2 carrier is expected to enter operation in 2020.
  - In 2015, a marine fuel cell generator began being tested by sandia national laboratories. This generator integrates hydrogen storage, proton exchange membrane fuel cell power generation and power inverter equipment that is able to power up to ten reefers with a total rated output of 100 kW at 240-volt AC.

Technological readiness:

Production: TRL 7 system (prototype demonstration in operational environment).

Technical feasibility (On board): TRL 7 system (prototype demonstration in operational environment).

The average installed power for an oil tanker (5,000 dwt–200,000 + dwt) is between the range of 1,274 kW – 27,685 kW based on the IMO third greenhouse study in 2014. After analysing the energy output installed on various projects listed by the (DNV GL, 2017), it is evident that hydrogen powered fuel cells have not even reached the technological maturity level to supply the energy output required to power an oil tanker below 5,000 dwt tonnage. If it is demonstrated in the future, then the primary question would be what are the design changes and stability implications that the ship has to undergo is largely unknown.

302 kW is the highest energy output (PEM based fuel cell) installed to date on a submarine.

Following the project "SF Breeze" which conducted a feasible study to install a 120 kW per module PEM powered by hydrogen with an total installed power of 4.2 MW. The study concluded that it is technically possible to build a high speed hydrogen powered ferry with full regulatory acceptance. This study proves the scalability of hydrogen based fuel cells but until, it become a reality under sailing conditions, it is hard to make any conclusions.

The above finding proves the (realistic) energy restrictions or lack of evidence yet on large scale fuel cell installations, during the time of the study.

Based on the above arguments and also due to the lack of demonstration of fuel cells in large vessels limits its application to a smaller fleet families. This has lead us to conclude that the hydrogen powered fuel cell technology has been demonstrated and validated on an operational environment but has more steps to cover before it could be available for ocean going shipping fleet families powering their main engines and successfully carrying liquefied hydrogen. Unless this changes within the short term with ongoing collaborations and research that has been going on to scale up the power output up to 3 MW.

Non-technological maturity: (Legal, financial, knowledge, market, culture, others):

- The International energy agency (IEA) established the hydrogen implementing agreement (HIA) to pursue collaborative hydrogen research and development and information exchange among its member countries. The goal is to perform comprehensive technical and market analysis of hydrogen technologies and resources and supply and demand related to the projected use of hydrogen .
- In 2017, (DNV GL, 2017) identified 23 ongoing projects in fuel cell technology using hydrogen as a fuel. Horizon 2020 supports fuel cell projects including plug and play. There has been significant efforts achieved in this field through the support of various government funded projects.
- Currently, IGF code only focuses on low flash point fuels such as LNG and CNG but work is ongoing within the subcommittee to extend its use by including methyl/ethyl alcohol and fuel cells which may constitute the part "E" of the IGF code. Currently chapter 2.3 of the IGF code provides the possibility for the approval of hydrogen and fuel cells by an alternative design process.
- Class rules exist for the installation and design process for fuel cells powered ships.
- The knowledge available to the stakeholders in the shipping industry with respect to economic and technical aspects of using hydrogen for shipping is limited compared to other transport sectors (Carlo Raucci, 2017).
- During the course of this research, we did acknowledged that available literature in this subject varies in its conclusion from hydrogen being considered as an alternative fuel in the midterm (ten years) to hydrogen only as a fuel option for a long term (twenty years and beyond).
- Currently there are no guidelines or recommendations exist that covers the shore part of the hydrogen fuel ship, bunkering. The ISO/TS 18683–guidelines for systems and installations for supply of LNG as fuel to ships is used to establish a safer bunkering of hydrogen and this is not suitable.

Market ready by 2030? A study by (Carlo Raucci, 2017) used modelling tools to explore conditions that would favour the significant uptake of hydrogen in the industry. He concluded that key circumstances include:

- the introduction of an emissions cap;
- a market-based measure mechanism in shipping;
- a hydrogen price ranging between US$ 4-8/kg;
- competitive investment costs for fuel cell and hydrogen storage technologies on board ships;
- the supply of hydrogen mainly based on natural gas and biomass, with carbon capture and storage or electrolysis technology.

BAU scenario will face the above barriers and as the above mentioned study points that since ships are the largest vehicles in the world, favouring economies of scale which reduces ultimately can bring down the installation and operating cost. But without addressing the above mentioned areas through EU level policies, incentives and subsidies, it is not foreseeable for hydrogen to be market ready by 2030 to enter the shipping industry with needed confidence to challenge fossil fuels.

Conclusion:
The possibility to scale hydrogen production through renewable means exists. Various research and development projects that has been going in the field of hydrogen powered fuel cells along with the successful small scale fuel cell demonstration projects in maritime such as Schibz creates an promising environment where it is possible to use hydrogen as an alternative fuel by 2030 but it comes with its limitation which removes large number of fleet families from the equation. Hydrogen will act as a viable solution for long cruising range where existing battery technology cannot support but the size of the hydrogen storage tanks may prohibit it. More research is needed on the hydrogen tank solutions for ships. Unfortunately, Hydrogen also cannot include the existing vessels which may threaten the shipping industry’s ambition to stay within the post 2030 carbon budget.

An increase in power to accommodate the medium and large merchant carriers along with a safe and reliable supply chain, which could reduce the amount of hydrogen carried on board and act as the assurance needed by the stakeholders to join the hydrogen based economy.

A.7 Batteries

Description:
Batteries open the way towards storing energy from renewable sources such as wind/solar or waste heat recovery system etc.To a certain extent, current batteries used in maritime applications are manufactured either with Lead acid battery, zinc-carbon dry cell or Nickel-cadmium and lithium-ion. Regardless of their evolution in the recent years, the following technological barriers barred them from extensively being used as an alternative means for propulsion in large scale marine systems:

- low energy density;
- low power density;
- high self-discharge rate or memory effect.

These technological barriers reduced their economic viability as well since batteries are considered to be expensive due to the material composition. But recent developments to address these issues including lower self-discharge rates and ultimately free of a memory effect has bought new hopes. New battery chemistries include metal-oxygen also referred to as metal-air. In this, the metal could be zinc, lithium or sodium.

The current best performance comes from lithium-air battery technology since it offers the higher power density, high efficiency and an acceptable lifetime. Lithium-air batteries are believed to have the capacity to hold up to five times more energy than the same lithium-ion batteries. This is the major shift that helped batteries to expand its maritime installation profile. The lithium-air battery unlike other chemical combinations which require to carry the oxidant, draws in necessary oxygen from the atmosphere during discharge and liberates it during charging. This requires the need of supply and removal of air, analogous to a fossil fuel and can liberate 11,780 Wh from the oxidation of one kilogram of lithium (Royal academy of engineering, 2013). At present, two types of lithium air batteries have been proposed; non aqueous and aqueous. The energy density per unit mass of non-aqueous lithium-air batteries is about 10 times higher than those of lithium-ion batteries (Imanishi, 2014). For a comprehensive literature review, we have taken into account the eight battery types that currently play a role or possibly could play one in the near future for marine applications.

Four battery technologies which have been used in maritime applications have been taken into account to compare the five most important parameters:

Table 5 – Battery types

Battery type	Theoretical specific energy density (Wh/kg)	Volumetric energy density (Wh/kg)	Efficiency (%)	Lifecycle (No of cycles)	Cost ($/kWh)	Lifetime (Yrs)
Lead acid	171	171	50-95	5,000-1,000	165	5 or less
Ni-MH	240	240	89-92	500-2,000	146	5 or less
Li-ion	398 - 843	398-843	85-99	400-9,000	400-500	5- 10
Li-Air	1,752 -2,582	-	-	-	-	-

Source: (Peng Wu, 2016).

The above table summarizes the leap taken by lithium based batteries and its capabilities to fill certain gaps that existed before. During the time of the battery, lithium air has not entered the market and all the maritime installation has used lithium ion based batteries.

Production: The production of batteries has an environmental cost. The environmental cost can be categorised as environmental CAPEX and OPEX.

Environmental CAPEX includes:

- energy storage (cells, module, sub packs, strings, cooling units);
- converter (AC to DC);
- Transformer;
- Cables.

Environmental OPEX is the fuel savings compared to diesel PSV.

The study conducted by (ABB, 2016) assessed the life cycle emission by compiling a life cycle inventory list of materials used in manufacturing a lithium-ion battery for a PSV vessels and adding other factors involved in the life cycle emissions such as transportation. This study took into account the total electrical energy consumption such as electrical consumption per cell and electrical consumption for welding etc. After an complete inventory, the calculation concluded that the majority of the emissions come from producing the energy storage part of the system mainly battery cells and sub packs. The emission originates from the global average electricity mix (ABB, 2016).

The above study points out the environmental CAPEX and its importance in assessing the actual emission savings a battery ship could potentially encounter compared to a conventional diesel engine. The production process should aim to produce batteries that contributes to the lowest amount of GHG emissions along with the possibility to safely dispose or recycle the battery. To feed an industry like shipping with Mw installations compared to kW installations for electric vehicles requires large amount of resources especially in means of electricity. The use of renewable energy in producing batteries could make the ultimate difference that could help the shipping industry to create a zero emission battery vessel environmentally viable.

Outcome (Production):

Like the some other alternative fuels, batteries if produced with a renewable electricity has the lowest GHG intensity. Along with the infrastructure and transparent system which will allow them to dispose or recycle the battery could reduce the production based emissions, which is the significant contributor since there is literally no emissions during the use of batteries.

Barriers: An holistic approach by taking into consideration in the entire life cycle of electrofuels is studied to identify and formulate the below mentioned barriers:

- **Cost:** The power density advantage of diesel offers significant economic advantage over batteries. MDO which is commonly used as the choice of fuel for coastal vessels costs 42.3 $/MWh and where as the best available commercial battery costs 73.2 $/MWh (Peng Wu, 2016), hence the slow take up. Lithium-ion batteries are more expensive to manufacture than other rechargeable batteries. It is 40% higher than the nickel-metal hydride batteries.
- **Economic case:** The economic side of shipping dictates the design, size, speeds, routes, operating profiles etc. which in turn influences the power/propulsion plant design. Battery technology at its current state potentially disturbs the economic case that shipping has been relying on since the cost of ownership (Cost of capital vs cost of operation) is high compared to many other alternative fuels e.g. Ammonia and hydrogen.
- **Emissions from production:** As seen in the production analysis, manufacturing the relevant energy storage parts is the most energy intensive process and within energy storage manufacturing the battery "cells" and packaging (sub packs) leads to the highest GHG emissions.
- **Pressure on grid:** The increasing dependence on the grid for power supply may increase the pressure on certain nations which is struggling to meet its current needs and additional capacity might be needed to support electric ships at a time when the priority is to replace existing capacity with renewable sources.
- **Lifetime:** Current battery technology are limited in lifecycle as well which can extend up to a maximum of ten years but typically of five years on average which brings to light the fact that during an average lifetime of a ship which is 25–30 years, the batteries have to changed twice or thrice.
- **Sea going merchant vessels:** The technical limitations that include energy density, power density and lifetime influences operational performance such as speed and range of the vessel as well as the need to provide recharging infrastructure, this limits the application of full battery powered propulsion for sea going merchant vessels ships especially the intercontinental ones whose efficiency is high (55%), it's not apparent how batteries can enhance their operation (Peng Wu, 2016).
- **Port infrastructure:** Vessels calling at the berth will also need to be equipped with the necessary electrical infrastructure to take advantage of shore power. This includes installing power transformers, switchboard, control panels and cable reel systems.
- **Dangerous substances:** It is good to note that, lithium batteries are listed in the international maritime dangerous goods (IMDG) code under class 9 (Miscellaneous dangerous substances and articles).
- **Lack of renewable means of production:** Hypothetically, if the entire new builds move towards battery solutions by 2030. This could lead to more GHG emissions from the mass production of batteries with the current EU electricity mix.
- **Recycling:** Currently, the maritime industry does not have a clear plan on how to safely recycle used maritime batteries or the materials (such as cathode) to reduce the overall GHG emissions of batteries, taking into account the lifecycle perspective.
- **End of life:** Currently, there is no infrastructure or system in place where the batteries which had reached the end of its life be returned to the manufacturer or certified recycling facilities (ABB, 2016). This is needed to prevent individuals from using old batteries which could potentially cause accident or create a waste handling issue.

Technical feasibility: In maritime application, the battery powered ships can be divided into three types based on the (DNV GL, 2015) study:

- **Full-electric ships (ES):** All the power for both propulsion and auxiliaries comes from batteries. The batteries are powered through shore power. The economic rational of this type of battery application is the lower cost of shore electricity when compared to the cost of generating electricity on-board (ABB, 2003). Along with this, in most cases fossil fuels need to be used to generate electricity which would be counterintuitive.
- **Plug-in hybrid ships (PHES):** The battery technology is installed along with a conventional engine. The batteries are charged using shore power. The ship can operate solely on battery during specific operations such as manoeuvring in port and during stand-by operations.
- **Hybrid ships (HES):** A hybrid ships uses batteries to increase its engine performance and does not use shore power to charge its batteries (DNV GL, 2015). This is predominantly installed in vessels that experience large load variations during operation, the batteries may allow the engine to operate optimally and reduce fuel consumption/savings.

- **Applicable to fleet families:** Currently, the battery system can be installed both in new builds and as a retrofit for existing vessels but its limitations in determining factors such as energy density, power density and lifecycle limits its application to sea going vessels with long cruise.
- **Technical requirements for installations (E.g. Modifications, if needed, required space, state of the engine, mass production of engines, yards, Tanks and pipes):**
  - Some of the technical factors that should be taken into account when designing a battery powered ships are propulsion power vs installed power, load profile, manuverability, redundancy and cruise range. Each of them will be ultimate deciding factor for electric ships by a naval architect.
  - A battery powered ship would have no need for fuel tanks, fuel processing, exhaust and air trunking, the diesel engine and its gear box while these things will be replaced by power electronic modules and electric propulsion motors which is already widely used in diesel electric ships. Major modifications would be needed for diesel mechanical propulsion ships.
  - The removal of above mentioned machinery or other supportive equipment's frees up space which could be used for extra cargo space especially the DC distribution system has a lower volume footprint ultimately changing the design of the new full battery powered ships.
  - Auxiliary requirements would change to some extent since the higher efficiency reduces the cooling load requirement, thus eliminating the requirement for uptake exhaust trunking, air intakes etc. (Peng Wu, 2016)

- At the current relatively poor volumetric and mass density of batteries, ships have to compromise performance leading to a lower design speed or reduced range. This will have implications on the operational profile of the ship thus influencing the design.
- Battery replacement has to take place on an average of 5 years which is determined by the total number of charge/discharge cycles (Royal academy of engineering, 2013). With the current technology which means there needs to be enough yard availability to address this periodic requirement throughout the life time of the ship.
- Since the current is generated in AC and then rectified into DC. This avoids the need of synchronization of the different generators and therefore removes the need for a main switch board. Propulsions motors and big consumers are equipped with a converter whereas small consumers are connected to the grid through an island converter resulting in motors and other consumers remain standard AC components (ABB, 2003).
- They can discharge rapidly when short circuited. Too rapid a discharge of lithium battery can result in overheating of the battery, rupture and even explosion (Safety4Sea, 2011). It also cannot withstand overcharge and also degrade when over discharged (Llyod's register, 2016).

- **Installation:**
  - **Purely battery-driven vessel:** Ampere, the world’s first large fully electric vessel. Batteries are charged through an AC/DC converter either located on the vessel or onshore (if operating profile allows for), ideally by means of renewable energy. The battery systems deliver the power to the thruster. (DNV GL, 2015). Between trips the 1 MWh lithium-polymer battery pack on board can be charged in ten minutes. As the power required to charge the vessel is beyond the capacity of the electrical grid serving the villages of Lavik and Oppedal, battery buffers have been installed at both ports. This vessel prevents 2,640 tonnes of CO_2 from entering the atmosphere.
  - **Hybrid ships with ICE:** The princesses benedikte is a hybrid electric ferry powered by advanced energy storage system (ESS). This ferry represents a successful conversion of a former diesel-electric ferry to a battery hybrid vessel completing 10,000 operating hours since the conversion. The battery can be recharged into about 30 minutes from on-board generator power and can propel the 14,822 ton ship for about 30 minutes on battery power alone. It is the largest hybrid propulsion marine energy storage system ever installed at 2.6 MWh and an in the operational implementation of marine battery hybrid technology.
  - **Retrofit:** Eidvesik owned offshore vessel “Viking queen” was one of the first vessel to have 1.6 MW battery system as a commercial retrofit.

Technological readiness:

Production: TRL9 (Actual system proven in operational environment).

Technical feasibility (On board): TRL 9 (Actual system proven in operational environment).

Even though battery has reached the technological readiness level of 9, its characteristics limits its application to vessels with lower propulsion power and shorter sailing distance**.** With this limitation, currently battery supports main engine power requirements for a very small fleet family and potentially support auxiliary systems for large ships (A max of 2.6 MW based on real life application of princesses benedikte.

Non-technological maturity: (Legal, financial, knowledge, market, culture, others):

- Due to the fact that large scale marine installations of other battery technologies have not taken places yet we lack the knowledge on the risks it poses to the safety of the ship and crew on board. Most literature and installations only provided the safety hazards of lithium-ion batteries.
- During the course of this research, we were able to find little or no information on the exact amounts of each individual part or size used in the manufacturing of a battery since they fall under the proprietary information which is not available. More transparency is needed in this area from battery manufacturers to the public in terms of GHG intensity as this will help the ship-owner to assess the actual savings of a battery compared to an internal combustion engine in terms of life cycle perspective.
- Electric systems need an complete different approach towards the training of the crew. The electrical officers on board a diesel electric may be more familiar with the system but need more training to handle large packs of batteries while the crew of other propulsion systems need complete new training and knowledge to handle these vessels safely.

Market ready by 2030? During time of the study, it is evident the following two key technical restrictions stops battery from entering a new segment of fleet families.

1. Energy density which reduces its ability to power long cruise vessels.
2. Lifecycle, Keeping it an average of 5 years, requires the entire battery system to be changed which increases the lifecycle OPEX of the ship.

The removal of diesel fuel tanks, the diesel propulsion chain and the auxiliaries associated with it will free up space but this is still insufficient to supply power for a vessel beyond the 400 gross tonnage threshold. It is evident that developments have to take place in the current battery technology and commercialisation of promising technologies like lithium-air has to take place before batteries breaks away from the current niche market to act as an energy provider for the larger fleet families. With this limitations, batteries are to about act as an energy provider only for small niche market (below 400 gross tonnage). According to the Clarkson's 2018, there are about 14,000+ ships (below 400 gross tonnage) which constitutes around 23% of the global shipping that could reduce or completely eliminate its CO_2 emission by using the current battery technology. While this approach comes with its own problems such as grid integration to ports, increase in grid capacity and ability to increase renewable electricity's share in the current EU grid mix.

Conclusion:

The change to battery systems would mean a step towards reduction of CO_2 in terms of lifecycle emissions and elimination of CO_2 emissions in terms of downstream emissions but the ultimate solution of a zero emission energy source will only be valid, if the entire grid which supplies power is decarbonised leading to supply of greener electricity to produce battery to an industry which consumes 298 million tonnes of fuel in 2017 (ICCT, 2017) and supply the industry with power whose average installed power has been on the rise since 1970. Our analysis concludes that batteries as an energy source to support all the fleet families is highly unlikely to be market ready by 2030 unless lithium oxide which is in their R&D stage makes its leap but batteries will play an active role as an energy source for a niche fleet family is foreseen, which is also predicted by DNVGL in their recent study which predicts batteries to provide 5% of the total energy by 2050 to the shortsea and non-cargo shipping which will use 40% of the total shipping energy and, in these segments, electricity will constitute more than a tenth (11%) of energy use (DNV GL , 2018).

A.8 Summary

Summary of barriers and technological readiness level for all the above alternative fuels:

Table 6 – Summary of barriers to the use of fuels in maritime transport

Fuels	Barriers in Production process	TRL Production	Barriers in application on-board of ships	TRL of application on-board of ships
Methanol	• Production cost • CH_4 & N_20 emissions • Low energy efficiency when produced through biomass • Gasification – Environmental impact • Lack of diversification	TRL 6	• Modifications needed for existing engines • Lack of information on fuel efficiency • Corrosive nature • Lower energy density (Compared with HFO) • Retrofit not possible for older marine engines • Double walled fuel pipes needed • Low flashpoint – Additional risk assessment	TRL 7
Ethanol	• Unattractive within alcohol based fuels • Availability of feedstock • Lack of 2nd generation feedstock • Low EU production share • Limited knowledge/experience • Additional processing needed to achieve marine drop in quality	TRL 8	• Low energy density (Compared with HFO) • Highest mass among all bio fuels • Corrosive in nature • Low flashpoint – Additional risk assessment • Low vapour pressure • Attracts water • Only applicable to multi fuel engines • Poor lubricating property • Lack of technical support to use ethanol in existing marine vessels • Lack of knowledge/experience	TRL 5
DME	• Lack of data on availability • Lack of recognition (Among alternative fuels) • Low production output • Lack of large scale infrastructure (Storing/handling/ bunkering)	NA	• Lack of experience (Marine main engines) • Retrofitting main engines have not taken place so far • Only low speed marine engines available • Low energy density (Compared with HFO) • Spark engines might require after treatment (NOx and PM) • Unsatisfying lubrication properties (Might require separate lubrication system)	TRL 4

Fuels	Barriers in Production process	TRL Production	Barriers in application on-board of ships	TRL of application on-board of ships
			• Energy loss (Requires higher Compression energy than Oil) • Lower ignition delay • Lack of incentives/subsidies (Especially since it requires the least technical modification)	
Biofuels	• Cost (Cultivating and harvesting) • Operational cost • Processing cost • Achieved only the demonstration stage so far • Issues regarding commercialization unsolved • Shift of focus among the R&D company • Water and nutrients • Lack of consistent fuel supply	TRL 3	• Lack of data • Lack of experience with marine engines (Both main and auxiliary) • Lack of data on the energy density and combustion characteristics	TRL 3
Ammonia	• High cost of electrolysers • lack of availability of high temperature electrolysers • Lack of green ammonia production • Low energy density (Compared to HFO) • Extension of ammonia bunkering infrastructure is improbable during the time of the study	TRL 7	• Ammonia ICE: – Need for combustion promoter – Combustion promoters could be fossil fuels or hydrogen – Fossil fuels as combustion promoter negates the possibility of zero carbon combustion. – Hydrogen as combustion promoter technology not developed yet – High toxicity – Control issues on rate of fuel flow on varying load exists • Ammonia (Fuel cells): – Lack of data and experience on the use. • Both (Fuel cells and ICE): – Corrosion sensitivity of fuel supply lines (Copper alloys) is evident – Fuel storage (Both compressed or liquid) changes the entire fuel tank space requirement and structure	Ammonia(ICE):TRL 5 Ammonia (Fuel cells): TRL 4

Fuels	Barriers in Production process	TRL Production	Barriers in application on-board of ships	TRL of application on-board of ships
Renewable hydrogen	• Cost (In comparison to hydrogen produced via fossil route) • Cost of catalysts are high • Lack of supply chain infrastructure. • Lack of experience and knowledge of marine hydrogen propulsion under deep sea sailing conditions during the time of the study • Lack of regulations (IGF Code does not include hydrogen yet) • Energy utilization of hydrogen compared to batteries. • Fuel cell lifetime • Hydrogen storage issues • Safety and risk assessment of hydrogen non-existent	TRL 7 (Vessels with low power requirements and short ranges)	• Knowledge on retrofit possibility not available • Fuel reformer needed • Storage, handling and bunkering of hydrogen is non-existent for maritime • Additional support plants for hydrogen fuel cells for large ships is not available • New design thinking on structure and stability needed (Sea going vessels with longer range) • Safety and risk assessment identified many risks during bunkering (Operational and crew safety) • Fuel cells retrofit only possible to electrical transmissions • Power limitations • Possibility of increased above water structures	TRL 7
Batteries	• Cost of lithium-ion batteries • Disturbs the current economic case of shipping • High GHG emissions (Production) • Will increase the pressure on grids • Cannot accommodate sea going vessels yet • Port infrastructure not available yet • Lithium batteries classified as dangerous substances • Lack of renewable means of production • Lack of recycling possibilities • Lack of infrastructure of system in place for battery end of life scenario	TRL 9 (Vessels with low power requirements and short ranges)	• Major modification needs for retrofits • Require structural/stability changes for retrofits • Implications on the operational profile of the ship • Lifecycle of batteries (5 yrs avg) • Can discharge rapidly when short circuited (Fire issues)	TRL 9 (Vessels with low power requirements and short ranges)

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