Final Report - Framework CO2 reduction in shipping

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1. Preface

Maritime transport is responsible for about 2.5% of global greenhouse gas emissions. Without countermeasures this share is expected to increase between 50% and 250% by 2050, depending on future economic and energy developments.

Several studies show that energy consumption and CO2 emissions can be reduced up to 75% by applying operational measures and implementing existing technologies.

Ship owners need reliable and accurate information about the effectiveness of the various technologies so that financial risks can be kept to a minimum.

Several good and extensive reports have been written on CO2 reduction in shipping. These reports were used as a basis for this research. However, new opportunities seem to emerge in a steady pace.

This reports aims to establish a coherent overview of developments and possible solutions for CO2 reduction in shipping including its strengths and weaknesses, opportunities and threats. These developments and solutions can also provide interesting opportunities for co-operation and further (fundamental) research.

This report will elaborate on several specific developments, sometimes only a reference will be given to an existing source. We have tried to keep the document concise and challenging for the many stakeholders in the maritime cluster.

This project is executed under the auspices of Netherlands Maritime Land and supported by the Ministry of Economic Affairs.

2. Introduction

More than 90% of global trade is executed over sea by the international shipping industry. Even though international shipping is the most efficient way of transport of goods for many years, there is always room for improvement. Especially with regard to harmful emissions of Carbon-dioxide (CO_2), Sulphur-oxides (SO_x), Nitrogen-oxides (NO_x) and Particulate Matter (PM).

Since the year 2000, the International Maritime Organisation (IMO) has put the theme of GreenHouse Gas emissions (GHG) high on her agenda. In international shipping CO_2 is the main contributor to GHG emissions. Three GHG Studies have been completed since then; in 2000, 2009 and 2014.

The first international requirements for the shipping industry regarding air emissions entered into force in 2005 (Marpol Annex VI). Since 2011 clear CO_2 performance indicators have been established by IMO with regard to the Energy Efficiency Design Index (EEDI) and the Ship Efficiency Management Plan (SEEMP).

On the 1st of January 2015 the SO_x Emission Control Area (SECA) was established in both European and North American waters. Recently the European Union requested the IMO to establish a NO_x Emission Control Area (NECA) in the North Sea and the Baltic Sea starting from 1st of January 2021.

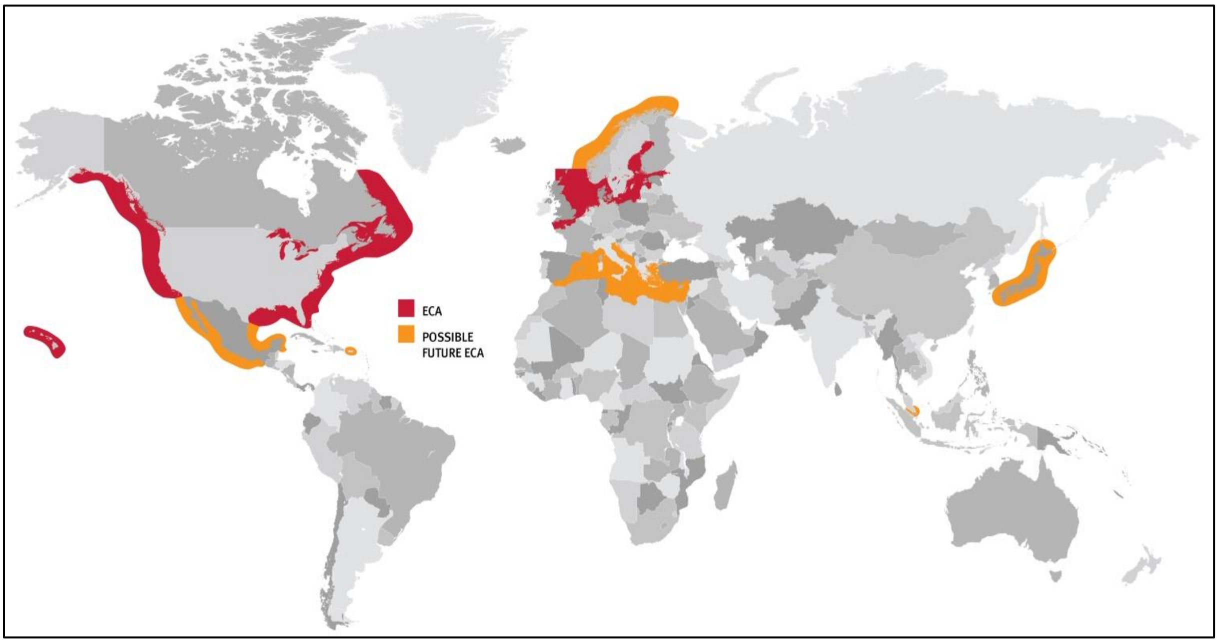

Figure 1: Established and possible future Emission Control Areas (ECA's) as from 1st of January 2015

The reduction of Green House Gasses is also high on the agenda of the European Commission. The headline targets of the Europe 2020 strategy for smart, sustainable and inclusive growth are:

- 20% improvement in energy efficiency
- 20% of EU energy from renewables
- 20% cut in greenhouse gas emissions (from 1990 levels)

The EU Emissions Trading System (ETS) is the EU's key tool for cutting greenhouse gas emissions from large-scale facilities in the power and industry sectors, as well as the aviation sector. Although transport and shipping are a non ETS sector, the EU member states also committed themselves to reduce greenhouse gas emissions for non ETS sectors in 2020 compared to 2005 levels. For example, in The Netherlands the required reduction for 2020 is 16%.

In July 2016 the European Commission presented a legislative proposal called the "Effort Sharing Regulation" setting out binding annual greenhouse gas emission targets for EU member states for the period 2021-2030 based on the principles of fairness, cost-effectiveness and environmental integrity.

Sectors of the economy not covered by the EU ETS are required to reduce emissions 30% by 2030 compared to 2005 as their contribution to the overall target. For the Netherlands the non ETS sectors (including transport and shipping) have a target of reducing greenhouse gas emissions with 36% in 2030 compared to 2005 levels.

The Commission's 2011 White Paper on transport suggests that the EU's CO2 emissions from maritime transport should be cut by at least 40% from 2005 levels by 2050, and if feasible by 50%. (European Commission, 2011)

Although international shipping is not covered by the EU's current emissions reduction targets, the Dutch maritime sector feels obliged to comply with these targets and present itself as a modern and sustainable industry sector.

2.1 Available pathways to reduction of harmful emissions in shipping

In order to reduce greenhouse gas emissions in shipping two major approaches can be followed.

On the one hand there are energy efficiency measures and technologies that can be applied on a ship to reduce fuel consumption and consequently also CO2 emissions on board. The accumulation of several smaller measures can have a great effect on the total CO2 emissions.

The Association Netherlands Maritime Technology recently started a portal containing almost 200 different technologies and measures to improve the sustainability of the shipping industry. (Netherlands Maritime Technology, 2016).

Chapter 3 of this report will outline single measures and technologies that lead to a substantial fuel reduction and subsequent reduction of CO2 emissions of more than 25%.

On the other hand there are CO2 prevention measures focussed on the prevention and elimination of CO2 from fossil fuels.

Chapter 4 of this report will elaborate on specific measures that lead to a substantial reduction of CO2 emissions of more than 25%.

Both approaches are equally important in order to reach the required emission targets.

Chapter 5 of this report will provide a short introduction to the removal of CO2 by using Carbon Capture Systems (CCS). These systems are normally utilized on land-based industrial plants, but might offer an opportunity for the shipping industry to substantially reduce CO2 emissions.

According to the report "Transition to Sustainable" of the Dutch Ministry of Economic Affairs transport contributes for almost 25% to the Dutch energy related CO2 emissions and for 20% to the total emissions of GreenHouse Gasses in the Netherlands. The CO2-emissions of the Dutch transport sector increased between 1990 and 2005 from 30.5 to 38 megaton CO2.

Since 2005 the CO2 emissions have stabilised and slowly decreased in the last two years. More than 50% of these CO2 emissions come from personal and public transport by road. About 25% of these CO2 emissions come from road transport of goods.

Inland shipping, fisheries and shipping in the Dutch continental waters are responsible for almost 20% of these CO2 emissions.

Liquefied bio fuels and (bio) LNG are most suitable for heavy road transport and shipping. Bio jet fuel is a sustainable energy carrier for the aviation industry. Furthermore bio fuels are regarded as the transition option towards electrification for short distance transport. (Rijksoverheid, 2016)

3. Overview of energy efficiency measures and technologies

3.1 An evolutionary approach

In the brochure “Time for international action on CO2 emissions from shipping” of the European Commission ten of the most effective and readily available technical and operational measures are summed up to reduce CO2 emissions in the shipping industry including their estimated CO2 reductions.

Technology	Claimed energy reduction
Speed reduction	17-34%
Waste heat recovery	2-6%
Hull coating	2-5%
Hull cleaning	1-5%
Propeller en rudder upgrade	3-4%
Weather routing	1-4%
Compensation of trim and ballast	1-3%
Propeller polishing	1-3%
Main engine tuning	1-3%
Autopilot upgrade	1-1,5%

Figure 2: CO2 savings compared to ‘business as usual’ in 2020 (Global Shippers Forum,2015)

Speed reduction is one of the best ways to reduce fuel consumption and harmful emissions in shipping. A ship that reduces its speed by 10% will realise a reduction of fuel consumption and harmful emissions of about 20%. A ship that reduces its speed by 30% can even realise a reduction of fuel consumption and harmful emissions of more than 50%. Of all measures mentioned in figure 2 speed reduction is the only measure that leads to a substantial reduction of fuel consumption and harmful emissions of more than 25%.

The potential of energy saving through speed reduction in shipping is a focus of many ship-owners, but also specialised companies like We4Sea (We4sea, 2016) assist ship-owners and designers to achieve better results for their ships by using big data and other state of the art technology.

Dutch ship-monitoring company We4Sea is launching a new project in order to help ship-owners increase fuel efficiency and reduce CO2 emissions by using big data technology.

Within the project’s framework, We4Sea plans to provide detailed insights on all aspects of ship-owners operations – technical, logistical and operational, that impact their fuel efficiency. The crucial insights will be provided on a web platform, according to We4Sea.

The company is to monitor 5 ships on every ship joining the project for a six months period at a fixed price. The worst-performing ship will be analysed in detail, with detailed proposals aimed at achieving fuel efficiency and reducing harmful emissions.

“We will not sit and wait to make a difference. We offer our knowledge and experience to increase sustainability in the maritime world. It is our goal to reduce CO2 emissions with 1 million tons before 2019,” Dan Veen, We4Sea’s CEO, notes. (World Maritime News, 2016)

An evolutionary approach to energy efficiency measures and technologies requires many small steps in order to gain benefits greater than 25%. A more revolutionary approach to energy saving methods should also be investigated in order to gain larger benefits.

3.2 A more revolutionary approach

In August 2015 the IMO started the Global Maritime Energy Efficiency Partnership (GloMEEP). This partnership has developed a portal with an extensive list of energy efficiency measures for shipping in order to reduce GreenHouse Gasses. (IMO, 2015)

This list includes more than thirty different technologies subdivided in machinery technologies, propulsion and hull improvements, energy consumers and optimised operations. (see Annex 1) Many of these technologies are semi mature or have already technically matured. Some technologies have not matured yet and are still in the research or early development stages.

This includes the following technologies.

- Air cavity lubrication – the use of air injection on the wetted hull surface to improve the ship's hydrodynamic performance.
- Fixed sails or wings – the use of sails and wings to replace some of the propulsion power
- Flettner rotors – the use of Flettner rotors to generate power from wind energy
- Kites – the use of kites to replace some of the propulsion power needed
- Solar panels – installing solar panels for conversion of solar energy to electricity

After desk research and interviews with representatives of the Dutch maritime scientific community the following subjects can be added to the above mentioned list.

- Nuclear propulsion
- Rail towed vessel
- Stevelduction
- Hull vane
- Flex tunnel
- Use of multiple propulsors
- Shore connection

The contribution of solar panels for energy efficiency in commercial shipping is regarded as very small and will not be subject to further study. The use of shore connections for ships in port can give a significant reduction in emission of greenhouse gas and other pollutant air emissions locally. However, the source of energy used by the shore connection will determine whether this is a sustainable solution. Therefore, shore connections will not be regarded in detail in this study.

Figure 3 sums up the most important technologies and operational measures to substantially reduce fuel and harmful emissions, plus several key parties involved in the current development process.

Technology	Party involved	Claimed energy reduction
Nuclear propulsion	TUD Van Dam	80-100%
Rail towed vessel	TUD Thill	50-100%
Fixed sails, wings and kites	Marin - Sail project Lade As - Vindskip	35-60%
Stevelduction	TUD Lodewijks	25-50%
Use of multiple propulsors	TUD - Streamline project	20-25%
Flettner rotors	C-Job design	10-20%
Air cavity lubrication	Damen Shipyards	10-15%
Hull vane	Van Oossanen	10-15%
Flex tunnel	Van der Velden	10-15%

Figure 3: More revolutionary energy efficiency technologies

It is interesting to note that the four most energy efficient technologies were already used in the past. The highest claim for reduction of fuel and emissions is the use of nuclear energy. Two other technologies, i.e. rail towed vessel and stevelduction are especially important for inland waterways and possibly for coastal waters. Fixed sails or wings can technically be used in inland, coastal and international shipping, although confined waters may restrict the use of sails considerably.

In the following paragraphs a short description is given of each technology that can achieve an energy reduction of 25% or more.

3.2.1 Nuclear propulsion

Nuclear propulsion is used in various types of naval ships and submarines. In commercial shipping nuclear propulsion is seldom used. Three nuclear merchant cargo ships were built in the sixties and seventies, but are out of service now. The only nuclear container vessel still in operation is the Russian Sevmorput which was built in 1988 (see figure 4). Russia also has six ice breakers still in operation outfitted with nuclear fission reactors and output powers up to 171 MW.

Figure 4: Nuclear powered container vessel Sevmorput

The efficiency of nuclear plants is different than internal combustion engines. On the steam turbine side they use the Rankine thermodynamic cycle with steam temperatures at saturated conditions. This gives a lower thermal cycle efficiency than the high temperature coal fired power plants. Thermal cycle efficiencies are in the range of 38%. Since the energy release rate in nuclear fission is extremely high, the energy transferred to steam is a very small percentage - only around 0.7 %. This makes the overall plant efficiency only around 0.27 %. But one does not consider the fuel efficiency in nuclear power plants; fuel availability and radiation losses take centre stage. (Bright Hub Engineering, 2016)

In November 2010 British Maritime Technology and Lloyd's Register started a two-year study with US-based Hyperion Power Generation (now Gen4 Energy), and the Greek ship operator Enterprises Shipping and Trading SA to investigate the practical maritime applications for small modular reactors. The research intended to produce a concept tanker-ship design, based on a 70 MW reactor. (Wikipedia, 2016)

In the Netherlands research on nuclear marine propulsion was executed by Prof. Dr. ir. H. van Dam of the reactor institute of TU Delft and Captain Crommelin in the Nereus project. The propulsion system is based on a pebble bed reactor, with nuclear fuel bedded in balls. (Crommelin, Crommelin, 2004)

Since nuclear propulsion is not regarded as sustainable source of energy and has such different characteristics than fossil and alternative fuels it will not further be taken into account in this study.

3.2.2 Rail towed vessel

Propulsion of (inland) vessels normally requires screw propellers. The maximum propulsive efficiency of propellers is less than 70%. The suction on the hull induced by the propeller, the generated swirl and especially for inland vessels the restricted size of the propellers due to the limited draught are also affecting the propulsive efficiency negatively. In the end, in shallow water conditions sometimes more than 80% of the mechanical propulsion energy is wasted and only 20% of the energy is effectively used.

In the past ships were towed by man or animal on the river bank for its efficiency. Punting was also preferred over rowing whenever possible. Early in the 20th century this principle was used in mechanical propulsion for ships when chain and cable vessels were operated on many rivers and canals in Europe and elsewhere. The obtained energy efficiency was significant, but traffic density and other problems caused inland shipping to adopt the internal combustion engine as the source of propulsion.

In parallel with modern wind power technology where ultra-modern windmills replaced the old ones, today’s technology can be used to develop an energy efficient towing system for inland vessels. Such a system offers significant contributions to inland shipping safety and increases its potential on smaller waterways that are not efficiently reached with screw propulsion.

The concept offers inland shipping a better penetration into the entire transport system and provides benefits regarding sustainability and reliability. Figure 5 gives an impression of a rail boat of the German ship owner “Vereinigte Elbeshiffahrtgesellschaft” built in 1885 with a length of 36 metres and draught of 0,65 metres. Prof. ir. B. Boon and Dr. -ing. C. Thill of TU Delft are partners involved in this innovative concept.

Figure 5: Model of rail towed vessel or Ketten-Schleppdampfer used on the Elbe Germany.

3.2.3 Fixed sails, wings and kites

There are many different ways to use fixed sails and wings in assisting ship propulsion. The EU project Sail describes 14 techniques using sails, wings or turbines. Energy savings of up to 50% are claimed using wind propulsion (NSRSail,2012). In the LR publication “Wind powered shipping” four main categories are observed:

Wingsails or rigid sails, are wing-shaped foils with varied geometry and configurations. They can be deployed as single foils or multiple foils attached to a single base. Flaps are often used. Depending on the size of the vessel, the available deck space and other restrictions, multiple sets can be deployed. The operating principle is the same as any aerofoil intending to create lift and drag. By rotating to the optimum angle of attack, the lift can be maximised.

Square rig sail systems are freestanding, rotating spars that carry canvas sails similar to those used by the old square-riggers or clipper ships. The modern incarnation is fully automated and has no rigging on the deck or mast. While traditional square rigs were limited in how they were positioned to the optimum angle of attack, this DynaRig concept overcomes the problem by having a rotating spar. The lift coefficients may be lower than with wingsails, but this is compensated by the larger surface (sail) areas, resulting in large lift forces being generated.

Towing kites are kites connected to a control pod at the forecastle, deployed at high altitude at sea and recovered to allow passage under bridges or through other navigational constraints. One or more towing kites can be used. The system comprises a towing kite fabricated from high-strength textile, a towing rope, a launch and recovery system, and a control system for automated operation. While wind speed is reduced near the water surface, kites fly at higher altitudes and therefore benefit from higher wind speeds.

Flettner rotors are cylindrical structures mounted on the deck and spun mechanically. Using motors powered by the ship’s electrical supply, the cylinders spin to create the Magnus effect and generate forward thrust. When wind passes across a rotating cylinder a lift force is produced. This force has a linear relationship with wind speed and, unlike conventional sails or aerofoils, a true cross-wind relative to the ship will produce a useful forward thrust at any ship speed even when this is greater than the wind speed. However, the vorticity produced by a rotor and its interaction with other rotors or the vessel’s superstructure is complex and requires a detailed assessment (using CFD) in order to evaluate the performance of the technology. (Lloyd’s Register Marine, 2015)

Figure 6: Vindskip concept claiming 60% energy reduction and 80% reduction of GHG emissions (Lade As, 2012)

Another interesting project that claims energy savings up to 60% and 80% reduction in green house gas emissions is the project Vindskip by the Norwegian company Lade As. Figure 6 gives an artist impression of the Vindskip concept. Lade As has a patented technology for a hybrid merchant vessel with a hull shaped like a symmetrical air foil and was nominated for the Next Generation Ship Award Nor-Shipping 2015. (IWSA, 2015)

3.2.4 Stevelduction

Stevelduction is an old technique to make use of the flow of the river and the force of gravity to propel a vessel without using sails or engines. It is the most energy efficient way of transportation. In the past rafts and sailing vessels facing head winds used stevelduction on rivers like the Waal and the Maas. This technique is prohibited nowadays because of the increased vessel traffic density on these rivers.

A flowing river is basically a inclined plane, where water flows downstream and is decelerated by the river bed and wing dams. The weight of the ship causes it to descent a little faster than the surrounding water a gives it speed in the water. Therefore the vessel remains manoeuvrable with a large rudder. In practice a speed of about two times the velocity of the river flow can be obtained. Inland vessels with lengths of 67 to 80 meters reached speeds of 12 to 14 kilometres per hour sailing on the river Rhine from Germany to The Netherlands.

The river Main and Neckar had no barrages, but a chain was used by specialized chain tug boats to help inland vessels upstream. This is a very efficient way to use tug boats without propulsion to assist inland vessels. For the downstream trajectory stevelduction was used.

The so-called Stevelduct claims to create a new container modality between Duisburg – Germany and Maasvlakte2 – The Netherlands (200 kilometres) with a transport capacity of 4.2 million containers and 51 million ton dry bulk without any harmful CO2 emissions. Prof. dr. ir. G. Lodewijks of TU Delft is one of the partners involved in this innovative concept. (Stevelduction, n.d.)

Figure 7 gives an example of stevelduction at Pont du Gard in France. The distance covered is 50 kilometres with a difference in height of 11.50 meters and a water flow of 1250 m3 per hour.

Figure 7: Stevelduction at Pont du Gard in France

4. Overview of CO2 reduction measures

4.1 Alternative fuels presently used in shipping

4.1.1 Natural Gas

There are many alternatives to Heavy Fuel Oil (HFO), Marine Gas Oil (MGO) and Marine Diesel Oil (MDO). At present Liquefied Natural Gas (LNG) and Compressed Natural Gas (CNG) are used as an alternative transport fuel in shipping in The Netherlands and methanol in the European context.

When compared to MDO, natural gas has a substantial better performance with regard to SOx, NOx and PM (less than 15% of the emission values of MDO).

With regard of CO2 emissions the differences between natural gas and MDO are less impressive. The energy consumed to transport natural gas from Well To Tank (WTT) is the lowest of all fossil fuels and amounts about 5 grCO2eq/km. The energy consumed to convert natural gas from Tank To Wheel (TTW) or in case of the shipping industry from Tank To Propeller (TTP) is also the lowest of all fossil fuels and amounts about 59 grCO2eq/km.

When these two values are added up, the Well To Wheel (WTW) or in case of the shipping industry the Well To Propeller (WTP) value of natural gas is 64 grCO2eq/km.

The MDO WTP value is 87grCO2eq/km (i.e. MDO WTT is 13grCO2eq/km and TTP is 74grCO2eq/km). This means that natural gas has a 26% better performance with regard CO2 emissions than MDO.

In the shipping industry natural gas must be compressed (CNG) or liquefied (LNG) in order to store it properly on board of a vessel.

Compression to 250 bar will increase the WTT value of natural gas from 5 grCO2eq/km to 21grCO2eq/km. Liquefaction of natural gas will also increase the WTT value to 20grCO2eq/km.

This means that for CNG at 250 bar and LNG the WTP value is about 80gr CO2eq/km. In that case, LNG and CNG only have a 8-9% better performance with regard to CO2 emissions than MDO.

4.1.2 Methanol

In a European context methanol is also used as a transport fuel with comparable results to natural gas with regard to emissions of SOx, NOx and PM.

With regard of CO2 emissions the differences between methanol and MDO are not impressive.

The Well To Propeller (WTP) value of methanol is 91 grCO2eq/km and even higher than MDO. MDO has a 4% better performance with regard CO2 emissions than methanol.

This methodology is commonly used to compare various (alternative) fuels and is expressed in a standardised format of CO2equivalent emission in grams per kilometre. The WTT and TTP values of the different fuels can vary considerably based on factors like the production process, transport conditions, engine performance, etc. This clarifies the different values for some of the studied (alternative) fuels (e.g. LNG and diesel).

Figure 8 provides an overview of Well To Propeller CO2 emissions of various transport fuels based on multiple sources. (Florentinus et al., 2012), (Nationaal LNG platform, 2014), (Verbeek et al., 2013), (Wikipedia, 2016). The Well To Tank (WTT) values are in blue, the Tank To Propeller (TTP) values are in red.

4.2 WTP CO2 performance of potential marine fuels

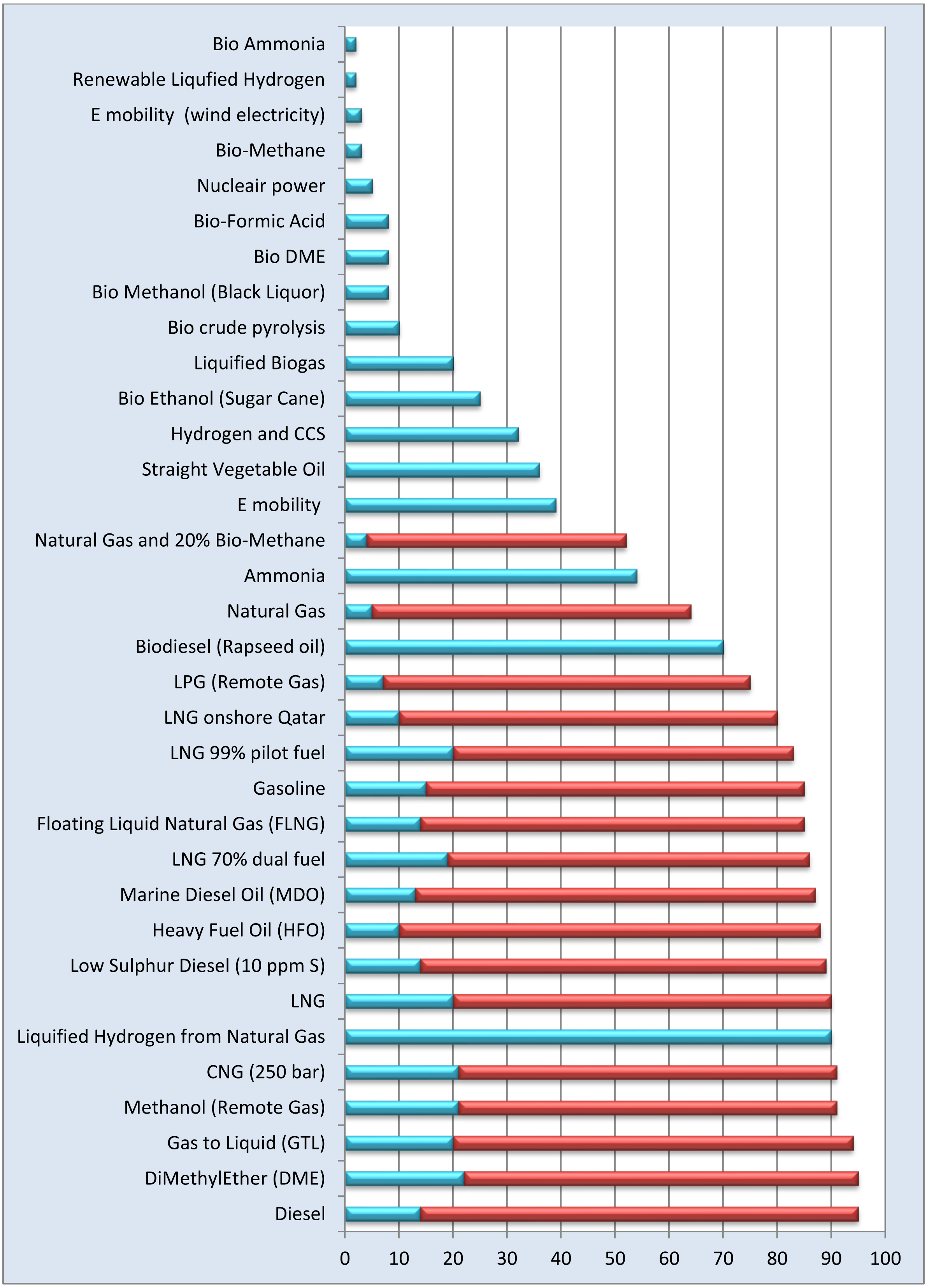

Figure 8: WTP CO2 performance (in gr CO2eq/km)

It is interesting to note that although Hydrogen is often referred to as the "Fuel of the Future", the current production of Liquefied Hydrogen from Natural Gas still gives a WTP value of 90 gr CO2eq/km. Production of Hydrogen combined with Carbon Capture Systems results in a WTP value of 32 gr CO2eq/km and only the production of Liquefied Hydrogen from renewable sources has an excellent performance with a WTP value of 2 gr CO2eq/km.

Special attention is given to measures that lead to a substantial reduction of CO2 emissions (i.e. more than 25% compared to MDO). Therefore, especially fuels with a WTP value of less than 65 gr CO2eq/km will be further investigated in this study.

4.3 LHV Fuel Efficiency of potential marine fuels

The feasibility of alternative fuels for shipping is not only determined by the CO2 emission values. The fuel efficiency of a fuel is also very important. As we have seen in the previous chapter, natural gas is a very clean fossil fuel. However, the storage volume of natural gas is too large to make it feasible on board of ships unless it is compressed (CNG) or liquefied (LNG).

The Lower Heating Value (LHV) of a fuel is of major importance when used for internal combustion engines. This lower heating value represents the fuel efficiency and is expressed in MJ/kg.

In shipping, the volume of the fuel is more important than the specific weight of that fuel. Therefore the LHV of a fuel is multiplied by the density (in kg/m3) of that same fuel in order to obtain the LHV per unit of volume.

For example, the LHV for natural gas is rather high (47.1 MJ/kg). The density of natural gas is only 0.718 kg/m3. The LHV of natural gas per unit of volume is 34 MJ/m3 while the LHV of MDO is 36363 MJ/m3. This means that the required storage volume on board for natural gas (in gaseous state) is more than 1000 times higher than the storage volume for MDO.

Another example, the LHV for Liquefied Natural Gas is 48.6 MJ/kg. The density of Liquefied Natural Gas is 422 kg/m3. The LHV of Liquefied Natural Gas per unit of volume is 20518 MJ/m3. The required storage volume for LNG is about twice as high as the volume for MDO.

Finally, the LHV for Liquefied Hydrogen is the highest of all fuels (120 MJ/kg). The density of Liquefied Hydrogen is only 70.8 kg/m3. The LHV of Liquefied Hydrogen per unit of volume is 8496 MJ/m3 requiring 4.2 times the storage volume of MDO.

It is not a surprise that the fuels currently in use in the shipping industry have the highest LHV values per unit of volume.

The Lower Heating Value (LHV) of Heavy Fuel Oil (HFO) per unit of volume is the highest of all marine fuels (40973 MJ/m3), followed by MDO (36363 MJ/m3).

The LHV per unit of weight of HFO and MDO are almost identical, but the density of HFO (960 kg/m3) is higher than MDO (850 kg/m3)

Figure 9 provides an overview of Lower Heating Values (LHV) per unit of volume of various (potential) transport fuels based on multiple sources.

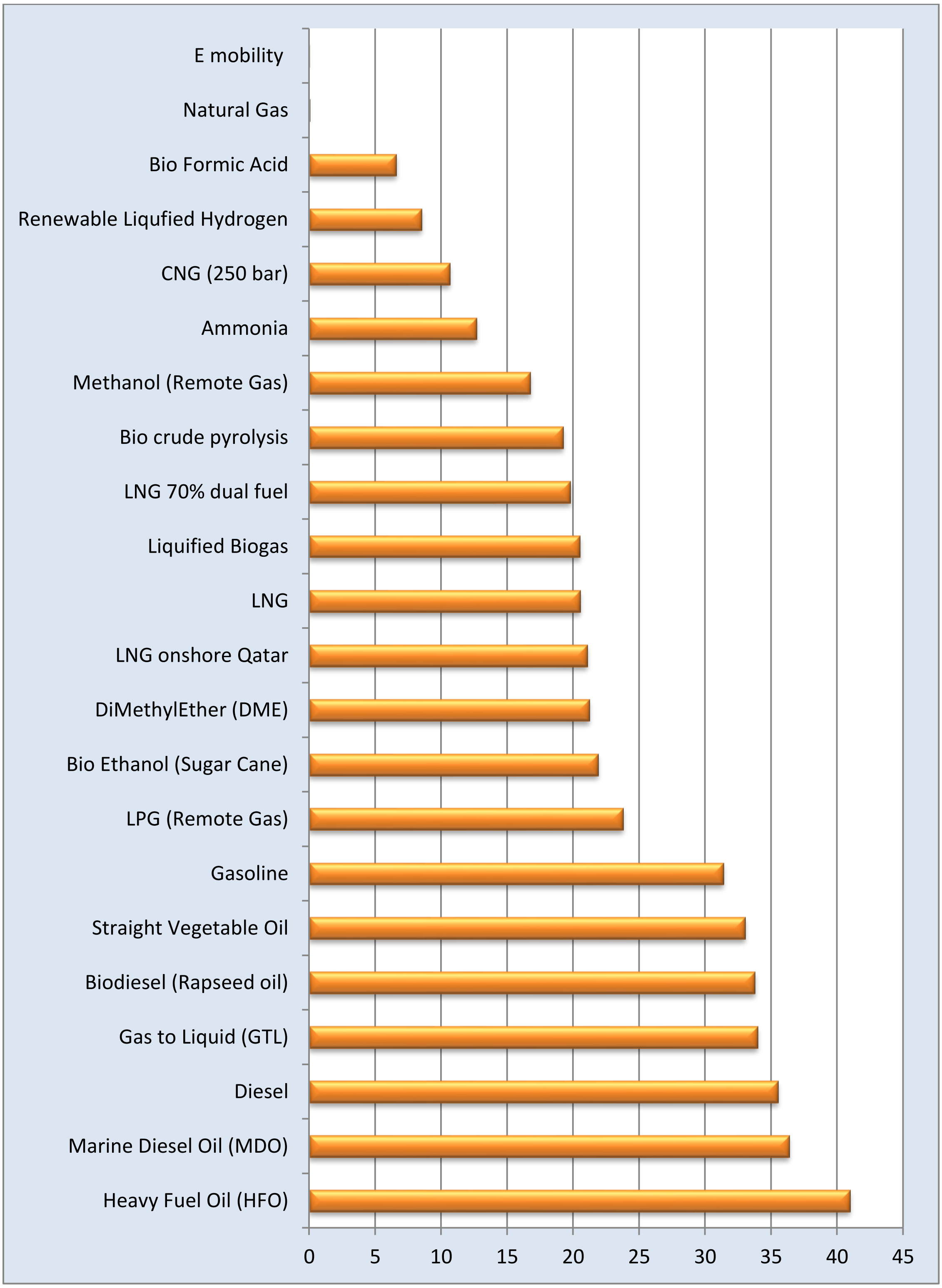

Figure 9: LHV Fuel Efficiency per unit of volume (in MJ/dm3)

The most favourable alternative fuels with regard to LHV Fuel Efficiency per unit of volume are Gas to Liquid (GTL), Biodiesel and Straight Vegetable Oil.

4.4 Calculation of the Overall Fuel Performance of potential marine fuels

The previous chapters showed that both Well To Propeller (WTP) CO2 performance and LHV Fuel Efficiency per unit of volume (LHV in MJ/m3) are very important parameters in shipping.

Combining these two values can give a good insight in the Overall Fuel Performance of an (alternative) fuel for the shipping industry.

4.4.1 Relative WTP CO2 performance

Paragraph 4.2 demonstrates that the best WTP CO2 performance of a fuel has the lowest emission value. (e.g. Renewable Liquefied Hydrogen with 2grCO2eq/km) while Diesel has the worst WTP CO2 performance (95grCO2eq/km).

The ranking of the WTP CO2 performance of a fuel is given in a relative value based on the worst WTP CO2 performance using the formula:

Relative WTP CO2 perf. = 1 - (WTP CO2 of the given fuel / WTP CO2 of Diesel)

For Diesel the Relative WTP CO2 performance formula is 1 – (95/95) = 0
For Renewable Liquefied Hydrogen the Relative WTP CO2 performance is 1- (2/95) = 0.98.

4.4.2 Relative LHV Fuel Efficiency per unit of volume

Paragraph 4.3 shows that the relative LHV Fuel efficiency per unit of volume can be calculated rather easy. Since HFO has the best performance with regard to fuel efficiency per unit of volume this can be done by using the formula:

Relative LHV Fuel Eff. = LHV of the given fuel / LHV of HFO.

For HFO the Relative Fuel Efficiency is 40973 / 40973 = 1
For MDO the Relative Fuel Efficiency is 36363 / 40973 = 0.89
For Renewable Liquefied Hydrogen the Relative Fuel Efficiency is 8496 / 40973 = 0.21

4.4.3 Overall Fuel Performance w.r.t. WTP CO2 performance and LHV Fuel Efficiency

The Overall Fuel Performance with regard to WTP CO2 performance and LHV Fuel Efficiency can be calculated with the following formula:

$$\text{Overall Fuel Performance} = (\text{Relative WTP CO2 perf.} \times \text{Relative LHV Fuel Eff.})^{½}$$

Figure 10 provides an overview of the Overall Fuel Performance with regard to WTP CO2 performance and LHV Fuel Efficiency. The most favourable alternative fuels with regard to both WTP CO2 performance and LHV Fuel Efficiency per unit of volume are Straight Vegetable Oil and Bio DME, followed by Bio Crude, Liquefied Bio Gas (LBG), Bio Ethanol and Bio Methanol.

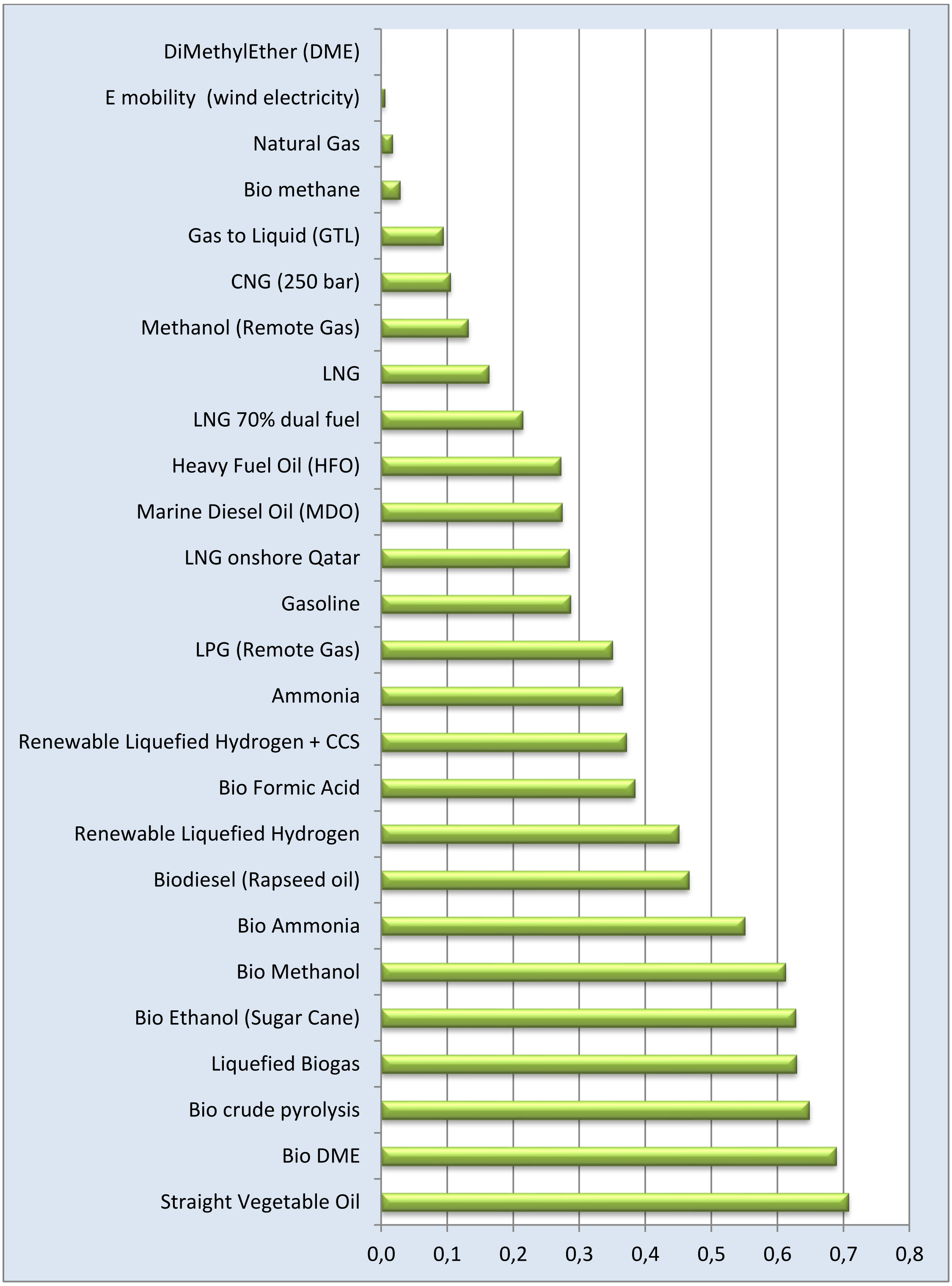

Figure 10: Overall Fuel Performance with regard to WTP CO2 performance and LHV fuel efficiency

In the next chapter a short description will be given of alternative fuels with an Overall Fuel Performance that is substantially larger than MDO. This implies fuels with an Overall Fuel Performance larger than LPG. Only LPG and Ammonia are fossil fuels. Ammonia also has a renewable alternative called Bio Ammonia. All other fuels are biofuels or renewable fuels.

5. Short description of alternative marine fuels

5.1 Liquefied Petroleum Gas

Liquefied Petroleum Gas (LPG) consists of a mixture of propane and butane gasses. Propane is a three-carbon alkane with the molecular formula C3H8. It is a gas at standard room temperature and atmospheric pressure, but compressible to a transportable liquid. As a by-product of natural gas processing and petroleum refining, it is commonly used as a fuel for engines, portable stoves, and residential central heating. Propane is the third most widely used motor fuel in the world. In 2013 almost 25 million vehicles were fuelled by propane gas worldwide. Over 25 million tonnes of LPG are used annually as a vehicle fuel. (Wikipedia, 2016)

Butane is an organic compound with the formula C4H10 that is an alkane with four carbon atoms. Butane is a gas at room temperature and atmospheric pressure. Butanes are highly flammable, colourless, easily liquefied gases. Normal butane can be used for gasoline blending, as a fuel gas, either alone or in a mixture with propane, and as a feedstock for the manufacture of ethylene and butadiene, a key ingredient of synthetic rubber. (Wikipedia, 2016)

LPG is sometimes mentioned as a potential marine fuel candidate. However, very limited information is available on LPG’s viability as a marine fuel. LPG is considered a premium product and is priced accordingly and too expensive compared to other alternative fuel options.

Although the supply is in place, its current markets are in automotive transportation and domestic heating and cooking, markets that have a different price reference than shipping. In terms of safety, propane is heavier than air and thus presents a safety hazard if it were to accumulate in the bilges or low sections of a ship’s engine room in the event of a leak in the fuel system. Therefore it is not considered safe for shipboard us. (Moirangthem, 2016)

5.2 (Bio) Ammonia

Ammonia is a compound of nitrogen and hydrogen with the formula NH3. It is a gas at standard room temperature and atmospheric pressure, but compressible to a transportable liquid. Ammonia is a colourless gas with a pungent smell. It contributes significantly to the nutritional needs of terrestrial organisms by serving as a precursor to food and fertilizers. Ammonia, either directly or indirectly, is also a building block for the synthesis of many pharmaceutical products and is used in many commercial cleaning products. The global industrial production of ammonia in 2014 was 176 million tonnes. (Wikipedia, 2016)

Ammonia is sometimes called the “other hydrogen” due to its structure of three hydrogen molecules and one nitrogen molecule. The ability of ammonia gas to become a liquid at low pressures means that it is a good “carrier” of hydrogen. Ammonia is over 50% more energy dense per unit of volume than liquefied hydrogen. Ammonia can thus be stored and distributed easier than elemental hydrogen. In addition to hydrogen fuel cells there are several fuel cells designed to use ammonia directly. This would eliminate the need to separate the ammonia into its hydrogen and nitrogen elements before it is used in the fuel cell. These cells enable high efficiency conversion of ammonia to electric power. (Hofstrand, 2009)

Combustion of Ammonia results in more engine power than any energy equivalent amount of hydrocarbons (gas, diesel), alcohols, or hydrogen. This is because burning NH3 produces more moles of gaseous combustion products (N2 and H2O) than the other fuels (CO2 and H2O). Companies like Proton Ventures of the Netherlands make modular NH3 plants using water electrolysis and the Haber Bosch process. (Kang, 2014)

Traditionally, hydrogen for the Haber-Bosch-process comes from coal gasification or from natural gas. The American company NHThree recently developed a so-called Solid State Ammonia Synthesis (SSAS) and claims an 43% efficiency improvement compared to the Haber-Bosch process. Nitrogen can be taken easily from the air. The challenge for sustainable production of ammonia is in the sustainable production of hydrogen from electricity or another sustainable manner. (Wassink, 2013)

5.3 (Renewable Liquefied) Hydrogen

Hydrogen with the formula H2 is the smallest and lightest of all gas molecules, thus offering the best energy-to-weight storage ratio of all fuels. In principle, internal combustion engines and turbines can also be used for combustion of hydrogen. Commercial engines for combustion of hydrogen are unavailable, and focus is primarily directed towards pilot projects including fuel cells which have superior fuel to electricity conversion efficiency. However, hydrogen as sustainable fuel is difficult and costly to produce, transport, and store. According to the U.S. Department of Energy, in 2004, 53 million metric tons of H2 were consumed globally. (Wikipedia, 2016)

There are two main pathways for producing hydrogen:

1. Electrolysis of water: Emissions associated with this are related only to power generation for the electricity. If renewable power (primarily solar or wind) is available, hydrogen can be produced emission-free, but for a typical electricity grid mix, emissions are significant.

2. Reforming of natural gas: Hydrogen is produced by the reaction of methane with steam, CO2 is separated and (should be) used as a by-product. An advantage of this method is that the CO2 can be captured at its source, the so-called Carbon Capture System (CCS).

The overall energy efficiency of producing hydrogen through electrolysis and using it in a fuel cell to produce electricity and power an electric motor appears to be substantially lower than the efficiency of the charging a battery and using this electricity to power the same electric motor. Charging a battery is associated with small energy losses, in the order of between 5 and 10%. Producing hydrogen through electrolysis has an efficiency of approximately 65%, while additional losses of at least 30 – 35% should be expected from a well-performing fuel cell.

From an energy utilization point of view, the use of hydrogen cannot be recommended. However, hydrogen could be a viable solution in applications where a long cruising range does not allow the use of existing battery technologies due to space and weight limitations, provided that the size of the hydrogen tanks is not prohibitive.

Special consideration has to be given to storage of hydrogen on board ships to ensure safe operations. Compressed hydrogen has a very low energy density by volume requiring six to seven times more storage space than HFO. It is estimated that depending on the pressure, the tank size must be 10-15 times larger than required for heavy fuel oil.

Liquefied hydrogen on the other hand, requires cryogenic storage at very low temperatures (-253^{o}C), associated with large energy losses and very well insulated fuel tanks. The hydrogen storage tanks, due to their size, can additionally result in loss of cargo space. These increased costs of the fuel and the current limited gains in CO2 emissions, combined with challenges regarding storage of hydrogen, safety, and the cost of fuel cells, mean that hydrogen and fuel cells are unlikely to play a major role in propulsion of shipping in the next ten to twenty years.

Fuel cells are the most commonly used devices to convert the chemical energy of hydrogen into electricity. When a fuel reformer is available, other fuels, such as natural gas or methanol can be used to power a fuel cell.

Examples include, FCS Alsterwasser, a 100-pax fuel-cell-powered passenger vessel based in the port of Hamburg (Germany). Additionally, in 2012, as part of the FellowSHIP project, a 330 kW fuel cell was successfully tested on board the offshore supply vessel Viking Lady, operating for more than 7000 hours. This was the first fuel cell unit to operate on a merchant ship, with the electric efficiency estimated to be 44.5% (when internal consumption was taken into account), with no NOx, SOx and particulate matter (PM) emissions detectable.

Although operational experiences have shown that fuel cell technology can perform well in a maritime environment, further research and development is necessary before fuel cells can be used to complement existing powering technologies for ships. (Moirangthem, 2016)

5.4 (Bio) Formic Acid

Formic acid is the simplest carboxylic acid with the formula HCO2H. It is a colourless liquid having a highly pungent, penetrating odour at room temperature. It is miscible with water and is somewhat soluble in hydrocarbons. In 2009, the worldwide capacity for producing formic acid was 720 thousand tonnes/annum. (Wikipedia, 2016)

New research shows that formic acid could be used as a safe, easy-to-transport source of hydrogen for fuel cells. Currently, methane and methanol top the list of hydrogen sources for fuel-cell vehicles. They are typically broken down via steam reforming, which requires temperatures of more than 200 °C and a reforming unit. Processes that work at lower temperatures would not need a reformer or much energy, and therefore could be more suitable for producing hydrogen for smaller fuel cells that power portable electronic devices. This new process works at temperatures of 26 to 40 °C.

Formic acid can also be used directly in a fuel cell. That might be easier, because it saves the extra step of first converting it into hydrogen. Tekion, based in Burnaby, Canada, is working with Germany-based chemical giant BASF, the largest producer of formic acid, to commercialize a fuel cell that uses formic acid directly. Tekion, which does not have a product on the market yet, claims that its formic-acid fuel cells are smaller and less complex than direct methanol fuel cells. But direct formic-acid fuel cells have the same drawback that makes methanol fuel cells expensive: both technologies are less efficient than hydrogen fuel cells. To make large quantities of hydrogen for fuel-cell vehicles, however, the process would have to compare with the current benchmark of steam-methane reforming. (Patel, 2008)

5.5 Bio Diesel

Bio Diesel, also called Fatty Acid Methyl Ester (FAME) is produced from vegetable oils, animal fats or waste cooking oils by transesterification. For marine operations, from a technical integration perspective biodiesel blends have been reported as the most promising bio-based alternative fuel (Florentinus et al., 2012). According to the OECD worldwide bio diesel production in 2014 amounted about 32 million tons. (OECD/FAO, 2015)

European Standard EN 14214:2008 also highlights that biodiesel can be used in marine diesel engines and can be blended with distillate fuels. IMO 2007 even reports that low blends of biodiesel up to 20% (B20) could be used without any fuel system degradation.

However, the technical standard ISO 8217 lists some concerns/challenges around biodiesel or FAME

- A tendency to oxidation and long-term storage issues
- Affinity to water and risk of microbial growth
- Degraded low-temperature flow properties
- FAME material deposition on exposed surfaces, including filter elements

Additionally, biodiesel can degrade over time forming contaminants in the form of peroxides, acids, and other insoluble particles. If biodiesel is stored for more than two months, the fuel should be closely monitored and tested to see that it remains within specification. However, the main problem with FAME is sustainability, because FAME production relies heavily on palm oil production, which is often in conflict with the preservation of natural rain forests. (Moirangthem, 2016)

In October 2015, Boskalis, Wärtsilä and GoodFuels Marine launched a development program for the next generation bio marine fuels that are sustainable, have the potential to be scalable and are long term affordable. Over a period of two years, the consortium will test several next generation biofuels at the Wärtsilä test facilities in Vaasa followed by live testing on various ships within the Boskalis global fleet across different locations and ports.

GoodFuels claims to only sell second generation biofuels, which are produced from waste or residue streams. This means that there is no competition with food, (in)direct land use change, or biodiversity loss. For these fuels, a CO2 emission reduction over 80% can be achieved. (GoodFuels, 2015)

5.6 (Bio) Methanol

Methanol is the simplest alcohol with the formula CH3OH. It is a light, volatile, colourless, flammable liquid with a distinctive odour very similar to that of ethanol (drinking alcohol). However, unlike ethanol, methanol is highly toxic and unfit for consumption. Methanol is used as an antifreeze, solvent, fuel, and as a denaturant for ethanol. It is also used for producing biodiesel via transesterification reaction. (Wikipedia, 2016)

The global methanol production currently amounts to about 45 million metric tonnes per year. Methanol produced using natural gas as a feedstock has “Well To Tank” emissions similar to other fossil fuels such as LNG and MDO. Bio-methanol produced from second generation biomass such as waste wood has a much lower global warming potential than fossil fuels and is lower than ethanol by most production methods. (SSPA, 2016)

Black liquor from the pulp industry has been identified as an interesting feedstock for renewable energy. Black liquor is formed as pulpwood is mixed with chemicals (white liquor) to produce pulp as a pre stage to paper production. Black liquor can be gasified and used for methanol synthesis. The chemicals are recovered and reused. Black liquor is available in large quantities worldwide and offers a feasible way to produce methanol. Worldwide, about 400 million tonnes of pulp and paper products are produced every year. For the manufacturing of every tonne of pulp approximately seven tonnes of black liquor are produced. (Wikipedia, 2016)

Bio MCN (www.biomcn.eu) in the Netherlands operates a commercial-scale plant producing bio-methanol from glycerine. In Iceland, renewable methanol is also produced by combing hydrogen and CO_2. At present, about 200 thousand tonnes of bio-methanol are produced per year.

Studies estimate that bio-methanol could reduce greenhouse gas emissions by 25- 40% compared to methanol from fossil fuels if the entire life cycle is taken into account. (Moirangthem, 2016) (Technology, IEA-ETSAP and IRENA, 2013).

5.7 Bio Ethanol

Ethanol is the principal alcohol found in beverages, produced by the fermentation of sugars and yeast, with the formula C_2H_5OH. It is a volatile, flammable, colourless liquid with a slight chemical odour. It is also used as an antiseptic, a solvent and a fuel.

Bio-ethanol is currently the most widely used biofuel around the world. According to the OECD (2015) worldwide bio ethanol production in 2014 amounted about 110 million tons.

Current commercial bio-ethanol production is based on fermenting sugar or starch. For each kilogram of bio-ethanol about one kilogram of CO_2 is co-produced. Note that this CO_2 is biogenic, i.e. it stems from the biomass. Emission of this CO_2 to the atmosphere does not increase the amount of CO_2 in the atmosphere because it was captured from the atmosphere by growing the crop. Sustainability of bio ethanol is a challenge, because production relies heavily on sugar cane and corn production, which can be in conflict with the production of food.

Ethanol can also be produced from ligno-cellulosic biomass, such as wood and grass. This could have some advantages for sustainability, costs (cheaper feedstock) and the yield per hectare, with trickle down effects on environmental aspects such as the overall greenhouse gas balance and biodiversity.

The global production of ligno-cellulosic ethanol is still low, but the number of research and development initiatives is enormous and the first commercial demonstrations are coming online. As of 2012 a total of 87 pilot and demonstration plants are listed based on ligno-cellulosic biomass.

It is expected that significant volumes of ligno-cellulose ethanol will be produced in the coming years. Ethanol has a few technical and logistical drawbacks. It increases vapour pressure, which means that the gasoline in which it is blended, must be adapted on beforehand. Furthermore, it attracts water which means that extra measures must be taken in shipping and storage. (Florentinus et al., 2012)

5.8 Bio LNG or Liquefied Biogas (LBG)

Liquefied Biogas or Bio LNG is methane produced from biomass. It is an interesting fuel to support the transition from fossil fuels to renewables and to achieve the greenhouse gas emission reduction targets.

Since it is chemically identical to fossil LNG there is increasing interest to use it in the shipping sector, also because it can benefit from the growing LNG infrastructure. LNG terminals in North West Europe currently can be found in Belgium, the Netherlands, UK, Denmark, Sweden and Norway.

Bio LNG is generally considered to be the most CO_2-friendly fuel of all. Bio LNG can be produced by upgrading biogas or by thermo-chemical conversion of lignocellulosic biomass, or other forms of biomass. The technical feasibility to produce bio-methane from biogas on a large scale has been demonstrated over the last decade. The production of bio-methane via thermo-chemical conversion is still at a demonstration stage with very limited commercial market penetration so far.

Bio-methane could be applied in exactly the same way as LNG and therefore not lead to any additional challenges. However, to switch from LNG to bio-LNG investments, technological development is needed to produce the required amount of biogas. At this point in time the scattered availability of biogas in Europe would limit the introduction of bio-LNG, as long as no intra-European biogas certification scheme allows local biogas production facilities to introduce their biogas to central LNG terminals within Europe. The EU had more than 300 bio-methane plants in 2014. (IEA Energy Technology Network, 2015) (Moirangthem, 2016).

5.9 Bio Crude

Bio Crude or Pyrolysis oil is potentially very cheap, because it can be produced from any biomass residue and anywhere around the world. Pyrolysis oil is a poor quality product. It consists of an emulsion with 20–30% water. The high oxygen content leads to low pH values, which makes the fuel acidic and corrosive, with low heating values and high viscosities. As a result, it is difficult to store and transport, and can damage engines and boilers. It is immiscible in petroleum oils and not auto-igniting in a diesel engine. It is possible to upgrade the oil to fossil fuel quality, but that may undo the cost advantage. The pyrolysis oil should than be introduced at refinery level in order to be introduced to the fuel supply of ships. (Florentinus et al., 2012)

Low cost waste, such as sawdust from plantation pine sawmilling, is suitable feedstock for the commercial production of highly valuable bio-crude oil. The Australian company Licella has developed a Catalytic Hydro-thermal Reactor (Cat-HTR) system for converting 'lignocellulosic' biomass into high value synthetic crude oil ideally suited to the production of mainstream transport fuels. This bio-crude has a very high energy density of up to 36 MJ/kg, while normal pyrolysis oil has an energy density up to 19 MJ/kg. (Licella, 2011)

The Dutch company GoodFuels also envisions a large scale lignin-2-fuel supply chain in 2020. Lignin is the second most abundant biomass resource in the world. Together with cellulose and hemi-cellulose it forms the structure of plants, trees and crops. It's currently mostly co-fired in power plants for so called green electricity. It is well suited to convert into sustainable biofuel creating a much better integrated business case for the bio-refinery of the future. (Good Fuels, 2015)

5.10 (Bio) Dimethyl Ether

Dimethyl ether (DME), is the organic compound with the formula CH3OCH3, simplified to C2H6O. The simplest ether, it is a colourless gas that is a useful precursor to other organic compounds and an aerosol propellant and is being studied as a future energy option. DME can easily be used in diesel engines. (Wikipedia, 2016)

The global DME production currently is estimated at 15 million metric tonnes per year. Asia-Pacific is the largest market of DME, accounting for nearly 95.66% of the total market size in terms of value in 2014. DME produced from coal accounted for the largest market share among other raw materials such as methanol, natural gas, and bio-based feedstock in 2014. The European market by volume is comparatively mature.

The major players of DME include Akzo Nobel N.V. and Royal Dutch Shell Plc. (The Netherlands), the Chemours Company (U.S.), China Energy Limited (Singapore), Mitsubishi Corporation (Japan), Ferrostal GmbH (Germany), Grillo Werke AG (Germany), Jiutai Energy Group (China), Oberon fuels (U.S.) and Zagros Petrochemical Company (Iran). (Markets and Markets, 2015)

The concept of converting black liquor (a by-product from pulp mills/paper mill residues) via syngas to Bio DME was demonstrated by the four-year Bio DME project funded by the EU's 7th Framework Programme, Swedish Energy Agency and participating companies.

The world's first Bio DME production plant is at Smurfit Kappa paper mill in Piteå, Sweden. The pilot plant was inaugurated in 2010 with a capacity of about 4 tons per day using forest residues as feedstock. The estimated cost of the plant was EUR 14 million. Up until the summer of 2013 more than 500 tons of Bio DME had been produced and distributed to 10 heavy duty trucks, which in total accumulated more than 1 million km in commercial service. (European Biofuels TP, 2016).

The overall TRL level of Bio-DME is only 5, since Chemrec's pilot plant in Sweden has not expanded. Significant scale-up of at least 30 times will be required to reach full commercial scale (Moirangthem, 2016)

5.11 Straight Vegetable Oil

Diesel engines can be modified to run on Straight Vegetable Oils (SVO), otherwise known as Pure Vegetable Oils (PVO) or Pure Plant Oil (PPO). Waste Vegetable Oils (WVOs) - waste cooking oil from the food industry - are often viewed as being sustainable.

The vegetable oil that is used for biodiesel production can also be used directly in engines. With minor modifications, most diesel car engines are suitable for the use of SVO. The viscosity of the SVO must be reduced by preheating it. This is often done through a dual fuel system, in which the car is started on regular diesel and after a short while switches to the use of SVO. With higher ambient temperatures the viscosity is automatically lower. Other bio oils, such as animal fat and used cooking oil can be used in heavy duty engines, provided that they have been cleaned.

Vegetable oil is suitable for replacing residual fuels. It is unknown if the vegetable oil has been tested for marine application, but there is some experience with land-based power stations that replaced HFO with vegetable oil, e.g. with engines from Man B&W and Wärtsilä.

Man B&W state that diesel engines designed for heavy fuel oil can be run on vegetable oil without problems, whereas engines designed for marine diesel or gas oil may have problems though due to higher density and viscosity of the vegetable oil. Wärtsilä has approved its engines to run on vegetable oils (within certain specifications).

It is unlikely that vegetable oil can be blended with HFO. ECSA members think this would lead to emulsions rather than blends. Occurrence of significantly different phases in one fuel is harmful for the engine operation. Even the application of very fine emulsions may lead to cavitation in the fuel system, at the point where the fuel is heated. Rather, vegetable oil would be applied as a pure replacement (100% blend) of HFO. In that case, the biofuel temperature has to be closely monitored to keep the correct viscosity levels. This ensures circulatory ability, optimal engine injection and efficient atomisation and combustion. For soybean and rapeseed oil, the viscosity is fine, palm oil needs to be heated before application to ensure a lower viscosity.

An advantage of the application of vegetable oil is that less energy is needed for the preheating of fuels. This would result in a net fuel saving (on energy basis). The application of vegetable oil requires adaptations in the ship's fuel systems and operation. Therefore, vegetable oil can, at first, only be applied to dedicated fleets with well-informed personnel and small operational changes. (Florentinus et al., 2012)

Over the last several years, the global production of vegetable oils has experienced constant growth. Since 2007, annual vegetable oil production had increased by more or less five percent, however slowed down in 2012/2013. Between 2013 and 2014, approximately 171 million metric tons of coconut, cottonseed, olive, palm, palm kernel, peanut, rapeseed, soybean and sunflower seed oils were manufactured all over the world. (Statista, 2016)

Listed below are the potential benefits of SVOs as fuel for power generation (Energypedia, 2016):

- SVOs are a renewable energy source low in greenhouse gas (GHG) emissions.
- Local production is possible and can contribute to value generation in rural areas.
- SVOs are liquid, hardly evaporate and are thus easily handled, stored and transported.
- SVOs are neither flammable nor explosive and do not release toxic gases.
- SVOs can be burnt in a relatively clean manner.
- SVOs do not cause major damage if accidentally spilt.

6. Global availability of alternative marine fuels

The current production capacity of various alternative fuels and the total amount of fuel required to replace the conventional fossil marine fuels is an important factor to be taken into account. According to the IMO Greenhouse Gas (GHG) study and as shown in Figure 11, the estimated consumption of fossil marine fuels is approximately 300 million tonnes per year.

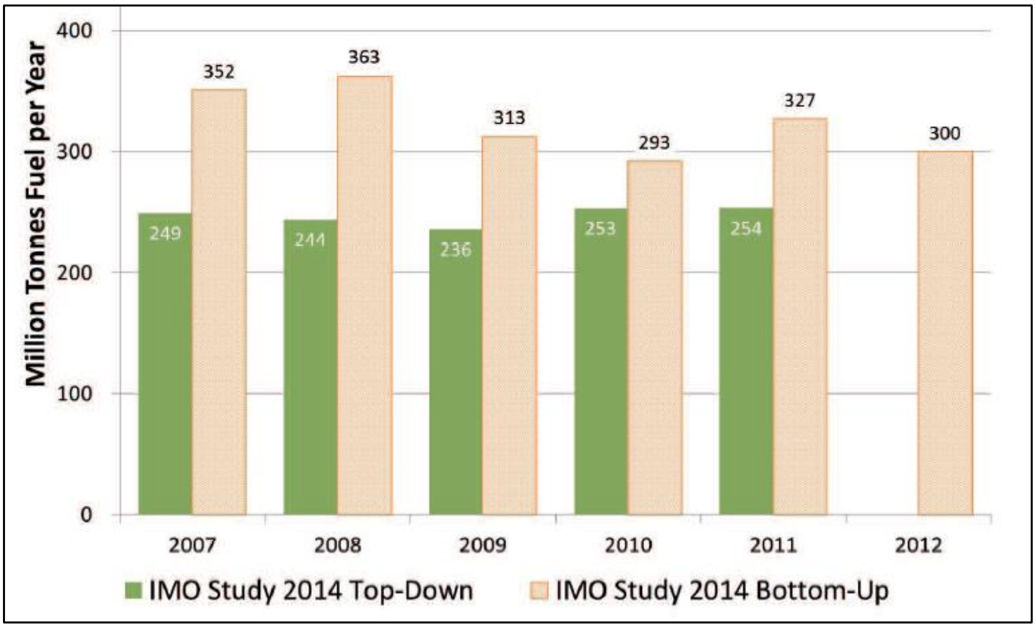

Figure 11: Estimated consumption of fossil fuels. (IMO, 2104)

The International Council on Clean Transportation (ICCT) has written a white paper on the long term potential for increased shipping efficiency through the adaption of industry leading practices (Wang, 2013). The ICCT estimates the annual global fuel consumption in 2015 at about 200 Million tonnes of HFO, 60 Million tonnes of MDO and 50 Million tonnes of MGO. This confirms a marine fossil fuel consumption of 310 million tonnes per year. In Figure 12 a prediction of the main marine fuels is given including the effects of the Energy Efficiency Design Index (EEDI) and other currently available and implemented energy efficiency measures.

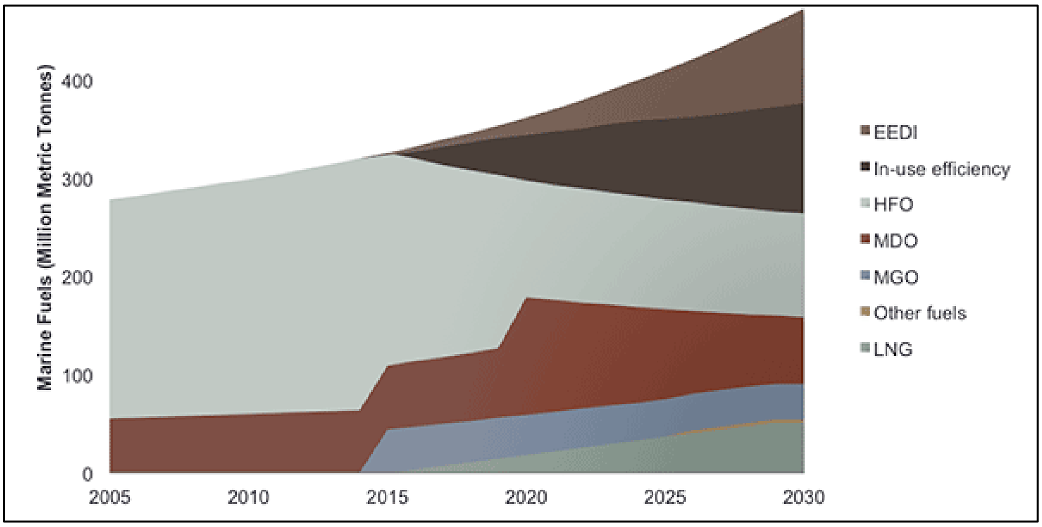

Figure 12: Global consumption of marine fuels. (Wang, 2013)

The required amount of marine fossil fuels for the shipping industry is enormous. When the required volume of alternative fuels for shipping is taken into account, only a few alternatives seem to be feasible as a serious option for the shipping industry in the near future.

LPG is still a fossil fuel and deemed unfit for the shipping industry. (Renewable) Hydrogen, (Bio) Formic Acid, Bio Crude and (Bio) DME are in their early development stages and the global production capacity is far too low.

The best options for the shipping industry in the near future include the use of Liquefied Bio Gas (LBG), (Bio)Methanol, Bio-Ethanol, Ammonia and Straight Vegetable Oil (SVO). Biodiesel is already tested as a blend in the shipping industry.

6.1 LNG and Liquefied Bio Gas (LBG)

Natural gas reserves are plentiful around the world, but many are too small or too remote from sizable population centres to be developed economically. Stranded gas is essentially gas that is wasted or unused. Estimates of remote or stranded gas reserves range from 40 to 60% of the world's proven gas reserves. When this wasted natural gas is not flared, but converted into useful fuels, LNG is a very interesting alternative fossil marine fuel. On the contrary, LNG still remains a fossil fuel. The current annual global production of LNG is about 130 million tonnes.

Although the production of LNG is one the highest of all alternative fuels, the annual production of LBG in Europe amounted only 1300 billion m3 of methane in 2013. This equates to approximately 1,3 million tons of LBG. This means that although LNG is considered as one of the most promising alternative marine fuels, the production and use of Bio LNG is only in its early stages.

6.2 Methanol and Bio Methanol

According to the IEA-ETSAP and IRENA Technology Brief I08 of January 2013 the current global methanol production is about 45 million tonnes per year and is mostly based on fossil fuels, mainly natural gas.

The production of bio-methanol amounts only 200,000 tonnes per year, with the expectation to increase within a few years to 1 million tons. Although bio methanol is one of the promising alternative marine fuels, the production is still in its early stages. When black liquor can be used to produce Bio Methanol on a large scale, Bio Methanol can become a very attractive and high potential alternative marine fuel.

6.3 Bio Ethanol

Bio Ethanol is currently one of the most widely used biofuels around the world. (predominantly in the USA and Brazil). According to the OECD worldwide Bio Ethanol production in 2014 amounted about 110 million tons.

A recent study for EMSA on methanol and ethanol concluded that both methanol and ethanol are very attractive fuel choices from an environmental perspective. With regard to availability and supply, methanol and ethanol are both widely available globally, but no specific infrastructure for marine fuel is in place. The costs for developing this infrastructure are considered low in comparison to the equivalent LNG infrastructure and it can also be done economically on a small scale. (SSPA, 2015)

6.4 Ammonia

Ammonia is produced in large amounts and also available worldwide. The global production capacity of ammonia in 2014 was 176 million tonnes.(Wikipedia, 2016)

Renewable ammonia however, from wind energy or solar power is in its early development stages. Of all non-renewable fuels and non-bio-fuels Ammonia is the best option with regard to the combined WTP CO2 performance and energy density per unit of volume. This makes Ammonia an interesting option to further investigate.

6.4 Straight Vegetable Oil

Straight Vegetable Oil (SVO) or Pure Plant Oil is also produced in large amounts, can easily be produced locally and is available worldwide. Between 2013 and 2014, approximately 170 million tons of coconut, cottonseed, olive, palm, palm kernel, peanut, rapeseed, soybean and sunflower seed oils were produced all over the world. (Statica, 2016)

SVO has a better WTP performance than all fossil fuels and a better energy density than Bio Ethanol. This makes SVO an interesting alternative fuel for marine use.

Large scale import of bio mass for energy (including bio fuels) offers opportunities for ports and high tech treatment companies. The Netherlands is a fore runner in Europe and this can be an 'unique selling point'. The EU regulation on renewable energy is the largest driving force for the development of bio fuels. The mixing of bio fuels is a cost effective way to comply with this EU regulation. At the moment the production of bio fuels is an interesting economic activity. The added value of the production of bio fuels in the Netherlands amounted about 100 Million Euro in the year 2011. De port of Rotterdam is an important hub for import and export of bio fuels. In 2012 bio Diesel production in the Netherlands amounted 52,8 PetaJoules. For reference the Dutch domestic demand amounted 10,1 PetaJoules (10^{15}).

Next to energy savings and large scale use of electric drives, green gas (including bio LNG) and liquefied bio fuels will become the green energy carriers for transport. In the long term bio fuels are regarded as the best alternative for fossil fuels for transport modes like aviation and shipping.

Also for heavy road transport bio fuels are regarded as the most important renewable option towards 2030. As long as the costs for production of bio gas and green gas are higher than those for fossil gas, this gas will follow the development of fossil gas in transport. Only a few niche modalities might be able to switch towards green gas. (Rijksoverheid, 2015)

A summary of various alternative fuels, pros and cons, and (estimated) global production is provided in Figure 13.

Fuel type	**Pros**	**Cons**	**Global production in million tons/yr**
Heavy Fuel Oil (HFO)	Comply with current regulation; present availability	Still a fossil fuel; Future compliance in question	160
Marine Diesel Oil (MDO)	Comply with current regulation; present availability	Still a fossil fuel; Future compliance in question	60
Marine Gas Oil (MGO)	Comply with current regulation; present availability	Still a fossil fuel; Future compliance in question	50
Liquefied petroleum gas (LPG)	Available in market; good supply infrastructure	Still a fossil fuel; Explosion hazard; not much experience on use as marine fuel	25
(Bio) Ammonia	Available in market; cleanest fossil fuel	No experience on use as marine fuel; low flashpoint; toxic	176
(Bio) Hydrogen and fuel cell	Best energy to weight storage ratio of all fuels	Commercial engines not available; Difficult and costly to produce, transport and store; Early development stage	53
(Bio) Formic Acid	Possible fuel of the future; fit for easy use.	Early development stage; only limited use in transportation	0,7
Biodiesel	Dominant biofuel; can increase flash point of other fuels when blended, increasing safety	Degrades over time; presently relies heavily on Palm oil	32
(Bio) Methanol	Recommended fuel by CEESA; dual fuel concept	Low flashpoint; toxic in contact with skin; vapour denser than air	45
Bio Ethanol	Dual fuel concept; large availability; in use as automotive fuel	Low flashpoint; toxic in contact with skin; vapour denser than air	110
(Bio) Liquefied Natural Gas (LNG)	Availability in market; government support	Cost of retrofitting; fuel storage volume; scattered availability in Europe;	130
Bio-Crude – Pyrolysis oil	Commercially viable technology; potential substitute for residual oil	Not yet certified for use in marine diesel engines; potentially unstable; Early development stage	< 5 (est.)
(Bio) Dimethyl ether	Non-toxic; degrades rapidly in atmosphere;	Early development stage; Technology readiness level 5.	15
SVO/PPO	Non-toxic; local availability; relatively safe; liquid fuel	Competes with food; not (easily) blendable	170

Figure 13: Summary of various (alternative) fuels

7. Carbon Capture systems

The use of Carbon Capture Systems (CSS) in the shipping industry is sometimes mentioned as a possible solution for capturing CO2. The CCS could be installed on board of the vessel or ashore. In the latter case the CCS will not process the exhaust gasses of the vessel directly but indirectly by filtering CO2 out of the air at a fixed location. There are many ways to remove CO2 from the atmosphere. Figure 14 provides a brief overview of proposed CO2-removal techniques.

TECHNIQUE	HOW IT WORKS
Bioenergy with carbon capture and storage (BECCS)	Crops grown for the purpose are burnt in power stations (providing energy), and the resulting CO_2 is captured for secure long-term storage.
Afforestation and reforestation	Large-scale tree plantations increase natural storage of carbon in biomass and forest soil.
'Blue carbon' habitat restoration	The recovery of degraded or over-exploited coastal ecosystems that have a high potential for carbon storage, such as saltmarshes and mangroves.
Biochar	Carbon from partly burnt biomass is added to soil, with potential for agricultural benefits.
Enhanced ocean productivity	Marine photosynthesis and CO_2 drawdown from the atmosphere is increased, either by adding nutrients to promote phytoplankton growth in the open ocean or through seaweed cultivation in shallow seas.
Enhanced weathering (using silicate rock)	Crushed olivine or other silicate rocks are added to soil surfaces or the ocean for chemical absorption of CO_2. (Could help to reduce ocean acidification.)
Direct air capture (DAC)	Chemicals (or possibly low temperatures) are used to extract CO_2 from ambient air. Safe CO_2 transport and storage are subsequently required.
Cloud treatment to increase alkalinity	Alkaline rain resulting from cloud treatments reacts with, and removes, atmospheric CO_2.
Building with biomass	A massive increase in the use of biomass (straw and timber) as a building material removes carbon for decades or centuries.

Figure 14: Overview of proposed CO2-removal techniques (Phil. Williamson, 2016)

Many of these techniques are in their early development stages. Whether any of these CCS techniques could work at the scale needed to deliver the goal of the Paris agreement depends on three things: feasibility, cost and acceptability. A crucial component of all of these approaches is the non-climatic impacts that large-scale CO2-removal could have on ecosystems and biodiversity.

According to Williamson it is time for the Intergovernmental Panel on Climate Change (IPCC), governments and other research-funding agencies to invest in new, internationally coordinated studies to investigate the viability and relative safety of large-scale CO2 removal.

More recently, other, potentially more controllable, ocean-based CO2-removal techniques have been suggested, such as the cultivation of seaweed to cover up to 9% of the global ocean. The specific environmental implications of this method have yet to be assessed. Yet such an approach would clearly affect, and potentially displace, existing marine ecosystems that have high economic value. (Shallow and coastal waters currently provide around 90% of global fish catches.) (Ref. P. Williamson, Nature, 11 february 2016)

The use of Carbon Capture Systems (CCS) on board of ships was investigated in the Eurostar project of DNV and PSE. The project, that was concluded in 2013, successfully developed a concept design for on-board chemical capture, liquefaction and temporary storage of CO2 for ships in transit until discharge into transmission and storage infrastructures at the next suitable port.

The results show that the concept is technically feasible and capable of reducing maritime CO2 emissions by up to 65%.

For a Very Large Crude Carrier (VLCC), this could correspond to capturing more than 70,000 tonnes of CO2 per year, transforming them from emissions to a tradable product.

Figure 15 shows an artist impression of a CCS on board of a VLCC. (PSE, 2013)

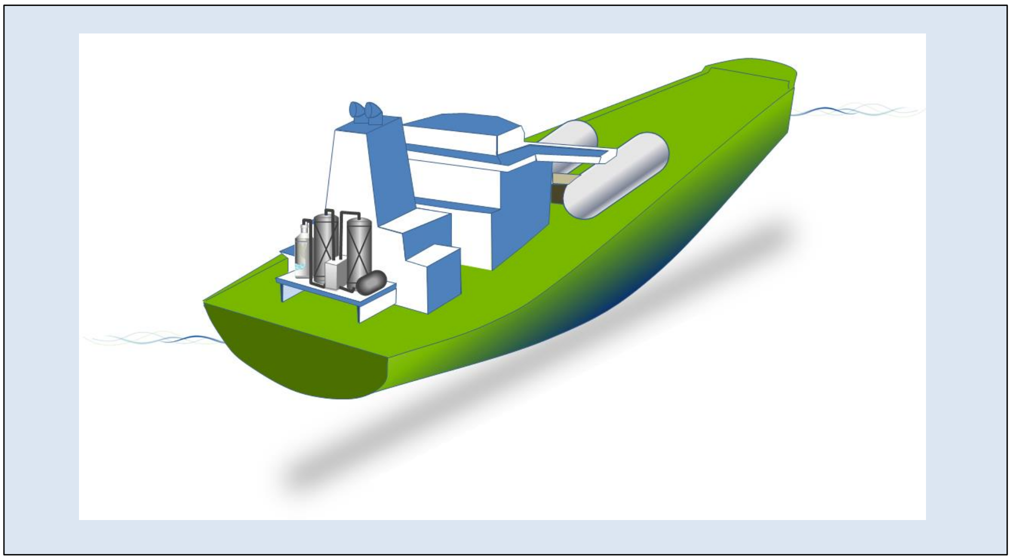

Figure 15: artist impression of a CCS on board of VLCC.

Installing a CCS on board of smaller vessels will most likely bring many challenges with available space on board and efficiency of the installation with regard to performance and costs. Installing scrubbers on short sea vessels (up to 2000 tons) in not feasible at the moment. Installing scrubbers and a CCS will even be a greater challenge.

8. Conclusions and recommendations

Integration, validation and verification of small steps

There are many ways to reduce the GHG emissions in shipping. Most of the single techniques or measures have a limited effect. If they are combined and integrated they can create a substantial reduction of GHG emissions in shipping. Initiatives like www.sustainable-maritime-solutions.nl provide the shipping industry with an overview of these measure and techniques. Validation and verification of these techniques and measures will definitely support ship-owners in their investment decision process.

Speed reduction

In order to achieve energy efficiencies larger than 25% in international shipping, speed reduction is one of the most important topics. The accurate planning and monitoring of ship voyages and operations with the combined use of big data provided by Voyage Data Recording, satellite data and Automatic Identification Systems (AIS) can assist ship-owners and captains in effectively reducing the GHG emissions not only on each individual vessel in operation, but also on the entire fleet of ships. Optimisation models for ship owners, shipping routes and trades should be developed with the help of modern simulation techniques.

Wind energy

Energy efficiencies in international shipping larger than 25% are also claimed by the use of wind energy. A lot of research is already carried out in this area. New concepts like Vindskip and SkySails are still under development and have no proven track record yet. The use of wind energy in shipping is an important field of research and can create substantial reductions in GHG emissions.

The International Windship Association (www.wind-ship.org) provides a useful platform for stakeholders in wind energy for shipping. The Association is open to various stakeholders in the maritime sector and has quite a few providers of wind energy technology. Unfortunately there are no members directly from the shipping industry yet.

Rail Towed Vessel

Rail Towed Vessel concepts are not applicable in the international shipping context, but offer highly energy effective solutions for inland waterways, confined and possibly coastal waters. The towing principle offers a wide range of variations, but specific applications have to be investigated in greater detail yet. This poses an interesting field of research where ship movements are closely related with infrastructural developments. The development of the rail towed vessel might have parallels with the old wind mills which were developed in the last decennia into modern wind turbine generators.

Stevelducting

Stevelducting also has a high energy reduction potential for inland waterways, confined and possibly coastal waters. Stevelducting can even be used in combination with the rail towing principle. Stevelducting can be used downstream and rail towing upstream. Stevelducting is a transport mode without any greenhouse gas emission and can offer interesting conceptual and fundamental research opportunities for maritime transport and logistics.

Current alternative fuels in the shipping industry

LNG and Methanol are good alternatives with regard to reduction of SOx, NOx en PM. Ships are build or converted with LNG and Methanol fuel systems and are establishing a proven track record. The WTP CO2 performance of LNG is only slightly better than conventional marine fuels. The WTP CO2 performance of methanol is worse than conventional fuels.

LBG (i.e. the non-fossil version of LNG) has the potential to become a very favourable alternative marine fuel since it has a very good Overall Fuel Performance with regard to WTP CO2 performance and LHV Fuel Efficiency. Unfortunately LBG is not produced on a large scale yet and big investments are required to reach the volumes required for the shipping industry.

Bio Methanol produced from Black Liquor also has the potential to become a very favourable alternative marine fuel because of a very good Overall Fuel Performance and the large volumes of Black Liquor as by-product in the global paper and pulp industry. At presents the amounts of Bio Methanol produced are very low and substantial investments are required to enable Bio Methanol to become a serious alternative marine fuel.

Development and research on the use of LBG and Bio Methanol on board of ships as well as research and development of LBG and Bio Methanol production facilities should be high on the priority list of both companies, knowledge & research institutes and governments.

Future alternative fuels in the shipping industry

Straight Vegetable Oil (SVO), Bio Ethanol and (Bio) Ammonia are interesting future alternative marine fuels. Renewable Hydrogen, Bio Formic Acid, Bio Crude and Bio DME are not regarded as interesting alternative marine fuels for various reasons. At present, these fuels are in their (very) early development stages and their global production capacity is very low.

Since Ammonia does not contain carbon atoms, the TTP CO2 emission of Ammonia is zero. The production of Ammonia requires 54 gr CO2eq/km and gives a better performance than Bio Diesel (70 gr CO2eq/km). When Bio Ammonia (renewable Ammonia) can be produced the Overall Fuel Performance of Bio Ammonia will only be slightly less than Bio Methanol and LBG.

Bio Ethanol is regarded as an interesting alternative marine fuel and it is recommended that research, development and pilots for the use of Bio Ethanol should intensify. Bio Ethanol is produced in large amounts from feedstock and already used in cars and busses. It is used in blends for diesel engines up to 95% (E95). Since the characteristics of methanol and bio ethanol are comparable there is also the possibility of future fuel flexibility. Bio Ethanol is already produced in large amounts worldwide (110 million tonnes per year). Sustainability of bio ethanol is a challenge, because production relies heavily on sugar cane and corn production, which can be in conflict with the production of food.

Straight Vegetable Oil (SVO) or Pure Plant Oil (PPO) is a very basic alternative fuel. The diesel engine was originally designed to run on vegetable oil so that farmers would have a source of fuel readily available. SVO is produced in large amounts worldwide (170 million tonnes per year). Presently, SVO and Bio Ethanol are the only alternative fuels that can be used on a larger scale in the marine industry. Sustainability of SVO also remains a challenge, since production relies on the production of various vegetable oils, which can be in conflict with the production of food.

Vegetable oil is suitable for replacing residual fuels. Testing of SVO for marine application by engine manufacturers is highly recommended. Engines running on HFO are reported to run on vegetable oil without problems. Wärtsilä has approved its engines to run on vegetable oils (within certain specifications).

Carbon Capture and Storage (CCS)

Carbon Capture and Storage is a technical feasible option for very large vessels. The economic feasibility of CCS on board of a vessel is still insecure. If the Dutch shipping industry wants to use CCS for reducing GHG emissions, the use of land based CCS industrial plants seems more viable.

At the moment, LNG and methanol seem to be the most promising alternatives with good market supply infrastructure in place. From a long term perspective, moving to LNG and methanol as near-future alternative fuels is also a strategically attractive move. This is because each of the two fuels has a biofuel counterpart bio methane (Bio-LNG) and bio methanol. This means that ships and infrastructure built for LNG and methanol can be used to supply bio methane and methanol without much complication. This could equate to using LNG and methanol as transition fuels before making a major shift to biofuels. Furthermore it is important for governments to assist in formulation of policies that will direct the present positive momentum in the shipping industry as it is doing for the road transport sector. (Moirangthem, 2016)

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Annex 1: Glomeep list of energy efficiency measures

TECHNOLOGY	DESCRIPTION
machinery technologies	optimizing aux systems tot operational profiles
machinery technologies	engine de-rating for 10-15% slower than design speed
machinery technologies	automatic increasing engine efficiency through tuning to operational profiles
machinery technologies	manual increasing engine efficiency through tuning to operational profiles
machinery technologies	heat recovery exhaust gas boilers
machinery technologies	electricity to replace modes of power consumption
machinery technologies	increasing auxiliary load by reducing the number of engines running
machinery technologies	produce electricity from main engine
machinery technologies	cold ironing in ports
machinery technologies	steam plant operation improvement
machinery technologies	recover thermal energy from exhaust gas
propulsion and hull improvements	air injection
propulsion and hull improvements	removing fouling on hull
propulsion and hull improvements	reduction of hull resistance through water
propulsion and hull improvements	optimisation of the hull for lower resistance
propulsion and hull improvements	retrofitting bulb, thruster tunnels or bilge keels to reduce resistance
propulsion and hull improvements	remove fouling from propeller
propulsion and hull improvements	retrofitting propeller
propulsion and hull improvements	installation of propulsion improvement devices
energy consumers	reduction of energy consumption during discharge operations
energy consumers	use of energy efficient lights (e.g. LED)
energy consumers	regulating frequency of motors for optimized loads
energy consumers	sails or wings to generate power from wind
energy consumers	flettner rotors to generate power from wind
energy consumers	kites to generate power from wind
energy consumers	solar panels for conversion from solar to electricity
optimised operations	optimised rudder control
optimised operations	optimised pitch settings and propeller speed
optimised operations	optimised DP mode
optimised operations	optimised vessel speed
optimised operations	optimised trim and draft
optimised operations	optimised weather routing

Annex 2: List of people consulted in the project

NAME	FUNCTION	ORGANISATION
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