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TNO report

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Alternative fuels for sea shipping

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Summary

The European Commission targets an overall CO_2 reduction in 2050 of 80-95% compared to 1990 (White Paper). For transportation, the target is lower, namely around 60%. Taking into account the continuous growth of transportation, this is a very ambitious target though.
The international shipping industry is committed to take its part in the reduction of CO_2 emissions. The primary route, they pursue, is the reduction of energy consumption through measures such as improved ship design and improvements in ship operation (via indicators as the Energy Efficiency Design Index (EEDI), and the Ship Energy Efficiency Management Plan (SEEMP)).

In addition to CO_2 emissions, fuel quality requirements are becoming more stringent due to pollutant emission legislation, and long term supply of diesel fuels becomes more difficult and more costly. In this report an assessment is done whether alternative fuels such as biofuels and LNG (Liquefied Natural Gas) can play a role in both CO_2 reduction and (economic) energy supply.

The objective of this study is to investigate a number of alternative fuels on their suitability for sea shipping for the coming decades. Several criteria were used to assess this, namely: availability and pricing, practical application in a sea ship and requirements for sustainability.

The study evaluated both the supply side, the availability, maturity and pricing of biofuels, and the demand side, the practical and environmental aspects of the application in sea ships.

The results of the study led to the following recommendation on fuels development for sea shipping (refer to figure 1):
Deep sea:

- continue to use Heavy-Fuel-Oil (HFO) as much as it becomes available and is allowed (environmentally), because HFO can only be converted into higher quality fuel at high energy costs
- start using LNG (new ships) since it is available, low priced and it helps to reduce the pollutant and GHG emissions

Short sea:

- continue to use Marine Diesel Oil (MDO) and Marine Gas Oil (MGO), because it is available.
- start using LNG where possible (new ships)
- evaluate if it makes sense to use pyrolysis liquid and to build up an infrastructure, since it is the most economic biofuel and needs only low investments in production capacity.

Short sea / Emission Control Area’s (ECA):

- use as much as possible LNG and PPO and possibly biodiesel.
- use MGO (after 2015) for as far as it is available and cannot be converted to diesel fuel for inland shipping and road / non road applications.
- evaluate if requirement can be fulfilled with pyrolysis liquid and if it makes sense to develop suitable engines and to build up an infrastructure.

Furthermore, the following is concluded regarding the types of fuel:

- The good possibility of sea ships to accept low quality liquid biofuels, is a strong reason to use those fuels for ships rather then in other fields.
- Low quality liquid biofuels (PPO, biodiesel and possibly even pyrolysis liquid) are suitable for the Emission Control Areas. This is where the value of these fuels is the highest and where application is recommended. Very suitable applications are ferries and short sea ships sailing these ECA's.
- LNG is considered to be a very suitable fuel for a wide range of ships, because it is a clean fuel with a low price and it has a good future availability. The only conditions are that a) the fuel consumed per year is relatively high such that the additional costs of the LNG tanks and powertrain can be compensated by a lower fuel price and b) bunkering of LNG is available.
- Bio-LNG, if available, is suitable for sea ships, but may have a higher value for road transportation and inland shipping (because of its high methane number).
- Liquid-H_2 is not very suitable for sea ships for practical, economic and energy efficiency reasons. When made from natural gas, energy efficiency is only about half of the energy efficiency of the LNG chain for example.
- It is recommended to use high quality diesel fuels such as HVO, BTL and H_2 for applications such as road transportation, non road machines and inland shipping, where these types of high quality fuels have much more added value than for sea transportation.

Finally, some recommendation are:

- The high efficiency of the large combustion engines for ships is a strong reason to stick to this power source and to use liquid (bio) fuels, including LNG.
- The use of alternative fuels for ECA's will help to solve the possible future shortage of low S diesel fuel.
- It is recommended to evaluate possible 'total energy' options for the production of fuels, especially for bio fuels.

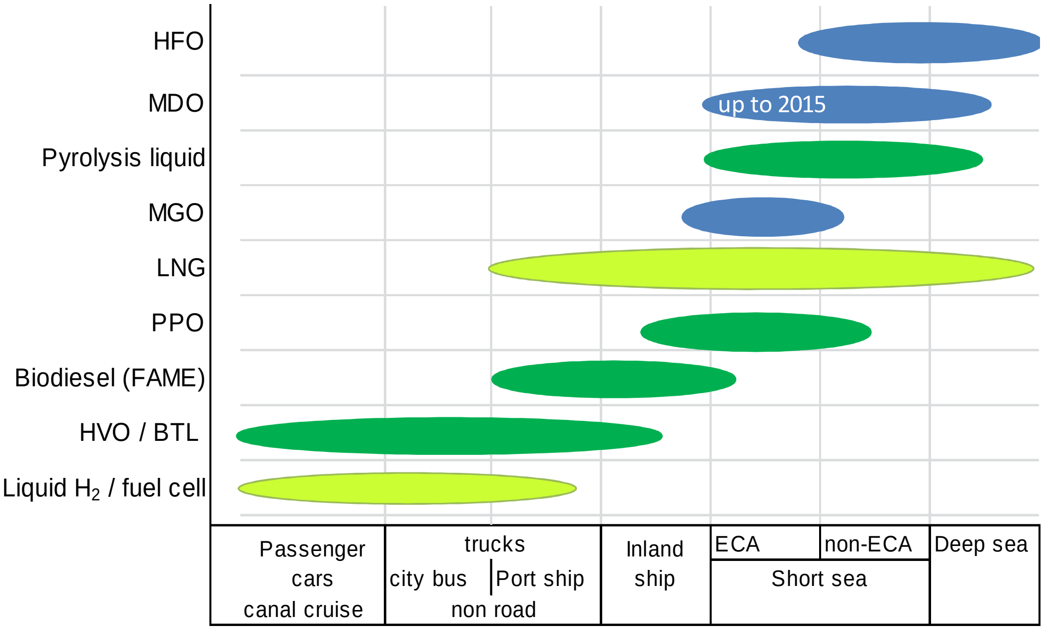

Figure 1: Recommended applications of fossil and bio fuels (ECA is Emissions Control Area)

Contents

1 Introduction

The European Commission targets an overall CO_2 reduction in 2050 of 80-95% compared to 1990 (White Paper). For transportation, the target is lower, namely around 60%. Taking into the continuous growth of transportation, this is a very ambitious target though. In figure 2 the growth of CO_2 emissions of international shipping up to 2050, according to various studies, is shown.

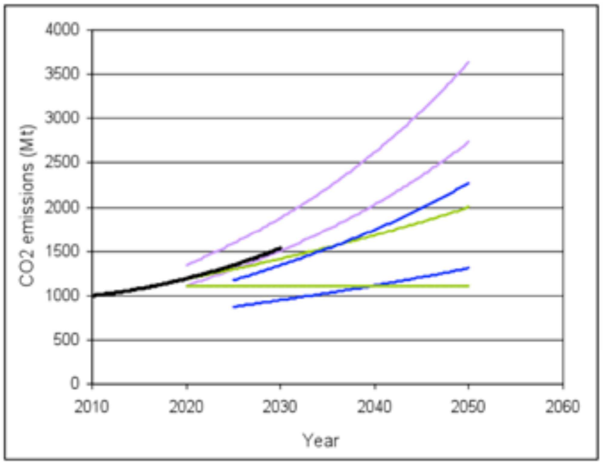

Figure 2: Projected CO_2 emissions from the future fleet from various studies; Purple – Buhaug et al. 2009 (high-low). Blue – Endresen et al. 2008 (high – low). Green – Eyring et al. 2005b (high – low). Black DNV position paper 05 (2010) Source: DNV position

Despite the CO_2-emissions per tonne-kilometre of ships being low, the total sea transport is gigantic (approx. 90% of all trade-goods transport). The overall emission of ships emits approximately 1.1 milliard tones of CO_2 per year[1], or some 4% of overall global CO_2 emissions.

The international shipping industry is committed to take its part in the reduction of CO_2 emission. The primary route, they see, is the reduction of energy consumption through measures as improved ship design and improvements in ship operation. The indicators developed for this are respectively the Energy Efficiency Design Index (EEDI), and the Ship Energy Efficiency Management Plan (SEEMP). A very effective method for reaching that goal of lower CO_2 emissions, is to lower shipping speeds, as energy consumption per kilometre (hence CO_2 emissions) has a squared relation to speed[2].

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[1] Op zich is dit zelfs hoger dan de mondiale CO_2-emissies van de luchtvaart (650 miljoen ton CO_2 per jaar). Echter, de condenssporen die vliegtuigen op grote hoogte trekken en overige emissies verhogen hun totale opwarmend effect met een factor twee tot vier. Ook schepen veroorzaken boven de oceaan vaak wolkvorming; deze laaghangende bewolking heeft (hoogstwaarschijnlijk) een *temperatuurdrukkend* effect. Door de grote wetenschappelijke onzekerheden in wolkvorming en stralingseigenschappen van wolken lopen de schattingen van de bijdrage van schepen aan de opwarming van de aarde uiteen van 2% tot 4%.

[2] On open sea at least. On a river the relationships are more complex due to the rivers current.

A 30% speed reduction thus halves the CO_2 emissions. However, downside of this approach is that 30% more (or bigger) ships (with crew) are needed for transporting the same amount of freight.

But there is more than energy consumption. Demand of crude oil derived diesel fuels is increasing while supply is becoming more difficult. In addition to this, pollutant emissions legislation for sea shipping will become much more stringent in the future. This is focused on reducing SOx and NOx emissions.

The need for those emission reductions and also the long term availability of fossil fuels is a reason to re-evaluate the standard fuels for sea shipping. Up till now HFO (Heavy Fuel Oil) dominated, especially for deep sea shipping. Alternative fuels include LNG, biofuels, hydrogen and possibly even wind and solar power or nuclear power.

This study is focused on evaluating a number of these fuel options. This is done using the following criteria: availability and pricing, practical application on a sea ship and potential of pollutant and GHG emission reduction. Since introduction and scaling up of new fuels takes a lot of time, a time frame of at least several decennia should be taken.

2 Alternative fuel for shipping

The alternative fuels for shipping can be split up in fossil and renewable alternatives. Some of the alternatives are almost identical products but can either be made from bio feedstock or from fossil feedstock. Examples are:

- LNG: either directly from natural gas or from bio methane (bio-LNG)
- Synthetic diesel:
    - GTL: from natural gas
    - HVO: from (liquid) bio feedstock such as vegetable oils and animal fat
    - BTL: from solid bio feedstock
- H_2:
    - fossil sources such as natural gas and coal
    - renewable sources such as solid bio feedstick, bio-methane.

The following criteria are used to judge the suitability of a fuel for sea shipping:

- Availability and price
- Practical application on a ship
    - energy storage capacity
    - safety
    - bunkering capability
- Sustainability (pollutant and greenhouse gas emissions)

2.1 Availability and price of alternative fuels

The IEA has drafted a roadmap for biofuels for transport[3]. Based on scenario studies they foresee that in 2050 biofuels will account for 27% of total energy use for transportation, see figure 3. This means that it is expected that in 2050 total biofuels use for transportation will be 32 EJ. Furthermore, it is expected that 11% of the biofuels in 2050 (=3.5 EJ) will be used in shipping.

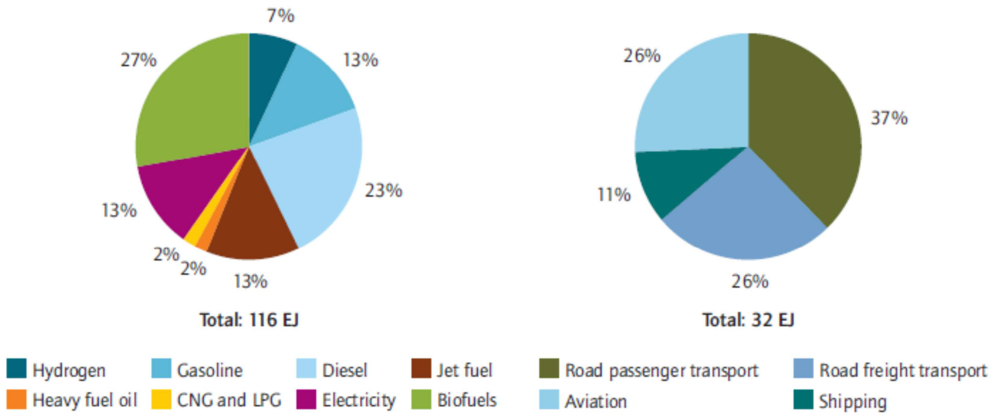

Figure 3: Global energy use in the transport sector (left) and use of biofuels in different transport sectors (right) in 2050 (Source IEA3)

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[3] IEA: Technology roadmap biofuels for transport. International Energy Agency, Paris, France, 2011

Meeting the 32 EJ of biofuels in 2050 would require 65 EJ of biomass feedstock, or ~100 million ha of land in 2050. Given the competition for land for food, feed, fibres and heat and power production this is challenging. However, with a sound policy the IEA considers this to be feasible.

For biofuels price development is, like many other commodities, determined by demand and supply. Prices are furthermore linked to food prices for some of the biofuels and to energy prices in general. On the short-term there can be considerable variations in the prices of biofuels. On the long-term the expectation is that prices of biofuels will be quite stable. In the Refuel[4] project prices of biofuels have been modelled up to 2030. In figure 4, price development up till 2030 is given for biofuels for road transport. The difference between the high and low case is limited compared to costs of the biofuels. There are differences between the various biofuels. The price of biodiesel (FAME) is somewhat higher than for PPO (Pure Plant Oil), the feedstock where it is made from. With the current price for PPO being 900-1000 Euro/ton, the current price of FAME is between 960 and 1110 Euro/ton.

Below a description of production, production potential and costs is given.

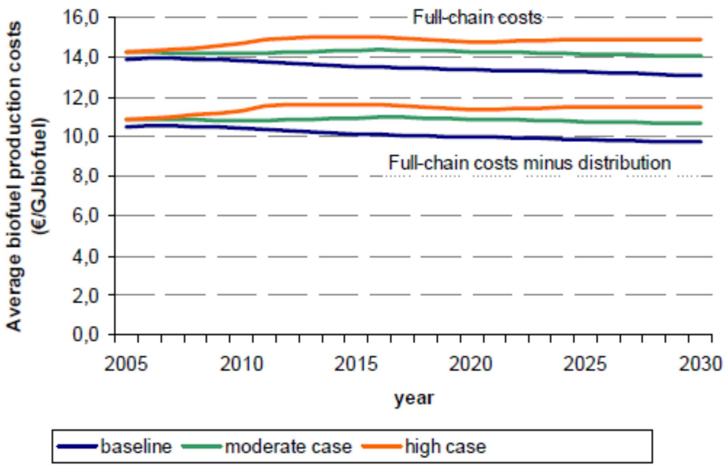

Figure 4: Development of average biofuel production costs (Source Refuel project4)

LNG

Production and maturity

LNG is produced from natural gas by liquefaction. In the production process minor components (like water, dust, acid gases, helium and hydrocarbons) that cause difficulties in the liquefaction process are removed. The gas is liquefied by a refrigeration system. Technology for liquefaction of natural gas is commercially available as well as technology for shipping LNG. Generally, liquefaction plants are located close to the gas field.

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[4] H.M. Londo et. al.: Biofuels cost developments in the EU27+ until 2030, Full-chain cost assessment and implications of policy options. REFUEL WP4 final report, www.refuel.eu, 2008

Potential

The potential of LNG is large. According to statistics[5] LNG trade already accounts for 300 billion cubic metres, or slightly more than 9% of world wide gas consumption.

Costs

Costs of LNG follow costs of other energy sources. Over the past 2 years, the costs of LNG are in the order 9-12 $/MMBTU or 6.4-8.5 Euro/GJ.

Pure plant oil

Production and maturity

Pure plant oil is one of the oldest alternative fuels in the world. Rudolf Diesel the inventor of the diesel engine used peanut oil as fuel in his first engine tests. Plants like rapeseed, soybeans, palm, peanuts and sunflower contain vegetable oils that in principle can be used as fuel. The vegetable oils extracted from these plants cover most of our need for plant based fat. Vegetable oils are used for food but also as ingredient in cosmetics, soaps, paint etc. As fuel an advantage of vegetable oils is that they contain no or hardly any sulphur.

Pure plant oil is produced by extracting vegetable oils from oil seeds or beans. The extraction process is similar to processes used in food industry and is a mature process. The oil is usually mechanically extracted from the heated feedstock. The residue after extraction is used as fodder. Rapeseed, in Europe, and soy beans, in the USA, are the important feedstocks for vegetable oil production for alternative fuels. The majority of the vegetable oil used as transportation fuel is converted into biodiesel by esterification. Basically, all type of plant oils may be used in energy production, although diverging properties make some oils more suitable than others.

Potential

For rapeseed it is expected that oil yield in the EU in 2020 is 1.49 tonnes of oil/ha[6].

Costs

Costs for rapeseed oil fluctuate over the years. Prices of rapeseed oil fluctuated of the past half year between 900 and 1000 Euro/metric ton.

Pyrolysis liquid

Production and maturity

Pyrolysis oil can be produced from all kind of different types of biomass. It is especially suitable for biomass developed to convert so-called lignocellulosic biomass like wood and straw. The biomass feedstock is heated in an oxygen free environment at temperatures of ~500 °C. By minimizing the residence time of the vapours formed in the process, the yield of liquid products is maximized. Depending on the type of process pyrolysis oil yields from lignocellulosic biomass

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[5] BP Statistical review of World Energy 2011

[6] Edwards, R. et. al. : Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, Weel-To-Tank Report Version 3c, European Commission Joint Research Centre, Institute for Energy, Report number EUR 24952 EN, July 2011

are in the range of 50-70 wt.%. Different types of pyrolysis processes have been developed and a number of them are in the demonstration phase.

The pyrolysis oil is a dark brown liquid with a lower heating value of ~18 MJ/kg. The pyrolysis oil consists of different organic molecules containing carbon, hydrogen as well as oxygen. The oxygen content of the pyrolysis oil is similar to the biomass feedstock, i.e. about 50 wt.%. The raw pyrolysis oil has a water content of about 30 wt.%. The pyrolysis oil mixes with water, is acidic (pH=2) and corrosive. Pyrolysis oil doesn't mix with petroleum based fuels. The pyrolysis oil contains hardly any sulphur[9].

The pyrolysis oil can be upgraded to a fuel compatible with petroleum based fuels at extra costs. Upgrading process required is at the laboratory stage.

Potential

Pyrolysis oil can be produced from biomass residues as well as from cultivated crops like wood. For woody residues and crops there is competition with the power sector. For pyrolysis oil from residues the potential is limited due to limited availability of the residues. For pyrolysis oil production from crops the potential is theoretically large. At an energy crop yield of 10 metric tons/hectare the pyrolysis oil yield is 5-7 metric tons/hectare.

Costs

The costs of pyrolysis oil are a function of the feedstock price. At a feedstock price of 100 Euro/ton, according to BTG[7] the costs of the pyrolysis oil is 300 Euro/ton or 18 Euro/GJ. TNO[8],[9] gives production costs of 1.8 Euro/GJ (excluding feedstock). At a feedstock price of 100 Euro/ton (or 5.6 Euro/GJ) and an energy efficiency of 70%, this would result in total production costs of about 10 Euro/GJ.

Biomass-to-liquid or BTL

Production and maturity

Fischer-Tropsch synthesis is a catalytic process to convert synthesis gas (hydrogen and carbon monoxide) into hydrocarbons. Fischer-Tropsch synthesis has been developed in the interbellum in Germany. After World War II it was on large-scale used in South-Africa with the synthesis gas produced from coal. Since about 20 years Shell operates in Malaysia Fischer-Tropsch synthesis, with the synthesis gas produced from natural gas, in Malaysia. This year Shell put a Fischer-Tropsch plant into operation in Qatar with a capacity of 140 000 barrels/day, also her synthesis gas is produced from natural gas.

Synthesis gas can be produced from any kind of carbon containing feedstock, thus also from biomass. Biomass is gasified to convert it into synthesis gas. After gas-cleanup the gas can be used for Fischer-Tropsch synthesis. The technology for Fischer-Tropsch synthesis is commercially available. The technology for biomass gasification is in the pilot/demonstration phase. Since about 10 years Choren in

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[7] Website BTG http://www.btgworld.com/index.php?id=22&rid=8&r=rd

[8] Gerrit Brem and Eddy A. Bramer: PyRos: a new flash pyrolysis technology for the production of bio-oil from biomass residues. TNO.

[9] Jan van der Steeg, Elke Rabé, R. Verbeek: Scheepsbrandstoffen voor een Schone Toekomst. TNO report OG-RPT-APD-2009-00025, March 2009.

Germany is commercializing biomass based Fischer-Tropsch synthesis. A typical characteristic is that the costs of Fischer-Tropsch synthesis are very sensitive to the scale of the plant. Therefore, it is to be expected that it will only be commercially possible on large-scales (similar to the scale of oil refineries).

Fischer-Tropsch synthesis produces aliphatic hydrocarbons similar to petroleum based fuels and can hence be blended with petroleum base fuels. Fischer-Tropsch fuels do not contain sulphur and aromatics. There are no concerns about the possibility to use Fischer-Tropsch fuels in marine applications.

Potential

The potential for Fischer-Tropsch synthesis is similar to the potential for pyrolysis oil. It will be based on gasification of lignocellulosic crops and residues. Due to its preferred size, very large, it will use lignocellulosic crops. At an energy crop yield of 10 metric tons/hectare and an energy efficiency of 56%, the yield of Fischer-Tropsch products is about 2.4 metric tons/ha.

Costs

The costs of biomass-to-liquid route are very sensitive to the scale employed. Both the gasification part and the Fischer-Tropsch synthesis part of the process are capital intensive and sensitive to scale.

Therefore, it is to be expected that it will only be commercially possible on large-scales (similar to the scale of oil refineries). For commercial technology at large-scale the costs have been estimated by Boerrigter[10]. Costs for biomass transport, pre-treatment and conversion range from about 22 Euro.GJ at a scale of 50 MW to 9 Euro/GJ at a scale of 8500 MW. At feedstock costs of 100 Euro/ton (5.6 Euro/GJ) and an energy efficiency of 56%, the costs of biomass feedstock are 10 Euro/GJ. This makes total costs of Fischer-Tropsch synthesis 32 Euro/GJ (at a scale of 50 MW) to 19 Euro/GJ (at a scale of 8500 MW).

Liquid hydrogen

Production and maturity

Liquid hydrogen can be produced from synthesis gas. Synthesis gas can be produced from any carbon containing source, with natural gas being the most important feedstock. Natural gas is converted into synthesis gas by reforming. Carbon monoxide present in the synthesis gas is catalytically converted into hydrogen. After carbon dioxide removal from the gas the hydrogen can be liquefied by similar cryogenic techniques as used for liquefaction of natural gas.

The technology required for hydrogen production from natural gas, petroleum and coal is mature and commercial available. Liquefaction technology for gasses is also mature and commercially available. A number of hydrogen liquefaction plants exist in the world, but use of liquid hydrogen for transportation is limited to a number of demonstration projects.

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[10] Boerrigter, H.: Economy of Biomass-to-liquids (BTL) plants, an engineering assessment. Energy research Centre of the Netherlands, Petten, ECN report C-06-019, 2006

Potential

The most important feedstock for hydrogen production is natural gas. The potential is therefore similar to LNG. The production of liquid hydrogen from natural gas consumes 2.13-2.42 $MJ/MJ_{product}$[11]. This means that the energy efficiency of the production of liquid hydrogen from natural gas is between 41 and 47%.

Long term potential

A further possible advantage of hydrogen as a shipping fuel can be the generation of hydrogen from sustainable sources such as photovoltaics or wind energy. This is no economically attractive options for the short and medium term. Hydrogen can also be used as a medium to store a surplus of energy if the grid cannot take the electricity (produced from photovoltaics or wind energy). Under those circumstances, the hydrogen price could become more competitive and application in shipping can be considered.

Costs

Costs of liquid hydrogen are of course related to the costs of the feedstock. For natural gas based liquid hydrogen a range of 2200-3300 Euro/ton is estimated.

In table 1 below the properties of various renewable and fossil fuels are summarized.

Table 1: Properties of renewable and fossil fuels for sea shipping. Dollar exchange rate: 1.30 $ per Euro.

Fuel	Costs [Euro/ton]	Costs [Euro/GJ]	Maturity production	Lower heating value	Energy efficien.	Yield [ton/ha]	Yield [GJ/ha]
PPO	900-1000	24-27	Commercial	~37 MJ/kg	63%[12]	1.5	56
Bio diesel	960-1110	25-30	Commercial	~37 MJ/kg	55%[13]		
BTL	800-1300	19-32	Pilot/ dem.	~43 MJ/kg	56%	2.4	100
Pyrolysis oil	160-300	10-18	demonstrat.	~16-17 MJ/kg	70%	5-7	81-114
Liquid H_2	2200-3300	18-28	Commercial	120 MJ/kg	41-47%	--[14]	
LNG	330-440	6.4-8.5	Commercial	~52 MJ/kg			
HFO	495[15] - 520[16]	12.2 -12.7	Commercial	~41 MJ/kg			
MDO	520[16] - 715[15]	12 - 16	Commercial	~43 MJ/kg			
MGO	725[15]	17	Commercial	~43 MJ/kg			

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[11] Edwards, R. et. al. : Well-to-wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, WTT appendix 2 Description and detailed energy and GHG balance of individual pathways, European Commission Joint Research Centre, Institute for Energy, Report number EUR 24952 EN, July 2011

[12] Based on energy use of 0.59 MJ/MJ_{fuel} for oil mill[11]. Does not account for marketing of co-product press cake as fodder, i.e. no allocation of energy use to co-product

[13] Based on energy use of 0.59 MJ/MJ_{fuel} for oil mill and 0.22 MJ/MJ_{fuel} for transesterification[11]. Does not account for marketing of co-products press cake as fodder and glycerine as chemical, i.e. no allocation of energy use to co-product

[14] Produced from natural gas

[15] Altena, Paul, KVNR. 'Modelshift of Modelshift back? SOx seminar 8 September 201,1 Platform Scheepsemissies, Putten.

[16] http://www.bunkerworld.com/prices/index/bwi

Figure 5 gives an example of a study of future fuel prices.

CO_2 emission charges could already become effective in 2013. Associated costs are based on IPCC reports.

In 2020, sulphur limits for fuel will globally apply. Diesel quality fuels demand a premium, estimated to be 50% of the HFO price.

The price for HFO will continue to increase in the long run (2.5% per year assumed).

Source: GL research. The analysis excludes inflation effects.

Figure 5. Development of future fuel prices for HFO and MGO.

Source: average of Singapore/Rotterdam/LA price @ Bunkerworld 2011-12-04

3 Practical application in a ship

3.1 Characterisation of sea shipping

Some characteristics of different size sea ships are given in table 2. A typical short sea ship has an engine of about 8 MW, while for deep sea engine size ranges from about 20 to 80 MW. The engine efficiency is around 50%. For the very large engines waste heat recovery systems such as a steam turbine can be used, using the heat in the exhaust gasses. It is likely that this will also be introduced for smaller ships in the future.
For short sea, the average power and the number of running hours per year are respectively 45% of the maximum engine power and 6300 hours [Verbeek 2011]. The same value is taken for the other ship types.

Table 2: Characteristics powertrain of different types of ships

Ship type	P_max	P_avg	Time/year	Mechanical energy per year	Engine efficiency
	[MW]	[%/P_max]		MWh	[%]
Short Sea	8	45%	6300	22680	46%
Deap Sea	20	45%	6300	56700	50%
Deap Sea	80	45%	6300	226800	53%

The amount of fuel energy needed per year per ship type is presented in table 3 (based on conditions of table 2). Based on this the storage requirements of alternative fuels can be estimated.

Table 3: Fuel energy required per year and projected tank size

Ship type	Fuel energy per year		Reference fuel	Fuel con-sumption	Estimated autonomy	Tank size
	MWh	GJ		ton/y/ship	days	ton
Short Sea	49304	177496	MDO	4128	40	629
Deap Sea	113400	408240	HFO	10155	60	2321
Deap Sea	427925	1540528	HFO	38322	60	8759

3.2 Application fuels for shipping

The energy storage parameters, namely the combustion energy per litre and per kg of a number of fuels are presented in figure 5[17]. It can be seen that the conventional fossil fuels and also the liquid biofuels have the highest energy density. The amount

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[17] R.P. Verbeek: Is (bio) diesel de brandstof van morgen? Presentatie VIV jaarcongres, Zeist, 28 October 2011.

of fuel which needs to be bunkered is dependent on this energy density plus the efficiency of the engine or powertrain. The efficiency of ship engines running on diesel fuel, biofuel or LNG is about the same[18]. This is also the case for H2 with fuels cells. Consequently it can be conclude that the storage volume and mass of LNG is about a factor of 2 higher, while for liquid H2 this is even about a factor of 6 higher.

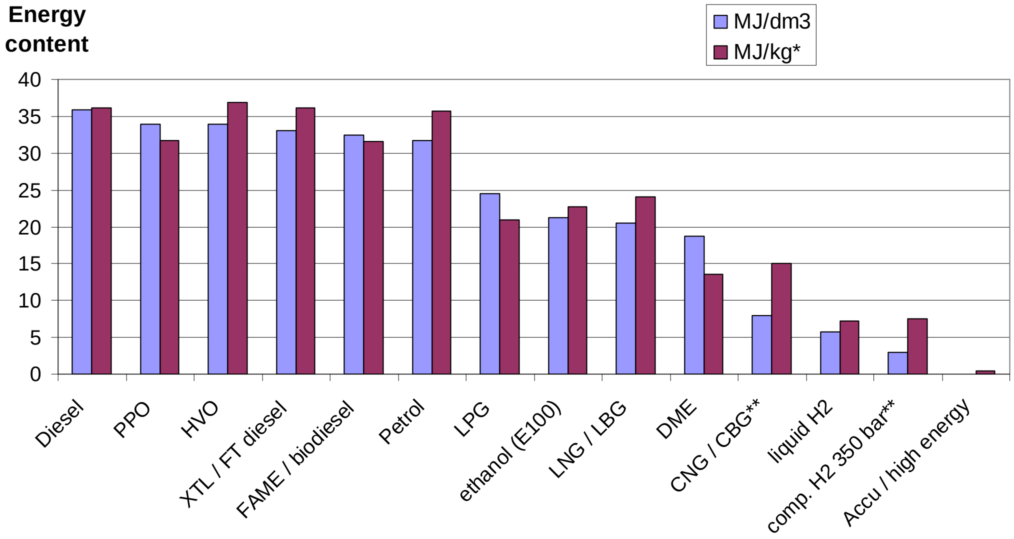

Figure 6: Energy content of fuels. Specific energy per kg is including tank weight.

HFO

The current standard fuel for deep sea sailing. Primary advantages are the very low price in combination with high energy storage capacity and relatively high engine efficiency. The current sulphur content is 2.7%. According to the IMO /MARPOL legislation this has to be lowered to maximum 0.5% in 2020 or alternatively a SOx scrubber has to be installed.

MDO

With a maximum of 1% sulphur, the current standard fuel for SECA (SOx Emission Control Areas) areas.

MGO

This is a fully distillate fuel with a maximum sulphur content of 0.1%. Because of its properties, it is suitable as a fuel for sailing in ports or for port ships. It is also used for on board electric power generation. From 2015 the MDO quality diesel fuel is required for SECA areas.

LNG

LNG is currently becoming a very popular fuel for both small (inland) and large ships. This is because the fuel combines a low price with low emissions. LNG requires an expensive vacuum insulated cryogenic tank and also a special engine.

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[18] Ruud Verbeek, et.al. Environmental and economic aspects of using LNG as a fuel for shipping in The Netherlands. TNO report TNO-RPT-2011-00166. March 2011

This is why is in most cases only feasible for new ships. The usage pattern should be continuous, preferably more than some 5000 running hours per year on a medium to high power output. This is needed to compensate for the higher installation costs of engine and fuel storage with the low fuel price.
With the appropriate lean burn or stoichiometric combustion, the emissions can be low (down to the Tier 3 level). Because of that, LNG is very suitable for both NECA and SECA areas.

Pure Plant Oil (PPO)
Relatively high quality fuel for sea shipping with an acceptable price. The SOx emissions will be very low because of its low sulphur content. Also the particulate emission is expected to be low, because PPO is a relatively clean oxygenated fuel. PPO is very suitable for SECA areas, because of its low sulphur content. In combination with SCR deNOx after treatment, PPO is also suitable for NECA areas.

Biodiesel (FAME)
Like PPO, a relatively high quality fuel for sea shipping. It has similar performance in NOx and particulate emissions as PPO and is consequently quite suitable for SECA and NECA areas as alterative for MGO in the future.

HVO / BTL
These are high quality synthetic diesel fuels. They seam to be too high quality for sea shipping and have more value for road and non-road sectors where emissions legislation is much more stringent. This is because the compatibility with standard diesel fuel EN590 is very good. Basically HVO and BTL are premium diesel fuels which can in blends with regular diesel, be used to upgrade diesel fuel

Pyrolysis liquid
Pyrolysis liquid can be seen as the biofuel equivalent of HFO. It is actually a low quality fuel, very acid and it has a low combustion value. A special fuel injection system would be needed which can withstand the acidity and also provide enough quantity. Pyrolysis liquid is suitable for SECA areas, because the sulphur content is sufficiently low. Practical and durability issues with engine and SCR NOx control have to be evaluated.

Liquid H_2 / fuel cell
Because of the low energy density, liquid H_2 is not suitable for sea shipping. The advantages of H_2, such as virtually absent pollutant emissions, have much more value with road and non-road applications. H_2 may also be suitable for dynamic applications where drive train efficiency with H_2 may be better than conventional alternatives. In this respect H_2 may also be quite suitable for port ships or for canal cruise ships.

The fuel prices and other characteristics of fossil and alternative fuels are summarised in table 4. It should be noted that both the fossil as well as the biofuel prices are very volatile. For example 1 year ago the fossil diesel fuel prices were about 25% lower. Also for biofuels very large differences have been seen.

Table 4: Prices and other characteristics of fossil and alternative fuels for shipping

Fuel	Costs		Energy density	Blending possibility with diesel	Multi-fuel	Retrofit or drop in
	EUR/ton[19]	EUR/GJ	MJ/kg			
HFO	495 - 520	12.2 -12.7	44.8	yes		
MDO	520 - 715	12 - 16	44.3	n.a.		
MGO	725	17	43	n.a.		
LNG	300-390	6.4-8.5	46.2	n.a.	yes	- -
PPO	900-1000	24-27	~ 39	yes[20]	yes	++
Biodiesel /FAME	960-1110	25-30	~ 37.3	0-100%	yes	++
BTL/GTL	800-1300	19-32	~ 42	0-100%	yes	++
Pyrolysis liquid	160-300	10-18		No	yes	o
Liquid H_2	2200-3300	18-28	120	No	no	- -

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[19] Refer to Table 1 page 12

[20] PPO has a high viscosity and low thermal and hydrolytic stability. Blending with a low viscosity fuel might be required.

4 Sustainability of alternative fuels

4.1 Emissions legislation

The emissions legislation for sea shipping is focussed on reduction of sulphur oxide (SOx) and nitrogen oxide (NOx). The coordination is with the International Maritime Organisation (IMO) and the treaty is called MARPOL (Marine Pollution). The legislation is in principle world-wide, but also special Emission Control Areas (ECA's) are put in place. In these areas the legislation is more stringent. This can be for SOx (SECA) and/or NOx (NECA). Examples are the East-Sea, North Sea and the US East and West coast.

The SOx control is implemented via limits of the fuel sulphur content. In table 5 the limits are shown for both the SECA and world-wide. The SOx limits can alternatively be met by using a SOx scrubber instead of using low sulphur fuel.

Table 5: Fuel quality requirements in order to limit SOx emissions

Fuel S content	2008	2010	2012	2015	2020
SOx Emission Control Area (SECA)	1.50%	1%		0.10%	
World-wide	4.50%		3.50%		0.50%

The NOx limits are presented in table 5 and in figure 7. In 2011 Tier II entered into force. The NOx limits are 15% to 25% lower than Tier I, which entered into force in 2005 (figure 7). The NOx limits for Tier III are 80% lower than for Tier I. Tier III is planned for NECA's for 2016. A NECA is currently planned for the Baltic Sea. This still needs to be decided for the North Sea.

Table 6: NOx emission limits

NOx (g/kWh)	Tier I	Tier II	Tier III
Year	2005	2011	2016
NOx Emission Control Area (NECA)			2 - 3.4
World-wide	9.8-17	7.7-14.4	

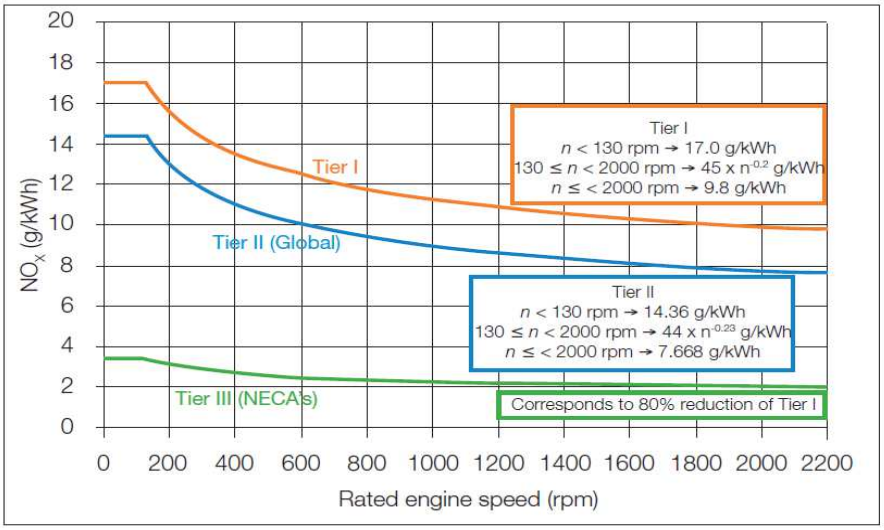

Figure 7: IMO MARPOL NOx limits

4.2 Pollutant emissions

The sulphur within the fuel is converted in the combustion process of the combustion engine to either SOx (primarily SO2) or SO4- or H2SO4 (sulphate). The latter agglomerates with the other particulate emissions and increases the mass of particulate. . Only about 5% of the fuel sulphur ends up in the particulate emission which never the less easily increases the particulate mass by more than 30%.

In table 7, the relation is given between the fuel sulphur content and the (gaseous) SOx emissions. This is also displayed in Figure 8.

Table 7: fuel sulphur content and specific SOx emissions of fossil and biofuels

Fuel	average S content [m/m]		SO2 emission		
			per kg fuel	per MJ fuel energy	per kWh power output
	ppm	g/kg	g/kg	g/MJ	g/kWh
HFO	27000	27	54	1.265	10.6
MDO	8000.00	8	16	0.375	3.1
MGO	800.00	0.8	1.6	0.0375	0.3
EN 590	8	0.008	0.016	0.000375	0.003
LNG	5	0.005	0.010	0.000204	0.002
PPO	10	0.01	0.02	0.000408	0.003
Bio diesel	10	0.01	0.02	0.000408	0.003
Pyrolyse l.	200	0.2	0.4	0.008163	0.068

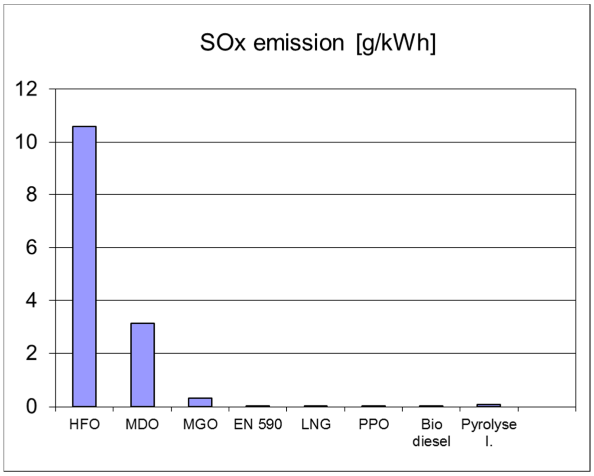

Figure 8: SOx emissions of fossil and bio fuels.

An overview of the emission performance of the fuels is given in table 8. The NOx emissions of MDO and MGO are better than those of HFO, because of the higher cetane number and the lower density. This leads to a more gradual combustion with consequently a lower NOx formation. The particulate emission is primarily lower due to the lower fuel sulphur content[21].

The biofuels PPO, biodiesel, HVO are comparable to a high quality diesel fuel. The NOx of PPO and biodiesel is generally a bit higher than EN590, but the PM emission is lower. The emissions of HVO and BTL are generally somewhat lower in both NOx and PM.

Little is known about the emissions of pyrolysis liquid. The fuel has a relatively low fuel sulphur content and a high oxygen content. This is likely to lead to relatively low PM emissions, although uncertain. The NOx emission may go up because of the high oxygen content, but information is not available.

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[21] Ruud Verbeek, et.al. Environmental and economic aspects of using LNG as a fuel for shipping in The Netherlands. TNO report TNO-RPT-2011-00166. March 2011.

Table 8. Projection of pollutant and GHG emissions performance of fossil and alternative fuels

Fuel	NOx	Particles	SOx	GHG / CO_2
HFO	100	100	100	100
MDO	90	44	30	100
MGO	80	23	3	100
LNG	15	<10	0	90
PPO	85	10	0	20 to 80
Biodiesel / FAME	85	10	0	25 to 85
HVO	80	10	0	25 to 85
BTL	80	10	0	-20 to 50
Pyrolysis liquid	?	< 100?	1	~0
Liquid H_2 / fuel cell	0	0	0	50 to 200

4.3 Greenhouse gas emissions

The greenhouse gas (GHG) emissions include primarily CO_2 and CH_4 components. Also N_2O is a strong GHG (with a multiplying factor of about 300), but these emissions are generally negligible.

For a large part the GHG emissions are dependent of the energy efficiency of the complete fuel chain and the carbon content of the fuel. In this respect natural gas has an advantage because it has an H-C ratio of 4 compared to about 2 for diesel fuels. This means that for natural gas (LNG) a high part of the energy comes from H-oxidation rather than from C-oxidation.

In figure 9, the Well To Propeller (WTP) for shipping is given for LNG from different sources in comparison to the diesel fuels for sea shipping[22]. It shows that the GHG emissions of LNG are about 10% lower. The GHG emission reductions of biofuels in comparison to fossil fuels are given in figure 10. This includes replacement fuels for both diesel and for gasoline.

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[22] Ruud Verbeek, et.al. Environmental and economic aspects of using LNG as a fuel for shipping in The Netherlands. TNO report TNO-RPT-2011-00166. March 2011

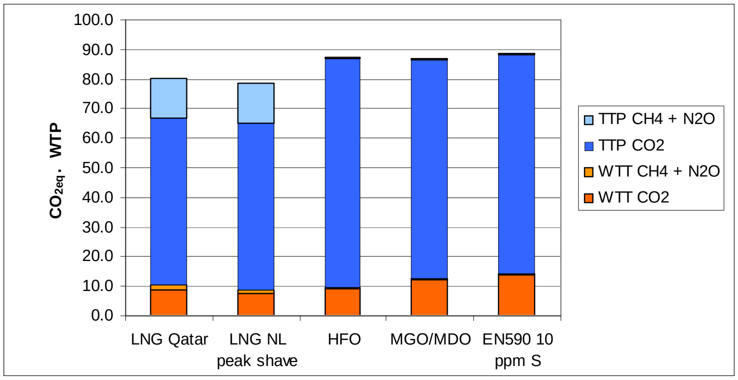

Figure 9: Overview Well To Propeller (WTP) GHG emissions [g CO2eq/MJ] of the 5 most realistic LNG and diesel fuel chains. From[21].

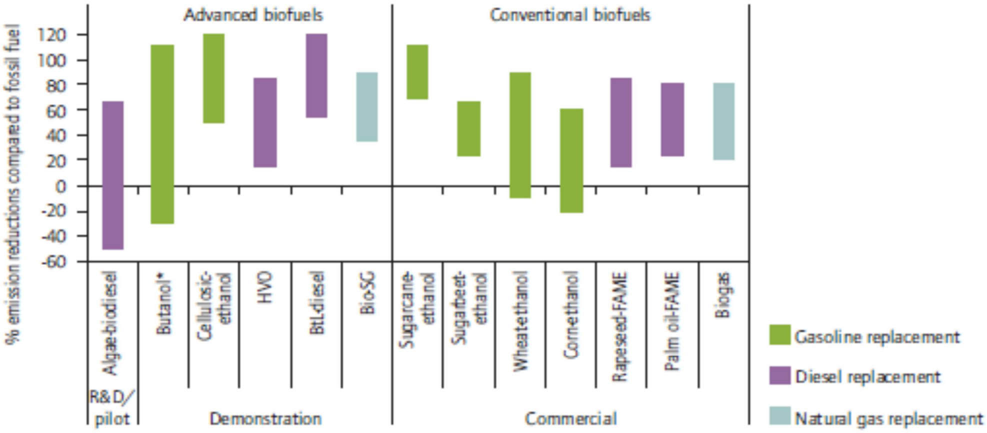

Figure 10. Life cycle GHG balance of different conventional and advanced biofuels, and current state of technology. Source: Technology roadmap “biofuels for transport” IEA (2011)

4.4 Energy efficiency

The energy efficiency of the fuel chain includes the efficiency of the fuel production, fuel transport and the efficiency of the power generation on board of a ship. Regarding the latter, ships are doing well. The large diesel engines (and also natural gas engines) run with an efficiency of around 45 to over 50%, which is even slightly better than the efficiency of the average electric power generation in the Netherlands (40%) and about the same as for fuel cells.

In Table, 9 the energy efficiency of the production (including transport) of fossil and renewable fuels is given. Of course the energy efficiency is higher if you start with the ‘easier’ fossil feedstocks such as crude oil and natural gas. An exception is possibly H_2 produced from natural gas. This has a relatively low energy efficiency. More than 50% of the energy content is lost. H_2 can also be made via electrolysis from electric energy from wind power with a similar efficiency. The route: liquid H_2 (LH2) from LNG, shown in the table 9, is by itself not very logical. It would be more efficient to produce liquid H_2 directly at the natural gas source and then transport it as liquid H_2. If this is however not feasible due to safety or economy of scale reasons, the route via LNG might be an option.

It should be noted that the numbers presented in Table 9 are approximate numbers. The numbers are quite dependent on the precise production process, the transportation distances and other assumptions.

Table 9. Energy efficiency of fuel production from fossil and renewable feedstock.

	Feedstock	Energy efficiency fuel production
HFO, diesel engine MDO/MGO, diesel engine	Crude oil	89% 85%
Pyrolysis liquid, diesel engine Pure Plant Oil, diesel engine Biodiesel, diesel engine Biomass to Liquid, diesel engine Biomass to H2, fuel cell Bio-LNG, gas engine	Biomass or waste	70% 63% 55% 56% 51% 49%
LH2, fuel cell To LNG to LH2, fuel cell LNG, gas engine	Natural gas	41-47% 38-40%? 81%

In figure 11, the energy efficiency of the fuel production is combined with the energy efficiency of the powertrain of the ship. This is the Well To Propeller (WTP) energy efficiency. The following assumptions are done for the powertrain efficiency:

- All diesel engines: 50%
- Natural gas engines: 48%
- Fuel cell: 50%

It can be seen that for the fossil fuels, the large combustion engines are unbeatable with respect to energy efficiency. Fuelled with either HFO, diesel or LNG, the WTP energy efficiency is around 40%, which is almost double of H_2 produced from natural gas with a WTP energy efficiency of around 22%. It should be noted that the fuel cell efficiency has the potential to increase in the future, because this technology is still in a development stage. In the literature fuel cell efficiencies of up to 70% (top of range) can be found.

With the renewable fuels, the differences are smaller. But also then, the H_2 pathways do not show an advantage compared to the more conventional pathways with for example biodiesel or bio-LNG. In this respect the H_2 application for sea ships is entirely different from the H_2 application in passenger cars. With passenger cars, the efficiency of the powertrain is much lower leading to clear advantages of H_2 with fuel cells compared to bio fuels with combustion engines[23].

An interesting result is the one for pyrolysis liquid. The energy efficiency of the fuel production is very high (around 70%), while it can still be combusted with the high

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[23] Energy consumption and green-house-gas emissions of electrified vehicles, Dr. Jörg Wind, Danny Kreyenberg, Daimler AG. European Electrified Vehicle Congress 2011, Brussels, October 26th 2011.

efficiency of the large diesel engine. It should be noted, that the acceptance of pyrolysis liquid as a fuel has several serious issues:

- Clearance of toxicity aspects with spillage and possibly combustion (REACH). Pyrolysis liquid contains several acids and aldehydes which can form a toxicity issue.
- Impact on the fuel injection system and other parts of the engine. Pyrolysis liquid is very corrosive and it may also form deposits/coke in injector nozzles for example. So substantial engine adaptation or development and possibly development of lubricants is necessary.

Large advantage of Pyrolysis liquid is that the production process is simple and low costs and that the feedstock competes much less with food.

It should be noted, that in some cases, the 'losses' of the fuel production can be used in other processes. For example in some cases, heat is produced, which might be used in other processes or for heating of buildings or houses. For PPO, the energy required for pressing out the oil from the crops is not very high and the remaining cake can be used for for example animal food or as biomass feedstock for other biofuels. It is recommended to evaluate the 'total energy' options of several path ways, because there are likely quite attractive options.

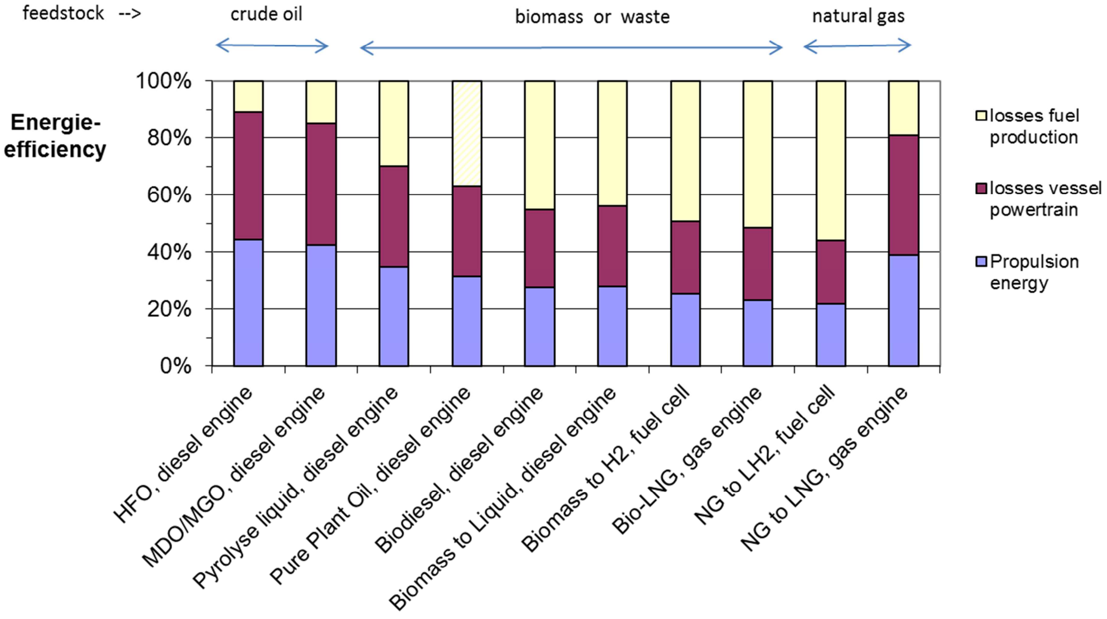

Figure 11: Well To Propeller (WTP) Energy Efficiency of fossil and renewable fuel path ways.

5 Comparison of fossil and alternative fuels

The characteristics of fossil and alternative fuels for sea shipping are summarised in table 10. This is based on the information from the previous paragraphs.

Table 10: Comparison of fossil and alternative fuels for sea shipping

	Future availability	Price	Practical application	Bunk-ering	Pollutant emissions*	GHG emission
HFO	++	++	++	++	- -	o
MDO	+	++	++	++	- -	o
MGO	-	+	++	++	-	-
LNG	++	++	o	o	+	+
PPO	+	o	++	o	o	++
Biodiesel (FAME)	+	o	+	o	o	++
HVO / BTL	- / o	-	++	-	o	++
Pyrolysis liquid	+	+	o	- / o	-	++
Liquid H2 / fuel cell	- - / ++	- -	- -	- -	++	- / +

* upgrade to ++ for all fuels possible with appropriate exhaust after treatment.

6 Discussion

Sea shipping has always been the ‘drain’ for low quality (low priced) fuels. This is slowly changing because via the IMO MARPOL legislation, pollutant emissions need to be reduced in the future. The restrictions are however very mild compared to most other sectors such as road vehicles, non-road vehicles and machines and inland shipping. This means that sea shipping can maintain to accept lower quality (fossil and bio) fuels for quite some time, which is also very logical from a costs point of view. Because of the compatibility with emission control systems, the mildly or not processed biofuels can no longer be used for new vehicles and machines in on shore applications after say 2014. These biofuels such as PPO and biodiesel (FAME) are however premium fuels for sea shipping. In this way a natural distribution of fossil and biofuels is falling into place: use a sufficient quality fuel for the (ship) application, but not better than necessary.

Interesting is the discussion how or from which feedstock should we produce the (increasing demand) of high quality fuel. For example good quality sulphur free diesel can be produced from HFO or it can be produced from vegetable oil (via hydro treatment). Probably the latter is simpler. This would mean that it is better to produce the diesel from vegetable oil and to use the HFO in the ship rather than putting the ‘crude’ vegetable oil in a ship and produce the diesel from HFO. It is recommended to further investigate this.
Starting in 2015, due to the SECA’s, there will be a much higher demand for low Sulphur or for distillate diesel fuel. This may lead to a shortage, due to lagging behind of investments in sufficient capacity and a steep rise in world-wide demand. It makes sense to fill in this gap with LNG and biofuels.

Basically what is concluded here is that the discussion about alternative and bio fuels should be looked at from the fuel supply side and not from the applications. So the question should be: what is the best place to use this biofuel? And not: what can we use in a ship? Well to Wheel and Well to Propeller energy efficiency are an important aspects with this respect. For example H_2 does not show any advantages with respect to energy efficiency for sea shipping, apart from the very practical aspects such as autonomy and safety. For automotive application, H_2 from renewable feedstock does show a higher energy efficiency than conventional powertrains. So that is than a better place to start using hydrogen.

Meanwhile, based on the current analysis, the following strategy is recommended for the coming 20 years for sea shipping, also refer to figure 12 and table 11.:
Deep sea:

- continue to use HFO as much as becomes available and is allowed (environmentally), because HFO can only be converted into higher quality fuel at high energy costs
- feed in LNG since it is available, low priced and it helps to reduce the pollutant and GHG emissions

Short sea:

- continue to use MDO/MGO, because it is available
- evaluate if it makes sense to use pyrolysis liquid and to build up an infrastructure for pyrolysis liquid, since it is the most economic biofuel.

Short sea / Emission Control Area:

- use as much as possible LNG and PPO and possibly biodiesel.
- use MGO (after 2015) for as far as it is available and cannot be converted to diesel fuel for inland shipping and road / non road applications.
- evaluate if requirement can be fulfilled with pyrolysis liquid and if it makes sense to build up an infrastructure.

Premium fuels such as HVO, BTL, H_2 and even biodiesel can best be reserved for road, non road applications and inland shipping, because there the higher quality of these fuels is important and the value is higher.

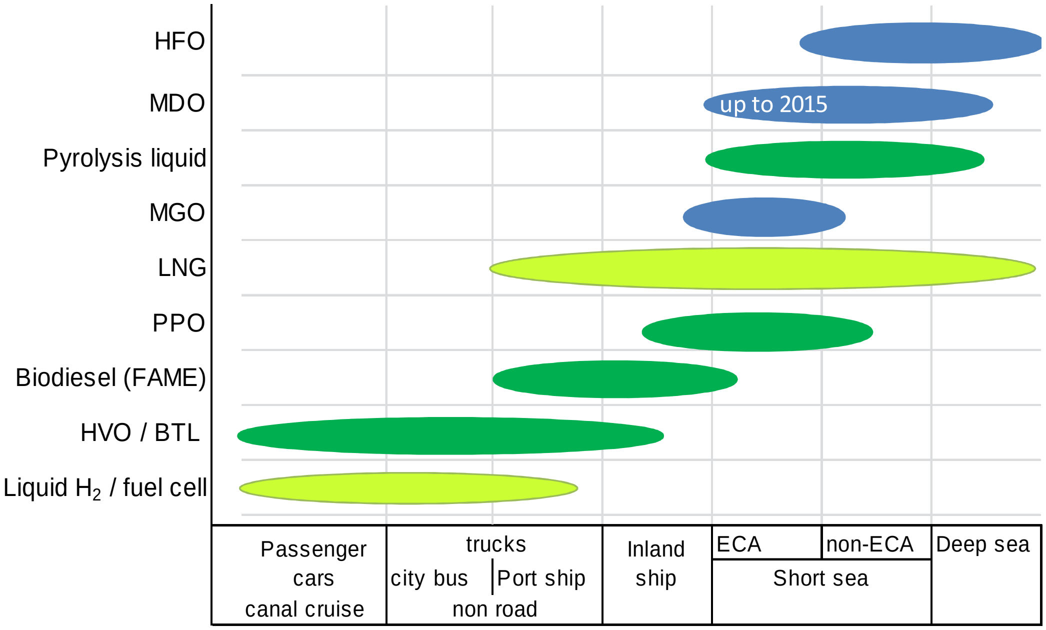

Figure 12: Recommended applications of fossil and bio fuels

In table 11, the characteristics and suitability for different application are summarized.

Table 11: summary of suitability of fuels for different applications of sea shipping

Fuel	**Characteristics**	**SECA**	**NECA**	**Deep sea**
HFO	Very economic fuel suitable for deep sea sailing	o**	o***	++
MDO	Needed within the current SECA areas.	++****	++*	+
MGO	Needed within the SECA areas starting in 2015.	++	++*	+
LNG	Economic fuel potentially at about the same price as HFO but with much better emissions and due to that: potentially broader application in shipping. Special engine needed plus special LNG storage. Best suited for new build ships. Requires infrastructure for bunkering	++	++	++
PPO	One of the most cost effective biofuels. Low pollutant emissions such as SOx and PM.	++	++*	o
Biodiesel (FAME)	Low pollutant emissions like PPO, but somewhat more expensive than PPO	o	o*	-
HVO / BTL	Low pollutant emissions like PPO, but more expensive than PPO and FAME. Fuel seams too premium for sea shipping	o	o*	-
Pyrolysis liquid	Potentially very cost effective biofuel. Low SOx emission. PM emission probably lower than HFO but uncertain. Special (corrosion resistant) fuel injection system needed. Requires infrastructure for bunkering and clearance for health aspects.	+	- / o*	++
Liquid H_2 / fuel cell	No pollutant emission in combination with fuel cells. Autonomy is unacceptably low (6x more space required than for diesel tank). WTP energy efficiency much lower than diesel. It can be consider for on-board electricity generation.	- -	-	- -

* Low NOx capability with SCR deNOx after treatment

** With SOx scrubber

*** With SOx scrubber and SCR deNOx

**** until 2015

7 Conclusion and recommendations

A number of alternative fuels were investigated on their suitability for sea shipping. This was done on a number of criteria including availability and pricing, practical application and potential of pollutant and GHG emissions reduction.

One of the main conclusions is, that it is best to balance the fuel quality with the needs for see shipping. These are quite low in comparison to road transportation, non-road machines, inland shipping and air planes. Consequently more in detail the conclusions are:

- The good possibility of sea ships to accept low quality liquid biofuels, is a strong reason to use those fuels for ships rather then in other fields.
- Low quality liquid biofuels (PPO, biodiesel and possibly even pyrolysis liquid) are suitable for the Emission Control Areas. This is where the value of these fuels is the highest and where application is recommended. Very suitable applications are ferries and short sea ships sailing these ECA’s.
- LNG is considered to be a very suitable fuel for a wide range of ships, because it is a clean fuel with a low price and it has a good future availability. The only conditions are that a) the fuel consumed per year is relatively high such that the additional costs of the LNG tanks and powertrain can be compensated by a lower fuel price and b) bunkering of LNG is available.
- Bio-LNG, if available, is suitable for sea ships, but may have a higher value for road transportation and inland shipping (because of its high methane number).
- Liquid-H_2 is not very suitable for sea ships for practical, economic and energy efficiency reasons. When made from natural gas, energy efficiency is only about half of the energy efficiency of the LNG chain for example.
- It is recommended to use high quality diesel fuels such as HVO, BTL and H_2 for applications such as road transportation, non road machines and inland shipping, where these types of high quality fuels have much more added value than for sea transportation.

Finally, some recommendation are:

- The high efficiency of the large combustion engines for ships is a strong reason to stick to this power source and to use liquid (bio) fuels, including LNG.
- The use of alternative fuels for ECA’s will help to solve the possible future shortage of low S diesel fuel.
- It is recommended to evaluate possible ‘total energy’ options for the production of fuels, especially for bio fuels.

8 Signature

Delft, 22 December 2011

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