Synthetic Fuels For Global Shipping

Rotterdam Mainport University

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Management Review

In the shipping industry, nowadays the main fuels that are used are heavy fuel oil (HFO), intermediate fuel oil (IFO) and marine diesel oil (MDO). These fuels produce high emissions, such as CO_2, NO_x, SO_x, CO and Particulate Matters.
These emissions lead to global warming, which damages the environment.
This is a problem for everyone because the earth is the base of life.
Each vessel that has running engines emit. Vessels using heavy fuel oil, intermediate diesel oil or/and marine diesel oil will have a problem in the future because the International Maritime Organisation changed the legislation for emissions. The IMO tier III, regulation 13 demands a lower NOx emission and will enter into force on 1 January 2016. Also on and after 1 January 2015 the SO_x and particulate matter emissions inside ECA areas are reduced and outside these ECA areas the emission will reduce on and after 1 January 2020. Finally the Ship Energy Efficiency Plan for reducing CO2 went into force on 1 January 2013. (www.imo.org)

Problem definition
The emissions of NO_x, SO_x, CO_2 and Particular Matters by the shipping industry are too high.

Questions
How can the emissions be reduced by use of Gas To Liquid (GTL), Biomass To Liquid (BTL) and Coal To Liquid (CTL)?

- What is Gas to Liquid?
  - What are the disadvantages of Gas to Liquid?
  - What are the advantages of Gas to Liquid?
  - How can emissions be reduced by the use of Gas to Liquid?
- What is Biomass to Liquid?
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  - How can emissions be reduced by the use of Biomass to Liquid?
- What is Coal to Liquid?
  - What are the advantages of Coal to Liquid?
  - What are the disadvantages of Coal to Liquid?
  - How can emissions be reduced by the use of Coal to Liquid?
- What are the legislations regarding to emissions?
- What is the application of synthetic fuel in sea-going vessels?

Research has been done through desk, from “What is gas to liquid?” to “What are the legislations regarding to emissions?”, and field research, “What is the application of synthetic fuels in sea-going vessels?”

Objective
The emission in the shipping industry has to be reduced.
The purpose is to do that with an increase of use of the fuels GTL, BTL and CTL.

Borders
This project did not take manufacturing cost of synthetic fuels and corresponding engines into consideration.
The fuel has only been fabricated theoretically; no corresponding engine has been fabricated within this project.
If it was found necessary to conduct experiments with fuels, the options would have been looked into. Further research is needed on this subject.

CTL, BTL and GTL have the same end product, the raw materials are different. All three of them have the same reactions and characteristics. The biggest difference is the price of the production. BTL costs three times the amount it costs to produce GTL. Therefore the research is focused on GTL.
Shell GTL Fuel can be used in currently used heavy diesel engines, without any adaptions. It’s easier to store, transport and handle than other gas fuels, such as LNG and CNG. This fuel is practically sulphur free and has a high cetane number, 75/80 as to conventional diesel which has a cetane number of 48/56, this means there Is a better burning and there is less visible black smoke, this could also reduce noise in certain engines. The fuel is practically aromatic free, therefore it is not toxic and almost smell free. Shell GTL fuel is biologically degradable and it also has good cold flow characteristics throughout the entire year, therefore this fuel is reliable all year long.
For now the transportation costs for GTL fuels are too high.

Content

1. Introduction

Problem description
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These emissions lead to global warming, which damages the environment.
This is a problem for everyone because the earth is the base of life.
Each vessel that has running engines emits harmful substances. Vessels using heavy fuel oil, intermediate diesel oil or/and marine diesel oil will have a problem in the future because the International Maritime Organisation changed the legislation for emissions. The IMO tier III, regulation 13 demands a lower NO_x emission and will enter into force on 1 January 2016. Also on and after 1 January 2015 the SO_x and particulate matter emissions inside ECA areas are reduced and outside these ECA areas the emission will reduce on and after 1 January 2020. Finally the Ship Energy Efficiency Plan for reducing CO_2 went into force on 1 January 2013. (www.imo.org)

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Objective
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2. Gas To Liquid

2.1 Explanation

Gas To Liquid or GTL is a synthetic liquid fuel for diesel engines made out of gas. The basic technology behind the process is the Fischer-Tropsch process. This is a chemical transformation process which was discovered in the twenties by German scientists. Shell for instance has been researching intensely for over 35 years which makes them leader in the GTL technology and production. (www.gtlfuel.nl)

2.2 Types of Gas To Liquid fuels

Overall Gas to Liquid fuels are made out of natural gas or other gaseous hydrocarbons. These are made into longer-chain hydrocarbons, for instance methane to methanol. The process of making methanol out of methane can be seen below.

Steam reforming

$CH_4 + H_2O \rightarrow CO + 3\ H_2$

Methane and steam react in the presence of a metal-based catalyst which is mostly nickel. After this reaction carbon monoxide and hydrogen has been formed.

Water shift reaction

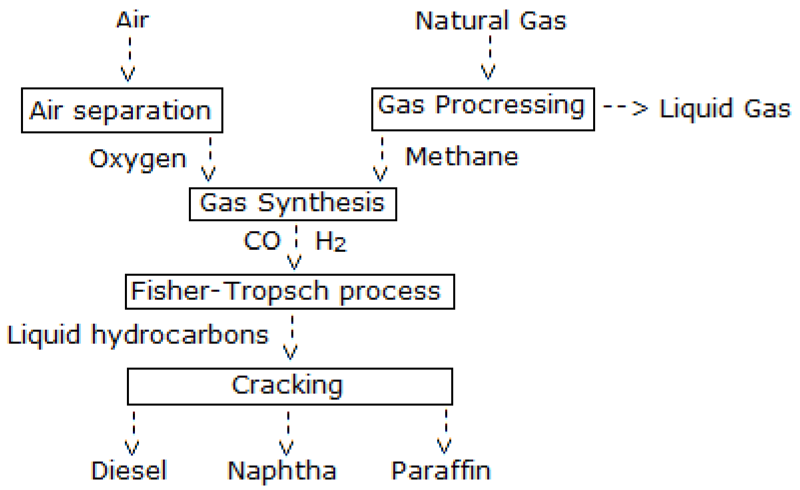
$CO + H_2O \rightarrow CO_2 + H_2$

The water shift reaction is the reaction between carbon monoxide and steam. This reaction forms carbon dioxide and hydrogen and this mixture is also known as water gas.

Synthesis

$2\ H_2 + CO \rightarrow CH_3OH$

Finally hydrogen and carbon monoxide forms another reaction which makes methanol.



All gaseous hydrocarbons which are processed into longer-chain hydrocarbons are all fossil fuels. Liquid hydrogen therefore is something very unknown yet and it does not emit any carbon dioxides, sulphur oxides, nitrogen oxides or soot. Fossil fuels do emit carbon dioxides, sulphur oxides, nitrogen oxides and soot which makes it interesting for the shipping industry to experiment on liquid hydrogen.

Probably no engine manufacturer in global shipping is making a hydrogen engine or is retrofitting a diesel engine for a vessel.

It is important for the shipping industry that the fuel storage does not influence the cargo storage. In other words when a vessel goes to a GTL fuel it is important that the used space for fuel stays on the same level or becomes lower as it did with HFO, IFO or MDO.

In the appendix are tables with the heating values per kilogram and per cubic metres to show how much energy fuels can provide per kilogram and per cubic metre.

2.3 Advantages

GTL has less damaging components like sulphur and aromatics than HFO. Also the emission of soot and NO_x are considerably lower than the nowadays used diesel oils. Besides that GTL is better for the environment. It is also better for health. (www.gtlfuel.nl)

Liquid hydrogen only emits water which makes it very interesting for the shipping industry because it emits no greenhouse gases. Second is that hydrogen can be made out of water and then be cooled to make it liquid and because it can be made out of water no fossil fuels are needed. Finally liquid hydrogen produces 120.07 $x10^6$ J/kg while HFO only produces 43.0 x 10^6 J/kg**.**

https://technifab.com/cryogenic-resource-library/cryogenic-fluids/liquid-hydrogen/

2.4 Disadvantages

GTL fuels are fossil fuels which means the fuel sources are not everlasting. It has more emission of greenhouse gases than liquid hydrogen. Another disadvantage is that there are only a few places where a vessel can bunker GTL

A disadvantage of liquid hydrogen is that it requires a lot of space because of its low density of 70.798 kg/m^3 at 20 Kelvin. Producing liquid hydrogen on a large scale is a problem. To produce 1000 kg/day of hydrogen gas, 51,000 kWh/day is required. To do this by means of solar energy with approximately 5 hours/day which makes 10,200 kWp (kWp is the measurement of solar energy, 1 kWp equals 1 kWh). 1 kWp of solar energy requires approximately 10 m^2 when using a solar panel of 10% efficiency. To produce 1000 kg/day 102,000 m^2 of solar panels is required.

Liquid hydrogen produces 120.07 x 10^6 J/kg energy.
1000 kg produces → 120.07 x 10^9 J/kg.
To produce 1000 kg hydrogen gas, 51,000 kWh is required.
1 kWh is 3600 J.
So to produce 1000 kg hydrogen 51,000 x 3600 = 1.836 x 10^{11} J is required.
The energy loss is 1.836 x 10^{11} – 120.07 x 10^9 = 6.353 x 10^{10} J

(http://www.fsec.ucf.edu/en/consumer/hydrogen/basics/production-solar.htm)

2.5 Reducing emissions

Gas to Liquid is a good way to reduce emissions because of the low sulphur and nitrogen content. But Gas To liquids are fossil fuels which cause emission of greenhouse gases. Liquid hydrogen is an option for short distance vessels because they need less fuel for a voyage which means they need less fuel than a vessel on a long voyage but for the vessels sailing a long distance this is more of a problem because the fuel takes a lot of space.

2.6 Application

Marine diesel engines do not have to be retrofitted for GTL. GTL Fuel is a so called drop-in-fuel. If a diesel engine is capable of running on current fuels it can run on Shell GTL Fuel as well.

3. Biomass to Liquid

3.1 Explanation

Biomass to liquid or **BTL** is a process that transforms biomass to a usable form of fuel, biofuel. The process used depends on the kind of biomass used to create this biofuel. The fuel is produced through modern biological processes, such as agriculture and anaerobic digestion. In contrast to fossil fuels such as coal or petroleum, biofuel can be directly derived from plants and seeds or indirectly from agricultural, commercial, domestic and industrial wastes, whereas fossil fuels take millions of years, heat and pressure to finally become oil, coal or natural gas. The fuel from these plants comes from a process called photosynthesis. Photosynthesis works as follows: the plant converts light energy from the sun with carbon dioxide and water into a chemical energy such as glucose.

In general there are three generations of biofuels. The first generation of biofuels are crops that are used as food for humans. The second generation of biofuels are made out of rest/waste products and the third generation of biofuels are algae and seaweed.

- **The first generation**: these are biofuels produced directly from food crops. The biofuel is derived from the starch, sugar, animal fats and vegetable oil. The most common feedstock for first generation biofuels are corn, wheat, sugar cane, soybeans, sugar beets, rapeseed, peanuts and lots of other nuts and seeds (https://www.iea.org/publications/freepublications/publication/2nd_Biofuel_Gen.pdf)
- **The second generation**: this generation of biofuels is made out of rest/waste products such as wood, straw, food waste, inedible parts of food crops, used vegetable oils.
- **The third generation**: although these biofuels are still in development, the third generation biofuels are produced from algae, bacteria or seaweed that are specially farmed for this purpose.

Processes used to create biofuels are described below.

The Fischer-Tropsch process is a process that was invented by Franz Fischer and Hans Tropsch in 1925 in Germany. The process converts a gas mixture made out of carbon monoxide and hydrogen to a liquid fuel. The process for biomass uses a catalyst, in case of biomass, based on cobalt. By oxidizing biomass in the absence of oxygen carbon monoxide is created. If during this process steam is added and passed through a catalyst, then purify the end product, eventually syngas will be formed. This process is commonly known as reforming. This syngas can then be further purified into naphtha, biodiesel and methanol.

Gasification is a process that converts the biomass into carbon monoxide, hydrogen and carbon dioxide (synthetic gas or syngas). This is done by having the material react at temperatures higher than 700 degrees Celsius.

Hydro thermal upgrading or HTU is a process that converts biomass into useable fuels. The reaction takes place in the absence of water and oxygen at a high temperature of 330 degrees Celsius and at pressures between 150-180 bars. The formed liquid is almost identical to heavy fuel oil and can therefore be used in the current engines that run on heavy fuel oil. Using a hydrogenation step this liquid can be converted to the required end product (e.g. biodiesel).

3.2 Advantages

The biggest advantage of BTL over CTL or GTL is that BTL, when burned, produces no extra carbon dioxide compared to CTL or GTL. This is due to the fact that the plants use carbon dioxide as an ingredient in its photosynthesis process. Therefore it is said that biofuels are carbon dioxide neutral and have no impact on the enhanced greenhouse effect.

Another advantage over fossil fuels is that if there is a spillage of large quantity in a concentrated area (e.g. sinking of a seagoing vessel), it would most likely kill living organisms and contaminate the surrounding soil or water, but the impact would be of a smaller scale compared to fossil fuels due to the fact that the biofuel is biodegradable. Organisms and other bacteria are able to use this biofuel as an energy source and therefore break them down in harmless by-product. In the case of fossil fuels, the area would be uninhabitable for a long period and also cause damage to the environment.

The first generation of biofuels has the advantage that the biomass required for this biofuel is easily grown and produced since they are mostly foods that would normally have been grown to be eaten by humans.

Second generation biofuels are better than the first because they would not have been used as food, so instead of letting it rot away the waste is now used for a better purpose. Wood, straw and inedible parts of food crops can be gasified to produce syngas and be further refined to biodiesel eventually.

The third generation of biofuels are designed for the use as fuels. They have a higher yield per acre compared to the first and second generation and have to be produced in water which would normally not have been used for the growth of crops for food. It is claimed that algae produce 20,000 gallons of biofuel per acre which is ten times better than the second generation.

(http://biofuel.org.uk/third-generation-biofuels.html)

When producing biofuels with hydro thermal upgrading almost all biomasses can be used, wet or dry.

3.3 Disadvantages

A general disadvantage of biofuels is that they can cause damage (clogging of filters and nozzles) to the engine when not refined properly.

A disadvantage of first generation biofuels is that the main feedstock could be used as food. To grow these food crops lots of water is needed thus less potable water is present in the area where the crops are grown. Indonesia, where palm oil is produced, is known for deforesting land in order to grow palm trees to produce this oil, having a negative effect on the local ecosystem. The fertilizer used to have the crops grow faster have a negative effect on the surrounding environment.

Second generation biofuels have almost no disadvantages compared to first generation biofuels. Normally, inedible parts of food crops are used as food for cattle. When using inedible parts of food crops or straw, livestock has to be fed with other food sources.

Third generation biofuels that were especially designed for the use as biofuels have no disadvantages besides the need for lots of water because algae are grown in large water basins.

3.4 Applications

The final products made using HTU are especially useful as a replacement for traditional heavy fuel oil. Their properties are almost identical to heavy fuel oil. Biodiesel can be used in existing engines running on MDO and therefore reducing the emissions of carbon dioxide.

4. Coal To Liquid

4.1 Explanation

Coal conversion or Coal To Liquid (CTL) fuels are used in cars and other vehicles, probably even vessels.

There are three common methods for manufacturing synthetic fuels: Fischer-Tropsch, Direct/indirect liquefaction and methanol conversion.

The Fischer-Tropsch process makes different types of hydrocarbons with various H2:CO ratios. The H2 and CO can be supplied from the coal gasifier. The original Fischer-Tropsch process describes the following equations:
$(2n+1)H_2 + nCO \rightarrow C_nH(2n+2) + nH_2O$
$C + H_2O \rightarrow H_2 + CO$
$2\ CH_4 + O_2 \rightarrow 4H_2 + 2\ CO$ if methane is used. (www.acla.org.au)
Most common catalysts used for the Fischer-Tropsch process are the transition metals cobalt, iron and ruthenium. Nickel is also used, but usually for the methane formation.

Converting coal to a liquid fuel is a process referred to as coal liquefaction. There are two methods to convert coal into liquid fuels. These methods are direct liquefaction and indirect liquefaction. Direct liquefaction works by dissolving the coal in a solvent at high temperature and pressure. The liquid products require further refining to achieve high grade fuel characteristics, but the process is highly efficient. Direct liquefaction can be divided into two different methods: pyrolysis and the Bergius process.

Pyrolysis is a method to convert coal into higher valuable fuels involving only a heating step to split coal into gas, tar and char. This is a simple method. The first step in any thermal coal conversion process is de-volatilisation. This means that pyrolysis is a controlling step with an important influence on product formation. If this pyrolysis step is carried out in a hydrogen atmosphere, while under pressure, chemical reactions can occur between the free radicals in the primary coal decomposition products and the hydrogen. The overall reaction can be controlled by the competing cracking and polymerisation and can increase the de-volatilisation rate. (www.iea-coal.org.uk)

The Bergius process is also a method of direct conversion of coal to liquids. This method uses the hydrogenation process. Hydrogen and coal is mixed with heavy oil. Which was recycled from the conversion process. A catalyst is added to the mixture. With a temperature between 400 °C to 500 °C and 20 to 70 MPa of hydrogen pressure, the reaction will occur: $n\ C + (n + 1)\ H_2 \rightarrow C_nH_2\ n + 2$ (en.wikipedia.org)

Coal can also be liquefied through a methane method. Methane will be preheated to 600°C and will suppress much of the required water, this will reduce the unwanted reaction with the coal. The methane also reduces the amount of heat absorbed by the gasification process. This eliminated the need for oxygen and combustion to maintain the 1,400 to 1,500 °C temperatures that the process requires. Not using oxygen does not only eliminate a source of carbon dioxide , but there is also no need for an oxygen plant. (www.technologyreview.com)

Indirect liquefaction gasifies the coal to form a “syngas”. This is a mixture of hydrogen and carbon monoxide. This gas is then condensed over a catalyst to produce high quality, clean products. This process is also called Fischer-Tropsch process. The gasification generates carbon dioxide. This comes partly from the combustion and partly through undesirable reactions between water and carbon. With undesirable reaction is meant that the water and carbon react to CO2. (www.worldcoal.org)

The table under shows the difference in process in direct and indirect liquefaction.

Direct liquefaction	**Indirect liquefaction**
Add hydrogen to breakdown coal	Complete breakdown of coal with steam and oxygen
Dissolves in a solvent, followed by hydrocracking	Sulphur is removed
Operates at 450 degrees Celsius and 170 bars	Syngas reacts over catalyst at 300 degrees Celsius and 20 bars
Light products are distilled	Lighter suite of products, high quality gasoline and petrochemicals
Vacuum distillation for medium and heavy distillates	Oxygenated chemicals
Liquid yields 70% of the dry weight of coal feed	
Further upgrade needed for use as transportation fuel	

(www.che.utexas.edu)

The three main processes of a CTL plant consist of:

- The first step in converting coal to liquid is gasification. This process converts carbon materials into carbon monoxide and hydrogen. Syngas production: converting a solid, liquid or gas materials into hydrogen and carbon monoxide. Coal is mixed with oxygen and steam at high temperatures and pressure to produce a gas.
- Fischer-Tropsch synthesis: syngas will be converted into liquid hydrocarbons, through a catalytic reaction. This will be done with cobalt as catalyst. The syngas will react with this catalyst. This joins less complicated hydrocarbon chains contained in the gas. This will produce syncrude, a longer liquid hydrocarbon chain.
- Refining: filtering and refining to produce the end products. (abarrelfull.wikidot.com)

4.2 Advantages

CTL can be made by countries who have large reserves of coal and rely heavily on oil imports. There are more than 250 billion tons of recoverable coal reserves in the U.S. Coal provides more than half of the nation’s electricity (www.nma.org). Coal to liquid lessens dependence on foreign oil. Coal is affordable and available worldwide.

Coal liquids can be used for many purposes: transport, cooking, stationary power generation and in the chemicals industry. The fuels are sulphur-free, low in particulates and low in nitrogen. It has low transportation costs. There is less chemical transformation required. Coal fuels have a higher efficiency than other non-synthetic fuels and the fuel is easy to store (www.che.utexas.edu).

4.3 Disadvantages

There is a sufficient amount of coal for the next 20 to 25 years, this is a given fact. The availability of coal in de following decades cannot be ensured. If CTL becomes a growing market the prediction on the availability of coal will be worse. CTL still carries most of the environmental baggage of traditional coal production, despite new technologies. CTL is also very water-intensive, it requires between six and ten barrels of water for every barrel of synthetic fuel . (www.gpo.gov)

When coal is liquefied and burned carbon dioxide is released. CTL can cause acid rain, because sulphur dioxide is one of the pollutant which is release when fossil fuels are burnt. This is a main cause of acid rain. Air pollution can result in health problems, such as asthma, chronic obstructive pulmonary disorder/ (COPD) and lung cancer. CTL is a non-renewable product. (www.conserve-energy-future.com)

Producing one barrel of liquid coal requires roughly half a ton of coal. Large-scale deployment of liquid coal plants would increase coal mining and its devastating effects. For example, coal mining creates hazardous and acidic waste, which can contaminate the groundwater. Building a coal-to-liquid plant can be very costly. It takes a lot of energy to loosen up the carbon bonds in coal. Using all that energy results in the emission of a lot of carbon dioxide. (www.scientificamerican.com) Emissions from liquid coal production plants are higher than the emissions from producing and refining crude oil into gasoline, diesel and other transportation fuels. The liquid coal plants releases CO_2 into the atmosphere. (www.nrdc.org)

4.4 Reducing Emission

Higher quality coal contain less hydrogen, oxygen and nitrogen, up to 95% purity of carbon is achieved at anthracite quality and above volatile matter. The volatile matter consists of aliphatic atoms, linked in chains, of aromatic hydrocarbons, one or more six-carbon rings characteristics of benzene series, and mineral matter. The ash consists of matter from the earth's crust, which are inorganic like aluminium and silica. The set of physical parameters of each type of coal are mostly controlled bij carbon content, volatile content and moisture.

Coal physical parameters

Aliphatic	The carbon atoms are linked in open chains, designating a group of chemical compounds
Aromatic	Contains one or more six-carbon rings characteristic of the benzene series
Hydrocarbons	Organic compounds that contain only carbon and hydrogen

Looking at the advantages and disadvantages of synthetic coal fuels can be concludes that coal to liquid will not be the synthetic fuel to use if emissions have to be reduced.

The use of coal as a marine fuel has seized in the early 20th century, because of the big disadvantages it has as opposed to oil. These disadvantages include the dirty, strenuous work associated with coaling a ship, which is also highly impractical to do at sea. Coal also produces much more smoke than oils, and has a lower thermal content, which necessitates a higher volume of fuel.
Using coal to liquid, direct liquefaction, increases the rate of heat release and a decrease of gas temperatures. The maximum in-cylinder pressure decreases a bit and then decreases a lot. The increase of ignition delay is due to the lower in-cylinder temperature resulting from the higher specific heat capacity of the recirculated gas and the lower oxygen concentration in the cylinder. The whole combustion process is shifted further in the expansion stroke. This contributes to a reduction in the flame temperature. With the increase of exhaust gas recirculation, the combustion temperature and the local oxygen concentration decreases. These play an important role in suppressing the NOx formation. Because direct coal liquefaction has a lower distillation temperature and cetane number, it forms more of a homogeneous mixture. The lower contents of sulphur and aromatics in direct coal liquefaction formation of soot precursors can be suppressed. The NOx emissions decrease and there is an improvement in soot emissions due to the chemical composition of direct coal liquefaction. This all makes direct liquefaction applicable in engines and therefore on vessels.

5. Legislation

Legislation is important when a new fuel will be applied in a marine diesel engine. The most important legislation parts are covered in this chapter. In the appendix more background information can be found.

Air pollution from ships causes a cumulative effect that contributes to the overall air quality problems encountered by populations in many areas, and also affects the natural environment, such as tough acid rain.

MARPOL Annex VI, first adopted in 1997, limits the main air pollutants contained in ships exhaust gas, including sulphur oxides (SOx) and nitrous oxides (NOx), and prohibits deliberate emissions of ozone depleting substances (ODS).

Following entry into force of MARPOL Annex VI on 19 May 2005, the Marine Environment Protection Committee (MEPC), at its 53rd session (July 2005), agreed to revise MARPOL Annex VI with the aim of significantly strengthening the emission limits in light of technological improvements and implementation experience. As a result of three years examination, MEPC 58 (October 2008) adopted the revised MARPOL Annex VI and the associated NOx Technical Code 2008, which entered into force on 1 July 2010.

This chapter is only about the important information, in the appendix is an extensive report of the legislation with regard to our subject.

NOx, SOx and particulate matter

Emission of nitrogen oxides (Tier III) (entered into force on 1 January 2016)

- 3.4 g/kWh when n is less than 130 rpm; 1
- 9 . n(-0,2) g/kWh when n is 130 or more but less than 2,000 rpm;
- 2.0 g/kWh when n is 2,000 rpm or more.

Emission Control Areas

For the purpose of this regulation, an Emission Control Area shall be any sea area, including any port area, designated by the Organization.

Sulphur Oxides (SOx) and Particulate Matter (regulation 14)

- 3.50% m/m on and after 1 January 2012; 2
- 0.50% m/m on and after 1 January 2020.

When ships are operating within an Emission Control Area, the sulphur content of fuel oil used on board ships shall not exceed the following limit:

0.10% m/m on and after 1 January 2015

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[1] n = rated engine speed or crankshaft revolutions per minute.
[2] m/m = the mass fraction = mass component / mass mixture

6. Field Research

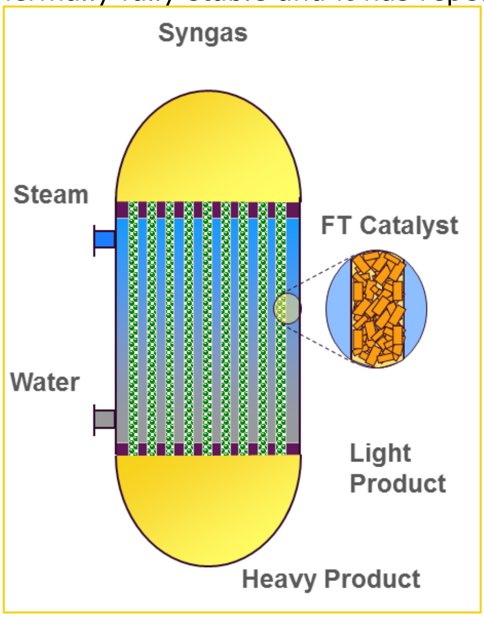
6.1 Shell Technology Centre Amsterdam

CTL, BTL and GTL have the same end product, the raw materials are different. All three of them have the same reactions and characteristics. The biggest difference is the price of the production. BTL costs three times the amount it costs to produce GTL. Therefore the research is focused on GTL.

Advantages
Shell GTL Fuel can be used in existing heavy diesel engines, without any adaptions. It's easier to store, transport and handle than other gas fuels, such as LNG and CNG. This fuel is practically sulphur free and has a high cetane number, 75/80 as to conventional diesel which has a cetane number of 48/56, this means there Is a better burning and there is less visible black smoke, this could also reduce noise in certain engines. The fuel is practically aromatic free, therefore it is not toxic and almost odourless. Shell GTL fuel is biologically degradable and it also has a good cold flow characteristics throughout the entire year, therefore this fuel is reliable all year long.

Shell gasification process (SGP)
The gasification process is to make a syngas. This can be done by reacting organic or fossil fuel at high temperatures higher than 700 °C with using a controlled amount of oxygen and/or steam. After this reaction the carbonhydrates are converted into carbon monoxiede, hydrogen and carbondioxide.
This process has chalanges and advantages. The chalanges are: conditions in which the process takes place like environmental influences, the materials of the construction because they need to be heat resistent for the high temperatures, the burner design to heat up the fuel at the desired temperature and control and the high pressure. The advantages of this process are: there is no catalyst needed and no steam, it has a high conversion efficiency, excellent overall availability and good syngas and refractory reliability.

Shell heavy paraffin synthesis (HPS)
The gas distribution across tubes is a challenge in this process and so is the catalyst loading and stability. As a catylist second generation cobalt is used. The reactors are thermally fully stable and it has repeated in-situ regeneration.



Syngas reactor

Shell GTL fuel reduces emmisions such as particulair matter and NO_x as shown in the chart below.

Shell GTL Fuel Experience: A local emissions report

	% Improvement compared to standard Diesel			
	PM/Soot	**NOx**	**HC**	**CO**
EURO I	18	16	13	22
EURO II	18	15	23	5
EURO III	10 to 34	5 to 19	<9*	12 to 20
EURO IV	31 to 38	5 to 16	10 to 28	9
EURO V	23 to 33	5 to 37	19 to 23**	8 to 22

Shell GTL Fuel is virtually sulphur-free and has practically no aromatics***

* Not statistically significant - estimate of upper boundary of benefit

** Not measured at standard test temperature (5°C and 40° rather than 23°C)

*** The theoretical SOx reduction benefit from Shell GTL Fuel is close to 100% for all Euro levels since Shell GTL Fuel contains virtually no sulphur.

Source of data: The benefits achieved are based on Shell in-house studies and collaborative field trials (with vehicle manufacturers and fleet operators) with Shell GTL Fuel.

(Arend Hoek, Team Lead XTL Technology, Shell Projects & Technology, Amsterdam, 2015)

(The best way to use GTL is to use it pure, but mixing it with diesel is also possible. This is called GTL diesel blends. The disadvantage of blending GTL with diesel is the beneficial reductions in emissions will decrease when blending GTL with conventional diesel fuel.)

6.2 Interview with Sander van de Laar

For the field research an interview has been held with Sander van de Laar, Business Development & Marketing Manager GTL at Shell. The complete interview can be found in the appendix.

The most important result of the interview is that Shell claims a reduction of 15% on NO_x and 30% on particulate matter and also a noise reduction of 3 dB, but the fuel is more expensive as the current marine fuels.

(Sander van der Laar, Business Development & Marketing Manager GTL, Royal Dutch Shell, 2015)

6.3 Gasoil vs GTL Fuel

In the appendix is a table with comparisons between Gasoil and Shell GTL Fuel.
The test on the Wärtsilä 8L20 shows that the specific fuel consumption (SFC) lowers by 6.5% with the use of Shell GTL fuel marine. This can be concluded from the tables and graphs.

Blending diesel and GTL fuel
In a test GTL fuel and European sulphur-free diesel fuel with containing 20% and 50% GTL fuel were investigated. The study was based on a Mercedes Benz 2.2L passenger car diesel engine. The vehicle emission test showed that the GTL fuel resulted in a reduction of HC and CO emissions of 90%. PM is reduced by 30%, but NO_x remains unchanged. (papers.sae.org/2005-01-2187)

Conclusion

How can the emissions be reduced by use of Gas To Liquid (GTL), Biomass To Liquid (BTL) and Coal To Liquid (CTL)?
CTL, BTL and GTL have the same end product, the raw materials and the first step make synthetic fuels different. All three end products have the same reactions and characteristics. The biggest difference is the price of the production. BTL costs three times the amount it costs to produce GTL. CTL costs two time it costs to produce GTL. Therefore the research is focused on GTL.

Shell GTL Fuel can be used in currently used heavy diesel engines, without any adaptions. It's easier to store, transport and handle than other gas fuels, such as LNG and CNG. This fuel is practically sulphur free and has a high cetane number, 75/80 as to conventional diesel which has a cetane number of 48/56, this means there Is a better burning and there is less visible black smoke, this could also reduce noise in certain engines. The fuel is practically aromatic free, therefore it is not toxic and almost smell free. Shell GTL fuel is biologically degradable and it also has a good cold flow characteristics throughout the entire year, therefore this fuel is reliable all year long.
In a test GTL fuel and European sulphur-free diesel fuel with containing 20% and 50% GTL fuel were investigated. The study was based on a Mercedes Benz 2.2L passenger car diesel engine. The vehicle emission test showed that the GTL fuel resulted in a reduction of HC and CO emissions of 90%. PM is reduced by 30%, NO_x is reduced by 15% compared to conventional diesel oil.
Shell GTL is sulphur free (below 10 ppm), therefore each vessel running on GTL can sail into all ECA areas.
For now the overall transportation costs for GTL are currently higher due to the excessively higher overall ULSD demand.

Recommendations

Of all the Fuels that were researched, GTL has the most potential to reduce the emissions. GTL has the same final product, only different reactants, which are cheaper. GTL, BTL and CTL have lower emissions than the current fuels, which is an important advantage with nowadays environmental condition. The shipping industry does not use these fuels, the most applicable reason is because of the costs, therefore more research has to be done on costs. The fuel is more expensive because of smaller demand and thus transportation, the fuel itself is not really expensive.

Recommended is that more research has to be done of the following aspects:
Logistic costs, the transport of GTL which is by the aid of ships, because no pipeline is available to transport GTL. The transport is relatively expensive because of the low demand. If demand rises the transport costs will decrease.

Because of the legislation, it is not necessary to use relatively expensive fuels such as GTL, BTL and CTL.
If the legislation will become stricter GTL, BTL and CTL will be more applicable.

Also more research in blending is recommended. Blending is not possible with every fuel. The ratio of blending is also very important to know how much GTL is needed to improve the basic fuel.

List of abbreviations

Fuels

HFO	Heavy Fuel Oil
MDO	Marine Diesel Oil
IFO	Intermediate Fuel Oil
GTL	Gas to Liquid
BTL	Biomass to Liquid
CTL	Coal to Liquid
ULSD	Ultra Low Sulfur Diesel

Substances production process

CH_4	methane
H_2O	water
CO	Carbon Monoxide
H_2	Hydrogen
CO_2	Carbon Dioxide
CH_3OH	methanol

Exhaust substances

NO_x	Nitrogen Oxides
SO_x	Sulfur Oxides
CO_2	Carbon Dioxide
CO	Carbon Monoxide
PM	Particulate Matter
SFC	Specific Fuel Consumption

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Appendix

Gas To Liquid

Fluids

Substance	Heating Value (J/kg)	Heating Value (J/m^3)	Density
Crude oil	42.686 x 10^6 J/kg	36.141 x 10^9 J/m^3	846.671kg/m^3
Gasoline	47.3 x 10^6 J/kg	34.042 x 10^9 J/m^3	719.7 kg/m^3
Diesel	44.8 x 10^6 J/kg	37.274 x 10^9 J/m^3	832 kg/m^3
Heavy Fuel Oil	43.0 x 10^6 J/kg	39.990 x 10^9 J/m^3	930 kg/m^3
Gas Oil	45.509 x 10^6 J/kg	38.000 x 10^9 J/m^3	835 kg/m^3
Ethanol	29.7 x 10^6 J/kg	23.444 x 10^9 J/m^3	789.346 kg/m^3
Methanol	23.0 x 10^6 J/kg	18.264 x 10^9 J/m^3	794.101 kg/m^3
Butanol	34.366 x 10^6 J/kg	27.826 x 10^9 J/m^3	809.687 kg/m^3
Liquid hydrogen	120.07 x10^6 J/kg	8.501 x 10^9 J/m^3	70.798 kg/m^3

Gases

Substance	Heating Value (J/kg)	Heating Value (J/m^3)	Density
Hydrogen	141.79 x 10^6 J/kg	12.761 x 10^6 J/m^3	0.090 kg/m^3
Ethane	51.9 x 10^6 J/kg	65.602 x 10^6 J/m^3	1.264 kg/m^3
Methane	55.53 x 10^6 J/kg	39.815 x 10^6 J/m^3	0.717 kg/m^3
Butane	49.51 x 10^6 J/kg	123.775 x 10^6 J/m^3	2.5 kg/m^3
Natural gas	47.141 x 10^6 J/kg	36.629 x 10^6 J/m^3	0.777 kg/m^3

Biomass To Liquid

A table with a few types of fuel of the first and second generation with their energy density, feedstock and amount of greenhouse gas that is produced when burned.

Fuel	Feedstock	Energy Density (mega joules/kilogram)	Greenhouse Gas CO_2(kg/kg)	Notes
First Generation				
Bio alcohol	Starches from wheat, corn, sugar cane, molasses, potatoes, other fruits	By Type	By Type	
Ethanol		30	1.91	
Propanol		34	N/A	
Butanol		36.6	2.37	
Biodiesel	Oils and fats including animal fats, vegetable oils, nut oils, hemp, and algae	37.8	2.85	
Green Diesel	Made from hydrocracking oil and fat feedstock	48.1	3.4	Chemically identical to fossil fuel diesel
Vegetable Oil	Unmodified or slightly modified	By Type	By Type	
Castor Oil		39.5	2.7	
Olive Oil		39	2.8	
Fat		32	N/A	
Sunflower Oil		40	2.8	
Bio ethers	Dehydration of alcohols	N/A	N/A	These are additives to other fuels that increase performance and decrease emissions, particularly ozone

Biogas	Methane made from waste crop material through anaerobic digestion or bacteria	55	2.74 (does not take into account the direct effect of methane, which is 23X more effective as a GHG than CO_2	Same properties as methane from fossil fuels
Solid Biofuels Wood Dried plants Bagasse Manure Seeds	Everything from wood and sawdust to garbage, agricultural waste, manure	By Type 16-21 10-16 10 10-15 15	By Type 1.9 1.8 1.3 N/A N/A	This category includes a very wide variety of materials. Manure has low CO_2 emissions, but high nitrate emissions.
Second Generation				
Cellulosic ethanol	Usually made from wood, grass, or inedible parts of plants			
Algae - based biofuels	Multiple different fuels made from algae	Can be used to produce any of the fuels above, as well as jet fuel	See specific fuels above	More expensive, but may yield 10-100X more fuel per unit area than other biofuels
Bio hydrogen	Made from algae breaking down water.	Hydrogen compressed to 700 times atmospheric pressure has energy density of 123	Does not have any greenhouse effect.	Used in place of the hydrogen produced from fossil fuels
Methanol	Inedible plant matter	19.7	1.37	More toxic and less energy dense than ethanol

Dimethyl furan	Made from fructose found in fruits and some vegetables	33.7		Energy density close to that of gasoline. Toxic to respiratory tract and nervous system
Fischer-Tropsch Biodiesel	Waste from paper and pulp manufacturing	37.8	2.85	Process is just an elaborate chemical reaction that makes hydrocarbon from carbon monoxide and hydrogen

(http://biofuel.org.uk/types-of-biofuels.html)

Legislation

Definitions by Annex VI

- Emissions: any release of substances, subject to control by Annex VI, from ships into the atmosphere or sea.
- Emission Control Area (ECA): An area where the adoption of special mandatory measures for emissions from ships is required to prevent, reduce and control air pollution from NOx or SOx and particulate matter or all three types of emissions and their attendant adverse impacts on human health and the environment.
- Fuel oil: any fuel delivered to and intended for combustion purposes for propulsion or operation on board a ship, including distillate and residual fuels.
- Irrational emission strategy: any strategy or measure that, when the ship is operated under normal conditions of use, reduces the effectiveness of an emission control system to a level below that expected on the applicable emission test procedures.
- Marine diesel engine: any reciprocating internal combustion engine operating on liquid or dual fuel.
- NOx Technical Code: the Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines adopted by resolution 2 of the 1997 MARPOL Conference.

Revised MARPOL Annex VI

The main changes to MARPOL Annex VI are a progressive reduction globally in emissions of SOx, NOx and particulate matter and the introduction of emission control areas (ECAs) to reduce emissions of those air pollutants further in designated sea areas.

Under the revised MARPOL Annex VI, the global sulphur cap will be reduced from current 3.50% to 0.50%, effective from 1 January 2020, subject to a feasibility review to be completed no later than 2018. The limits applicable in ECAs for SOx and particulate matter were reduced to 0.10%, from 1 January 2015.

Progressive reductions in NOx emissions from marine diesel engines installed on ships are also included, with a “Tier II” emission limit for engines installed on a ship constructed on or after 1 January 2011; and a more stringent "Tier III" emission limit for engines installed on a ship constructed on or after 1 January 2016 operating in ECAs (North American Emission Control Area and the U.S. Caribbean Sea Emission Control Area). Marine diesel engines installed on a ship constructed on or after 1 January 1990 but prior to 1 January 2000 are required to comply with “Tier I” emission limits, if an approved method for that engine has been certified by an Administration.

The revised NOx Technical Code 2008 includes a new chapter based on the agreed approach for regulation of existing (pre-2000) engines established in MARPOL Annex VI, provisions for a direct measurement and monitoring method, a certification procedure for existing engines and test cycles to be applied to Tier II and Tier III engines.

MEPC 66 (April 2014) adopted amendments to regulation 13 of MARPOL Annex VI regarding the effective date of NOx Tier III standards.

The amendments provide for the Tier III NOx standards to be applied to a marine diesel engine that is installed on a ship constructed on or after 1 January 2016 and which operates in the North American Emission Control Area or the U.S. Caribbean Sea Emission Control Area that are designated for the control of NOx emissions.

In addition, the Tier III requirements would apply to installed marine diesel engines when operated in other emission control areas which might be designated in the future for Tier III NOx control. Tier III would apply to ships constructed on or after the date of adoption by the Marine Environment Protection Committee of such an emission control area, or a later date as may be specified in the amendment designating the NOx Tier III emission control area.
Further, the Tier III requirements do not apply to a marine diesel engine installed on a ship constructed prior to 1 January 2021 of less than 500 gross tonnage, of 24 m or over in length, which has been specifically designed and is used solely, for recreational purposes.

The amendments are expected to enter into force on 1 September 2015.
Revisions to the regulations for fuel oil quality were also made with regulations on fuel oil availability added.

The revised measures are expected to have a significant beneficial impact on the atmospheric environment and on human health, particularly for those people living in port cities and coastal communities.

Emissions from Sea-bed Mineral Activities
Emissions directly arising from the exploration, exploitation and associated offshore processing of sea-bed mineral resources are, exempt from the provisions of this Annex. Such emissions include the following:

- Emissions resulting from the incineration of substances that are solely and directly the result of exploration, exploitation and associated offshore processing of sea-bed mineral resources, including but not limited to the flaring of hydrocarbons and the burning of cuttings, muds, and/or stimulation fluids during well completion and testing operations, and flaring arising from upset conditions;
- The release of gases and volatile compounds entrained in drilling fluids and cuttings;
- Emissions associated solely and directly with the treatment, handling, of storage of sea-bed minerals; and
- Emissions from marine diesel engines that solely dedicated to the exploration, exploitation and associated offshore processing of sea-bed mineral resources.

Equivalents (regulation 4)

- The Administration of a Party may allow any fitting, material, appliance of apparatus to be fitted in a ship or other procedures, alternative fuel oils, of compliance methods used as an alternative to that required by Annex VI if such fitting, material, appliance or apparatus of other procedures, alternative fuel oils, or compliance methods are at least as effective in terms of emissions reductions as that required by this Annex, including any of the standards set forth in regulations 13 and 14 (NOX SOx and Particulate Matter).
- The Administration of a Party which allows a fitting, material, appliance of apparatus or other procedures, alternative fuel oils, or compliance methods used as an alternative to that required by this Annex shall communicate to the Organization for circulation to the Parties particulars thereof, for their information and appropriate action, if any.
- The Administration of a Party should take into account any relevant guidelines developed by the Organization pertaining to the equivalents provided for in this regulation.
- The Administration of a Party which allows the use of an equivalent as set forth in paragraph 1 of this regulation shall endeavour not to impair or damage its environment, human health, property, of resources or those of other States.

Nitrogen Oxides (NOx) (Regulation 13)

Application

This regulation shall apply to each marine diesel engine with a power output of more than 130 kW installed on a ship.

Emission of nitrogen oxides (Tier III)

- 3,4 g/kWh when n is less than 130 rpm; [3]
- 9 . n(-0,2) g/kWh when n is 130 or more but less than 2,000 rpm;
- 2,0 g/kWh when n is 2,000 rpm or more.

Emission Control Area's

For the purpose of this regulation, an Emission Control Area shall be any sea area, including any port area, designated by the Organization.

Sulphur Oxides (SOx) and Particulate Matter (regulation 14)

- 3,50% m/m on and after 1 January 2012; [4]
- 0,50% m/m on and after 1 January 2020.

When ships are operating within an Emission Control Area, the sulphur content of fuel oil used on board ships shall not exceed the following limit:

0.10% m/m on and after 1 January 2015

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[3] n = rated engine speed or crankshaft revolutions per minute

[4] m/m = the mass fraction = mass component/mass mixture

Fuel Oil Availability (Regulation 18)

- Each party shall take all reasonable steps to promote the availability of fuel oils which comply with this Annex and inform the Organization of the availability of compliant fuel oils in its ports and terminals.
- A ship shall notify its Administration and the competent authority of the relevant port of destination when it cannot purchase compliant fuel oil.
- A party shall notify the Organization when a ship has presented evidence of the non-availability of compliant fuel oil.

Fuel Oil Quality (Regulation 18)

Fuel oil for combustion purposes derived by methods other than petroleum refining shall not:

- exceed the applicable sulphur content set forth in regulation 14 of this Annex;
- cause an engine to exceed the applicable NOx emission limit set forth in Tier III in regulation 13;
- contain inorganic acid;
- jeopardize the safety of ships or adversely affect the performance of the machinery, or be harmful to personnel, or contribute overall to additional air pollution.

This regulation does not apply to coal in its solid form or nuclear fuels.
<u>Paragraphs with a * of this regulation do not apply to gas fuels such as liquefied Natural Gas, Compressed Natural Gas or Liquefied Petroleum Gas.</u> The sulphur content of gas fuels delivered to a ship specifically for combustion purposes on board that ship shall be documented by the supplier.

* For each ship subject to regulations 5 and 6 of this Annex, details of fuel oil for combustion purposes delivered to and used on board shall be recorded by means of a bunker delivery note which shall contain at least the following information:

- Name and IMO number of receiving ship
- Port
- Date of commencement of delivery
- Name, address, and telephone number of marine fuel oil supplier
- Product name(s)
- Quantity in metric tons
- Density at 15°C, kg/metric tons
- Sulphur content (%m/m)
- A declaration signed and certified by the fuel oil supplier's reseprentative that the fuel oil supplied is in confirmity with the regulation 14 of this Annex.

* The bunker delivery note shall be kept on board the ship in such a place as to be readily available for inspection at all reasonable times. It shall be retained for a period of three years after the fuel oil has been delivered on board.

* the bunker delivery note shall be accompanied by a representative sample of the fuel oil delivered taking into account guidelines developed by the Organization. The sample is to be sealed and signed by the supplier's representative and the master or officer in charge of the bunker operation on completion of bunkering operations and retained under the ship's control until the fuel oil is substantially consumed, but in any case for a period of not less than 12 months from the time of delivery.

in connection with port State inspections carried out by Parties, the Parties further undertake to:

1. Inform the Party or non-Party under whose jurisdiction a bunker delivery note was issued of cases of delivery of noncompliant fuel oil, giving all relevant information; and
2. Ensure that remedial action as appropriate is taken to bring noncompliant fuel oil discovered into compliance.

Interview with Sander van de Laar

Is GTL fuel not expensive compared with the current fuels?
In comparison with Heavy Fuel Oil it is, but when the legislation for the emission becomes too strict so HFO cannot be used anymore as a fuel, then GTL fuel would be a good alternative and not much more expensive compared with regular fuels.

Is it possible to blend GTL fuel with Marine Diesel Oil?
Yes it is, GTL fuel can be blended with other diesel fuels but only if the base product has the EN590 standard.

What is the ratio to blend MDO with GTL fuel?
GTL is made to reduce the local emissions of NO_X and particulate matter. So it comes down that how purer a diesel engine runs on GTL, the better it is for the environment because of the lower emission values.

Can GTL also be blended with HFO?
It is possible when the base product has the EN590 standard, but why would you blend a relative expensive product with HFO while it has almost no advantages?

Most times shipping companies do not want to change to GTL, the reason for this is actually always the price. Would it be possible to reduce the price of GTL?
The product is a bit more expensive but it gives other advantages. For example, there is a shipping company with 24 rivercruiseships , four of these vessels are now sailing on GTL. The most important reason for this is that GTL cannot be smelled. This is very nice for the people who, for example, sit in a Jacuzzi so that they are not always getting smoke over them. So GTL would be well applicable in the global shipping on cruise ships or superyachts.

Is the market still too careful with the use of GTL?
It depends on it, the biggest problem with GTL is that it still does not meet with the EN590 standard. It fully complies with the requirements of EN590 except with the density. The product is slightly lighter than diesel. We are now very busy to get approval from manufacturers like MTU, Wärtsilä and Volvo. The hard thing is that you lose your warranty, because it is in principle an experimental fuel. However, a new standard is in the making this is the EN15940 standard. This is a standard for paraffinic fuels and vegetable oils. When this standard is adapted it will be easier for fabricants to give permission, because they then know what the specification of the product is.

So it is only a matter of time that there is switched to GTL?
The problem is there are no environmental requirements for larger vessels. A stage 5 standard would come in 2017/2018 but this is only not for the bigger vessels. So there is no need to change and if the legislation is adapted, which will become in 2020, then the need for changing to a more environmental friendly fuel is there. In global shipping will GTL come forward when HFO cannot be used anymore according to the legislation.

Leads the use of GTL to less wear to the engine?
Yes, that is what we think. The lubrication oil stays longer in condition. In the future engines will also get after-treatment equipment. For example, we see that the load of the soot filter with GTL is much lower than the load of the soot filter with diesel. An example is a bus, the average speed of a bus in the city is very low. On this way the soot filter generating process does not get into motion. The result is that the bus now and then has to stop and has to increase idling to scarf the filter. Hereby 8 to 12 litre diesel is blown into the exhaust to scarf the filter. With GTL this will be hardly necessary. At this point we see cost reduction.

So no adjustments to the engine are needed to use this fuel?
You do not need, for example after-treatment equipment to reduce emission, because the emission is already considerable lower by the use of GTL. However, the problem is that the industry does not know where they should work towards as long as there are no standards.

Is with the use of GTL still the need of a pilot fuel?
No, there is not. When a diesel engine is started it could only be done on GTL, so there will be no need of a pilot fuel anymore.

Are there more points of motivation for global shipping to switch to GTL?
The biggest step is the sustainability of the fleet. It still has to be proven for slow-running engines that GTL results in a reduction of maintenance. We claim a reduction of 15% on NO_X and 30% on particulate matter. GTL has also a noise reduction of 3 dB, it has a longer expiration date than diesel and it has no summer and winter quality while diesel does.

Gasoil vs Shell GTL Fuel Marine Comparison (based on field results)

Engine	Cat 3512B	Cat 3512B DITA	Cat 3512B DITA	Deutz RBV 6M 545	Cat C18	Stork DRO216K	Cummins KTA 50	Cat 3508 DITA	Wartsila 8L20
Rated Speed [rpm]	1600	1600	1600	380	357	441	932	714	1000
Rated Power [kW]	1014	1119	1119	596	1800	750	1800	1800	1440
Gasoil									
NOx [gr/kWh]	5,47	9,24	5,53	12,98	9,53	7,22	12,74		11,26
CO2 [gr/kWh]	635,96	641,03	658,32	680,80		741,30	650,50		497,60
CO [gr/kWh]	0,59	0,73	0,91	0,28		0,48	3,56		0,36
HC [gr/kWh]	0,17	0,16	0,15	n/a					0,38
PM [gr/kWh]	0,23	0,09	0,09	n/a					0,11
SFC [gr/kWh]	202,13	204,30	213,90	217,61	202,70	235,73	208,80		195,90
Shell GTL Fuel Marine									
NOx [gr/kWh]	4,85	8,39	4,81	7,42	7,14			10,84	8,84
CO2 [gr/kWh]	608,32	608,14	621,77	622,04	605,48			591,20	
CO [gr/kWh]	0,52	0,66	0,85	0,35	0,70			1,38	
HC [gr/kWh]	0,12	0,13	0,14	n/a	0,07				
PM [gr/kWh]	0,11	0,06	0,08	0,24	0,24				
SFC [gr/kWh]	197,08	200,00	209,50	200,60	196,60	215,18		192,65	183,16
Differences [%]									
NOx	-11,3%	-9,2%	-13,0%	-42,8%	-25,1%				-21,5%
CO2	-4,3%	-5,1%	-5,6%	-8,6%					
CO	-11,9%	-9,6%	-6,6%	25,0%					
HC	-29,4%	-18,8%	-6,7%						
PM	-52,2%	-33,3%	-11,1%						
SFC	-2,5%	-2,1%	-2,1%	-7,8%	-3,0%	-8,7%			-6,5%