Future fuel for worldwide tanker shipping in spot market

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Abstract

Ship exhausts contain high levels of sulphur oxides, nitrogen oxides, carbon dioxide and particles due to the heavy fuel oil, HFO, used for combustion and the combustion characteristics of the engine. As a result of upcoming stricter regulations for shipping pollution, as well as growing attention to greenhouse gas emissions, air pollution and uncertainty of future petroleum oil supply, a shift towards a cleaner burning fuel is needed.

This work explores potential alternative fuels, both conventional and unconventional, and abatement technologies, to be used by tankers in the worldwide spot market to comply with upcoming environmental regulations in the near and coming future. As a reference the product tanker M/T Gotland Marieann is used and recommendations for which fuel that shall be used by the reference ship in 2015 and 2020 are presented.

The environmental assessment and evaluation of the fuels are done from a life cycle perspective using results from Life Cycle Assessment, LCA, studies.

This study illustrates that, of the various alternatives, methanol appears to be the best candidate for long-term, widespread replacement of petroleum-based fuels within tanker shipping. It does not emit any sulphur oxides nor particles and the nitrogen oxides are shown to be lower than those of marine gas oil, MGO. The global warming potential of the natural gas produced methanol is not lower than that of MGO, but when gradually switching to bio-methanol the greenhouse gas emissions are decreasing and with methanol the vision of a carbon free society can be reached.

For 2015 a switch towards methanol is not seen as realistic. Further research and establishment of regulations and distribution systems are needed, however there are indications that a shift will be possible sometime between 2015 and 2020. For 2015 a shift towards MGO is suggested as it involves low investment costs and there is no need for infrastructure changes. As MGO is more expensive than methanol, a shift is preferable as soon as the market, technology and infrastructure are ready.

Keywords: marine fuels, environmental impact, shipping pollution, heavy fuel oil, marine gas oil, methanol
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Abbreviations and acronyms

CaCO$_3$   Calcium carbonate
CaSO$_4$   Calcium sulphate
CH$_2$O   Formaldehyde
CH$_3$OH   Methanol
CH$_4$    Methane
CI     Compression ignition
CO    Carbon monoxide
CO$_2$ Carbon dioxide
DME   Dimethyl ether
ECA   Emission control area
EGR   Exhaust gas recirculation
EEDI Energy Efficiency Design Index
EU European Union
GWP Global warming potential
HFO   Heavy Fuel Oil
IACS International Association of Classification Societies
ICE Internal combustion engine
ICS International Chamber of Shipping
IEA International Energy Agency
IEEC International Energy Efficiency Certificate
IFO   Intermediate Fuel Oil
IMO International Maritime Organisation
LBG   Liquefied bio gas
LCA   Life cycle assessment
LHV   Lower heating value
LNG   Liquefied natural gas
LPG   Liquefied petroleum gas
LSHFO Low sulphur heavy fuel oil
MARPOL International convention on the prevention of pollution from ships
MCR Maximum continuous rating
MDO Marine diesel oil
MGO Marine gas oil
NaOH Caustic soda
NECA NO$_X$ Emission Control Area
NO Nitrogen monoxide
NO$_2$ Nitrogen dioxide
NO$_X$ Nitrogen oxides
PM Particulate matter
RME Rapeseed methyl ether
SCR Selective Catalytic Reduction
SECA Sulphur Emission Control Areas
SEEMP Ship Energy Efficiency Management Plan
SO$_2$ Sulphur dioxide
SO$_X$ Sulphur oxides
WCED The World Commission on Environment and Development
### Terminology

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>Spot market</td>
<td>Instant contract based market</td>
</tr>
<tr>
<td>Sustainability</td>
<td>Meet the needs of the present without compromising the ability of future generations to meet their own needs. Requires preserving the environment and that human activity only uses nature’s resources at a rate at which they can be replaced naturally.</td>
</tr>
</tbody>
</table>

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1. As defined by The World Commission on Environment and Development in 1987
PART I

BACKGROUND
CHAPTER 1

INTRODUCTION

The most widely used fuel within tanker shipping today is heavy fuel oil, which has been used as the main fuel since the 1960s. Traditionally low quality fuels with high sulphur contents have been used, but as stricter regulations enter into force shifts to cleaner fuels are required. The use of scrubbers to reduce the sulphur content in the exhaust gases will still be allowed, but is not a complete solution. Other driving forces for a fuel change are uncertainty of future oil supply, as well as increased attention to greenhouse gas emissions.

From January 2015 the sulphur content allowed in SECA, sulphur emission control area, will decrease from 1.0% to 0.1%, which requires a change to a low sulphur fuel for all vessels entering the SECA. Globally the highest allowed sulphur content will be reduced from 3.5% to 0.5% from 2020 or at the latest 2025 depending on availability of alternative low sulphur fuel on the market 2018.

Since 1 January 2010 the sulphur content of marine fuels used by ships on inland waterways and at berth within the European Union, is limited to 0.1% by mass. Therefore the fuel used in auxiliary engines is low sulphur marine gas oil or ultra low sulphur heavy fuel oil with sulphur content of less than 0.05%, depending on local regulations.

For some time now large ferries on the Baltic Sea have used heavy fuel oil with sulphur content of no more than 0.5%, but globally there is only about 0.5% of the marine fuels used that is heavy fuel oil with as low sulphur content as 0.5%. Today there is not enough of this low sulphur fuel oil on the market for everyone to shift to it and it is unclear whether the situation will be changed in the future. If the refineries are to increase the production capacity there are indications that they will invest in the more profitable diesel production instead of desulphurisation facilities for heavy fuel oil. A likely scenario is that LSHFO with sulphur content 1%, will be mixed with MGO to obtain a fuel with 0.5% sulphur. However, as the global sulphur limit falls to 0.5%, a more preferable solution is to abandon the use of heavy fuel oil and switch to an alternative fuel.

In line with reducing emissions and improving efficiency, IMO imposes mandatory energy efficiency measures for international shipping from 1 January 2013. New tankers will be obliged to comply with a specified Energy Efficient Design Index, EEDI, and old tankers with a Ship Energy Efficiency Management Plan, SEEMP. In the future the EEDI regulations for new ships will be more stringent, which means that there will be a new generation of fuel-efficient and environmentally friendly vessels on the market. That means for example that a ship built in 2012 in 8 years time will compete with ships built 2020 having 20% better energy efficiency.

For new buildings it is possible to reduce the energy consumption through optimising the design of the ship, such as improving hull shape, bow bulbs, rudders, propellers as well as engine efficiency. For existing ships the ways to reduce energy consumption are less, wherefore alternative energy sources
with lower carbon emissions must be used for reducing the negative effects on the environment. When switching to an alternative fuel it is important to make sure that other environmental impacts are not higher than those of the fuel used today, even though some environmental tradeoffs are inevitable.

The big issue is to reduce emissions of sulphur oxides in order to comply with the stricter regulations. Moreover it is desirable to reduce the greenhouse gas emissions and nitrogen oxides emissions as future regulations are expected. Apart from that it is also important to reduce the emissions of particulate matter, since serious concerns about the negative health effects have been arisen and regulations may be expected in the future.

1.1 Current fuel situation

The most commonly used fuel within tanker shipping today is heavy fuel oil. Economically it has advantage, but since it is a residue of oil refining it has high contents of sulphur and other harmful substances. The lower the sulphur content of the fuel, the higher the price. Usually as low fuel costs as possible are desirable and generally the fuel with the highest allowed sulphur content is used. Tankers use mainly two types of fuel and that is so-called HFO and LSHFO. IFO380 is the most common HFO. LSHFO is low sulphur heavy fuel oil with sulphur content less than 1% and is what now is used within SECA.

When at berth in EU harbours the regulations are stricter, thus the auxiliary engines operate on marine gas oil, MGO, which is a distillate fuel. MGO has better quality than marine diesel oil, MDO, and is similar to the diesel used in cars but with better lubricity. The fuel supply of MDO is limited and nowadays MGO is what is mainly used.

1.2 Aims and objectives

The purpose with this master thesis is to investigate fuels that are possible to use in worldwide tanker shipping in the spot market in the near and coming future. The aim is to examine which fuel that shall be used in order to meet the upcoming environmental requirements. As a reference the product tanker M/T Gotland Marieann is used and the data of the reference ship is shown in Appendix 1. The fuel consumers of the reference ship are the main engine, the auxiliary engines, the steam boiler and the inert gas generator. A recommendation on which fuel that shall be used by the reference ship in 2015 and 2020 shall be presented. Three main questions have been assessed in this thesis:

1. Which fuel, that fulfils the requirements, has the highest potential of being environmentally friendly, sustainable and economically competitive?

2. Is there any such alternative fuel on the market today that can be used, and if not, what is needed for a fuel shift?

3. What will the consequences for the reference ship be for such a fuel shift?

Further comparisons of the energy efficiency and profitability of the alternative fuel and heavy fuel oil shall be made and the following aspects are to be examined:
• Fuel supply in remote places
• Ship design aspects such as fuel requiring more space or location, interfering with cargo space or stability aspects
• Impact on safety on-board
• Crew and operational change
• Engine technique requiring engine retrofit or unconventional fuel handling
• Investment cost if conversion is required
• Fuel price, especially if not worldwide market
• Bunker management
• Possibility of dual fuel engine
• Fuel vs. food, company social responsibility perspective

1.3 Methodology and environmental assessment

There are a wide range of environmental assessment tools that can be used for evaluation of different fuels and technology options. A well established tool is LCA, Life Cycle Assessment, which assesses potential environmental impacts from a cradle-to-grave perspective. In order to be able to compare different fuels and technologies the same system boundaries have to be used. In this report results from existing well-to-wheel analyses are compared.

In most cases LCA analyses for marine fuels are used, but for some fuels there are not yet any studies specifically for shipping available. Therefore studies exploring alternative fuel chains for road fuels are used in addition, as much data from these studies can be used to evaluate shipping fuels.

1.4 Outline of the thesis

In the first part of this report the emissions and environmental problems are described and the regulations of exhaust emissions for marine transportation are explained. In the next section a wide range of different potential fuels and abatement technologies are studied. This is followed by evaluation of the different alternatives and recommendations on which fuels that shall be used by tankers in 2015 and 2020 are stated. In the last part of the report the consequences of the recommended fuel shifts for the reference ship are described, followed by conclusions, discussion and suggestions for future studies.
CHAPTER 2

EMISSIONS AND ENVIRONMENTAL PROBLEMS

Over the past 50 years the ever increasing population and unsustainable habits have increased environmental pressures dramatically in many ways. The world is experiencing a global crisis and is facing grand challenges to make a transformation to global sustainability. A turning point is reached and a mind-shift is needed.

The main environmental challenges are to combat global warming, preserve the ozone layer and to deal with acid rain. It is also important to maintain a healthy environment by controlling the level of harmful particles in the exhaust gases.

2.1 \( \text{SO}_X \) emissions

Sulphur oxides, \( \text{SO}_X \), are formed when sulphur in the fuel reacts with oxygen in the air. The prime constituent of \( \text{SO}_X \) formed in marine engines is sulphur dioxide, \( \text{SO}_2 \). The amount of \( \text{SO}_X \) emissions are directly proportional to the sulphur content in the fuel.

Sulphur oxides give rise to acid rain when reacting with water in the atmosphere. The acid rain contributes heavily to the acidification of lakes and forests, which among other things leads to death of fish, dehydration of leaves and damaged nutrition systems of plants. Acid rain is also corrosive to many materials and damages buildings and constructions.

2.2 \( \text{NO}_X \) emissions

For the amount of nitrogen oxides, \( \text{NO}_X \), produced the fuel properties only have a minor influence. Oxides of nitrogen, nitrogen dioxide (\( \text{NO}_2 \)) and nitrogen monoxide (\( \text{NO} \)), are formed during the high temperature combustion process due to a reaction between atmospheric nitrogen and oxygen in the combustion chamber. Only a small part originates from nitrogen in the fuel. The diesel combustion process generally produces relatively high levels of \( \text{NO}_X \). Typical \( \text{NO}_X \) emissions from large two-stroke engines are 17g/kWh without catalyst (Cooper et al., 2004).

Like sulphur oxides, nitrogen oxides give rise to acid rain when reacting with water in the atmosphere. Nitrogen oxides also contributes to eutrophication and photochemical ozone as well as affecting human health. Approximately 15% of the total anthropogenic emissions of \( \text{NO}_X \) are estimated to originate from shipping (Eyring et al., 2010).
2.3 Greenhouse gas emissions

The emissions of greenhouse gases, such as carbon dioxide and methane, contribute to the increased greenhouse effect, causing global warming. Ships transport 85% of the world’s goods and shipping burns approximately 335 million tonnes of fuel per year (Hjortberg, 2012). The associated emission of CO\(_2\) is around 1 billion tonnes of CO\(_2\) per year, and the emissions from shipping are expected to continue to rise, due to sector growth. As a comparison the total CO\(_2\) emissions from fuel combustion is around 30 billion tonnes per year (IEA, 2012).

According to the World Bank (2012), the world is likely to warm between 3.5 and 4°C during this century. The consequences of such a global warming are devastating and may lead to inundation of coastal cities; increasing risks for food production potentially leading to higher malnutrition rates; many dry regions becoming dryer, wet regions wetter; unprecedented heat waves in many regions, especially in the tropics; substantially exacerbated water scarcity in many regions; increased frequency of high-intensity tropical cyclones; and irreversible loss of biodiversity, including coral reef systems etc.

Most coral reefs are at risk unless climate change is drastically limited and even a 2°C warming, which is commonly perceived as safe, will have an effect and most coral reefs are expected to die (Frieler et al., 2012). Also the Arctic ice is melting much faster than believed in 2007 and can be ice-free during the summers in 30 years (Wang, et al., 2009). According to Solomon et al., 2009, the temperature changes, sea level rise and changes in precipitation are irreversible in a 1000-year perspective due to the greenhouse gas emissions.

During the United Nations Framework Convention on Climate Change conference in Cancun in 2010 an agreement was made that countries should take urgent action to limit the increase in global average temperature to less than 2°C relative to pre-industrial levels. If this is to be achieved with “moderate” certainty (greater than 66%), a peak in emissions has to be reached in this decade, and fall below 2010 levels by 2020 (Rogelj et al., 2011).

2.4 Particulate matter

Particulates are usually divided into primary and secondary particles. Primary particles result mainly from incomplete combustion of the fuel and from ash, while secondary particles are formed in the atmosphere when SO\(_X\) and NO\(_X\) create sulphate and nitrate aerosols, and by coagulation and condensation of vapours. The main concern about emissions of particles is the impact on human health, and long-term exposure to fine particles has been shown to increase the risk for premature mortality. According to Corbett et al. (2007), 3-5% of global mortalities caused by fine particles are attributed to marine transportation.

Emissions of particles from ships engines depend on the fuel type. According to a study by Winnes et al. (2009), where emission measurements of MGO and HFO were carried out on a product tanker, the average emissions of particles vary between 0.18 and 0.48 g/kWh for MGO and 0.56-2.12 g/kWh for HFO.
CHAPTER 3

REGULATIONS OF EXHAUST EMISSIONS FROM MARINE TRANSPORTATION

The main international convention regulating pollution from shipping is MARPOL 73/78, which was first adopted by the IMO in 1973. It includes six technical annexes and the latest one, Annex VI - 'Regulations for the Prevention of Air Pollution from Ships', entered into force in May 2005. It regulates ship exhaust emissions of sulphur oxides, nitrogen oxides and ozone-depleting substances (IMO, 2006). In July 2011 it also adopted mandatory measures to reduce greenhouse gases (IMO, 2011).

3.1 \( \text{SO}_X \) regulations and emission control areas

From 1 January 2012 the global maximum allowed sulphur content is 3.5% in fuel. It is planned to be reduced to 0.5% in 2020, depending on the outcome of a review of the availability of low sulphur fuel that is to be made in 2018. If it turns out that there is not enough low sulphur fuel on the market, the implementation of the stricter regulation may be postponed to 2025. Within certain geographical areas stricter regulations apply and these are stepwise to become even more stringent as well as the areas included are extended.

Currently the European sulphur emission control area, SECA, includes the Baltic Sea, the North Sea and the English Channel. From 1 July 2010 the sulphur limit in this area is 1% and it will be reduced to 0.1% 2015. From 1 August 2012 a 200 nautical mile area around the East and West Coast of the North American continent was included in SECA, known as the North American ECA, however Canada postponed the enforcement to 1 November 2012. The sulphur limits within these areas follow the same levels as the European SECA. Proposed new SECAs are the Mediterranean, Japan, South Korea and around Australia. Figure 3.1 shows the MARPOL Annex VI sulphur limits and Figure 3.2 shows the current SECAs and the ones under consideration.

There are also regional regulations related to the use of marine fuels in, for instance, Europe and the United States. From 1 January 2010 the maximum sulphur content of marine fuels used by ships at berth and on inland waterways within the European Union is 0.1%. California Air Resources Board, CARB, has from 1 January 2012 imposed a limit of 0.1% sulphur content of all marine fuel used by all machinery within 24 nautical miles from the coastline of California.
A compilation of the different sulphur regulations, the areas and the dates of enforcement is shown in Table 3.1.
### Table 3.1: Sulphur regulations

<table>
<thead>
<tr>
<th>Date</th>
<th>Ship type</th>
<th>Area</th>
<th>Sulphur %</th>
<th>Regulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010-01-01</td>
<td>All</td>
<td>All EU ports and inland waterways</td>
<td>0.1</td>
<td>EU</td>
</tr>
<tr>
<td>2010-07-01</td>
<td>All</td>
<td>SECA</td>
<td>1</td>
<td>MARPOL</td>
</tr>
<tr>
<td>2012-01-01</td>
<td>All</td>
<td>California’s territorial waters</td>
<td>0.1</td>
<td>CARB</td>
</tr>
<tr>
<td>2012-01-01</td>
<td>16 greek ferries</td>
<td>Greek ports</td>
<td>0.1</td>
<td>EU</td>
</tr>
<tr>
<td>2012-01-01</td>
<td>All</td>
<td>Global</td>
<td>3.5</td>
<td>MARPOL</td>
</tr>
<tr>
<td>2012-08-01</td>
<td>All</td>
<td>North American ECA</td>
<td>1</td>
<td>MARPOL</td>
</tr>
<tr>
<td>2015-07-01</td>
<td>All</td>
<td>SECA</td>
<td>0.1</td>
<td>MARPOL</td>
</tr>
<tr>
<td>2020 / 2025</td>
<td>All</td>
<td>Global</td>
<td>0.5</td>
<td>MARPOL</td>
</tr>
</tbody>
</table>

3.2 NOX regulations

The emissions of NO\(_X\) allowed in MARPOL Annex VI regulations depend on the engine speed as shown in Figure 3.1. The engine speed of the reference ship is 124rpm. For engines produced after year 2000 at least Tier I standards must be fulfilled and for engines produced after 2011, Tier II standard applies, which corresponds to a reduction of NO\(_X\) emissions by approximately 20%. For ships having keel laying after 1 January 2016, Tier III will apply when operating within a NO\(_X\) Emission Control Area, NECA, which corresponds to a 80% reduction compared to Tier I standards. Currently the only NECA adopted is the North American ECA, which was enforced 1 August 2012. A request of designation of the Caribbean coasts as NECA has been submitted to IMO and The North Sea and Baltic Sea countries are currently investigating the impacts of the designation of their seas as NECAs (IMO 2011).

![Figure 3.3: MARPOL Annex VI NO\(_X\) emission limits](image)

3.3 Regulations of greenhouse gas emissions and EEDI

Greenhouse gas emissions from shipping are not regulated by the Kyoto Protocol, and instead the responsibility is delegated to IMO. According to Buhaug et al. (2009), the absence of global policies to control greenhouse gas emissions from international shipping, may lead to an increase of the
emissions by 220%-310% by year 2050, compared to 2007 years emissions. The reasons are due to expected growth in international seaborne trade. To prevent this trend a decision to impose mandatory measures of the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), was taken by the IMO in July 2011.

The EEDI is intended to set a minimum requirement for fuel energy efficiency for new ships and enable comparisons of similar vessels. “New ship” means a ship for which a building contract is placed on or after 1 January 2013, or the keel of which is laid or which is at a similar stage of construction on or after 1 July 2013, or the delivery of which is on or after 1 July 2015. If a major conversion of an existing ship is done, such as alteration of dimensions or engine power, it is considered as a “new ship” and applicable to EEDI (Bergholtz, 2012).

The SEEMP incorporates best practices for the fuel efficient operation of existing ships, such as improved voyage planning, speed management and hull maintenance, and shall be verified on board and an International Energy Efficiency Certificate (IEEC) shall be issued. These measures are intended to significantly reduce fuel consumption and thus reduce greenhouse gas emissions. The International Chamber of Shipping (ICS), is confident that through technical and operational measures, that will deliver improved energy efficiency, will lead to reductions of the CO₂ emissions per tonne-kilometre from shipping by more than 20% by year 2020 compared to 2007 baseline.

Comment: A consequence of the imposition of the EEDI is the risk for underpowered ships. An IACS proposal about guidelines for minimum propulsion power in adverse weather is subject to MSC 91, the ninety-first session of IMO’s Maritime Safety Committee, endorsement 26-30 November 2012, as well as guidelines for speed and power trials are under development. The EEDI-regulations are yet not finalised and significant work is still required to determine the appropriate EEDI calculation for a number of specialist ship types.

### 3.4 Regulations of particulate matter

Particulate matter is regulated under MARPOL 73/78 Annex VI together with sulphur, although there are actually yet no specific limit for fine particles. However, lowering the sulphur content of fuel linearly affects the mass volume of particles, as does lowering its ash contents (Kalli et al., 2009).
PART II

POTENTIAL FUELS AND EXHAUST ABATEMENT TECHNOLOGIES
Chapter 4

Fossil Fuels

Fossil fuels are mixtures of hydrocarbons that when combusted form carbon dioxide, CO$_2$, and water, H$_2$O. They are formed by natural processes, usually during millions of years, and are not renewable within the human timescale. Fortunately there are still significant worldwide resources left and they will not end in the near future, but become scarcer, more difficult to extract and more expensive (Olah et al, 2009). It is projected that if the consumption continues at the 2006 rates, the oil reserves will last for another 40 years, the natural gas resources another 70 years and the more plentiful coal may last for another 200 years (Shafiee et al, 2009). There are however various assessments of the amount of resources left and because of the ever increasing population of the world, these predictions are nothing else than estimates, but important are that these resources must be considered as finite. The most common fossil fuels are petroleum oil, natural gas, coals, tar-sands and shale bitumen. In this chapter potential marine fuels based on oil, natural gas and coals will be scrutinised.

4.1 Petroleum oil

4.1.1 Introduction to the world of petroleum oil

Crude oil is formed by the degradation of organic materials, which settled on the seafloor many millions of years ago. It is a mixture of different hydrocarbons and small amount of impurities. Depending on the origin, different crudes have different properties and contain different amount of undesirable elements such as sulphur, nitrogen, water and sediment. Different crudes may also yield differing quantities of finished products. For the crude oil to be used, it must be processed in a refinery to separate out individual finished products including petrol, diesel, heating oil, jet and residual fuel. Generally the higher up in the fractionating tower the lower the viscosity and the less impurities, such as sulphur, and the lower the viscosity the higher the price. The sulphur content lowers the energy content by replacing the hydrocarbons with sulphur molecules. A simplified fractionating column is shown in Figure 4.1.
4.1.2 Fuel oil

The most common marine fuel today is heavy fuel oil, which is a residual fuel taken from the bottom of the barrel remaining after the production of more profitable fuels such as petrol and middle distillates. It is seen as an undesirable fuel, since it is sludgy with high sulphur content and it is highly viscous, thus requiring heating in order to pump through the systems. It is burnt in low speed compression ignition engines, which means that no spark is needed for the fuel to ignite (Downey, 2009).

There are several types of fuel oils with different properties, such as viscosity. The most common one is IFO380, which also sometimes is referred to as Bunker C and is the presently used fuel of the reference ship Gotland Marieann. IFO stands for “intermediate fuel oil”, which means that it may contain up to 6-7% of middle distillates. The IFOs are categorised after their viscosity, thus the viscosity of IFO380 is 380cSt at 50°C. Currently both high sulphur fuel oil and low sulphur fuel oil are used depending on the regulations. The average sulphur content of fuel oil is 2.7% and the low sulphur fuel oil contain less than 1% sulphur. Per kilo heavy fuel oil combusted 3.228kg carbon dioxide is released. The total fuel consumption of Gotland Marieann is approximately 40 tonnes per day at sea, which equals a release of 130 tonnes CO₂ per day.

4.1.3 Distillate

When heavy fuel oil has to be abandoned, the easiest is to switch to distillate fuels, such as MGO, within the restricted geographical areas. The energy density of MGO is slightly higher than the energy density of HFO, but the price per volume is about 50% higher. Bunker prices of IFO380 and MGO are shown in Appendix 2. It is desirable to use HFO in the areas where it is allowed, and switch to MGO when entering areas with the stricter requirements. The fuels can be used separately or blended in different proportions, however a switch from one pure fuel to another is not a straightforward procedure. There are some technical aspects that has to be overcome and switching time is required.

Distillate fuels are taken a bit higher in the fractioning column, while HFO is a residual oil taken from the bottom of the column. The fuels have many different properties, but they are also similar.
in many ways, wherefore engines can be constructed for being run effectively on both fuels. One of 
the main property differences is the operation temperature of the different fuels. IFO380 has to be 
heated to about 120-135°C to obtain the suitable viscosity of approx. 15cST, while MGO has the 
required properties at room temperature and does not need preheating. If switching from HFO to 
MGO too quickly there is a risk that the system is not cool enough causing the MGO to evaporate. 
The fuel cannot be pumped into the cylinders and the engine stops (Mikkelsen et al, 2010).

Distillates, as the name implies, are in gaseous form when taken from the fractionating columns, 
and are therefore a relatively clean fuel and there is no need for purification before injection in the 
engine. When switching to MGO from HFO there is likely that the MGO dissolves sediment from 
the HFO, that remains in the fuel system and the engine, causing the fuel oil filters to clog. This 
will however just be a problem the first time if switching continuously between the different fuels, 
but can be problematic for ships having long turns outside the emission control areas.

Worldwide the maximum allowed sulphur content of MGO is 1.5% by mass according to ISO 
8217:2012. From 1 January 2008 the maximum allowed sulphur content of MGO used within the EU 
territory is 0.1% by mass. When bunkering MGO before entering the restricted areas it is therefore 
important to request low sulphur MGO and make sure that it actually is the right quality of the 
bunkered fuel.

It has been shown that a switch to distillate fuels will not decrease the greenhouse gas emissions in a 
life cycle perspective. There are reductions of CO₂ emissions during the operation due to higher ef-
ficiency, but this reduction is offset by the higher CO₂ emissions in the feedstock and fuel processing 
stages of the life cycle (Corbett et al., 2008). Therefore it can be seen, as there are no significant 
changes in CO₂ emissions between HFO and MGO on a total fuel life cycle.

4.2 Natural Gas

Like petroleum oil natural gas was formed by the degradation of organic materials for many millions 
of years ago. Depending on the depth at which the process occurred the biomass formed either oil 
or gas. Natural gas consists of a mixture of hydrocarbon gases and in its purest form it consists 
mostly of methane.

4.2.1 LNG - Liquefied Natural Gas

An alternative fuel for which the interest has increased around the world during the last two decades 
is LNG, Liquefied Natural Gas. It consists of a mixture of paraffin hydrocarbons such as methane, 
ethane, propane and butane, of which about 70-98% is methane, depending on its origin. Natural 
gas is converted to LNG when it is cooled down to -162°C and the volume is reduced by a factor of 
more than 600, thus easier to transport (Kumar, et al., 2011).

The use of LNG can significantly reduce the emissions of sulphur oxides, nitrogen oxides and particles. 
Several studies (e.g. Kumar, et al. 2011. Bengtsson, et al. 2011. Herdzik, J. 2011.) have shown 
that sulphur oxides are reduced almost 100%, nitrogen oxides almost 80% and particle emissions are 
reduced to near 99% compared to diesel fuels. This means that LNG complies with SECA 2015 and 
Tier III NOₓ requirements, without abatement technologies.

The role of LNG in greenhouse gas reduction in comparison to petroleum products have been studied 
by many researchers. According to Arteconi et al. (2010) the greenhouse gas emissions are 10-14% 
lower for LNG than petroleum equivalent. In a study by Graham et al. (2008) a variety of heavy-
duty vehicles and engines operating at different fuels were compared. The results showed that on a
whole life cycle perspective LNG could reduce greenhouse gas emissions at the tailpipe by 10-20% on a CO$_2$ equivalent basis compared to diesel fuel.

An important issue is that methane itself is a greenhouse gas with higher global warming potential than CO$_2$; 25 times higher in time horizon 100 years (Richter et al., 2011). This means that small leakages in the supply chain can have a large effect on the global warming potential. It is often argued that LNG reduces the CO$_2$ emissions by 25%, but the effect on greenhouse gas emissions is counteracted by possible methane slip. According to Bengtsson et al. (2011). LNG does not reduce the global warming potential by more than 8-20% and through a full life cycle perspective the reduction of greenhouse gas emissions, compared to other fossil fuels, are lower than expected.

LNG is at liquid only at cold temperatures, below -162°C, and requires new infrastructure in terms of terminals, bunker possibilities, new storage facilities on-board and engines. The diesel engines used today cannot be fuelled with LNG without conversion. Also the tanks need to be about 2.5 times bigger than the HFO tanks because of the smaller energy density and needed thermal shields. Currently the tanks need to be cylindrical, which may demand a 4 times bigger volume. Depending on the location of the tanks, worsened stability may be an important issue (Herdzik et al., 2011). For tankers the stability is not a problem, however the size of the tanks may involve remodelling of spaces on board.

On long-stays the fuel tanks must be emptied because of fuel vaporisation (Herdzik et al, 2011). Within the worldwide tanker shipping long stays are common and it is difficult to know beforehand how long a stay would be. For instance the reference ship Gotland Marieann stayed 62 days in Lagos, Nigeria, May-July 2012 and she has had several stays lasting 10 days, 15 days, 25 days etc.

Currently LNG is available at various ports in Europe, North America and Asia, and the infrastructure and supply are steadily developing, however the accessibility is limited in South America, Africa and Oceania (Djønne, 2011). Figure 4.2 shows the world availability of LNG as it was 2011-06-01.

![Figure 4.2: LNG availability 1 June 2011, (Djønne, 2011)](image-url)
4.3 Coal

Roughly 360 to 290 million years ago coal was formed from the anaerobic decomposition of then-living plants. Because of the lack of oxygen the plants only partially decayed resulting in a carbon-rich material that first became peat and then hardened into coal. This energy source was then buried for millions of years and coal is the most polluting fossil fuel compared to oil and gas, per unit energy released. It usually generate large amounts of CO₂ and emits significant levels of pollutants, especially sulphur dioxide, nitrogen oxides and particulates. Coal as a marine fuel is not looked into in this study, however fossil methanol produced from natural gas or coal is considered in Chapter 6 Alcohol based fuels.
**Chapter 5**

**Bio-fuels**

Biofuels are considered to be carbon neutral during their life cycle, since the carbon dioxide released during combustion of the fuel is the same as the carbon dioxide captured by the plant during its growth. Fossil fuels, on the other hand, release carbon dioxide that has been locked up for millions of years (Bengtsson et al., 2012).

Biofuels are categorised as first and second generation. The first generation biofuels are primarily produced from agricultural crops, which can compete with land and water used for food and fibre production. The most commonly used oils for biofuel production are made from soybean, sunflower, palm, rapeseed, canola, cottonseed and jatropha (Singh et al., 2010). As biofuel production expands forests and pristine lands are converted to cropland causing a loss of carbon dioxide capturing source. When this land-use change is taken into account there are varied assessments of the magnitude of the net greenhouse gas reduction. According to Havlik et al. (2011) biofuel expansion may increase deforestation drastically, which would create a carbon depth for more than 20 years. Furthermore deforestation causes massive biodiversity losses destroying the eco-systems (Klum et al, 2012).

The second-generation biofuels, sometimes called advanced biofuels, can, on the other hand, be produced from lingo-cellulosic materials such as forest residues, which may not compete with food production. It is argued that many of the problems concerned with first generation biofuels can be avoided with the second generation, even though they still face technical and economical challenges (Havlik et al, 2011). Second generation biofuels can be produced through gasification followed by Fischer-Tropsch synthesis. The Fischer-Tropsch process consists in a catalysed chemical reaction in which carbon monoxide and hydrogen are converted into liquid hydrocarbons of various forms. This technology is currently highly energy consuming, giving complex product mixtures and generating large amount of carbon dioxide and thereby contributing to global warming.

**5.1 Biodiesel**

An alternative to distillates is biodiesel, which also can be blended with the fossil MGO in any proportions (Moreira, 2009).

Biodiesel can be produced from numerous crops such as soybean, rapeseed, palm and jartropa. In terms of oil yield and production costs, the palm oil is superior, since it requires a smaller area of land to produce oil than other crops and it is the cheapest vegetable oil available on the market. It also has the highest fossil energy balance, energy produced over energy consumed (Jidon et al., 2009). The oil palms can however only grow close to the equator and according to the European Commission (SWD(2012) 343), biodiesel produced from palm oil has the highest greenhouse gas emissions among
major biofuels when deforestation and degradation of peatland are taken into account. According to Petrov (2010), the surface needed by different crops to produce 1 litre of biodiesel are:

- Soybean: 21.6m²
- Rapeseed: 8.01m²
- Palm: 1.62m²

Several studies about perspectives of the sustainability of biodiesel (e.g. Janaun, 2010; Havlik et al, 2011; Delucchi 2011) have been made and serious concerns about negative environmental impact of the use of first generation biofuels have been raised. Recently the European Commission have proposed new directives for the land-use in Europe, which will favour the production of biodiesel produced from feedstock that does not compete directly with food and feed crops (European Commission, 2012, MEMO/12/787). The production and processing costs of first generation biodiesel are high and have difficulties to compete with petroleum products without government subsidies. The environmental performance of first generation biodiesel is limited, as well as the production capacity (Sims et al., 2010). The new EU directives states that since first generation biofuels do not lead to substantial greenhouse gas savings, if land-use change is taken into account, they should not be subsidised after 2020 (European Commission, 2012, MEMO/12/787).

An environmental downside with biodiesel is that it can produce more NOₓ than MGO when burned, however the results from different studies vary (Downey, 2009). According to Cerne et al. (2008), the NOₓ emissions from rapeseed methyl ester (RME) showed to be 9% higher compared to a fossil diesel fuel, while the particle emissions were 38% lower than for diesel fuel. According to Petzold et al. (2011) there were no significant differences between the NOₓ emissions from MGO and four different vegetable oils. Also the particle emissions were shown to be of the same magnitude. The reason for these different results can be due to how the engines were adopted to the use of biofuels (Bengtsson et al., 2012). Today biodiesel can fulfil MARPOL Annex VI Tier II, but to comply with Tier III selective catalytic reduction, SCR, or exhaust gas recirculation, EGR, would be needed.

The main barriers for producing biodiesel are the amount of available agricultural land, the quantity of economically recoverable waste streams and the availability of proven and cost-effective conversion technology (Moreira, 2009). Yet, second generation biodiesel is not a real option, but as technology develops it might be a future opportunity for tanker shipping.

If switching to biodiesel the present infrastructure can be used and there is no need for large investments since no major change of engine technology is needed. Currently the price of biodiesel differs between countries depending on the amount of government subsidies. In some parts of the world biodiesel is cheaper than petroleum diesel, and in some parts it is more expensive. It is difficult to tell the future prices as the market develops and technology improves, but currently biodiesel is more costly than MGO. According to Sims et al. (2010) it is believed that the price of biodiesel will be above USD 0.8/litre of petroleum equivalent in the near and coming future.

Biomass is a limited resource and it has been argued that it should be used as efficiently as possible. According to a comparative study by Grahn et al. (2007), the biomass is more cost-effectively used for heat production than for transportation. However for shipping, a future shift towards biodiesel, or other biofuels, might be an option towards a decrease of the global warming potential (Bengtsson et al., 2012).
5.2 Biogas

Biogas can be produced through anaerobic digestion of biomass, which is a first generation biofuel, or from gasification of biomass followed by methanation, also called bio-methane, which is a second generation biofuel (Bengtsson et al., 2012).

When biomass is converted into biogas a large amount of energy is needed and the conversion efficiency varies between different feedstock. According to Bengtsson et al. (2012) the biofuel potential in 2050 is about 4-16·10^{19} J per year if an average conversion efficiency of 40% is assumed. However, in 2009 the biogas production in Europe was 3.5·10^{17} J, which can be compared to the global use of marine fuels of 14·10^{18} J in 2007 (Buhaug et al., 2009). Apart from the availability the price of biogas is more than 50% more expensive than that of natural gas (Bengtsson et al., 2012).

5.2.1 LBG - Liquefied Bio Gas

For the same reason as for using liquefied natural gas, that is easier transportation etc, instead of pressurised natural gas, biogas can be liquefied. In the marketing of LNG the possibility of switching to liquefied biogas, LBG, is one advantage that is put forward. LBG can be blended with LNG and if the production efficiency increases in the future it can be an alternative for ships running on LNG to mix LNG with LBG. As for LNG the lack of infrastructure in form of terminals, bunker possibilities, new storage facilities etc is still an obstacle.
CHAPTER 6

ALCOHOL BASED FUELS

6.1 Ethanol

A bio-fuel that already is produced on a fair scale worldwide is ethanol (14-26 Mtonne/year according to Hamelinck et al., 2005). It is commonly used as a land transportation fuel and is blended in petrol.

About 90% of all ethanol is produced from crops by fermentation, mainly from sugar and starch crops. The rest is produced synthetically (Hamelinck et al., 2005). Thus ethanol is competing directly with food and fibre production. As for other bio-fuels, when this land-use change is taken into account, the use of ethanol does not lead to substantial greenhouse gas savings.

According to Petrov (2010), the surface needed by different crops to produce 1 litre of bio-ethanol are:

- Wheat: 3.33m²
- Maize: 3.07m²
- Sugar beet: 1.25m²
- Sugar cane: 1.23m²

As an example, if conventional petrol and diesel were to be completely replaced by corn or wheat bio-ethanol, more than the surface of the whole European Union would be needed to cultivate these energy crops, whereas sugar cane would still need the surface of Mexico.

6.2 Methanol and Dimethyl ether (DME)

Another substitute for diesel fuel, is methanol. Firstly it does not contain sulphur and when combusted it does not produce smoke, soot or particulates. Since it burns at lower temperatures it produces lower emissions of NOₓ than those produced from conventional fuels (Olah et al., 2009).

The greenhouse gas emissions depend on the feedstock. Today the majority of all methanol produced is made from natural gas, except in China where 75% of the methanol is produced from coal (Yang et al., 2012). The potential resource base for methanol is huge, since it can be made from any organic material, including biomass and waste. It is also a way of utilising the natural gas in remote places, since the liquid methanol is easier to transport with tankers, than natural gas in pipelines.

Currently a limited number of studies have assessed the environmental life cycle performance of
methanol as a transportation fuel, and the ones available are about methanol produced from natural gas and sugarcane bagasse. There are ongoing projects about methanol as a marine fuel, but at present time the final results are not available. However data from studies exploring methanol production and methanol chains for road fuels can be used to evaluate it as a fuel for shipping (e.g. Strømman, et al. 2006., Xino, et al. 2009). What can be seen is that methanol is less energy efficient than LNG, since it requires energy to convert the natural gas into methanol. On the other hand the liquefaction of natural gas to LNG also costs energy, but not as much. Natural gas to LNG conversion is about 90% efficient, while natural gas to methanol is about 70% efficient. Therefore methanol is more expensive than LNG, but it is also easier to transport, since it is a liquid at room temperature and can thus be transported in ordinary tankers. Methanol can be made accessible in remote places and has other advantages that gives it potential as a substitute fuel, both for the near and coming future.

Firstly methanol can, as mentioned, be produced from many different materials, giving it potential to be sustainable when produced from renewable resources in the future. Secondly it is similar to petrol and can use the present infrastructure if small modifications in the harbours are made. Currently there are about 50 million tonnes of methanol that are traded as chemicals per year and transported by chemical tankers. The accessibility, distribution and storage are important aspects and methanol requires no major changes.

One downside with methanol, apart from the energy consuming production, is the volumetric energy density, since it directly affects the size of the fuel storage tanks. The energy density of methanol is about 2.2 times less than that of diesel fuel (Olah et al., 2009). Other downsides are that methanol is toxic and there might be risks for emissions of the toxic and volatile CH$_2$O, formaldehyde. On the other hand, methanol is transported today in chemical tankers and it will not be in contact with the crew. An important aspect is that methanol is a low flash point fuel, like petrol, and currently there are no existing regulations allowing allowing these fuels as marine fuels. There are work in progress in IMO that are said to be finished during year 2014. Until those regulations are finalised it is not allowed to install methanol fuel systems, but it may be possible if thorough risk analyses are made. Dispenses have to be applied for from the flag states.

A closely related fuel to methanol, that has gained popularity lately, is DME, dimethyl ether, which is a liquefied gas much like LPG (liquefied petroleum gas). Today DME is produced almost exclusively by the dehydration of methanol, but it can also be directly converted from synthesis gas, and it can be produced from various feedstock. It is usually produced from fossil fuels, such as natural gas and coal, but can also be synthesised from renewable resources or through reductive CO$_2$ recycling (Higo et al., 2010). At atmospheric conditions DME is at gaseous state, but it it generally handled as a liquid and stored in pressurised tanks (0.5MPa). It is colourless, non-toxic, non-corrosive, has almost no odour and causes no negative health effects. It has the advantage that it can be used in compression-ignition engines and it is more calorific than methanol (Arcoumanis et al., 2008). DME is usually described as a diesel fuel, making it more suitable for the marine engines of today, while methanol is more similar to petrol. On the other hand engine manufactures are able to convert engines to be run on methanol.

DME is the simplest of all ethers and in contrast to diethyl ether and other higher ethers, DME does not form an explosive peroxide and is thereby safe to use. Another important safety characteristic is that when burning, DME displays a visible blue flame. Like methanol, DME requires more than twice the injected volume to supply the same amount of energy as MGO, due to its lower energy density and combustion enthalpy (Crookes et al, 2007. Arcoumanis et al., 2008).

Environmentally DME, like methanol, does not emit any SO$_X$ or particles (Higo et al., 2010). NO$_X$
are shown to be slightly lower compared to MGO, however they seem to vary depending on the fuel supply system and engine conditions (Arcoumanis et al., 2008). The greenhouse gas emissions during the whole life cycle of the fuel depend on the feedstock. It is argued that the well-to-wheel analysis of DME produced from fossil fuels are not better than for most other fuels, as a result of the high fuel production energy and relevant CO$_2$ emissions. Nevertheless, since DME can be produced from renewable resources that can be added to that produced from natural gas, without any change in fuel properties, it has been found to be promising as an alternative fuel for compression-ignition engines (Arcoumanis et al., 2008).

Bio-DME projects in Sweden demonstrate the advantages of DME in terms of lower specific emissions in heavy duty vehicles compared to diesel fuel. A Bio-DME plant in Smurfit Kappa Kraftliner Mill in Piteå, Sweden, currently has a production capacity of 4 tonnes/day and in September 2012 it had produced about 340 tonnes of DME. Since early January 2012 the four DME tank stations in Sweden has received bio-DME and no fossil DME. Currently 10 Volvo trucks are run on DME and the results are shown to be promising, but of course DME merits further research before a final decision on its potential as a mass production fuel for transportation can be taken.
Chapter 7

Unconventional fuels

7.1 Sun, Wind and Wave

7.1.1 Sun - Solar panels

Using the sun as an energy source is possible in the form of solar panels. In the Wallenius project Zero, the use of solar power has been evaluated as a mean to reach the vision of an emission free ship. A result from their tests is that the maximum future potential for a large ship is 400kW electric power from solar power. The energy is not sufficient to drive the main engine, which is about 10MW, but solar power can be used for auxiliary equipment.

7.1.2 Wind - Kite

It is possible to reduce the fuel consumption of large low speed cargo ships by using an automatically controlled towing kite system. The principle is shown in Figure 7.1.

![Kite system](image)

Figure 7.1: Kite system

The use of kites has been tested during the regular operation of a cargo vessel in the EU-project WINTECC, Wind Propulsion Technology for Cargo Vessels. The project showed that 5% fuel savings can be achieved on an average route mix, which corresponds to fuel cost savings of about 135-220 000 Euro per year at bunker oil prices of 430-700 Euro per tonne. The estimated price of a 320 m² kite is about 1 million Euro (European Commission, 2006). If the bunker oil prices do not drop below 430 Euro per tonne, the investment would be returned within five to six years, and it is uncertain if the lifespan of the kite would even be as long.
Other possibilities to use the wind as propulsions could be by the use of fixed sails or wind turbines. Problem with fixed sails is the height and the use of wind turbines are still under investigation.

### 7.1.3 Wave - buoys

There are different methods to make use of wave energy, however not yet commercial. One is to harvest wave energy via buoys attached to the hull sides by pivoting arms. The hull remains relatively stable, the buoys would bob up and down on the waves, causing the arms to pivot back and forth and drive a generator producing up to 0.5-1 megawatt of electrical power. Batteries are planned to have a capacity of 20 megawatt-hours. A full charge would take at least 20 hours. This concept was presented at the Clean Technology Conference and Expo in Boston 2011 and is illustrated in Figure 7.2.

![Figure 7.2: Buoy system](image)

### 7.2 Nuclear power

As the pressure on reducing all types of air polluting from shipping increases, the option of using nuclear-powered engines in commercial ships has also gained interest. The nuclear technology has been used on board navy ships for many years, e.g. submarines and air craft carriers, as well as ice breakers. The technology has also been used for commercial purposes, but has not been profitable. Because of this background there is an existing legal framework for this type of ships. The basic requirements for nuclear-powered ships are provided by Chapter VIII of the SOLAS Convention and there is also a more detailed Code of Safety for Nuclear Merchant Ships, which was adopted by the IMO in 1981.

A French study (Picard, 2006) has analysed the outlook for the use of nuclear power for commercial purposes. One advantage with nuclear powered ships is that there is no need for refuelling and there is no need for fuel tanks, giving more space for cargo. For military purposes, such as submarines, this is favourable, since the ship never needs to go to port and can run for several years. Also there is almost no limit for maximum power. Either it is possible to build larger ships or increase the speed substantially. For instance there would be possible for big ships to cross the Atlantic at more than 40 knots opening up for competition with air planes.

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Today there is one nuclear-powered commercial ship in operation, the Russian NS Sevmorput, and there has been four merchant cargo ships in total, but none of them has been profitable. The investment cost is high, requiring long depreciations of about 20 years, and for existing ships a conversion is not feasible. The operation is expensive and requires special trained and well educated crew demanding high wages. The insurances for nuclear vessels are also expensive. Also nuclear powered
ships are not allowed to enter all harbours. In addition to this, nuclear power involves a high risk and environmentally, even though it does not emit either SO$_X$, NO$_X$ or CO$_2$, the radioactive waste has half-life of several thousands to millions of years. Nuclear waste requires sophisticated treatment and management to successfully stay isolated from the biosphere. Long-term solutions involving storage, disposal or transformation of the waste into non-toxic form need further development.
Chapter 8

Exhaust Gas Cleaning

8.1 SOx abatement technology

Instead of switching to an alternative fuel, when the new stricter regulations enter into force in 2015, MARPOL Annex VI allows ships in SECA s to continue using HFO if the exhaust gases are cleaned from sulphur using an on-board exhaust cleaning system. Currently there are basically two main types of technologies that are suitable for ships; seawater scrubbing (“open-loop scrubber”) and freshwater scrubbing (“closed-loop scrubber”), both using water as the scrubbing medium. It is also possible to use a combination of these two, e.g. closed-loop operation in harbours and sensitive areas like the Baltic sea, while open-loop operation in open ocean water.

8.1.1 Seawater scrubbing

The seawater scrubbing technology is based on neutralisation of the exhaust gases by absorption of the SOx molecules by the seawater. When the SOx comes into contact with the CaCO3 in the seawater, there is a fast reaction forming CaSO4 and CO2. After extracting and storing the sludge from scrubbing, the seawater are then discharged back into the sea. The waste must be stored on-board prior to final delivery to a shore reception facility (EMSA. 2010).

An important aspect with seawater scrubbing is that the IMO Wash Water Guidelines are still in progress. IMO and EU are developing wash water criteria and geographical definition. Currently some ports and coastal areas within SECA s do not allow discharge of waste water, and it is not sure how the future regulations for the whole SECA will be. In case discharge of waste water within SECA will be prohibited, vessels using seawater scrubber technology will be forced to leave SECA for discharging the water. Other disadvantages with seawater scrubbers are the large amount of water required and the dependent efficiency on salinity and alkalinity of the water.

8.1.2 Freshwater scrubbing

In sea areas where the natural alkalinity of the sea water is not sufficient to perform reactions with sulphur oxides on its own, for example in brackish inland seas and rivers, freshwater scrubbing can be used, which is a variation of the technology where caustic soda, NaOH, is added to form a reaction. The freshwater scrubbing is a closed loop system, which means no discharge within enclosed area. As for seawater scrubbing, the extracted contaminants have to be stored on-board prior to disposal in port.

The main advantage with the freshwater scrubbing is that it works everywhere and is not dependent on the alkalinity of the sea water. It requires smaller water flow than seawater scrubber, needs
lower pumping power and the corrosion issues are easier. Downsides are the need for NaOH and freshwater, and more important the need for wash water reception facilities.

8.1.3 Environmental and technical considerations

Uncleaned wash water might pose environmental risks in the form of heavy metals, oil, nitrous compounds and different pH-value than that of sea water. To minimise these risks the IMO has set regulations for the quality of the wash water.

There is no finished solution for handling the waste products. The current set-up is daily maintenance of replacing bag filters 35kg/day and the crew carries the waste in bags to waste stations on land. When entering e.g. USA the crew needs to take the waste bags into port which is time consuming.

The weight of a scrubber is about 600kg, but it can replace the silencer without increasing the sound level. However it is about 40% higher, which can cause space problems. The stability problems, which can occur because of the higher located weight, is not a significant concern for tankers.

According to EMSA (2010) indicative retrofit investment cost of seawater and freshwater scrubbers are about 2.4 million euro, while it is about 3.0 million euro for the hybrid system. The use of scrubber may also cause an increased fuel consumption of 1-3%, which in turn leads to major increased costs.

The existing scrubbers of today are relatively simple one-engine installations and they have large problems with corrosion. Severe operation problems, such as fires, have also been shown.

8.2 NO$_X$ abatement technology

There are different available options to reduce NO$_X$ emissions from shipping and the most common technology is selective catalytic reduction, SCR. Another alternative is humid air motor abatement technology, HAM, but according to Bengtsson (2011) it is not expected to reach the NO$_X$ Tier III requirement. It is also possible to use exhaust gas recirculation, but that has varying potential depending on the amount of gas circulated. In this report SCR is the only technology included, since that is the one with the highest reduction potential.

8.2.1 Selective Catalytic Reduction, SCR

In SCR for marine applications, a water solution with urea is injected to the hot exhaust gases upstream of the catalytic converter. The urea is decomposed into ammonia and when the ammonia reacts with the NO$_X$ in the exhaust gases, nitrogen and water is formed. The efficiency depends on the amount of urea injected as well as the temperature of the exhaust gases. Normally a temperature of at least 300°C is needed for efficient operation. For two-stroke engines when the temperature is lower, the SCR is less efficient and there is also a start up time when the SCR cannot be used at all (Bengtsson, 2011). When the exhaust gas temperature is too low, there is a risk for ammonia slip. If the reaction between NO$_X$ and urea is incomplete, ammonia is released into the air. This can also occur if the wrong urea dose is used. To reduce the ammonia slip an oxidation catalyst can be used after the SCR (Bengtsson, 2011).
Part III

Fuel choice
Chapter 9

Fuel choice

The different alternative fuels explored in this paper are distillates, LNG, biodiesel, LBG, ethanol, methanol, as well as sun, wind, wave and nuclear power. Also abatement technologies are discussed.

Nuclear power is not a new technology and has been used for marine propulsion for many years. From an environmental perspective it is a clean burning fuel since it does not emit either SO\textsubscript{X}, NO\textsubscript{X} or CO\textsubscript{2}. However it involves high safety risk, need for special educated crew and there are issues with the radioactive waste. In addition to this the investment cost is high and conversions of existing ships are not feasible. For the near and coming future nuclear powered tankers is not a likely option.

There has been studies of using the free energy sources sun, wind and wave to get an emission free ship. Neither of these energy sources can supply sufficient energy to drive the main engine. The use of a kite to reduce the fuel consumption is an option, but if the oil prices remain at current levels the return of investment would be five-six years, which might be longer than the lifespan of the kite, wherefore this is not seen as profitable within the near future.

For biodiesel it is often argued that the net greenhouse gas emissions are low due to the carbon dioxide captured by the plant during its growth. However today the biodiesel on the market is first generation biodiesel produced from agricultural crops competing with food production and involves increased deforestation. Second generation biodiesel can be produced from lingo-cellulosic materials that do not compete with food production, but this technology is currently highly energy consuming, generating large amount of carbon dioxide as well as it is not cost effective. Yet second generation biodiesel is not a real option and a shift towards biodiesel is not needed in order to meet the regulations concerning the sulphur emissions. Also biodiesel produces higher NO\textsubscript{X} than marine gas oil. As the technology develops it might be an option to reduce greenhouse gas emissions from tankers, but not in the near future.

Like biodiesel, the use of ethanol does not lead to substantial greenhouse gas savings, when the land-use changes are taken into account, and it competes directly with food and fibre production. Ethanol is not an alternative for tankers.

The options left are MGO, HFO with scrubbers, LNG and methanol. All of these alternatives have potential as future marine fuels, however all are not suitable for tanker shipping.

LNG reduces sulphur oxides to almost 100%, nitrogen oxides to almost 80% and particle emissions to near 99%. It also reduces greenhouse gas emissions by 8-20% compared to petroleum equivalent. However since it is a liquified gas it requires new infrastructure in terms of terminals, bunker possibilities, new storage facilities on-board and engines. Currently LNG is available at various ports.
in Europe, North America and Asia, but the accessibility is limited in South America, Africa and Oceania. Also because of fuel vaporisation the tanks need to be emptied during long stays, which are common for tankers. LNG can be an option for other ships, for instance on specific routes operating solely within SECA, but for tanker shipping in the spot market it is not possible within the near future. Thus LBG is not an option either.

Instead of switching to an alternative fuel, HFO can still be used if scrubbers are installed. Today there is however no secure scrubber solution leading to risks of entering a restricted area with too high sulphur levels. The investment cost for scrubbers is also high compared to the output. It is expensive, but technology is developing fast and there might be a more reliable solution within a few years, but until that the use of scrubbers is not a preferable alternative for tankers.

Methanol on the other hand is a fuel that has been used as a land transport fuel in otto engines with good results. It does not emit any SO\textsubscript{X} or particles and since it burns at lower temperatures than petroleum fuels it emits lower NO\textsubscript{X}. Natural gas based methanol does not have a lower global warming potential than marine gas oil, but since it can be produced from many different materials it has potential to be sustainable in the future.

Regarding the infrastructure methanol is very similar to petrol and can use the same infrastructure if small modifications in the harbours are made. Methanol is easy to store and transport. It has been tested in diesel engines using a glow plug concept and also by using a pilot fuel for ignition. The forecast of the availability looks promising.

A downside with methanol is that it has about half the energy density than HFO and diesel, but unfortunately, all alternative fuels are less energy dense per volume compared to diesel. Any of the alternative fuels would require larger tanks. Of the various choices, methanol appears to be the best candidate for long-term, widespread replacement of petroleum-based fuels within tanker shipping.

The fuel which is easiest to switch to when the new regulations are enforced is MGO, since, with small modifications, engines can run effectively on both HFO and MGO. Downsides are that the price of MGO is about 25-50% higher than the price of HFO and that a switch to MGO does not decrease the greenhouse gas emissions in a life cycle perspective.

For 2015 a switch towards methanol is not seen as realistic. Further research and establishment of regulations and distribution systems are needed, however there are indications that a shift will be possible sometime between 2015 and 2020. Therefore methanol is suggested as the fuel to be used in 2020, but for 2015 a shift towards marine gas oil is what is recommended. When shifting to marine gas oil only small modifications of the fuel system has to be made and the investment cost is low, but the fuel price is higher than methanol, why a shift towards methanol is preferred as soon as the market is ready.
PART IV

RECOMMENDED FUELS AND CONSEQUENCES
FOR THE REFERENCE SHIP
CHAPTER 10

RECOMMENDATION 2015 AND CONSEQUENCES FOR THE REFERENCE SHIP

For 2015 a shift towards marine gas oil within emission control areas is recommended.

10.1 Fuel supply

Several studies have assessed the availability of low sulphur fuel in 2015. According to the estimates by a UK study (Maritime and Coastguard Agency., 2009), a Finnish study (Kalli, et al., 2009) and a Swedish study (Swedish Maritime Administration., 2009) there will be sufficient quantities of low sulphur fuel, MGO, available when the 0.1% requirement enter into force. Kalli, et al., (2009) concludes that even though it is difficult to predict the availability, any problem of supply will not be due to the increased demand in SECA.

According to Christina Simonsson, Senior Refinery Development Engineer at Preem AB, (Simonsson, 2012) the oil production is currently expanding. There is an overcapacity of refineries in Europe and it is possible to increase the production capacity even more. Preem AB sees the new regulations as a business opportunity. They are not currently running all their desulphurisation facilities and they will increase the production of 1000ppm distillates, 0.1% MGO, along with the increased demand. In 2020 the low sulphur fuel supply is more unclear as the global demand will increase, on the other hand the availability will be evaluated in 2018 and the enforcement of the new regulations will be postponed if there is not enough supply. Most likely there will not be any problems with insufficient supplies in 2015, but the stricter regulations will affect the costs.

10.2 Fuel systems

Since the properties of HFO and distillates differ, the fuel systems have different layout. There is only one booster module, the system that supplies the main machinery with fuel. A typical system layout is shown in Figure 10.1.

10.2.1 HFO system

When bunkering, the HFO is placed in the storage tanks, which are heated in order to keep the HFO as a liquid and pumpable. The HFO is pumped by a transfer pump to a settling tank, where the clean oil is separated from the water and smudge present in the oil. This is done when the temperature is increased and the viscosity of the oil decreases in line with the higher temperature and the water and sludge are placed in the bottom of the tank due to their higher density and can
be drained out.

From the settling tank the oil is pumped to a separator and on the way the oil is heated even more to achieve the appropriate properties. In the separator the oil is cleaned even more, but instead of using density differences the separator rotates at a very high phase so that the oil is cleaned by the centrifugal force. After the separator the oil is pumped to the service tank, before reaching the booster module, which supplies the fuel pumps with the right amount of oil with the right viscosity.

10.2.2 Distillate system

Distillate fuels require significantly less treatment before being injected into the engine. The storage tank does not need any heating, since the fuel is pumpable at room temperature, and the fuel is directly pumped to a separator. The clean fuel is then pumped to the service tank, which is not heated either.

![Diagram](image)

Figure 10.1: Typical system layout

10.3 Switch between IFO380 and MGO

The switch between fuel oil and MGO is not a completely straightforward procedure, since the characteristics of the fuels differ significantly. The components are manufactured for HFO operation and complications can arise. Ideally would be to switch instantly from HFO to MGO, when entering a restricted area, without mixing of the different fuels, since MGO is more expensive and it is preferably to operate on HFO as long as possible. This is however not practicable, since the operational temperatures are different. In order to be pumpable, IFO380 has to be heated to 35°C. Therefore the tanks on board are heated, normally 40-50°C in the storage tanks and higher temperatures the closer to the engine. When injected into the cylinders, the viscosity of the fuel needs to be 15cSt. IFO380 has to be heated to 120-135°C in order to achieve this, while MGO has the required properties at room temperature. If the switching procedure is too quick, there is a risk that the system is not cool enough causing the MGO to evaporate. The fuel cannot be pumped into the
cylinders and the engine stops.

The challenging switch is from HFO to MGO. In order to avoid evaporation of MGO, the fuels have to be mixed gradually and the temperature of the fuels shall not be changed at a faster rate than 2°C/min. This changeover procedure takes between one and two hours.

### 10.4 Consequences on board

The engine can be run on either HFO or MGO and it is possible to switch to MGO; however, the engine is optimised to operate on HFO and the external fuel oil system on-board is designed to keep a high temperature for HFO operation. To ensure a safe and reliable performance some considerations have to be made. The viscosity and lubricity of the fuel have to be controlled, the fuel pump pressure has to be kept high and most likely a cooler in an external fuel supply system has to be installed. It might be needed to install new injection pumps due to lower temperature level, lower density of fuel and the necessary clearance between plunger and barrel. Also the exhaust valve in the engine may need to be changed.

### 10.5 Bunker management

Currently there are four HFO tanks, one LSHFO tank and one MGO tank. The tanks are:

- HFO Starboard 1: 446m³
- HFO Starboard 2: 423m³
- HFO Port 1: 446m³
- HFO Port 2: 227m³
- LSHFO: 240m³
- MGO: 100m³

When the new sulphur limits are enforced within ECA there are no longer need for LSHFO. Instead the fuels that will be used are HFO with sulphur content 3.5% and MGO with sulphur content 0.1%. Depending on how frequent fuel shifts are needed and how much the ship operates in ECA, different numbers of HFO vs MGO tanks are needed. For tanker ships operating worldwide, a suggestion is to use the LSHFO tank for MGO and if needed also HFO Port 2 can be used for MGO. HFO Port 2 is located next to the MGO tank and it would be possible to permanently open up between the two tanks to get one 327m³ MGO tank. This will give 1315m³ HFO tanks and 567m³ MGO tanks.

### 10.6 Crew

Switching from HFO to MGO within the restricted areas will not imply significant differences for the crew. What is important for the machine operators is to control the changeover process and regulate supply and reverse of the fuels so that HFO is not pumped back into the MGO tanks contaminating that fuel. When switching from HFO to MGO, the reverse has to be changed first when the system is completely free from HFO.
10.7 Costs

According to Delhaye, et al. (2010) fuel represents 33% of the daily costs for tankers, including all costs such as fuel, capital investment, manning, gross margin, repairs, maintenance etc. Currently MGO is about 50% more expensive than IFO380. It is argued that increased fuel costs may increase the risk of modal backshift and weakened competitiveness.

According to Kolwzan et al., (2011) the total cost for retro-fit technical adjustments could be in the region $150,000 and including adding tanks and piping, mixing tanks, and purifiers; modifications to fuel pumps, injectors, nozzles, lubrication systems; class society approvals and inspections especially for NO\textsubscript{X} Technical Code compliance and retrofitting of distillate fuel cooler.

10.8 LCA and effects on exhaust levels

Switching to MGO in 2015 will not decrease the greenhouse gases in a life cycle perspective, but the stricter sulphur regulations will be met, which is the main driving force. Also particulate matter will be reduced up to 80%. For existing ships built before 2011, the NO\textsubscript{X} regulation Tier I has to be fulfilled, which the reference ship Gotland Marieann does.

10.9 Safety of operation

If the switching procedures are performed accordingly, there are no increased safety risks with running on MGO compared to HFO, but if the temperature is increased too quickly during the changeover procedure there is a risk that the engine stops.
CHAPTER 11

RECOMMENDATION 2020 AND CONSEQUENCES FOR THE REFERENCE SHIP

For 2020 a shift towards methanol is recommended.

11.1 Fuel supply and infrastructure

Methanol is widely available and can easily and safely be transported to all geographies. The shipping is much the same as petrol and is typically shipped in product or chemical tankers. Infrastructure such as tanks, pipelines, barges, and trucks are also similar to oil products like petrol and diesel (Iosefa, 2013). Figure 11.1 shows the previous worldwide methanol production as well as the future forecast. Since methanol is mainly produced from natural gas, the feedstock is almost abundant. According to Methanex, the largest methanol producer in the world, methanol production is expected to increase and in 2020 there will most likely be sufficient methanol on the market to be used as marine fuel. The demand for methanol is growing at about 8% per annum driven mainly by the use of methanol as a fuel, which today represents about 35% of global methanol demand. Methanol supply is limited only by availability of financial capital to build the plants, as it can be produced from renewable feedstocks, gas, coal, and petroleum (Iosefa, 2013).
11.2 Engine concepts

Different engine concepts can be used using methanol in marine applications. Two that use methanol as a liquid are the dual-fuel concept and the methanol-diesel concept.

In the dual-fuel concept the gas valve on a DF-engine is replaced, or the engine is completed, with a methanol injector. The compressed pre-mixed methanol-air mixture is ignited with a small pilot fuel diesel spray. The mixture is burned according to the Otto-principle.

Methanol has a high heat of vaporisation and therefore modifications of ignition energy or preheating of combustion air might have to be carried out. Raw methanol, methanol containing considerably amount of water, could make the ignition process problematic and knocking can limit the output.

In the methanol-diesel concept methanol is injected with high pressure and is ignited with a small amount of pilot diesel. Knocking problems are avoided, since the diesel principle is used. Also because of the pilot fuel, raw methanol will probably be more easily used than in a dual-fuel engine.

11.3 Consequences on board and safety of operation

The engine has to be converted to methanol operation. If the methanol-diesel concept is chosen, the cylinder heads need to be changed, but the pumps are kept. In that case it is possible to run on both methanol and HFO. Also the tanks need to be painted or washed thoroughly.

The rules and regulation for using methanol and other low flash point fuels on-board ships are not
finished yet but are anticipated to be finished by IMO by 2014. Expectations are that the tanks will need to be adjusted. Firstly through painting and washing, but also open voids around and that the tank should be accessible without the need to pass through another room before. Apart from this the ventilation system and the fire extinguishing system need to be overlooked. When methanol is mixed with air explosive gases are formed and therefore inert gases on top of the methanol in the tanks will be needed.

### 11.4 Bunker management

Since methanol is a liquid at room temperature, no pressure tanks are needed and the same tanks as currently used for HFO and MGO can be used if coated or washed thoroughly. However, since the energy density is about half as the one of HFO, larger fuel tanks will be needed. Today there are tanks with MGO, LSHFO and HFO of total 1882m³. The suggestion is to use methanol when the global sulphur limit fall to 0.5%. Then there is no need for high sulphur HFO. Depending on the worldwide availability a decision has to be taken if the ship is supposed to operate solely on methanol. In that case it might be sufficient with five methanol tanks. Otherwise, if there still is a need to run on MGO, there will be a need to install one or two more methanol storage tanks.

### 11.5 Crew

The crew has to learn how to operate a methanol engine, since the operation differ from a diesel engine, but there is no need for special education. Methanol will not involve significantly more operations.

### 11.6 LCA and effects on exhaust levels

The analyses that have been made so far on methanol produced from natural gas show that there are no SO₂ emissions and the NOₓ almost reaches Tier III. According to Wärtsilä they are confident that they will reach Tier III without a catalyst within the near future (Stenhede, 2012). A ship engine can be operated on methanol containing 5% water. Diesel technology means higher temperatures, which gives lower formaldehyde, but also more NOₓ. The use of methanol containing more water lowers NOₓ emissions and makes the results approaching Tier III.

Yet there are no finished LCA studies on methanol as a marine fuel, but the data available indicates that the global warming potential of natural gas based methanol is not less than that of MGO. However, these results are for fossil methanol, but as more bio-methanol are blended with fossil methanol a gradual decrease of the net greenhouse gas emissions are expected.

### 11.7 Costs

The major costs are investment, fuel and spare parts. To get an estimate of the expected cost for retrofitting the engine, negotiations with the engine manufactures have to be done. As an addition to that the cost for painting or washing the tanks thoroughly will come. The fuel price of methanol per energy unit is expected to be in line with fuel oil. Current pricing is approximately $360/tonne in China and $400-410 in main ports elsewhere in the world (Josefa, 2013). Prices vary by location due to logistics and other considerations. Since methanol is corrosive there will be a need to change plunges more often than today, but there is no cost estimation for this yet.
CONCLUSIONS

There is no easy or straightforward solution and there is not a single fuel that can replace all heavy fuel oil used within tanker shipping. For every single ship it has to be evaluated which fuel that is most suitable. What can be seen is that renewable energy is one of the most efficient ways to achieve sustainable development. Increasing its worldwide share will help prolong the existence of fossil fuels, combat climate change threats as well as enable better energy supply on a global scale. Most renewable energy resources are undergoing commercial development, but the technologies are improving at a fast rate and it is likely that new solutions are available before 2020, before the more stringent global sulphur limits are enforced.

The fuel that in this report has been shown to have the largest potential for long-term, widespread replacement of petroleum-based fuels within tanker shipping is methanol. It does not emit any sulphur oxides nor particles and the nitrogen oxide emissions are lower than those of marine gas oil. Currently there are no greenhouse gas regulations for shipping and with methanol the upcoming sulphur and nitrogen regulations can be met. Today most methanol is produced from natural gas and the net carbon emissions during the life cycle of the fuel is not less than that of heavy fuel oil and MGO. However, since methanol can be produced from any organic material including renewable resources and waste, fossil methanol can work as a bridge towards a clean burning shipping fuel. As the bio-methanol production increases, bio-methanol can be blended with fossil methanol in any proportions stepwise lowering the greenhouse gas emissions and coming closer to the vision of a carbon free society.

The studies on methanol are ongoing and as it looks today the technology will not be ready before 2015, but sometime between 2015 and 2020. For 2015 a shift towards marine gas oil, MGO, when entering the restricted areas is suggested as it involves low investment costs and the current infrastructure can be used. As MGO is more expensive than methanol per energy unit, a shift is preferable as soon as the market, technology and infrastructure are ready.

The engine manufacturers have not yet been able to reach Tier III, the most stringent nitrogen oxide emission limit, but are confident that they will do in the near future. For the retrofitting it is important that Tier II is fulfilled, which is done with methanol and for the reference ship all upcoming environmental regulations are likely to be met with methanol. However, what has to be known before taking the decision to convert to methanol is whether such a conversion would count as a major conversion or not. If it would, the ship would be classified as a new ship and for instance Tier III would have to be fulfilled, making methanol a less attractive option, since selective catalytic reduction, SCR, or similar technology would have to be used in addition.
DISCUSSION AND FUTURE STUDIES

It is difficult to predict future prices of petroleum fuels and when the demand for heavy fuel oil, HFO, decreases, the gap between HFO and MGO may increase even more, resulting in a comparative advantage for the shipowners that have invested in scrubber technology. The forecast is however that this change will happen after the global sulphur regulations have entered into force in 2020 or 2025. As the price outlook for methanol is almost same price level as HFO, an investment in engine retrofitting would pay back quickly as methanol would be about 20-30% cheaper than MGO, depending on how the petroleum market develops.

Before methanol can be used as a fuel, more studies regarding the environmental impacts and different production systems have to be made. Also more studies regarding which type of engine conversion that would be most suitable have to be performed.

This thesis has focused on fuels that can be used in the relatively near future to meet the upcoming requirements. Since shipping industry is now standing in a turning point where a shift is needed, the focus has been on what can actually be used on these specific ships in 2015 and 2020. As the result in this study is not the sustainable vision desired, it would be interesting to study fuel options to be used in 2050 and beyond coming closer to emission free shipping.
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Appendix 1 Gotland Marieann Particulars and General Arrangement

The reference ship M/T Gotland Marieann is a medium range product oil tanker of Gotland Class Super Ice. The main particulars are shown in Table 11.1 and the machinery, fuel consumption and tanks are shown in Table 11.2.
<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length over all</td>
<td>183.0m</td>
</tr>
<tr>
<td>Length b.p.</td>
<td>174.5m</td>
</tr>
<tr>
<td>Breadth moulded</td>
<td>32.2m</td>
</tr>
<tr>
<td>Keel to masttop</td>
<td>47.6m</td>
</tr>
<tr>
<td>Depth moulded</td>
<td>18.2m</td>
</tr>
<tr>
<td>Draft (design)</td>
<td>12.0m</td>
</tr>
<tr>
<td>Draft (scantling)</td>
<td>13.5m</td>
</tr>
<tr>
<td>Deadweight at design draft</td>
<td>43510t</td>
</tr>
<tr>
<td>Deadweight a scantling draft</td>
<td>51510t</td>
</tr>
</tbody>
</table>

*Table 11.1: Ship main data*

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main engine: Wärtsilä Sulzer 7RT-flex50</td>
<td></td>
</tr>
<tr>
<td>MCR:</td>
<td>11340kW at 124rpm</td>
</tr>
<tr>
<td>CSR:</td>
<td>9640kW at 117.5rpm</td>
</tr>
<tr>
<td>Aux. engines (four): Wärtsilä 6L20</td>
<td></td>
</tr>
<tr>
<td>Aux. engine power:</td>
<td>875kW each</td>
</tr>
<tr>
<td>Fuel cons. main engine:</td>
<td>approx. 39.5 mt/day</td>
</tr>
<tr>
<td>Fuel cons. aux engine (at sea):</td>
<td>approx. 1.8mt/day</td>
</tr>
<tr>
<td>Fuel cons. aux engine (discharge operation):</td>
<td>approx. 10.3mt/day</td>
</tr>
<tr>
<td>Service speed, design draft:</td>
<td>15knots</td>
</tr>
<tr>
<td>Service speed, ballast draft:</td>
<td>16 knots</td>
</tr>
<tr>
<td>HFO tanks:</td>
<td>2054m³</td>
</tr>
<tr>
<td>MGO tanks:</td>
<td>146m³</td>
</tr>
</tbody>
</table>

*Table 11.2: Machinery, fuel consumption and tanks*
Figure 11.3: Gotland Super Ice Class, General Arrangement
Appendix 2 Bunker Prices

The current price (6 Dec 2012) of IFO380 is 628$/mt and for MGO it is 978$/mt. The world wide mean prices of IFO380 and MGO for the last year are shown in Figure 11.4 and Figure 11.5 respectively.

Figure 11.4: Bunker price IFO380

Figure 11.5: Bunker price MGO
Appendix 3 Bunker Price Outlook

The bunker price outlook for different HFO blends, MGO and LNG according to Preem during a presentation at Energy Seminar for The Swedish Shipowners Association in Gothenburg, 2012-11-14. The prices are shown in $/tonne.

<table>
<thead>
<tr>
<th>Year</th>
<th>3.5% HFO</th>
<th>1% HFO</th>
<th>0.5% HFO</th>
<th>0.1% MGO</th>
<th>US LNG</th>
<th>Europe LNG</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012</td>
<td>650</td>
<td>700</td>
<td>750</td>
<td>950</td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>2015</td>
<td>575</td>
<td>600</td>
<td>650</td>
<td>850</td>
<td>300</td>
<td>475</td>
</tr>
<tr>
<td>2020</td>
<td>550</td>
<td>600</td>
<td>650</td>
<td>875</td>
<td>350</td>
<td>450</td>
</tr>
<tr>
<td>2025</td>
<td>600</td>
<td>650</td>
<td>750</td>
<td>975</td>
<td>375</td>
<td>450</td>
</tr>
</tbody>
</table>

Table 11.3: Bunker price outlook, $/tonne

Notes:
- LNG includes liquefaction costs
- Some prices are estimates for blends not currently being marketed
- Wholesale prices at the dock, excludes bunkering fees
APPENDIX 4 MGO AND METHANOL; MAIN CHARACTERISTICS

The main characteristics of MGO and methanol are shown in Table 11.4.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>MGO</th>
<th>Methanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density:</td>
<td>0.85 kg/l</td>
<td>0.79 kg/l</td>
</tr>
<tr>
<td>Boiling point:</td>
<td>150-370°C</td>
<td>65°C</td>
</tr>
<tr>
<td>Flash point:</td>
<td>60°C</td>
<td>11°C</td>
</tr>
<tr>
<td>Auto ignition:</td>
<td>240°C</td>
<td>464°C</td>
</tr>
<tr>
<td>Viscosity:</td>
<td>~13.5cSt at 20°C</td>
<td>~0.6cSt at 20°C</td>
</tr>
<tr>
<td>LHV:</td>
<td>42.9 MJ/kg</td>
<td>20 MJ/kg</td>
</tr>
<tr>
<td>Cetane No.</td>
<td>45-55</td>
<td>Octane 108 RON</td>
</tr>
</tbody>
</table>

Table 11.4: Main characteristics of MGO and methanol