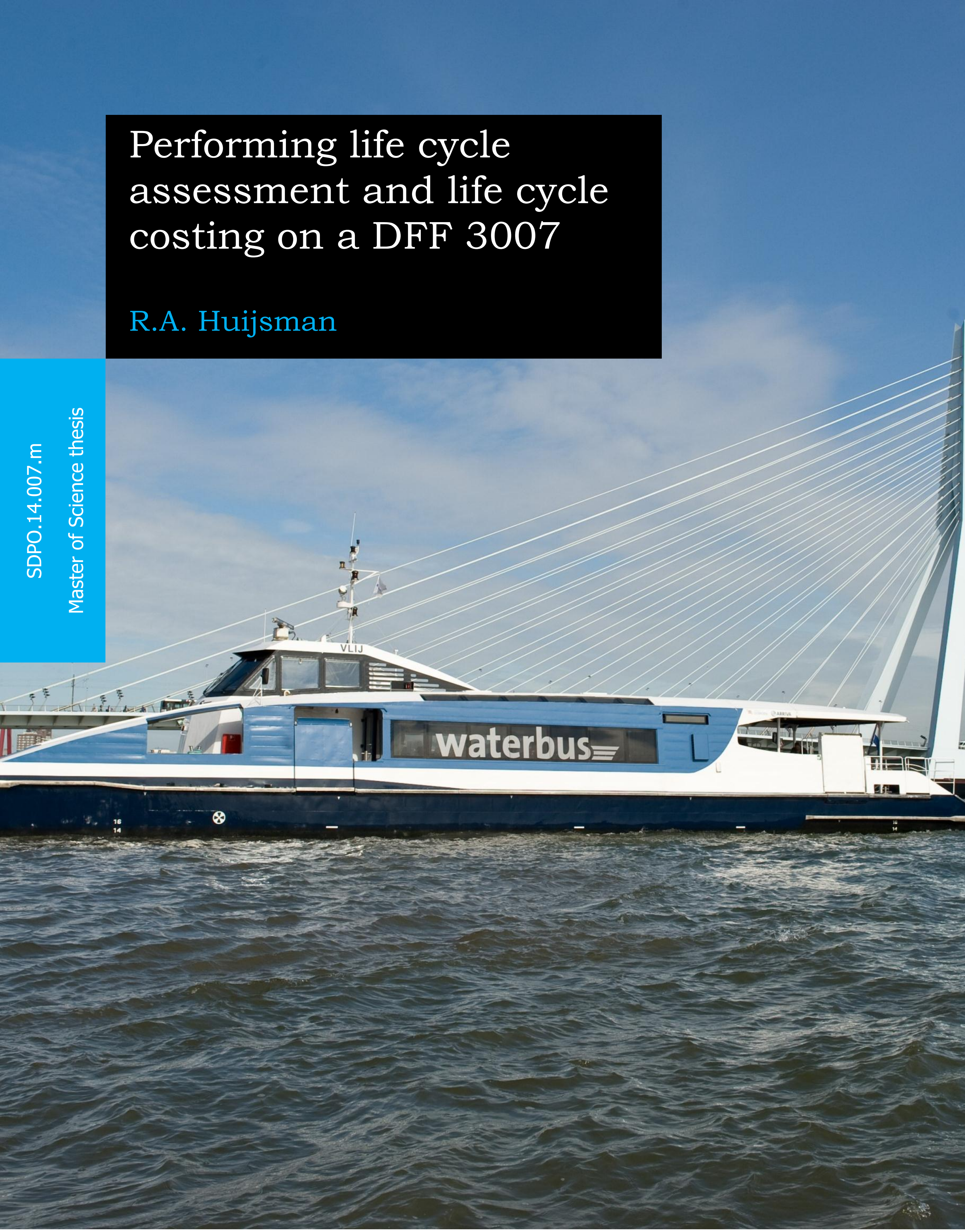


# Performing life cycle assessment and life cycle costing on a DFF 3007

R.A. Huijsman

Master of Science thesis

SDPO.14.007.m

TU Delft Delft University of Technology

DAMEN

Challenge the future

# Performing life cycle assessment and life cycle costing on a DFF 3007

## A study into the advantages and disadvantages of these methods for Damen

By

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in partial fulfilment of the requirements for the degree of

**Master of Science**

in Marine Technology

at the Delft University of Technology

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# ABSTRACT

The shipping industry is essential for the World economy; however the shipping industry emits large quantities of $CO_2$, $SO_X$ and $NO_X$. To reduce the environmental impact of ships, they have to be more environmental friendly. The amount of harmful emissions has to be reduced. This is also realised by the International Maritime Organizations who is responsible for the safety and security of shipping. MARPOL annex VI states the regulations regarding emissions, $CO_2$, $SO_X$, $NO_X$ and PM and these have become stricter. Besides MARPOL different areas around the World have even more strict regional emission regulations.

Ship owners have different solutions to comply with these stricter regulations. Among others they can switch to sail on cleaner fuels, like LNG, or they can install exhaust gas treatment systems. These EGTS clean the exhaust gases to levels which are within the limits as stated in the regulations.

This report provides an insight in the calculation of the effect of these adjustments on environmental and financial aspects. The methods that are used are life cycle assessment (LCA) and life cycle costing (LCC). The life cycle assessment focusses on the environmental and the life cycle costing on the financial aspects of a product or system over its lifetime. Both methods already exists a couple of decades, but especially LCA, has been used more often lately.

To get the advantages or disadvantages of both these methods, multiple assessments are performed. All assessments are performed with a developed excel-based software program. This program can compare up to four different ship configurations and only takes the operational phase of a ship into consideration.

The assessed ship is a Damen Fast Ferry 3007, “Waterbus”. This is a 30m long aluminium catamaran, currently operating as a public liner between Rotterdam and Dordrecht. Measurements on board the ship are performed resulting in an operational profile to use in the LCPA. Four different configurations, the current sailing configuration, LNG, MGO or a ship with a scrubber sailing on HFO as fuel are assessed.

The assessments had three goals in order to determine whether life cycle performance assessment is a good method for Damen to use. The first goal was to determine if it is possible to show the environmental and financial impact of different fuels in combination with exhaust gas treatment systems over the ships life time. The result is that the LCPA shows which configuration had the lowest financial and environmental impact. The second goal was to investigate the effect of change in fuel prices on the financial result. One of the results is that the higher the fuel price, the bigger effect price changes have on the outcome of the LCPA. Another result is that a fuel price change of one euro results in a NPV change of 0.50 % and IRR changes with 0.20 %. The last goal was to determine the effect of installed EGTS on both the environment as well as the additional costs. The program can provide this information and it shows that a combined EGTS is relatively cheaper than one single EGTS. These LCPA results indicate that this program can be used by Damen to assess the impact of different engine configurations.

# ACKNOWLEDGEMENTS

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This thesis is written in collaboration with the Research department at Damen Shipyard Gorinchem. I would like to thank Damen Shipyard for offering me the possibility to write my master thesis on the life cycle assessment and life cycle costing methods. I like to thank the colleagues of the Research department for their knowledge and support. It was inspiring and educational to see how an international shipyard operates.

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Finally I express my gratitude to my friends and family for their support during my study.

Gorinchem, 14 March 2014

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# LIST OF SYMBOLS

| | |
|---|---|
| AP | Acidification Potential |
| API | American Petroleum Institute |
| bcf | Billion cubic feet = 1 million mmBtu |
| BFOE | Brent, Forties, Oseberg and Ekofish |
| CAPEX | Capital expenditures |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| DFF | Damen Fast Ferry |
| E3 | Environmental friendly, Efficient in operation and Economically Viable |
| ECA | Emission Control Area |
| EEDI | Energy Efficiency Design Index |
| EEOI | Energy Efficiency Operational Indicator |
| EGTS | Exhaust Gas Treatment System |
| EIA | United States Energy Information Administration |
| EP | Eutrophication Potential |
| EVA | Energy Ventures Analysis Inc. |
| FLNG | Floating Liquefied Natural Gas |
| FP7 | Seventh Framework Programme |
| FTA | Free trade agreement |
| GHG | Greenhouse Gas |
| GL | Germanischer Lloyd |
| GWP | Global Warming Potential |
| HFO | Heavy Fuel Oil |
| IEA | International Energy Agency |
| IHSGI | IHS Global Insight Inc. |
| IMO | International Maritime Organization |
| INFORUM | Interindustry Forecasting Project at the University of Maryland |
| IRR | Internal Rate of Return |
| ISO | International Standards Organization |

| | |
|---|---|
| KPI | Key Performance Indicator |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Costing |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LCPA | Life Cycle Performance Assessment |
| LCSA | Life Cycle Sustainability Assessment |
| LNG | Liquefied Natural Gas |
| LR | Lloyds Register |
| LSF | Low Sulphur Fuel |
| MBM | Market Based Mechanism |
| MCR | Maximum continuous rating power |
| MDO | Marine Diesel Oil |
| MEPC | Marine Environment Protection Committee |
| MFO | Marine Fuel Oil |
| MGO | Marine Gas Oil |
| mmBtu | Million British thermal unit = $10^{-6}$ bcf |
| $NO_X$ | Nitrogen oxide |
| NPV | Net Present Value |
| NYMEX | New York Mercantile Exchange |
| ODS | Ozone Depleting Substance |
| OPEX | Operating expenditures |
| PM | Particulate Matters |
| SCR | Selective Catalytic Reduction |
| SECA | Sulphur Emission Control Area |
| SFC | Specific Fuel Consumption |
| SEEMP | Ship Energy Efficiency Management Plan |
| SLCA | Social Life Cycle Assessment |
| $SO_X$ | Sulphur oxide |
| TCO | Total Cost of Ownership |
| VOC | Volatile Organic Compounds |

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# 1. INTRODUCTION

The shipping industry affects us more than we know. Look around and almost everything you see has been transported by ship. Over 80 % of the World's trade is transported by ship. If there was no shipping, the World would have looked different. In the supermarket there would not be kiwis from New Zealand or coffee from Brazil. Also the transportation of raw materials would be difficult, because iron ore cannot be transported by plane in the quantities that ships can.

The shipping industry transported over 80 % of the Worlds trade and according the last IMO study in 2009 it was responsible for 3.3 %[1] (2.7 % international, 0.6 % domestic and fishing) of the World's total $CO_2$ emission in 2007. Although this seems a good achievement, it is worthwhile to put this in perspective. The total $CO_2$ emission caused by shipping is higher than the total $CO_2$ emission of Germany, Europe's most industrialized country and sixth most $CO_2$ emitting country globally. If the shipping industry would be a country it would rank sixth between Japan and Germany. Besides it is worth mentioning that the projected $CO_2$ emission of the shipping industry, in case of business as usual, would rise to 18 % of the World's total $CO_2$ emission by 2050. The financial crisis has probably affected these numbers, but there is no doubt that the influence of shipping is rising and will continue to rise when no adequate action is taken.

The shipping industry has to be aware of their growing impact on the environment and therefore shipping has to become more environmentally friendly. This means ships have to reduce their emission of carbon dioxide, nitrogen oxides, particulate matters and sulphur oxides. This is realized by regulating authorities like the International Maritime Organization (IMO). The IMO develops stricter emissions regulations. There are multiple solutions to reduce the emissions like $CO_2$ and $SO_X$ from ships, but they are costly. For instance a ship can switch to low sulphur fuel which is more expensive or can install exhaust aftertreatment systems to reduce $SO_X$ emissions. Another option is to use LNG as fuel to reduce $CO_2$ emission.

Damen realized that, as leading international shipbuilder, they had to take responsibility and design environmentally friendlier ships. In 2008 Damen started the E3 Tug project[2], where E3 refers to Environmentally Friendly, Efficient in Operation and Economically Viable. In other words a ship has to have a minimal impact on the environment. Furthermore it should be competitive and still economically valid, thus not disproportionately expensive in relation to a "non-green" ship with same capacities. The E3 label, which followed out of the E3 tug project, maintains the same guiding principles but extended to fit the broad range of products offered by Damen. It is a hallmark for sustainable products within the Damen Group. This is part of the Damen philosophy; Damen wants to be proactive in developing sustainable and cost-effective ships and services.

**The objective of this master thesis is to analyse life cycle assessment (LCA) and life cycle costing (LCC) methods and determine how useful these methods will be for Damen. This means to define what the advantages and disadvantages are and to describe whether**

[1] (Buhaug, et al., 2009)
[2] (Damen E3 project, 2013)

**these methods can be used to compare different ship configurations in terms of total emissions and total cost of ownership (TCO).**

This thesis can be divided into five parts; the first part contains the introduction and the problem definition. The explanation of the LCA and LCC methods, the emissions rules and measures to reduce air emissions are also covered in the first part. The second part of this thesis describes the impact of future fuel prices on the outcome of LCC. Fuel prices are a big part of the operational costs and influences LCC. This part also describes the software program that is used to perform the LCA and LCC. The life cycle assessment and life cycle costing are described in the third part of this thesis. Part four contains the results of the LCA and describes whether the LCA is also applicable to other Damen ships and whether it is useful for Damen to perform more LCA in the future. In the last part the conclusion and recommendations are stated.

# 2. PROBLEM DEFINITION

In the late 1980s IMO started work on prevention of air pollution from ships. During the seventeenth session of the IMO assembly in 1991 the urgent need for an international policy regarding prevention of air pollution from ships was mentioned. It took however till 1997 before shipping regulation cited air emission for the first time; this was $CO_2$ emission in resolution 8. The current regulations regarding air emission are stated in MARPOL annex VI and these regulations become stricter over time.

During the World Energy Conference in 1963 the result of the believed to be first LCA study was published by Harold Smith. Smith calculated the cumulative energy requirements for the production of chemical intermediates and products. In 1969 researchers of The Coca Cola Company laid the foundation for the current methods of life cycle inventory analysis by determining which beverage container had the least impact on the environment[3]. Despite an increasing number of LCA studies in the seventies and eighties, it took until 1997 before the International Standards Organization (ISO) started to develop the LCA standard. This standard was revised in 2006.

Life cycle costing finds its origin also in the sixties when studies for the Department of Defence showed that costs of ownership were much higher than the acquisition costs of the weapons[4]. Despite the fact that LCA and LCC methods are a couple of decades old the use of especially LCA is still limited.

In the light of the emerging emission abatement technologies and the sometimes significant added operational costs of those systems, LCC might proof to be good assessment tool to contribute in selecting the right technology for the right application.

To determine which emission reducing measures are sustainable for ships, life cycle assessment and life cycle costing can be applied.

## 2.1 MAIN OBJECTIVE

**DETERMINE THE USABILITY OF LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING FOR DAMEN**

Life cycle assessment and life cycle costing will be performed on a Damen Fast Ferry (DFF) 3007 to determine the effect of these methods for Damen. The results of these analyses will be used to determine the advantages and disadvantages of these methods. The conclusions will be used to assess these methods as comparison tool for different ship configurations; to determine which configuration is more sustainable in terms of total emission and total cost of ownership. These analyses are performed in chapter 8 and the results are given in chapter 9 and 10.

## 2.2 SUB-QUESTIONS

**WHAT ARE LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING?**

[3] (Curran, 2006)
[4] (Gluch & Baumann, 2004)

To understand life cycle assessment and life cycle costing methods, the definition of both methods and how to use these methods will be described in chapter 3.

### WHAT ARE THE RULES THAT HAVE TO BE TAKEN INTO ACCOUNT?

Ships have to comply with rules. These rules will be stricter in the future. Current rules will be used to establish a reference to determine the effect of reducing measures. Future rules describe the goal that those measures have to achieve. Chapter 4.2 will describe the rules and chapter 5 explains which measures can be applied to make ships comply with the rules.

### WHAT IS THE INFLUENCE OF FUEL PRICES ON THE OUTCOME OF THE ANALYSES?

The life time of a ship is 20 to 30 years, so it is assumed that the acquisition costs are small in comparison to operational costs. One of the biggest contributors to a ships' operational cost is fuel cost. Due to the decrease of oil resources, prices of fuel could rise in the future, increasing their influence on the outcome. Chapter 6 indicates the impact of fuel prices on the outcome of LCC. This chapter also provides an indication/estimation of future fuel prices.

### WHICH PROGRAM WILL BE USED TO PERFORM LCA AND LCC?

There are several programs on the market that can perform LCA and LCC. It is also a possibility that a new program/tool will be designed during this thesis. Multiple criteria are stated to which the program has to apply. These criteria will be used to weight all programs to determine which program is best suited to use. Which program eventually will be used is determined in chapter 7.

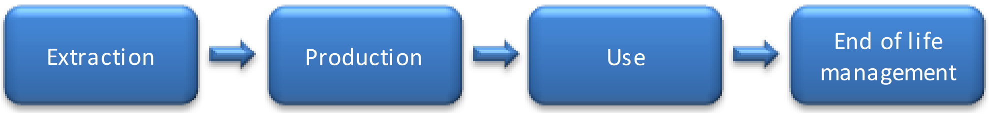
# 3. SUSTAINABILITY ASSESSMENT

The used assessment methods in this graduation project are part of a life cycle sustainability assessment (LCSA), which is also called life cycle performance assessment (LCPA). LCSA can be divided into three parts, an economic, an environmental and a social part[5]. The social part is weighed with a social life cycle assessment (SLCA), which will be explained later this chapter. The economic part is calculated with life cycle costing (LCC) and the environmental part is assessed with a life cycle assessment (LCA). These methods can be used to analyse products, services and processes, which will further be referred to as products. First the principles of LCA will be described.

## 3.1 LIFE CYCLE ASSESSMENT

A life cycle assessment is a method to assess the environmental aspects of a product during its lifetime; this is also known as a life cycle analysis. LCA focuses on the environmental impact of that product from the beginning, the raw material acquisition, through production and use up to the end, the final disposal of the product. This is a so-called cradle to grave cycle and is shown in figure 1. Other cycle examples are cradle to gate, cradle to cradle, gate to gate, well to wheel.

FIGURE 1: CRADLE TO GRAVE CYCLE




The International Organization of Standardization (ISO) developed two standards; ISO 14040 and ISO 14044 which provide guidelines on how to perform LCA. ISO 14040[6] describes the principles and frameworks and ISO 14044[7] the requirements and guidelines. These standards were issued in 1997 and revised in 2006. According these standards the goal of LCA is defined as:

> *"The goal of LCA is to compare the environmental performance of products in order to be able to choose the least burdensome. The term 'life cycle' refers to the notion that for a fair, holistic assessment the raw material production, manufacture, distribution, use and disposal (including all intervening transportation steps) need to be assessed. This then is the 'life cycle' of the product. The concept can also be used to optimize the environmental performance of a single product (ecodesign) or that of a company" (ISO, 2006).*

In other words LCA provides a complete environmental impact study of all processes involved and all materials used during the life time of a product. According ISO 14040 LCA consists of the following four phases, as illustrated in figure 2:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

[5] (Hunkeler, et al., 2008)
[6] (ISO 2006a, 2006)
[7] (ISO 2006b, 2006)

This assessment however is not a 'plug and play' method but needs to be adjusted for each product. For instance the depth of the study is different for each product.

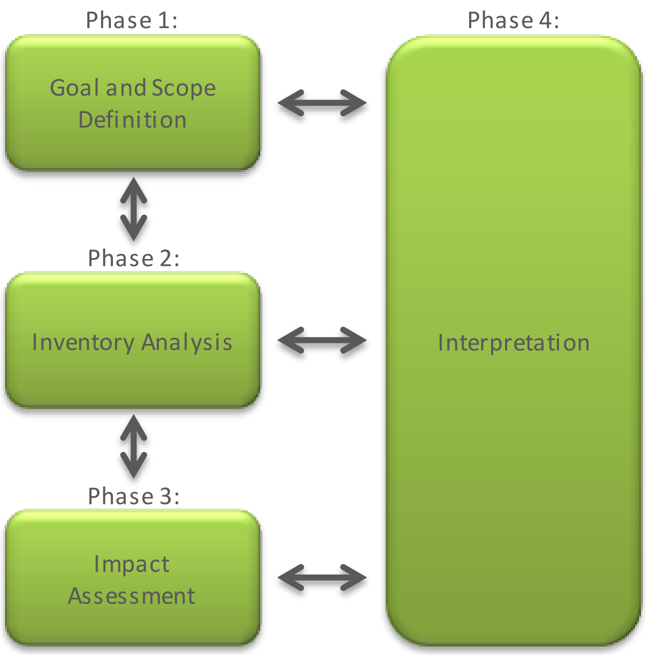



**FIGURE 2: LIFE CYCLE ASSESSMENT FRAMEWORK**

### 3.1.1 GOAL AND SCOPE DEFINITION

The first phase is the goal and scope definition and this describes and defines the product. It describes the context in which the assessment is made, so why the assessment is carried out. For example is it to compare different products or to investigate which stage of the cycle emits the most emission? The boundaries of the assessment are also defined in this stage, because as mentioned earlier there are different cycles that can be analysed. The environmental effects that will be investigated in the impact assessment are defined in this first phase. The last definition is the functional unit. This functional unit is for example one ton cargo transported over one nautical mile. All the results, or in other words Key Performance Indicators (KPI) will be given in this functional unit. The next phase is the inventory analysis.

### 3.1.2 INVENTORY ANALYSIS

Life Cycle Inventory analysis (LCI) basically covers a flow model with all the in- and outputs within the products boundaries as defined in the previous phase. An example of the flows of a single stage in the product cycle, in this case production, is shown in figure 3.

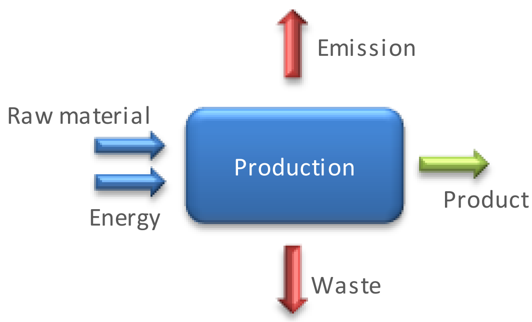


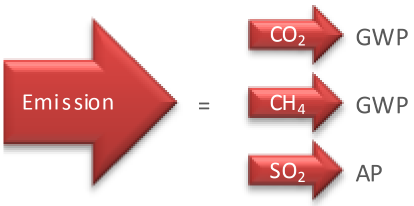

**FIGURE 3: PRODUCTION STEP INVENTORY ANALYSIS**

The inputs (blue arrows) are raw materials and energy. During the production of the product, emissions and waste are generated. Together with the product, these are the outputs. During the inventory analysis all the values of the flows are collected and calculated and given in the functional unit as defined in the goal and scope definition. Sometimes issues occur and a revision of the goal and scope definition is required. Due to the data collection and calculation this inventory analysis phase is complex and determines the accuracy of the final result. The input data has to be as accurate as possible to get a reliable result.

### 3.1.3 IMPACT ASSESSMENT

The previous phase shows all the flows during the life cycle of the product. This phase, the Life Cycle Impact Assessment (LCIA) evaluates the potential environmental impacts based on the LCI result. This is done by categorizing all flows into potential environmental impacts. Figure 4 illustrates an example of this categorization. There are however more indicators like land usage or water related.

FIGURE 4: EXAMPLE IMPACT ASSESSMENT OF EMISSION

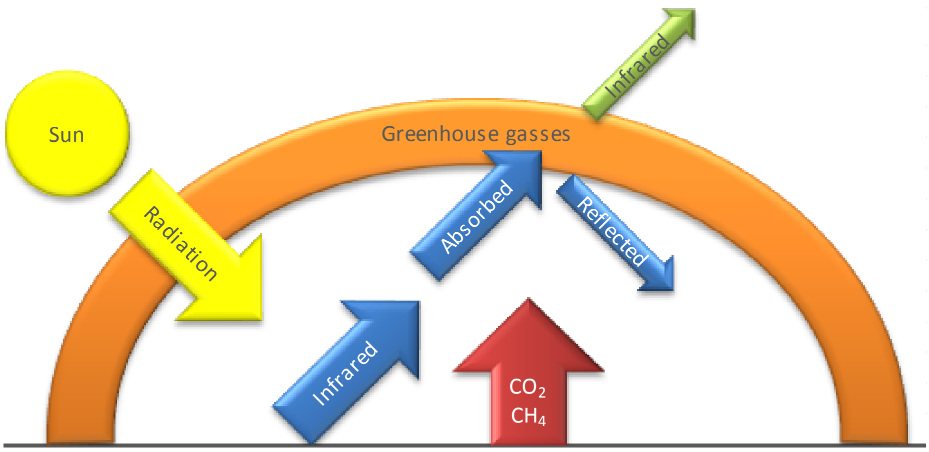



In this thesis those impacts are global warming potential (GWP), eutrophication potential (EP) and acidification potential (AP) and these environmental impacts will be described and the flows will be characterized[8].

#### GLOBAL WARMING POTENTIAL

GWP is closely related to the greenhouse effect, thus the greenhouse effect[9] will be described first. The sun is radiating heat in forms of UV and visible light towards the earth. Most of the harmful UV-light is 'blocked' by the Earth's ozone layer. Visible light that reaches the Earth's surface is absorbed or reflected back into the atmosphere. Incoming light has a high frequency in contrast to light that is reflected. This light is within the infrared spectrum and has a lower frequency. High frequencies can pass through the atmosphere without being blocked, whereas lower frequencies are absorbed and reflected by the several naturally occurring gases, the greenhouse gases (GHG) in the atmosphere. This is the greenhouse effect which is also illustrated in figure 5.

FIGURE 5: GREENHOUSE EFFECT




[8] (Jivén, et al., LCA-ship, Design tool for energy efficient ships - A Life Cycle Analysis Program for Ships, 2004)
[9] (Jivén, et al., Earth's Annual Global Mean Energy Budget, 1997)

It is believed that an increase of GHG in the atmosphere results in more heat absorption or reflection back to the Earth causing the Earth to warm up. Due to this warming, snow will melt and the reflection capacity of Earth is reduced. The Earth will absorb more heat and therefore more snow will melt. This is called the Albedo effect.

In 2007 the Intergovernmental Panel on Climate Change[10] defined global warming potentials as follows:

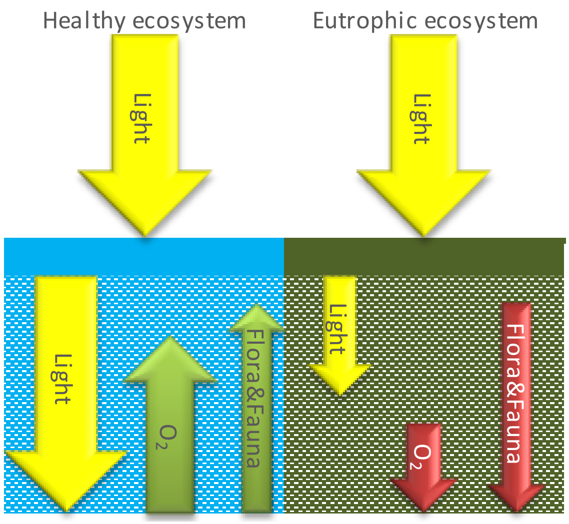
> *"Global Warming Potentials compare the integrated radiative forcing over a specified period (e.g., 100 years) from a unit mass pulse emission and are a way of comparing the potential climate change associated with emissions of different greenhouse gases." (IPCC, 2007)*

In other words GWP indicates what over a certain period of time the influence of a particular gas in the atmosphere is. So how much heat is trapped in the atmosphere by that gas. It takes into account the lifetime of that gas in the atmosphere and how much energy it can absorb. This number is expressed in carbon dioxide, meaning the GWP of $CO_2$ is one. A higher number means that the gas absorbs more energy and therefore contributes more to the warming of the Earth. GWP can be calculated over different timespans, but a period of 100 years is customary. Gases decay over time so GWP will also fluctuate over time. Looking for example at methane ($CH_4$) the GWP over 20 years is 72, but over 100 years it will be 25. So over 20 years, the emission of $CH_4$ is 72 times as bad as $CO_2$, but over 100 years it is 'only' 25. This is the characterization phase of the impact assessment. Other GWP values are given in appendix A.

### EUTROPHICATION POTENTIAL[11]

Nutrients are chemicals that organism like algae need in order to grow. The anthropogenic enrichment of those nutrients is called eutrophication. Figure 6 illustrates this process and this eutrophication process will be described into more detail.

**FIGURE 6: EUTROPHICATION EFFECT**




When algae are enriched the growing process will accelerate which could result in blocking of sunlight, so less sunlight is reaching the lower depth of the water. Photosynthesis uses light (energy) to convert carbon dioxide into oxygen. When (sun)light is blocked and cannot reach deeper parts of the water, there will be less photosynthesis

[10] (Solomon, et al., 2007)
[11] (Smith & Schindler, 2009)

and thus less oxygen production. Also decomposition of dead algae which sunk to the bottom is a cause of lower oxygen levels; since this decomposition process uses oxygen. This will result in lower water quality. The left side represents a healthy ecosystem, so a lot of light can penetrate the water, resulting in enough oxygen production also deeper in the water. The right side however represents an eutrophication ecosystem where the light cannot penetrate the water deeply, resulting in lower oxygen levels and shifting the flora and fauna balance in the water. The balance is shifting because some organisms cannot survive in these conditions, while others can and therefore increase significantly. EP is standardized in phosphate ($PO_4$) and the values are also given in appendix A.

#### ACIDIFICATION POTENTIAL

Acidification potential expresses, as the name stated, the contribution to acidification by a particular gas. The most common phenomenon is acid rain. Examples of contributing emissions are $SO_2$ and $NO_X$ which react respectively to sulphuric acid ($H_2SO_4$) and nitric acid ($HNO_3$). High amounts of $SO_2$ and $NO_X$ emissions result in more acid rain which contributes to acidification of land and sea. Acidification of the sea results in a decrease of pH causing carbonate to be less available. Carbonate in combination with calcium is used by sea animals like coral, mussels, snails and plankton to construct calcium carbonate shells or skeletons. With less carbonate available, the growth of sea animals is reduced, changing the complete food cycle and eco balance of the sea. The acidification process is illustrated in figure 7. The AP is standardized in sulphur dioxide and appendix A shows the values.

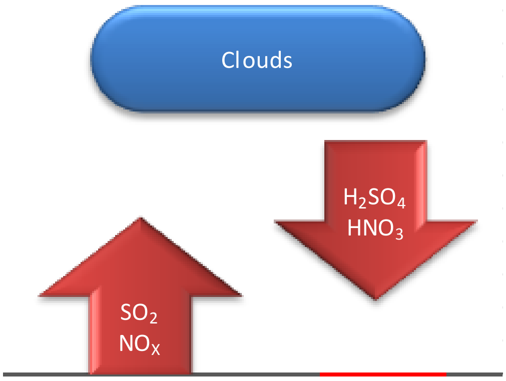



**FIGURE 7: ACIDIFICATION EFFECT**

### 3.1.4 INTERPRETATION

The last phase of life cycle assessment is the interpretation of all the previous phases/results. These results are summarized and discussed to determine the final conclusion with known assumptions and uncertainties. This result is used for direct applications, like strategic planning or marketing. According ISO 14044 the following three outcomes should be included in the interpretations:

- An identification of the significant issues based on the results of the LCI and LCIA phases of LCA
- An evaluation that considers completeness, sensitivity and consistency checks
- A conclusion, stating the limitations and possible recommendations

With this last phase completed, the life cycle assessment is finished. The environmental impacts of the investigated product are known, but the financial aspects are not taken into account. These financial aspects can be analysed with a life cycle costing analysis. This will be explained next.

## 3.2 LIFE CYCLE COSTING

This part of the chapter will explain the principles of life cycle costing. LCC is an economic analysis of all product related costs during its lifetime, so from initial investment costs to the disposal costs. With this method effects of an investment on for instance the operational costs can be analysed.

The total costs can be divided into two parts, the acquisition or investment costs and the sustaining or operational costs as shown in figure 8[12]. The acquisition costs include all the costs that occur during the acquirement of the product. The sustaining costs include all the costs that occur during the life time of the product, so also the costs associated with the disposal of the product. Not only costs but also revenues can be taken into account.

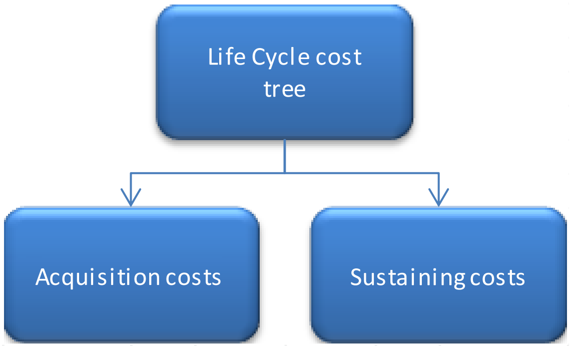



**FIGURE 8: COST OVERVIEW OF LCC**

LCC is not the same as total cost of ownership (TCO); in fact LCC is a method to calculate TCO. In case of comparing multiple investment alternatives LCC could determine which investment has the lowest TCO. It could be that investing in a better and therefore more expensive engine results in lower operational costs and therefore a lower TCO.

The LCC framework is similar to the LCA[13]. The main difference is the impact assessment phase. For LCC this phase is simpler because all the costs are given in the same currency. This currency is related to one point in time to incorporate the time value of money. This will be explained further.

### 3.2.1 TIME VALUE OF MONEY

If you could choose between two options, option one is to receive 100 euros today and option two is to receive 100 euros over one year, which option would you choose? At first sight it would look that it doesn't matter which option you would choose, but take in mind that the value of money changes over time. How much the value will change is hard to predict. It depends on what you would have done with the money. If you would choose the first option and deposit the money into a savings account with an interest rate of 3 %, over one year, that same 100 euros will be worth 103 euros, so money today has earning potential and is therefore more valuable. That is the reason why time is an important uncertainty in LCC analysis. The money value over time is called the discount rate.

#### DISCOUNT RATE

The discount rate is used to 'convert' estimated future value of money into the present value of that same amount of money. This is not the same as inflation. Each company has a different discount rate, because this rate is determined by several variables. One of

[12] (Barringer, 2003)
[13] (Davis Langdon, 2007)

these variables is the risk of the investment; if an investment has a high risk profile, the discount rate will also be high. Another variable is the duration of the investment. It is hard to predict what happens in the far future due to more uncertainties, so a longer duration results in higher risk and thus in a higher discount rate.

The last variable that influences the discount rate is the cost of capital. Cost of capital could mean cost of equity if the company is solely funded through equity. Another form of cost of capital is cost of debt when it is solely funded through debt. The last cost of capital is a combination of both. For a stable company the discount rate will be lower than for an unstable company. To summarize, the discount rate takes the risk of investment, opportunity costs and inflation into account.

If a chosen discount rate is too low, costs savings in the future will have a big impact on the outcome. However when the discount rate is too high, the future costs will have negligible impact on the result. The result of LCC is greatly influence by the chosen discount rate as shown in the previous example. The discount rate is used in the net present value calculation.

### NET PRESENT VALUE

The net present value (NPV) is used to convert the sum of future cash flows into today's money by discounting. This discounting is done with the discount rate. In case NPV is above zero there is an excess of cash flow and consequently in case NPV is below zero there will be a shortage of cash flow in terms of present value. If NPV is zero the discount rate is the same as the internal rate of return (IRR). NPV is calculated with the following equation[14]:

**EQUATION 1: NET PRESENT VALUE**

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i}$$

| | | | |
|---|---|---|---|
| NPV = | | Net present value | [ € ] |
| $C_0$ | = | Initial investment | [ € ] |
| $C_i$ | = | expected cash flows at time i | [ € ] |
| r | = | discount rate | [ - ] |

The following example shows the influence of the discount rate on NPV. There are three cases with each an investment at the beginning of the first year. This investment generates income over the following years. The income in the first case is spread evenly over the years. The second case represents a scenario where all the income is generated in the last year and in the third case the income occurs in the year after the investment. The sum of income is the same for all the cases as shown in table 1.

**TABLE 1: EXAMPLE EFFECT DISCOUNT RATE ON NPV**

| | Year | 0 | 1 | 2 | 3 | 4 | 5 | NPV at 4% | IRR |
|---|---|---|---|---|---|---|---|---|---|
| Cash flow | Case I | -1000 | 225 | 225 | 225 | 225 | 225 | 1.66 | 4.1% |
| | Case II | -1000 | 0 | 0 | 0 | 0 | 1125 | -75.33 | 2.4% |
| | Case III | -1000 | 1125 | 0 | 0 | 0 | 0 | 81.73 | 12.5% |

[14] (Lee & Lee, 2006)

Table 1 showed the used data for the NPV calculation. The NPV for different discount rates is illustrated figure 9.

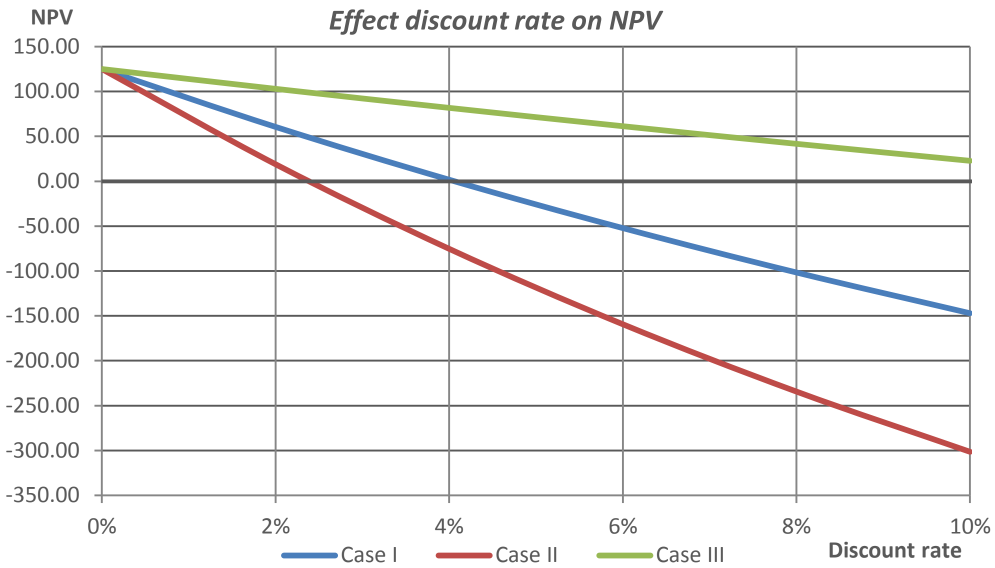



**FIGURE 9: EFFECT DISCOUNT RATE ON NPV**

As expected the NPV is decreasing when the discount rate is increasing. Also the time of cash flow is important. The third case is preferable, because this case has the highest NPV for each discount rate. This can be explained because the cash flow occurs soon rather than late in the investigated period, so the money is not discounted by much. It is the other way around in the second case when all the income is generated in the last year and is thus discounted the most. This example illustrates that the case with the highest internal rate of return results in the highest NPV. That is true for this particular example, but this is not always true as the next example shows.

In this example case I has the highest IRR, but case II has a higher NPV if, for example, a discount rate of 4 % is used. However at another discount rate, the NPV of case I could be higher, as shown in figure 10. The data used for this example is shown in table 2. This example shows that it is not wisely to only look at IRR but also look at NPV at the given discount rate.

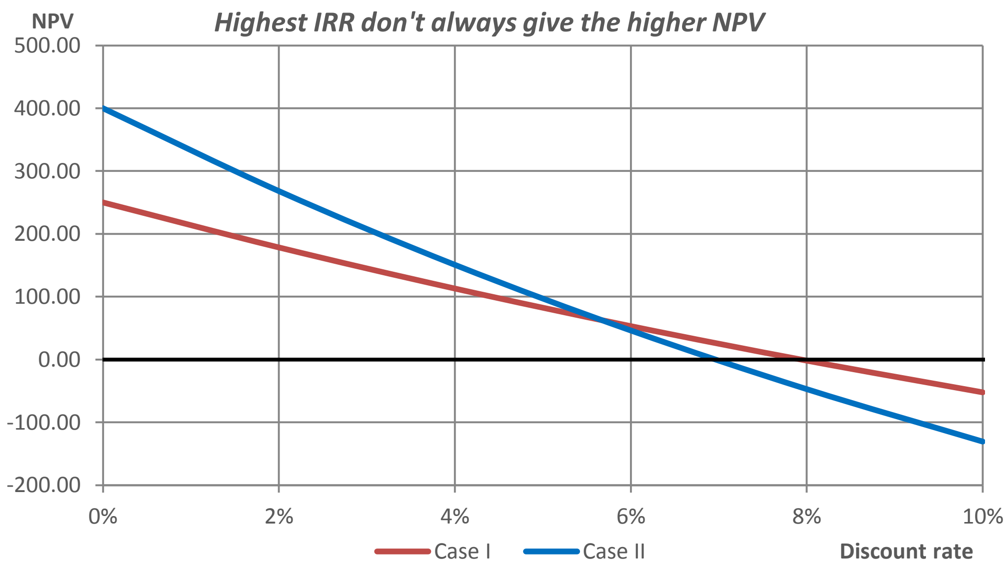



**FIGURE 10: EXAMPLE HIGHEST IRR IS NOT EQUAL TO HIGHEST NPV**

**TABLE 2: EXAMPLE HIGHEST IRR IS NOT EQUAL TO HIGHEST NPV**

| | Year | 0 | 1 | 2 | 3 | 4 | 5 | NPV at 4% | IRR |
|---|---|---|---|---|---|---|---|---|---|
| Cash flow | Case I | -1000 | 250 | 250 | 250 | 250 | 250 | 112.96 | 7.9% |
| | Case II | -1000 | 0 | 0 | 0 | 0 | 1400 | 150.70 | 7.0% |

The conclusion of LCC analysis is to take all the costs into account and discount those costs with an accurate discount rate to get a reasonable result, because the discount rate has a great influence on the outcome. Furthermore a LCC analysis can show which investment is better in terms of total costs of ownership. Maybe the investment with lower acquisition costs isn't the best investment over time.

The two main methods used in this graduation project are described and with these two methods the economic and environmental impact, or in other words the viability of a product can be defined. To determine how sustainable the product is, the social component must also be taken into account.

## 3.3 SOCIAL ASPECT

As mentioned in the introduction of this chapter, a sustainability assessment includes a social life cycle assessment. This assessment is not within the scope of this thesis, but a small description will be given. The outcome of the two previous assessments can be calculated. It doesn't matter which person is performing the assessments, the outcome should be the same. This will however not be the case for SLCA. SLCA is a method to determine social impacts of a product during its life cycle[15]. The United Nations Environment Programme has defined social impacts as follows:

*"Social impacts are consequences of positive or negative pressures on social endpoints"*
*(UNEP 2009)*

SLCA focuses on human well-being. Causes of social impacts can be categorized into three dimensions, behaviours, socio-economic processes and capitals. The first dimension behaviour is for instance child labour or prohibition to form unions. An example of socio-economic processes is the effect of an investment decision to build infrastructure in a community. Socio-economic processes can be on macro or micro level. The last dimension, capitals, can be subdivided into human, social and cultural capital. The impact of human capital can be working environment or safety of individuals. Social capital can be de-isolation of a particular group of people due to connect that group to the rest of the world. An example of cultural capital is the impact of a product on a tribe in the rain forest. These causes have dynamic relationships. When there is management pressure to reduce cost prices this could cause suppliers to force child labour behaviour. In this case socio-economic processes results in behaviour causes.

The framework for SLCA is like LCC the same as LCA. The impact phase is however difficult to quantify. Therefore social impacts are sometimes referred to as social effects to indicate the inability to calculate impacts, because how to weight social impact of products[16]. One person could weight human capital more than behaviour but for another person it could be the other way around. The outcome of a SLCA is because of this person dependent. The purpose is however that the outcome is independent of the person who is

[15] (Andrews, et al., 2009)
[16] (Macombe, Leskinen, Feschet, & Antikainen, 2012)

performing the assessment. This is not (yet) the case for SLCA, because the person who is performing the analysis has a huge impact on the outcome of the social aspect. This is the reason why SLCA is not within the scope of this thesis.

## 3.4 CHAPTER CONCLUSION

A life cycle sustainability assessment is a powerful tool to assess a product or system in terms of environmental, economic and social aspects. The environmental and economic aspects can be calculated, while social aspects have to be weighted. This is why for this dissertation only the environmental and economic aspects are taken into account. With only those two aspects the viability of a product is assessed, instead of the complete sustainability if social aspects were also taken into account. The next chapter will describe the emission rules and regulations that have to be taken into account for the environmental part.

# 4. EMISSIONS

Previous chapter states what the different methods are. For the environmental part, emissions have to be calculated. This chapter will describe the emissions and the rules that have to be taken into account. The description of current and future rules in 4.2 provides insight in the intended air emissions reductions and the reasoning behind it. The formation mechanisms of the harmful exhaust emissions of internal combustion engines are described in 4.1. This provided insight offers an indication in how to reduce emissions. Emission reduction measures to reach future emission goals are elaborated on in chapter 5.

The introduction already mentioned that in 2007 the shipping industry was responsible for 3.3 % of the total $CO_2$ emission. This is more than the total $CO_2$ emission of Germany. Despite these numbers, in comparison to other forms of transportation, sea transportation has the lowest $CO_2$ emission per transported unit of cargo, per unit of distance.

$CO_2$ is not the only product of combusting fossil fuels. Other airborne emissions, which are described in this chapter, are $SO_X$, $NO_X$ and Particulate Matters (PM). Ozone Depleting Substances (ODS) are not within the scope of this research because installations which contains ODS, other than hydro-chlorofluorocarbons, are prohibited on ships constructed on or after 19 May 2005, as shown in appendix B. The amount of Volatile Organic Compounds (VOC) emission is relatively low compared to other emissions[1] and therefore, like ODS, VOC is not within the scope of this research. Also other non-airborne emissions, sounds and discard water emissions are outside the scope of this research.

## 4.1 FORMING OF EMISSIONS

Air emissions from ships are hazardous. $CO_2$ is a greenhouse gas (GHG) which is believed to be responsible for global warming. Smog is a result of $NO_X$ in the atmosphere and $SO_X$ is responsible for acid rain. These are some effects of air emissions and in order to know how to reduce those the forming of these emissions has to be known. This will be described below.

### 4.1.1 CARBON DIOXIDE ($CO_2$)

Carbon dioxide is one of the most important greenhouse gases. It is formed during the combustion of hydrocarbon fuel, like marine diesel fuel. The fuel reacts with air which is mostly oxygen ($O_2$) to produce carbon dioxide and water. A general equation, shown in equation 2, for 'complex' hydrocarbon fuels (with x carbons and y hydrogen atoms) is.

**EQUATION 2: REACTION BURNING HYDROCARBON FUEL**

$$C_xH_y + \left(x + \frac{y}{4}\right) O_2 \rightarrow xCO_2 + \frac{y}{2} H_2O$$

For example when the fuel is Liquefied Natural Gas (LNG) which contains mostly methane ($CH_4$), the equation will be as illustrated in equation 3

**EQUATION 3: REACTION BURNING LNG**

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$$

These two equations are idealized, because air consists not only of oxygen, but also nitrogen and some other smaller particulars. The effect of nitrogen in air is discussed in the following section of this chapter.

### 4.1.2 NITROGEN OXIDE ($NO_X$)

Nitrogen Oxide includes mostly Nitric Oxide (NO) and Nitrogen Dioxide ($NO_2$) and in smaller parts Nitrous Oxide ($N_2O$) and other nitrogen oxide combinations. These $NO_X$'s are formed when nitrogen and oxygen in air reacts at high temperatures. The formation of NO can be described by the Zel'dovich mechanism. The following two equilibrium reactions show this mechanism[17].

EQUATION 4: ZEL'DOVICH MECHANISMS

$$N_2 + O \leftrightarrow NO + N$$

$$N + O_2 \leftrightarrow NO + O$$

Combining these two reactions, give the following equilibrium.

EQUATION 5: COMBINED ZEL'DOVICH MECHANISMS

$$N_2 + O_2 \leftrightarrow 2\,NO$$

The extended Zel'dovich mechanism adds a third reaction in the formation of NO.

EQUATION 6: EXTENDED ZEL'DOVICH MECHANISM

$$N + OH \leftrightarrow NO + H$$

These equations, equation 5 and equation 6, show the formation of NO which is the predominant compound in nitrogen oxide. Earlier was mentioned that $NO_X$'s are formed at high temperatures. $N_2$ molecules have strong triple bonds (N≡N) which needs high temperatures to break. This is the reason why the formation of NO is higher at higher temperatures. By reducing the temperature the formation of NO will also reduce.

### 4.1.3 SULPHUR OXIDES ($SO_X$)

Sulphur oxide includes mostly sulphur dioxide ($SO_2$). Sulphur oxides are formed due to the sulphur content in hydrocarbon fuels. This sulphur content is directly linked to the sulphur oxide emission. Higher sulphur content results in the forming of more sulphur oxide.

EQUATION 7: FORMING OF SULPHUR DIOXIDE

$$S + O_2 \rightarrow SO_2$$

In respect to carbon the chemical properties for sulphur are similar which causes sulphur to react with oxygen to sulphur dioxide as shown in equation 7.

### 4.1.4 PARTICULATE MATTERS (PM)

Particulate matters are the solid based emission and can be divided into two main fractions. The first fraction is insoluble and contains carbon or ashes from incombustible parts of the fuel or lubrication oil. This fraction is influenced by the type of fuel and lubricant; also the injection system and the working conditions inside the engine have a large influence on the formation of this kind of PM. An example of this type of PM is soot, visible as black smoke exiting the funnel.

The second fractions are sulphates which are formed by the reaction of sulphur oxides and water. This second fraction is linked to the sulphur content of the fuel. The higher the

[17] (Stapersma, 2003)

sulphur content in the fuel, the more sulphates can be formed. Equation 8 shows the forming of these sulphates.

EQUATION 8: FORMING OF SULPHATES

$$SO_2 + H_2O \rightarrow H_2SO_3$$

$$SO_3 + H_2O \rightarrow H_2SO_4$$

Both types of PM occur in different sizes which are categorized as $PM_{10}$ and $PM_{2.5}$. The number behind indicates the maximum diameter in µm of the PM. Figure 11 shows the size of PM compared to a human hair.

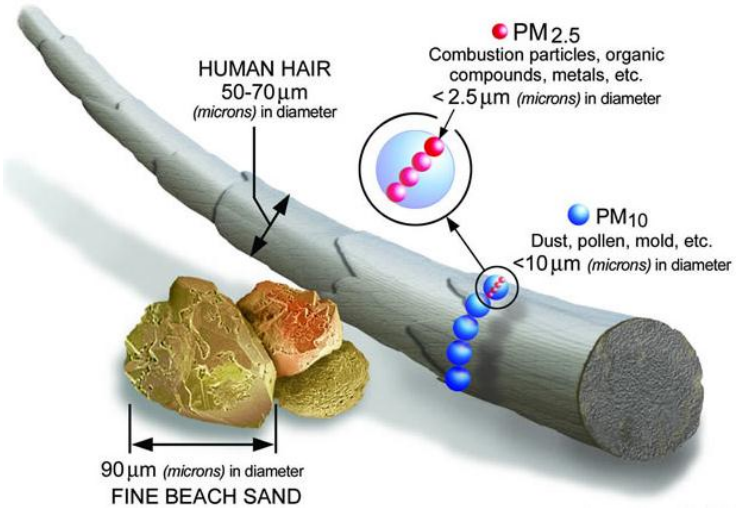



FIGURE 11: PM COMPARISON (EPA)

As this figure shows PM can be very small causing serious health problems when PM gets deep into lungs. Table 3 and table 4 show a summary of this part of chapter 4.1. Table 3 shows sources of emissions.

TABLE 3: SOURCE OF EMISSION

| Component | Source |
|---|---|
| Carbon Dioxide ($CO_2$) | Carbon in the fuel and oxygen in the air |
| Nitrogen Oxide ($NO_X$) | Nitrogen and Oxygen in the air |
| Sulphur Oxides ($SO_X$) | Sulphur in the fuel and oxygen in the air |
| Particulate Matters (PM) | Sulphur in the fuel and ash in the fuel/lubricant |

Table 4 shows the impact of emission on local, regional and global levels.

TABLE 4: IMPACT OF DIFFERENT EMISSIONS [*FIAZ A., WORLD BANK (1991)*]

| Impact | | $CH_4$ | $CO_2$ | $NO_X$ | PM | $SO_X$ |
|---|---|---|---|---|---|---|
| Local | Health and welfare | | | X | X | X |
| Regional | Acidification | | | X | | X |
| | Photochemical oxidants | | | X | | |
| Global | Indirect greenhouse effect | X | | X | | |
| | Direct greenhouse effect | X | X | | X | |
| | Stratospheric ozone depletion | | | X | | |

With the forming of all the important air emissions is described, the rules regarding these emissions will be explained in the next part of this chapter. These rules will be used to determine if the emitted emissions are within the limits.

## 4.2 EMISSION RULES

In 1997 the Kyoto protocol[18] was adopted but the shipping industry is not directly regulated by the Kyoto Protocol. The protocol states the following in article 2.2:

*"2.2 The Parties included in Annex 1 shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively." (Kyoto Protocol, 1997)*

The International Maritime Organization (IMO) is one of the several specialized agencies of the United Nations. The IMO is responsible for the safety and security of shipping. The IMO is governed by an assembly and a council. The council can be subdivided in different committees who deal with different aspects of shipping, for instance safety on sea or pollution. The Marine Environment Protection Committee (MEPC) deals with the prevention of pollution from ships. The most important convention of the IMO regarding marine pollution is MARPOL[19]. MARPOL is an international regulation, but there are also regulations for particular areas like the European Union, described in 4.2.2, California described in 4.2.3 and the Baltic Sea Area in 4.2.4.

### 4.2.1 INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS (MARPOL)

MARPOL 73/78 stands for Marine Pollution and 73/78 refers to the years (1973) in which the convention was adopted and the year (1978) that the protocol was adopted. This convention covers the prevention of pollution of the marine environment by ships from operational or accidental causes and this is the main convention which is internationally used. Although the convention was adopted in 1978, it did not enter into force before October 1983. Over the years multiple amendments were added to the convention starting with the prevention of pollution by oil to the sixth and last and most important amendment for this research thesis; the prevention of air pollution from ships. This last amendment was a response to the Kyoto Protocol as mention earlier this chapter. The purpose of this amendment is to minimize the earlier mentioned airborne emissions. The sixth amendment was adopted in 1997, but it entered into force on the 19$^{th}$ of May 2005. In October 2008 it was revised with significantly tightened emission limits. This revised Annex VI entered into force on the first of July 2010. Until 30 September 2013 73[20] countries (representing 94.12 % of the World's tonnage) have ratified this convention.

$CO_2$ was the first emission that was mentioned in resolution 8 in 1997 but it took until October 2012 before $CO_2$ emission was regulated in MARPOL annex VI. A new and fourth chapter[21] was added and also some regulations in the existing chapters were amended. For instance in chapter one, regulation two, *definitions,* some lines were added to define for which ship types the fourth chapter is applicable. The fourth chapter is the result of years of developing in multiple MEPC sessions and working groups, which started in 1997 during the 40$^{th}$ MEPC session until the finalization in the 64$^{th}$ MEPC session in 2012. During

[18] (Kyoto protocol to the United Nations framework convention on climate change, 1998)
[19] (IMO MARPOL, 2013)
[20] (IMO Conventions, 2013)
[21] (IMO MARPOL annex VI, chapter 4, 2013)

the 63rd MEPC session, four guidelines were adopted to assist in the implementation of the new regulations. This addition came into force on the first of January 2013.

MARPOL annex VI currently contains four chapters, starting with a general chapter, followed by a survey, certification and means of control. Chapter three describes the requirements for emission control from ships and the last chapter, chapter four as described above, states regulations on energy efficiency for ships.

Appendix B shows the useful sections of the revised MARPOL annex VI. The useful sections are the following and will be described into more detail in the next part of this chapter.

- Chapter 1: *General*
  - Regulation 2: Definitions
  - Regulation 3: Exceptions and exemptions
- Chapter 3: *Requirements for control of emissions from ships*
  - Regulation 12: Ozone Depleting Substances
  - Regulation 13: Nitrogen Oxides ($NO_X$)
  - Regulation 14: Sulphur Oxides ($SO_X$) and Particulate Matter (PM)
- Chapter 4: *Regulations on energy efficiency for ships*

## CARBON DIOXIDE ($CO_2$)

The fourth chapter of MARPOL annex VI is related to $CO_2$ emission. This chapter consists of five regulations starting with regulation 19 which states the application of the fourth chapter. The 19th regulation defines which ships are taken into account and which are not. In general, taking into account the definitions from the first chapter of MARPOL annex VI, all ships of 400 GT and more have to comply with this chapter and thus these regulations, unless as stated in application 1.2.1 of the 19th regulation[22]:

*"1.2.1 ships solely engaged in voyages within waters subject to the sovereignty or jurisdiction of the State the flag of which the ship is entitled to fly. However, each Party should ensure, by the adoption of appropriate measures, that such ships are constructed and act in a manner consistent with chapter 4, so far as is reasonable and practicable."*
*(MARPOL Annex VI, 2005)*

Other exceptions are ships that have a diesel-electric, turbine or hybrid propulsion system. For these ships the 20th and 21st regulations are not applicable.

The 20th regulation describes the attained Energy Efficiency Design Index (EEDI) value. The EEDI calculates the amount of $CO_2$ emission per transported work over a nautical mile. The EEDI formula is shown in figure 12.

$$\frac{\overbrace{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}^{\text{Main engine(s)}} + \overbrace{\left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}\right)}^{\text{Auxiliary engine(s)}} + \overbrace{\left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right)}^{\text{Energy saving technologies (auxiliary power)}} - \overbrace{\left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}^{\text{Energy saving technologies (main power)}}}{\underbrace{f_i \cdot f_c \cdot Capacity \cdot f_w \cdot V_{ref}}_{\text{Transport work}}}$$

**FIGURE 12: EEDI FORMULA**

[22] (IMO MARPOL annex VI, regulation 19, 2005)

This EEDI formula is basically a cost/benefit calculation where the cost is the effect of $CO_2$ on the environment and the benefit the transported goods. It can be explained as the installed engine power with possible correction factors divided by the transported work. These correction factors can be for the use of solar or wind power or the use of waste heat recovery systems. The lower the EEDI factor, the less $CO_2$ that ships emits, compared to other ships with the same capacity. The simplified formula will be:

EQUATION 9: SIMPLIFIED EEDI FORMULA

$$EEDI = \frac{CO_2\ emission}{Capacity \cdot distance}\left[\frac{g}{t\ \cdot Nm}\right]$$

The guidelines that IMO has developed for the calculation method of EEDI can be found in resolution MEPC.212 (63)[23]. It is basically a two stages verification process. An application for EEDI pre-verification will be made and submitted to the verifier/classification society. When this pre-verification is accepted, the constructing of the ship can commence. When the pre-verification is not accepted, it is not allowed to start building the ship. The second stage is the final verification which will take place during sea trails. This EEDI is calculated for all new ships over 400 GT as defined in MARPOL annex VI, regulation 2.25 until 2.35.

The required EEDI, as the 21$^{st}$ regulation shows is not (yet) applicable to regulations 2.32 till 2.35, but probably it will be a matter of time before this change in the future. During the 66$^{th}$ MEPC meeting in 2014, there will be discussed if the required EEDI will also be mandatory for more ships like for instance LNG carriers and Ro-Ro ferries. The required EEDI has to be as high as or higher than the attained EEDI as the following formula shows:

EQUATION 10: ATTAINED EEDI FORMULA

$$Attained\ EEDI\ \leq \left(Required\ EEDI = \frac{1-\mathrm{x}}{100} \cdot Reference\ line\ value\right)$$

The x is the reduction factor in percentage which depends on ship type, deadweight and date of keel-laying. This reduction factor can be found in table 5 and will be lower for each next phase.

TABLE 5: REDUCTION FACTORS FOR REQUIRED EEDI IN PERCENTAGE

| Ship Type | Size [DWT] | Phase 0: 1 Jan '13 – 31 Dec '14 | Phase 1: 1 Jan '15 – 31 Dec '19 | Phase 2: 1 Jan '20 – 31 Dec '24 | Phase 3: 1 Jan '25 and onwards |
|---|---|---|---|---|---|
| Bulk carrier | ≥ 20.000 | 0 | 10 | 20 | 30 |
| | 10.000 – 20.000 | n/a | 0 – 10* | 0 – 20* | 0 – 30* |
| Gas carrier | ≥ 10.000 | 0 | 10 | 20 | 30 |
| | 2.000 – 10.000 | n/a | 0 – 10* | 0 – 20* | 0 – 30* |
| Tanker | ≥ 20.000 | 0 | 10 | 20 | 30 |
| | 4.000 – 20.000 | n/a | 0 – 10* | 0 – 20* | 0 – 30* |
| Container ship | ≥ 15.000 | 0 | 10 | 20 | 30 |
| | 10.000 – 15.000 | n/a | 0 – 10* | 0 – 20* | 0 – 30* |
| General Cargo ships | ≥ 15.000 | 0 | 10 | 15 | 30 |
| | 3.000 –15.000 | n/a | 0 – 10* | 0 – 15* | 0 – 30* |
| Refrigerated cargo carrier | ≥ 5.000 | 0 | 10 | 15 | 30 |
| | 3.000 – 5.000 | n/a | 0 – 10* | 0 – 15* | 0 – 30* |
| Combination carrier | ≥ 20.000 | 0 | 10 | 20 | 30 |
| | 4.000 – 20.000 | n/a | 0 – 10* | 0 – 20* | 0 – 30* |

** Reduction factor to be linearly interpolated between the two values dependent upon vessel size. The lower value of the reduction factor is to be applied to the smaller ship size.*
*N/A means that no required EEDI applies.*

[23] (IMO resolution MEPC.212(63), 2012)

An indication what the effect of these phases are in relation to DWT can be seen in figure 13.

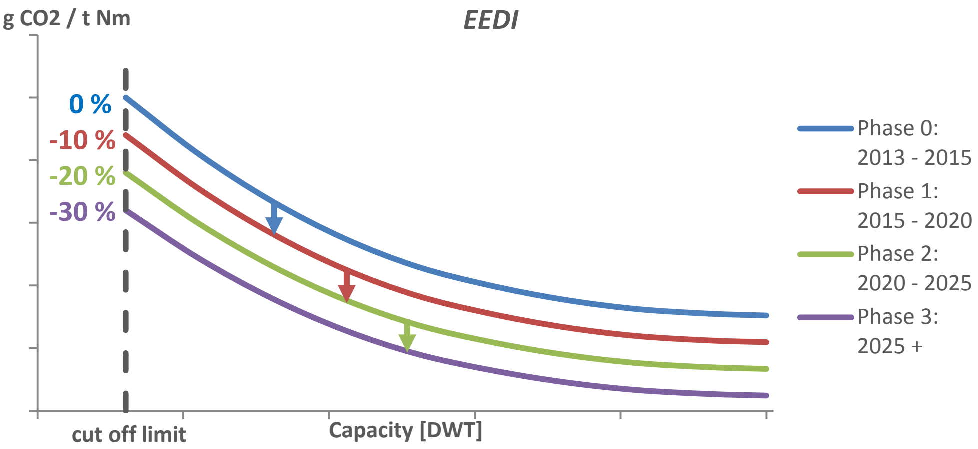



FIGURE 13: EFFECT OF EEDI FOR DIFFERENT PHASES

The reference line value is also different for each type of ship. The used formula for each type is the same, only with different parameters.

EQUATION 11: REFERENCE LINE VALUE

$$Reference\ line\ value = A \cdot B^{-C}$$

The parameters for the formula are shown in table 6.

TABLE 6: PARAMETERS FOR FORMULA TO CALCULATE REFERENCE LINE

| | Ship type | A | B | C |
|---|---|---|---|---|
| 2.25 | Bulk carrier | 961.79 | DWT of the ship | 0.477 |
| 2.26 | Gas carrier | 1120.00 | DWT of the ship | 0.456 |
| 2.27 | Tanker | 1218.80 | DWT of the ship | 0.488 |
| 2.28 | Container ship | 174.22 | DWT of the ship | 0.201 |
| 2.29 | General cargo ship | 107.48 | DWT of the ship | 0.216 |
| 2.30 | Refrigerated cargo carrier | 227.01 | DWT of the ship | 0.244 |
| 2.31 | Combination carrier | 1219.00 | DWT of the ship | 0.488 |

In contrast to the EEDI the Ship Energy Efficiency Management Plan (SEEMP) is mandatory for all ships, new and existing, over 400 GT. This is described in regulation 22 which can be found on page 136 of this thesis. The goal of the SEEMP is to improve the ship's energy efficiency and will be part of ship's Safety Management System (SMS). The SEEMP consist of four parts, planning, implementation, monitoring & self-evaluation and improvement. The monitoring can be done using Energy Efficiency Operational Indicator (EEOI) or other key performance indicators. IMO resolution MEPC.213 (63) provides guidelines for the development of SEEMP. The last regulation, 23, is the promotion of improvement of energy efficiency.

Basically this fourth chapter introduces two mandatory mechanisms to establish measurable energy efficient benchmark for ships, the EEDI and the SEEMP. These values are related to the $CO_2$ emission of the ship and enable to compare similar ship types. The next part of this chapter mentioned the rules regarding nitrogen oxide.

## NITROGEN OXIDE ($NO_X$)

MARPOL Annex VI regulation 13 describes the limitations of $NO_X$ emissions. The $NO_X$ emission limits are a function of the engines maximum operating speed. The regulation only applies to marine diesel engines, not used for emergencies only, with an installed power output of more than 130kW. When the ship undergoes a major conversion as described in regulation 13 section *major conversion*, other limitation can be applied. There are three different types, Tier I, Tier II and Tier III, each with their own limitation. The formulas for calculation the $NO_X$ limits for the different tiers are given in table 7.

TABLE 7: $NO_X$ LIMITS [G/KWH]

| Tier | Date | n < 130 | 130 ≤ n < 2000 | n ≥ 2000 |
|---|---|---|---|---|
| I | 2000 | 17 | $45 \cdot n^{-0.2}$ | 9.8 |
| II | 2011 | 14.4 | $44 \cdot n^{-0.33}$ | 7.7 |
| III | 2016 | 3.4 | $45 \cdot n^{-0.2}$ | 1.96 |

These limitations are shown graphically in figure 14. As the figure shows, the reduction in respect to Tier I is for Tier II 20 % and for Tier III even 7 5%.

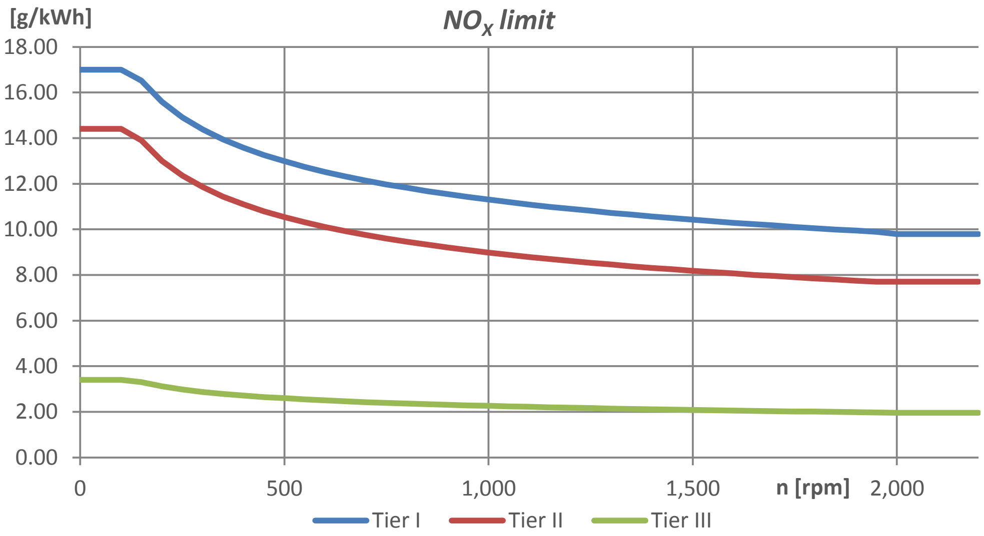



FIGURE 14: $NO_X$ EMISSIONS LIMITS

Tier I is applicable to engines installed on or after the first of January 2000 and before the first of January 2011. Tier II is applicable to engines installed on or after the first of January 2011 which from 2016 are not operating in an Emission Control Area (ECA). The definition of an ECA will be described later this chapter. Tier III is applicable for marine diesel engines which are installed on or after the first of January 2016 and which are operating in an ECA. There is however a side note to this date. During the 65th MEPC[24] meeting it was suggested to delay the Tier III implementation until 2021. This will be discussed during the next (66th) MEPC meeting in March 2014.

## SULPHUR OXIDES ($SO_X$)

MARPOL annex VI, regulation 14 limits the sulphur content of any fuel oil used on board. These limitations are different for the area the ship is operational. If the ship is operating in an ECA, the rules will be stricter than when the ship is operating outside an ECA. The difference is shown in table 8.

TABLE 8: SULPHUR LIMIT IN FUEL [% M/M]

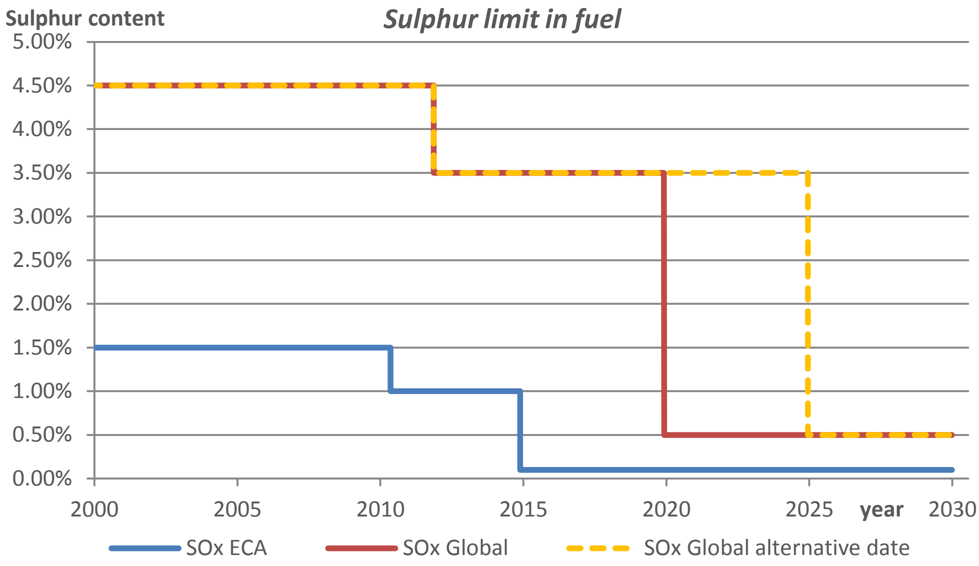
| Date | Outside ECA | Inside ECA |
|---|---|---|
| 2000 | 4.5 % | 1.5 % |
| 2010-07 | | 1.0 % |
| 2012 | 3.5 % | |
| 2015 | | 0.1 % |
| 2020* | 0.5 % | |

** will be reviewed in 2018, to extend the time to 2025*

24 (IMO MEPC 65, 2013)

As the table shows, reduction of sulphur content in fuel is done in predefined steps. The only date that is not fixed yet is the limitation of sulphur content of 0.5 % outside the ECA. In 2018 there will be a feasibility review if 2020 will be the date when it will be put into force or if the date is postponed to 2025. A possible reason for postponing the date is the availability of low sulphur content fuel. There will be no exception, because the rules are known to ship owners for quite some time. However if the ship owner can prove that due to aftertreatment systems the ship complies with the $SO_X$ emission limits the ship is allowed to sail on fuel with higher sulphur content. These limitations are graphically shown in figure 15.

FIGURE 15: SULPHUR CONTENT OF FUEL LIMITS




### PARTICULATE MATTERS (PM)

Regulations regarding particulate matters are covered in the same regulation as sulphur oxides. The reduction of PM is linked to the reduction of $SO_X$, meaning reducing the amount of sulphur in fuel results in a lower particulate matters emission.

### EMISSIONS CONTROL AREAS (ECAS)

The previous paragraphs mentioned emission control areas. The purpose of an ECA is to reduce and prevent adverse impacts on the environment and human health in those areas due to $SO_X$, $NO_X$ and/or PM emissions. Each area can be designated for $SO_X$ and PM or $NO_X$ or for all three types. Table 9 shows which four areas are current defined in MARPOL annex VI. These areas are not the same as the special areas that are defined in other annexes of the MARPOL convention.

TABLE 9: EMISSION CONTROL AREAS

| Area | Emission | Year into force |
|---|---|---|
| Baltic Sea | $SO_X$ | 2005 |
| North Sea | $SO_X$ | 2005/2006 |
| North American ECA | $NO_X$, $SO_X$ and PM | 2010/2012 |
| US Caribbean ECA | $NO_X$, $SO_X$ and PM | 2011/2014 |

These ECA and possible future ECA are shown in figure 16. The figure shows that there are plans to define the Mediterranean Sea and Strait of Malacca as ECA. Busy ports like Hong Kong and Busan are also investigating how to become an emission control area to reduce air emissions in the cities. For the future it is foreseen that the amount of ECAs will only increase.


**FIGURE 16: CURRENT AND POSSIBLE FUTURE ECA**

## 4.2.2 EUROPEAN UNION

As described earlier this chapter, MARPOL is not the only regulation for emission. Some countries or areas, like the European Union, have their own even stricter rules. The European Union has rules regarding the sulphur content of marine fuels during berth in all Community port, except ports on the Azores, Canary Islands, the French oversees departments and Madeira. The latest rules are stated in Directive 2012/33/EU[25] which was adapted on 21 November 2012. The complete regulations are shown in Appendix C. Directive 2012/33/EU is amending Council Directive 1999/32/EC. The most important articles are the following:

*"Article 2 Definitions: for the purpose of this Directive:*

*3i. ships at berth means ships which are securely moored or anchored in a Community port while they are loading, unloading or hoteling, including the time spent when not engaged in cargo operations;*

*Article 4b Maximum sulphur content of marine fuels used by ships at berth in Community ports*

***1.** With effect from 1 January 2010, Member States shall take all necessary measures to ensure that the following vessels do not use marine fuels with a sulphur content exceeding 0.1 % by mass:*

*(b) ships at berth in Community ports, allowing sufficient time for the crew to complete any necessary fuel-changeover operation as soon as possible after arrival at berth and as late as possible before departure.*

*Member States shall require the time of any fuel-changeover operation to be recorded in ships' logbooks." (Directive 2012/33/EU, 2012)*

There are some exceptions for instance when the ship is less than two hours at berth, as stated in point two of article 4b. Another exception can be when ships are using approved emission abatement technology.

[25] (Directive 2012/33/EU, 2012)

### 4.2.3 CALIFORNIA

Like the European Union, also California has stringent regulation regarding air emission. The California Air Resources Board is a department of the California Environmental Protection Agency. In June 2009[26] the Californian Air Resources Board implemented new regulations regarding the fuel use within 24 nautical miles from the Californian coastline. Like all the other regulations, this regulation is also stated in Barclays Official California Code of Regulations. More specific under title 13: Motor vehicles, division 3: Air Resources Board, chapter 5.1: Standards for Fuels Non-vehicular Sources, paragraph 2299.2 Fuel Sulfur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline. The whole section is shown in appendix D. The most important text, part (e) Operational Requirements, (1) Fuel Sulfur Content Limits (A / B) point 3, of the regulation is cited:

*"Part (e) Operational Requirements, (1) Fuel Sulfur Content Limits (A / B) 3. Except as provided in subsections (c) and (h), beginning January 1, 2014, a person subject to this section shall operate any (A) auxiliary diesel engine / (B) main engine or auxiliary boiler, while the vessel is operating in Regulated California Waters, with marine gas oil (MGO) with a maximum of 0.1% sulfur by weight or marine diesel oil (MDO) with a maximum of 0.1% sulfur by weight, rounded as specified in subsection (i)(3)." (CARB, 2009)*

The purpose of this regulation is to reduce emissions of nitrogen and sulphur oxides and particulate matters from both main and auxiliary diesel engines and diesel-electric engines on ocean going ships. Also auxiliary boilers are affected by this regulation. The vessels that are excluded from this regulation are given in Appendix D. As of 2016 these rules seems obsolete because MARPOL gives the same limitations to sulphur content, unless the MARPOL rules are delayed.

### 4.2.4 BALTIC SEA

As earlier described, the Baltic Sea is defined as ECA in MARPOL and has therefore stricter emission limits. Besides those mandatory regulations, ports in the Baltic like Stockholm[27] offers discount on normal port tariffs in case ships operate on low sulphur fuel or emits low $NO_X$. Other ports like Gothenburg also offer discount or surcharge depending on which type of fuel is used. The exact environmental discounts are given in appendix E.

Norway has also an interesting tax regulation, the so-called $NO_X$ fund[28]. In order to reduce $NO_X$ emissions in Norway, this fund was established in 2008 between fifteen Norwegian business organizations, representing 92 % of all emissions subject to $NO_X$ tax and the Norwegian Ministry of the Environment. The purpose of this fund is that it can provide support up to 80 % of the total cost of $NO_X$ reducing measures to companies. Annually the $NO_X$ fund can provide around 80 million euro as support. The money for this subsidy is paid by domestic shipping, industry and gas production companies who pay an amount of money for each kg $NO_X$ they emit. The amount of $NO_X$ emissions is calculated by multiplying fuel consumption with an emission factor. This fund has already granted support to 49 ships.

[26] (CARB, 2009)
[27] (Stockholms Hamnar, 2013)
[28] (Directorate of Customs and excise, 2013)

### 4.2.5 POSSIBLE FUTURE RULES

Some rules that are mentioned above are not into force at the moment. For instance the Tier III rules will be implemented in 2016, if that date is not postponed. There are more rules that are currently not into force but in the future they could be. An example is IMO's Polar code which aims to protect the fragile Artic areas. The code is currently applicable to MARPOL annex I, II and V and the goal is to establish a zero discharge protection. In the future this code can also be applicable to Annex VI, especially when more ships are using the shorter Northern Sea Route from Asia to Europe or the Northwest Passage from Europe to the West coast of America. The time that those routes are impassable due to ice is shortened and also the amount of ice that ship who sails those routes can encounter is dropping.

Another rule that is still being developed is the Market-Based Mechanism (MBM)[29] regarding $CO_2$ emissions. This was started in October 2006 during the 55$^{th}$ MEPC meeting and the idea is to price GHG emissions. This provides for the shipping industry an incentive to reduce its GHG emission. Although the planning was to have a regulation regarding MBM at the end of the 63$^{rd}$ MEPC meeting, during the 65$^{th}$ MEPC meeting it was agreed to suspend the MBM discussion to a future meeting.

### 4.2.6 OTHER RULES

The Convention of Hong Kong[30] is not directly related to air emissions but is about recycling of ships and the Green Passport. The Green Passport is currently known as the Inventory of Hazardous Materials on board ships. The aim of the Hong Kong Convention is to guarantee that ships do not pose unnecessary risk to the environment or to safety and human health during the recycling stage. This can be achieved when all the hazardous materials on board the ship are known by the people who recycle that ship. These hazardous materials can then be removed safely. In 2013 the Kingdom of Norway is the only country that has ratified this Convention.

The Convention will enter into force after two years when more than fifteen States that represent at least 40 % of the world merchant shipping by gross tonnage have ratified this Convention. Furthermore these States cannot have a combined maximum annual ship recycling volume of more than 3 % of their combined tonnage.

## 4.3 CHAPTER CONCLUSION

There are different areas in the World, each with different rules. The trend is that in close proximity to populated places rules are stricter. Also the rules become stricter over time and the expectation is that this will continue to be so in the future. As part of IMO, MARPOL has the most influential, but not the strictest rules in the World. Because of this influence and size, MARPOL has a drawback; it takes time to apply new rules.

Due to new and stricter rules in the future, emissions have to be reduced. In order to understand how to reduce emissions, this chapter described the origin of most emission. Chapter 5 will describe measures to reduce emissions to comply with current and future rules.

[29] (IMO MBM, 2013)
[30] (IMO Hong Kong, 2013)

# 5. EMISSION REDUCTION MEASURES

The previous chapter described regulations and emission limits. It showed that those limits will become stricter in the future. The formation of emissions is an important indicator on how to reduce those emissions and the forming was described in the chapter 4.1. Table 3 provides the main sources for each emission.

There are different ways to reduce air emission from ships. The first solution is to reduce the ships resistance in order to reduce the necessary installed power. By optimizing the hull for instance, the resistance will be lower, so the required power to achieve the same top speed is lowered. The second way is to optimize the propulsor, meaning optimize the conversion from engine power to propulsion. By having less energy loss from the engine into the water, the amount of required power is reduced. These two solutions are based on reducing the amount of required power in order to reduce emissions. The third and last option is to optimize the power plant itself. This power plant can be subdivided into three parts, as shown in figure 17.

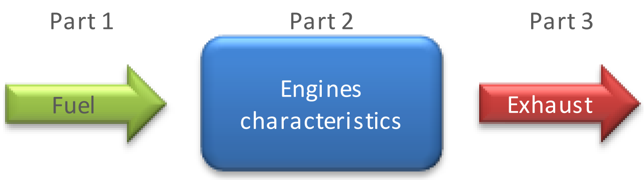



**FIGURE 17: SUBDIVISION OF POWER PLANT**

The first part is the input (fuel) of the power plant. The second part is the characteristic of the power plant; the combustion temperature, valve control etcetera. The third part of the power plant is the exhaust gas.

The power plant and specifically the engines in- and outflow are most interesting. The hull is assumed to be optimized, so the friction resistance is as low as possible. The propulsor is also believed to be as efficient as possible leaving the power plant as the only option to reduce the air emissions. Looking closer at the power plant it is assumed that the manufacturer has optimized the engine characteristics. The only two parts that can be used for emission reduction are the type of fuel and the use of possible exhaust gas treatment systems.

## 5.1 FUELS (ISO 8217)

The type of fuel that is used has a significant impact on the emission. This emission is not limited to only one, but can be multiple emissions. As mentioned in chapter 4.1 the forming of $CO_2$ and $SO_X$ is influenced by the fuel content of respectively carbon and sulphur. By lowering the amount of carbon and sulphur content in fuel, the emission of respectively $CO_2$ and $SO_X$ is reduced. This following part will describe different types of fuel and the effect those fuels have on emissions, starting with the most commonly used, heavy fuel oil (HFO).

### 5.1.1 HEAVY FUEL OIL

Another name for heavy fuel oil is marine fuel oil (MFO) though HFO is commonly used. HFO is residual fuel oil derived from the distillation process of crude oil. HFO has a high density and viscosity and is the cheapest but also the dirtiest fuel as shown in figure 18.

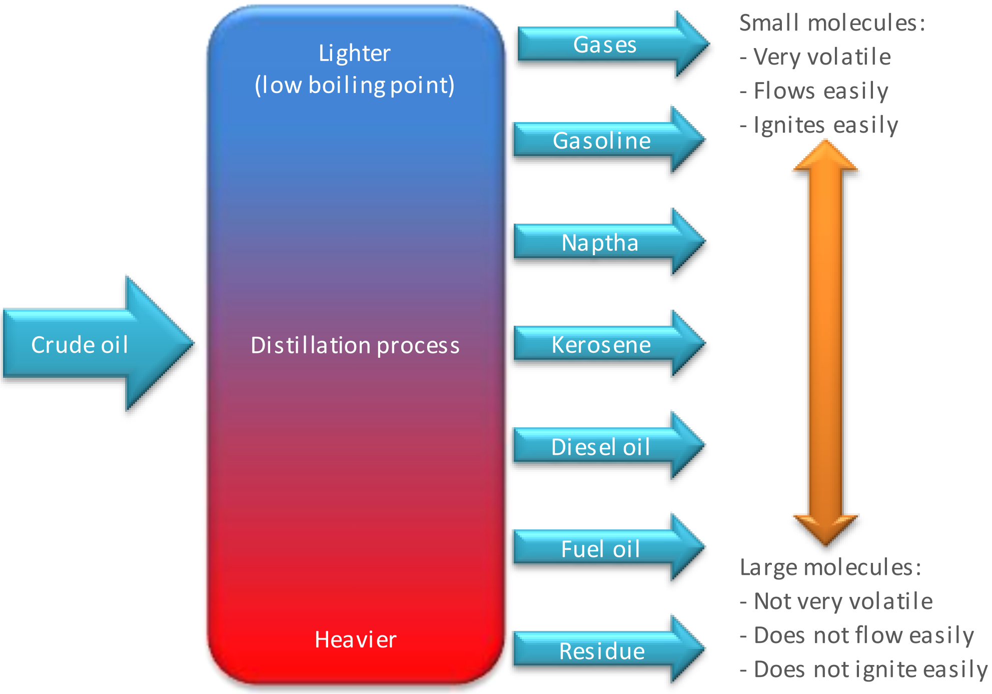



**FIGURE 18: REFINING OF CRUDE OIL**

All cleaner fuels are already extracted and HFO is left. The sulphur content varies, but aftertreatment in the refinery it is below the necessarily 3.5 % as set in MARPOL annex VI, regulation 14.

### 5.1.2 LOW SULPHUR OIL

Low sulphur fuels (LSF) are fuels with sulphur content of 1 % (10000 ppm) or lower. There are two techniques to produce LSF out of heavier fuel oils; the first is hydrotreating or hydrodesulphurization. This method is based on the reaction of fuel with hydrogen to form hydrogen sulphide. This reaction takes place under heat and high pressure in the presence of a catalyst as equation 12 shows.

**EQUATION 12: HYDROTREATING OR HYDRODESULPHURIZATION**

$$C_aH_bSH + H_2 \rightarrow C_aH_{b+1} + H_2S$$

The sulphur content in fuel is reduced and converted into hydrogen sulphide. The catalyst is needed to accelerate the rate of the reaction.

The second technique is hydrocracking which is similar to hydrotreating. The only difference is that hydrocracking also converts heavier molecules into lighter ones. Cracking is used on heavy fuels when hydrotreating requires too much hydrogen.

Marine gas oil (MGO) is an example of low sulphur fuel. It is a light distillate type of fuel that doesn't require hydrotreating or hydrocracking to reduce the sulphur content. Marine diesel oil (MDO) not to be confused with the earlier mentioned MFO, is a mixture of HFO and MGO to lower the sulphur content. The results of low sulphur fuels are that $SO_X$ emissions and PM are reduced with respectively 80 % and 20 % in case the sulphur content is lowered from 2.7 to 0.5[31]. However $NO_X$ emission is not influenced by the use of LSF.

[31] (Cleantech, 2013)

### 5.1.3 LIQUEFIED NATURAL GAS

Liquefied Natural Gas (LNG) is natural gas cooled at atmospheric pressure to around -162°C to convert gas into a liquid. By liquefying natural gas, the volume is reduced by almost 600 times. Natural gas is a gas mixture predominated by methane. The composition depends on where the gas is extracted. This composition has an influence on the calorific heating value of LNG.

Compared to conventional marine fuels LNG has a higher hydrogen-to-carbon ratio, which results in lower specific $CO_2$ emissions. $NO_X$ emission is as described earlier related to temperature and because the peak temperature of LNG is lower than conventional marine fuels, the $NO_X$ emissions are reduced up to 90 %. The last emissions, $SO_X$ and PM, are almost eliminated due to the removal of sulphur during the "cleaning" of the gas before the liquefaction process. The gas is cleaned before liquefaction because otherwise those components will freeze during the cooling process which could create problems downstream. A ship fuelled by LNG can operate in an ECA without any exhaust gas treatment system. However in terms of emissions there is one drawback with LNG and that is methane slip. The impact of methane is as mentioned earlier 25 times worse than the impact of $CO_2$ over 100 years. This methane slip problem is expected to be solved in the (near) future.

The expected total emission reduction of LNG is, compared to conventional fuels, for $CO_2$ around 14 %, for $NO_X$ around 80-90 % and for $SO_X$ and PM around 100 %. LNG seems the perfect solution for the shipping industry, however due to the energy content of LNG in comparison to diesel oil, LNG required 1.8 times more space to store the same amount of energy. When taking the storage tanks and additional requirements for LNG into account, LNG requires three times more volume in comparison to diesel oil. This is a reason why LNG is mostly used in new build and not in retrofit. Another point worth mentioning is the availability of LNG. The infrastructure for LNG like bunker stations is growing, but this takes time.

## 5.2 ENGINES

There are different types of fuels for marine engines. Some fuels are liquid and other gaseous which requires different types of engines. Three types of engines will be described, diesel engines, gas engines and dual fuel engines. There are also gas turbines and steam turbines; however, these are not in the scope of this thesis, because Damen never installs these turbines.

### 5.2.1 DIESEL ENGINES

Diesel engines are based on the diesel process. This process consists of four steps, the intake, compression, combustion and outlet. Air is let into the cylinder during the inlet stage which is compressed in the next stage. During the combustion stage, fuel (HFO or MDO) is injected into the compressed air which instantly ignites due to the high temperature. The last stage is the outlet, where the exhaust gases are pushed out of the cylinder. Diesel engines can be categorized in two parts, two stroke engines and four stroke engines. The difference is that two stroke engines completes the cycle in one crankshaft rotation and four strokes needs two crankshaft rotations to complete the cycle.

### 5.2.2 GAS ENGINES

Gas engines are based on the lean burn principle. This means that the air-fuel ratio is high and this lowers combustion temperatures, causing a reduction in $NO_X$ emission. In comparison to diesel process, gas is mixed with air before the inlet valves, so an air gas mixture enters the cylinder. During the inlet stage, gas is also fed into a small pre-chamber and this gas mixture is rich compared to the gas mixture in the cylinder. The gas mixture in this chamber is ignited by a spark during the combustion stage and this ignites the gas mixture in the cylinder. The outlet stage is the same as in a diesel process.

### 5.2.3 DUAL FUEL ENGINES

Dual fuel engines can operate on both gas and liquid fuel. In comparison to the above described lean burn process the process is similar, only the pre-chamber is not filled with gas. In dual fuel engines ignition is triggered by injecting diesel into the compressed gas mixture. Dual fuel engines can run on gas, liquid fuel or both and the power output is the same for each fuel. Outside an ECA they can run on cheap HFO and to comply with ECA emission rules engines can switch to run on cleaner gas. This makes dual fuel engines flexible. The problem with gas fuels however is, as mentioned earlier, the methane slip which is an important greenhouse gas. Engine manufacturers expect to solve this problem in the (near) future.

## 5.3 EXHAUST GAS TREATMENT SYSTEMS

The previous part described the effect of different fuel on the forming of emission. This part describes two main exhaust gas treatment systems (EGTS); scrubbers and selective catalytic reduction (SCR). In case an EGTS is installed, the increase in backpressure must stay below engine limits. Otherwise it could result in higher fuel consumption and loss of power. In case backpressure is too high, an induced draft could be installed in the exhaust duct to decrease backpressure to acceptable levels. Besides backpressure EGTS could also slow down the gas velocity which affects the design of the funnel. Ships with EGTS can install a bypass creating an alternative path for exhaust gas when the EGTS is not operational, for instance outside an ECA. This bypass is also useful in case of maintenance work on the EGTS.

### 5.3.1 SELECTIVE CATALYTIC REDUCTION

Selective catalytic reduction (SCR) is a method to reduce $NO_X$ content in exhaust gas. The system is shown in figure 19. SCR converts nitrogen oxides into nitrogen and water and this reduces $NO_X$ emission by 80-90 %[32]. This conversion is done by injecting urea (ammonia) solution into gases leaving the engine. This exhaust gas mixture is lead through a catalyst which converts nitrogen oxides into nitrogen and water. The following reactions[32] take place of which the first reaction is the dominate one.

**EQUATION 13: SELECTIVE CATALYTIC REDUCTION EQUATIONS**

$$4\,NO + 4\,NH_3 + O_2 \rightarrow 4\,N_2 + 6\,H_2O$$

$$2\,NO + 2\,NO_2 + 4\,NH_3 \rightarrow 4\,N_2 + 6\,H_2O$$

$$6\,NO_2 + 8\,NH_3 \rightarrow 7\,N_2 + 12\,H_2O$$

[32] (Lloyd's Register, 2012)

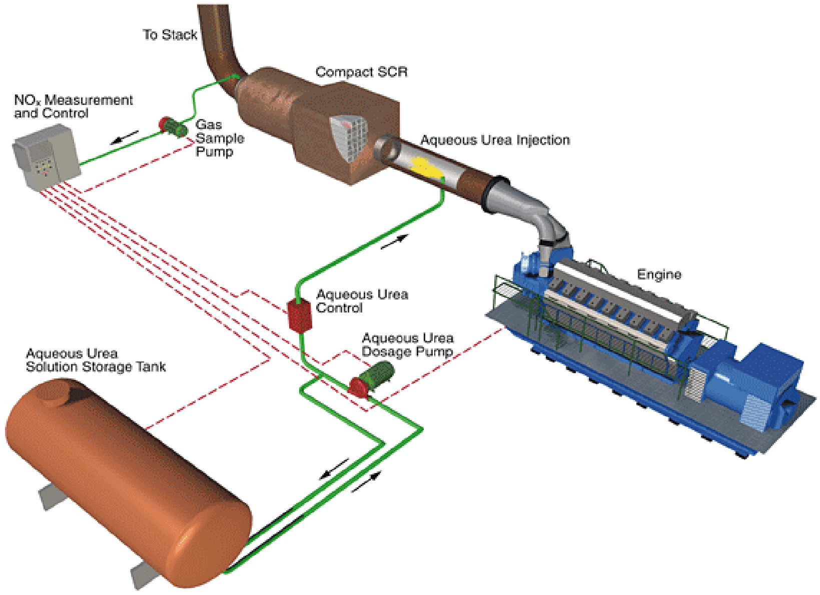



FIGURE 19: SELECTIVE CATALYTIC REDUCTION

The exhaust gas temperature has to be between 300°C and 500°C. If the temperature is above 500°C the catalyst could be damaged. Below 300°C the catalyst will not operate efficiently and sulphur in the exhaust could clog the catalyst. This last problem could be solved if SCR is combined with a scrubber which removes sulphur from the exhaust gas; however the exhaust gas has to be reheated to have an efficient catalyst process.

## 5.3.2 SCRUBBERS

Scrubbers are used to 'wash' exhaust gases in order to reduce PM and $SO_X$ emission. Scrubbers can be divided into two main types, wet scrubbers and dry scrubbers. A graphic picture of the scrubbers is shown in appendix F.

### WET SCRUBBERS

Wet scrubbers can be divided further into open loop, closed loop or hybrid systems. Wet scrubbers use water to scrub exhaust gas. In case the wet scrubber is an open loop system, sea water is used to scrub exhaust gas. The following reaction, divided into $SO_2$ and $SO_3$, will take place inside the scrubber.

For $SO_2$ the reactions[32] are:

EQUATION 14: WET SCRUBBER OPEN LOOP $SO_2$ REACTIONS

$$SO_2 + H_2O \rightarrow H_2SO_3 \rightarrow H^+ + HSO_3{}^- \rightarrow 2H^+ + SO_3{}^{2-}$$

$$2SO_3{}^{2-} + O_2 \rightarrow 2SO_4{}^{2-}$$

For $SO_3$ the reactions[32] are:

EQUATION 15: WET SCRUBBER OPEN LOOP $SO_3$ REACTIONS

$$SO_3 + H_2O \rightarrow H_2SO_4$$

$$H_2SO_4 + H_2O \rightarrow H_3O^+ + HSO_4{}^-$$

$$HSO_4{}^- + H_2O \rightarrow H_3O^+ + SO_4{}^{2-}$$

Water that is used in the scrubber will be treated to remove sludge before discarding the water into sea. The removed sludge is collected in sludge tanks and these tanks are periodically emptied in the harbour. This type of scrubber can remove up to 98 % $SO_X$ in the exhaust. This is equivalent to switch from 3.5 % to 0.1 % sulphur fuel. Sea water temperature has influence on the complete progress. At higher sea water temperatures, the solvability of $SO_2$ and thus the reduction will be less.

The difference between open loop and closed loop systems is that closed loop system uses fresh water with sodium hydroxide (NaOH) for scrubbing and that, as the name states, the loop is closed. The following reaction will take place inside the scrubber.

For $SO_2$ the reactions[32] are:

EQUATION 16: WET SCRUBBER CLOSED LOOP $SO_2$ REACTIONS

$$Na^+ + OH^- + SO_2 \rightarrow NaHSO_3$$

$$2\ Na^+ + 2\ OH^- + SO_2 \rightarrow Na_2SO_3 + H_2O$$

$$4\ Na^+ + 4\ OH^- + 2\ SO_2 + O_2 \rightarrow 2\ Na_2SO_4 + 2\ H_2O$$

For $SO_3$ the reactions[32] are:

EQUATION 17: WET SCRUBBER CLOSED LOOP $SO_3$ REACTIONS

$$SO_3 + H_2O \rightarrow H_2SO_4$$

$$2\ NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2\ H_2O$$

After scrubbing the sodium hydroxide water is cleaned before being recirculated. Small quantities of water are discharge out of the loop into sea or stored in holding tanks on board when discharging at sea is prohibited. Water is discharged to reduce the concentration of sodium sulphate in the loop. To restore the amount of water in the loop, fresh water is pumped into the system.

A closed loop system is more complex compared to an open loop system. As shown in appendix F closed loop systems need more equipment. However the power consumption of a closed loop system is half of an open loop system. Another advantage of closed loop system is that it could operate in enclosed waters.

A hybrid system is a combination of an open and closed loop system. As shown in appendix F equipment for both systems is installed so the operator can choose which system will be used. This means that the ship is more flexible in where to operate. The open system can be used to save NaOH and fresh water and the closed system can be used in areas where used (sea) water cannot be discharged into sea. This hybrid system is even more complex and expensive than a closed loop system.

### DRY SCRUBBERS

Dry scrubbers are commonly used in land based machinery. Instead of water, calcium hydroxide ($Ca(OH)_2$) granules are used for scrubbing. In a scrubber, the following reaction takes place:

For $SO_2$ the reactions[32] are:

EQUATION 18: DRY SCRUBBER $SO_2$ REACTIONS

$$SO_2 + Ca(OH)_2 \rightarrow CaSO_3$$

$$2CaSO_3 + O_2 \rightarrow 2\ CaSO_4$$

$$CaSO_4 + 2\ H_2O \rightarrow CaSO_4 \cdot 2H_2O$$

For $SO_3$ the reactions[32] are:

EQUATION 19: DRY SCRUBBER $SO_3$

$$SO_3 + Ca(OH)_2 + H_2O \rightarrow CaSO_4 \cdot 2H_2O$$

This system is like closed loop system ideal for areas where discharging is limited. A disadvantage is that the used granules need to be stored on board which takes up place. In comparison to wet scrubbers, dry scrubbers use less power. The only power demand is the screw conveyor which transports the granules. Dry scrubbers are significantly heavier than wet scrubbers due to the stored granules. This could be four to six times heavier in comparison to wet scrubbers. This is a reason why dry scrubbers are mostly used in land based installations. A comparison table is given in appendix F.

TABLE 10: SUMMARY OF EMISSIONS

| Emission | Cause | Remedy |
|---|---|---|
| Carbon dioxide ($CO_2$) | Carbon in the fuel and oxygen in the air | - Low C/H ratio fuels, like LNG or pure hydrogen |
| Nitrogen oxide ($NO_X$) | Nitrogen and oxygen from air | - Lowering combustion temperatures<br>- Install selective catalytic reduction |
| Sulphur Oxides ($SO_X$) | Sulphur in the fuel and oxygen in the air | - Lowering the sulphur content in the fuel<br>- Install scrubbers |
| Particulate Matters (PM) | Sulphur in the fuel<br>Ash in the fuel/lubricant | - Lowering the sulphur content in the fuel<br>- Install scrubbers |

All scrubbers are effective in reducing particulate matters. This is done by removing $SO_X$ as well as by cleaning particles that come in contact with water of granulates. Manufacturers claim to remove between 70 to 90 % of particulate matters with scrubbers. This will reduce the black plume out of the funnel, but in case of the wet scrubbers, water vapour could occur due to the reaction where water is formed.

## 5.4 CHAPTER SUMMARY

This chapter described measures to reduce emissions. There are different possibilities and some measures can be combined like scrubbers in combination with SCR, although this still poses challenges. Also some measures reduce more than one type of emission. For example, the fuel change from HFO to LNG results in a reduction of $CO_2$, $NO_X$ and $SO_X$. LNG however emits more $CH_4$ than HFO. Which solution is most suitable depends on the area where the ship is operating. All measures require space on board, which has to be available. Also the availability of required fuel determines which solution is preferred. In next chapter this will be explained into more detail. Table 10 summarizes causes of emissions and a remedy to reduce these emissions.

# 6. FUTURE DEVELOPMENT BUNKER COSTS

The impact of bunker costs, also known as fuel costs, varies per ship type; fast ships have a higher share of bunker costs than slow steaming ships. In almost all cases, bunker costs are a big part of ships operational costs as the example for a Ro-Pax ship in figure 20 illustrates. Because of this big share, bunker costs have significant impact on the outcome of LCC. LCC, as described earlier, will be used to compare different ship configurations for instance LNG to HFO with scrubber option.

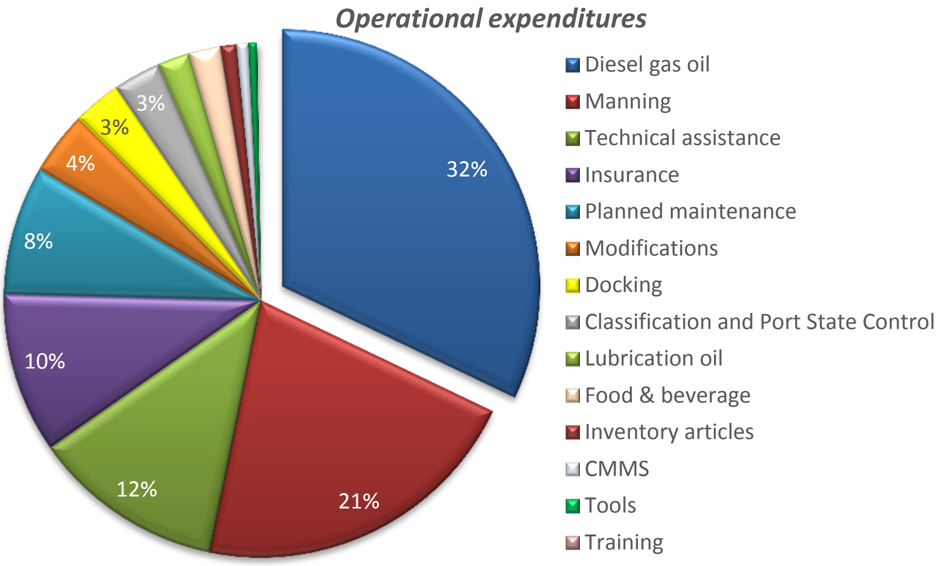



FIGURE 20: EXAMPLE OPERATIONAL EXPENDITURES COMMERCIAL SHIP (DAMEN MS GROENLAND PROJECT)

Table 11[33] shows an example of the influence of investment costs of needed equipment and prices for LNG and HFO with scrubbers on NPV. In this particular example a lifetime of 25 years is chosen and an additional costs of 11 million NOK for LNG equipment (32 million NOK) over the scrubber option (21 million NOK.)

TABLE 11: NPV [MILLION NOK] OF LNG FUELLED SHIPPING COMPARED TO HFO WITH SCRUBBER AND CATALYST EQUIPMENT AT DIFFERENT LNG AND HFO PRICES (GYA, ET AL., 2010)

| HFO price [$/tonne] \ LNG price [$/Tonne] | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 | 750 | 800 | 850 | 900 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 350 | 45 | 20 | -6 | -32 | -82 | -84 | -110 | -136 | -162 | -188 | -214 | -240 |
| 400 | 80 | 54 | 28 | 2 | -24 | -50 | -76 | -102 | -128 | -154 | -180 | -206 |
| 450 | 115 | 89 | 63 | 37 | 11 | -15 | -41 | -67 | -93 | -119 | -145 | -171 |
| 500 | 149 | 123 | 97 | 71 | 45 | 19 | -7 | -33 | -59 | -85 | -111 | -137 |
| 550 | 184 | 158 | 132 | 106 | 80 | 54 | 28 | 2 | -24 | -50 | -76 | -102 |
| 600 | 218 | 192 | 166 | 140 | 114 | 88 | 62 | 36 | 10 | -16 | -42 | -68 |
| 650 | 253 | 227 | 201 | 175 | 149 | 123 | 97 | 71 | 45 | 19 | -7 | -33 |
| 700 | 287 | 261 | 235 | 209 | 183 | 157 | 131 | 105 | 79 | 53 | 27 | 1 |
| 750 | 322 | 296 | 270 | 244 | 218 | 192 | 166 | 140 | 114 | 88 | 26 | 36 |
| 800 | 356 | 330 | 304 | 278 | 252 | 226 | 200 | 174 | 148 | 122 | 96 | 70 |
| 850 | 391 | 365 | 339 | 313 | 287 | 261 | 235 | 209 | 183 | 157 | 131 | 105 |
| 900 | 425 | 399 | 373 | 347 | 321 | 295 | 269 | 243 | 217 | 191 | 165 | 139 |

As this table shows it depends on the bunker costs which option is more economical and economical means a positive NPV. The positive NPV are shown in green and this means that the best solution is to sail on LNG as fuel. The negative and red values indicate that the best solution is to sail on HFO with scrubber and catalyst equipment.

[33] (Gya, et al., 2010)

In order to get an accurate LCC result, this chapter will predict future prices of the following fuels, HFO, low sulphur fuel, like MGO and LNG. These fuels are suggested in previous chapter to be used in order to comply with future rules. This study into future development of prices focuses mainly on crude oil and natural gas. These resources are raw material for distillation and production of respectively marine fuel and liquefied natural gas. Price fluctuations of crude oil are directly reflected in fuel prices. The correlation for instance between Brent Oil and HFO over the period 2001 to 2011 is 0.97[34].

# 6.1 PRICING

In order to be able to predict and estimate future prices, the pricing mechanisms of oil and gas has to be known. First a short background on the different markets will be provided, followed by a description of the used benchmarks to which the prices are related.

## 6.1.1 MARKETS

The earlier mentioned fuels can be divided into two types, natural gas and crude oil based. Because these markets differ from each other, both markets will be described separately.

### OIL MARKET

There are two types of oil trade, short term called spot market trade and medium to long term contracts. Around 90 % of physical crude oil is traded according medium or long term contracts[35]. Long term contracts are used because the daily volumes are very large. The other 10 % is traded on spot market. Spot market trading's are more accurately described as near-term forward transaction because almost all spot trades are delivered more than 10 days after entering the contract. These spot trading's are mostly one-off deals for physical oil that is not covered in long term contracts which are for instance due to wrong supply or demand estimations.

### GAS MARKET

Gas markets can be divided in four groups[36]. A market where there are plenty of buyers and sellers is called a gas-on-gas market. Examples of this market are North America and the United Kingdom. The second group is a market where gas prices are indexed to substitute energy prices to encourage users to switch between fuels. This market group is mostly used in Continental European countries. The third group is mostly seen in Asia and in this market gas prices are linked to oil. Gas pricing in China is an example of the fourth market group. China has a regulated gas market, which means that all gas supply is entered in a State controlled pool which is also priced by the State.

It is worth mentioning that there are some more aspects influencing the United States' gas market. The US has free trade agreements (FTA) with 20 countries[37]. These 20 countries are stated in appendix G. There are also regulations which influences US natural gas market. The two main regulations are the Natural Gas Act of 1938, which states that no gas exports may occur without federal permission and the Energy Policy and Conservation Act. This act gives the president of the United States the power to restrict export of natural gas and other fossil fuels. The Department of Energy has to approve requests to

[34] (Danish Maritime Authority, North European LNG Infrastructure Project, 2012)
[35] (Dunn & Holloway, 2012)
[36] (Yuying, Jinsong, Zhou, & Zhang, 2013)
[37] (White, 2012)

trade natural gas. For FTA countries this request is automatically approved and therefore more than 99 % of all natural gas exports flowed easily though pipelines into FTA countries Canada and Mexico[37]. For non-FTA countries like Japan, China, Taiwan and India getting approval to import LNG is much more difficult due these stricter regulations. In fact, during the period 1967 to 2012, the Department of Energy has approved just eleven orders to export LNG to such countries. These eleven orders are shown in table 12.

**U.S. LNG export authorizations**

*For shipments to non-free-trade agreements countries.*

| Year | Amount | Who received permission | Duration | From | Destination |
|---|---|---|---|---|---|
| **1967** | 50 bcf a year | Phillips / Marathon | 15 year ending 1984, May 31 | Nikiski, Alaska | Japan |
| **1982** | 50 bcf a year | Phillips / Marathon | 5 year ending 1989, May 31 | Nikiski, Alaska | Japan |
| **1988** | 52 bcf a year | Phillips / Marathon | 15 year ending 2004, March 31 | Nikiski, Alaska | Japan |
| **1989** | 660 bcf a year | Yukon Pacific | 25 years from first shipment | Valdez, Alaska | Japan, South Korea and Taiwan |
| **1992** | 64.4 bcf a year | Phillips / Marathon | Through 2004, March 31 (amended 1988 order) | Nikiski, Alaska | Japan |
| **1993** | up to 10 bcf total | Phillips / Marathon | 2 years from first shipment | Nikiski, Alaska | Anywhere (spot market) -1 shipment to Japan occurred |
| **1999** | 64.4 bcf a year | Phillips / Marathon | 5 years ending 2009, March 31 | Nikiski, Alaska | Japan |
| **2000** | up to 10 bcf total | Phillips / Marathon | 2 years from first shipment | Nikiski, Alaska | Anywhere (spot market) - 1 shipment to Russia occurred |
| **2008** | 98.1 bcf total | ConocoPhillips / Marathon | 2 years ending 2011, March 31 | Nikiski, Alaska | Pacific Rim countries |
| **2010** | rest of 98.1 bcf authorized in 2008 | ConocoPhillips / Marathon | 2 years ending 2013, March 31 | Nikiski, Alaska | Anywhere |
| **2011** | 803 bcf a year | Cheniere Energy | 20 years from first shipment | Sabine Pass, LA. | Anywhere |

**TABLE 12: U.S. LNG EXPORT AUTHORIZATIONS (WHITE, 2012)**

Applications to trade with non-FTA countries can take a long time to be permitted; for example the application of Yukon Pacific took almost two years before it was approved. Also Cheniere Energy's application took more than eight months in comparison to another application of Cheniere to export LNG to an FTA country. That approval only took less than one month.

### 6.1.2 BENCHMARKS

Just as the previous paragraph, this part is also divided into gas and oil. As described in chapter 5.1, most fuels are distilled out of crude oil. Crude oil is found in different places in the World and like LNG, the composition differs. Because of these different compositions, benchmarks are used in market-related pricing. For the benchmark definition crude oil is taken as example, but the same principle applies for natural gas.

### DEFINITION BENCHMARK

Benchmarks act as an overall barometer of supply and demand in the market. Benchmarks are used in so-called formula pricing mechanisms. The price of a particular crude oil is defined in comparison to the benchmark and price differences are added or subtracted, related to the difference in quality and transportation costs. The market determines which oil is comfortable to be used as benchmark. The main requirement is that no single entity or operator should be able to control the benchmark solely. Furthermore crude oil production should be of enough volume and sustainable levels to ensure enough supply in the future. Seaborne crude is therefore more preferable as benchmark than landlocked pipeline crude.

### CRUDE OIL BENCHMARK

Crude oil is categorized to sulphur content, sweet or sour and to density, according API gravity in light or heavy as shown in figure 21.

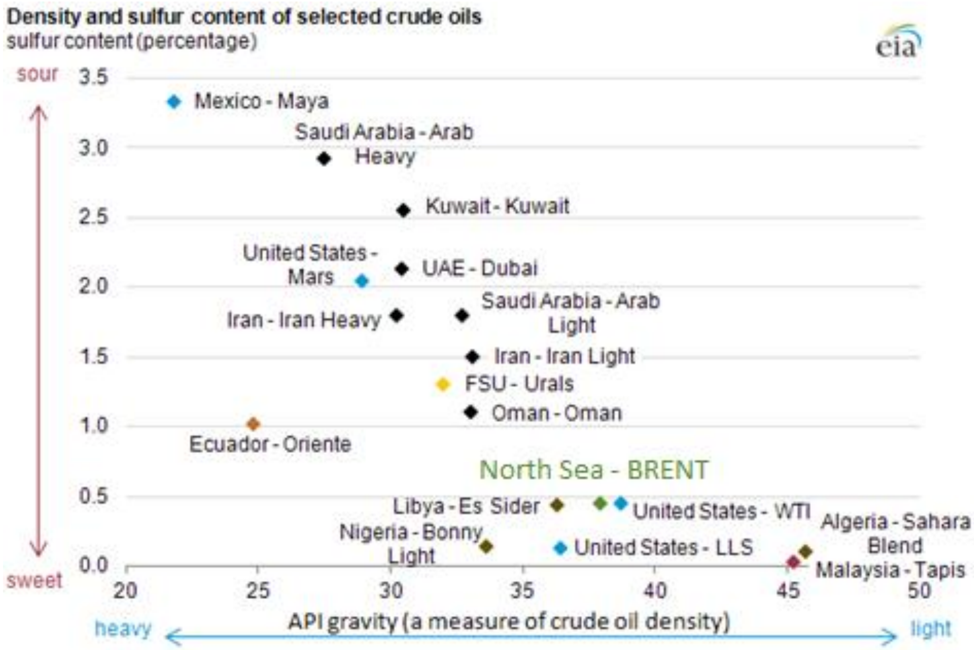



FIGURE 21: GRADES OF CRUDE OIL (EIA 2012)

The lower the sulphur content, the less sulphur has to be removed to comply with sulphur limits in fuel. Brent is used as international crude oil benchmark since 1984. This was caused by a favourable tax regulation for oil producers in the United Kingdom, which also benefits from stable legal and political institutions[38]. Brent production started in the eighties with a large and stable production which declined over time. This decline is illustrated in figure 22.

To ensure enough production volume more crudes, Forties, Oseberg and Ekofish[35], were added to Brent benchmark with BFOE as abbreviation. This 'new' benchmark is also referred to as Brent Blend. In 2012 the Brent Blend contains crude oil from around 20 different fields in the North Sea which are gathered and pumped to Sullom Voe oil terminal on the Shetland Islands. Thereby the production levels are sufficient to be a benchmark. Due to all those different fields, ownership of Brent benchmark is divers, which reduces individual producers' pricing power. Another advantage is that Sullom Voe oil terminal is sea based which has less possible bottlenecks than land locked terminals.

[38] (Fattouh, 2011)

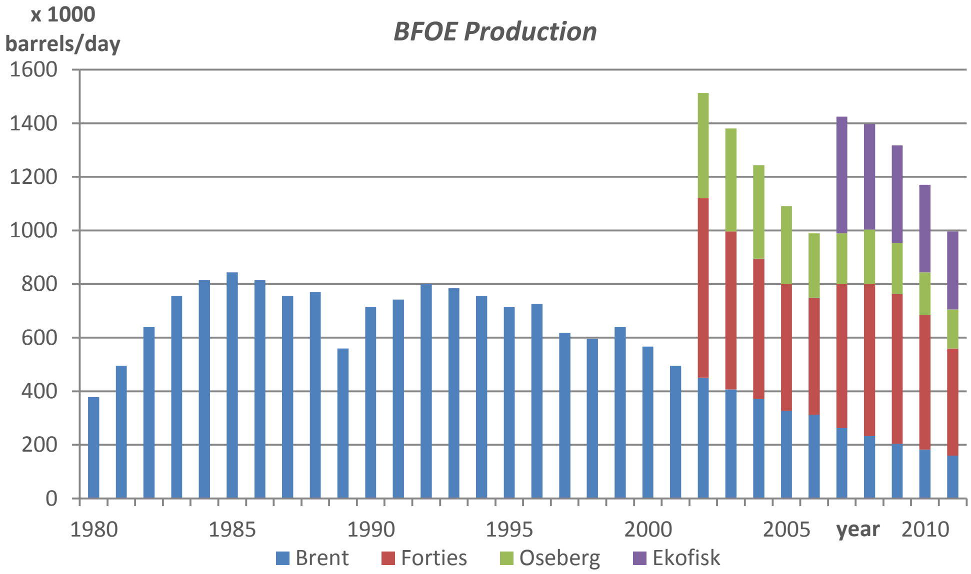



FIGURE 22: BFOE PRODUCTION VOLUMES IN THOUSAND BARRELS PER DAY (BP STATISTICAL REVIEW OF WORLD ENERGY JUNE 2012)

### NATURAL GAS BENCHMARK

In 1989 the New York Mercantile Exchange (NYMEX) selected United States based Henry Hub, which is a gas distribution hub, as official delivery mechanism for the World's first natural gas futures contracts. From that moment Henry Hub became the benchmark for natural gas, which it still is in 2014. The average prices of natural gas, from thirteen interconnected pipelines which are connected to Henry Hub, are used as benchmark for natural gas.

## 6.2 HISTORY

Price history of both benchmarks, Brent and Henry Hub, is illustrated in figure 23. A graph with the oil prices since 1986 is provided in appendix H. Crude oil is expressed in dollar per barrel, but natural gas is given in dollar per million British thermal unit (mmBtu). To compare these prices, crude oil is converted into mmBtu with a conversion factor of 5.41[39].

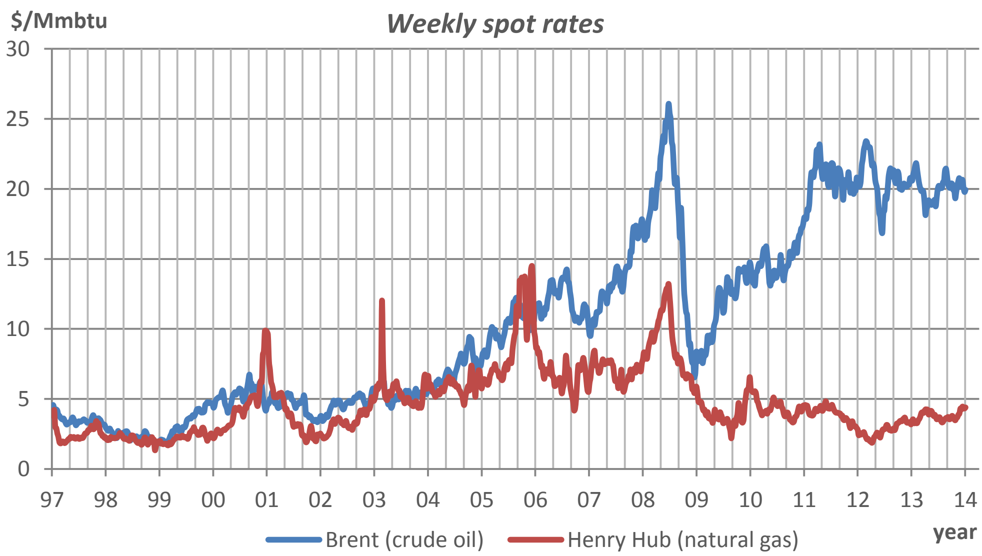



FIGURE 23: HISTORY WEEKLY SPOT RATES FROM 1997

[39] (BP, Conversion factors, 2014)

As figure 23 shows, prices of crude oil and natural gas remained similar until the summer of 2005. From that point, natural gas prices dropped and oil prices stayed the same. In 2008, when economy was booming, both prices increased again, however oil price more than natural gas. Due to the financial crisis prices dropped in 2008 significantly which stabilised in 2009. Price of natural gas remained around the same level, but oil prices continue to rise again. The steeper increase in crude oil price in 2011 was amongst other caused by 'Arab Spring'[40]. This disturbance in supply indicated that reserve capacity is needed. Another influence was, as described in chapter 4.2, stricter regulation for $NO_X$ emissions which came into force in 2011 and respectively for sulphur content in 2012. How big the influence of those new regulations was on crude oil price is hard to say.

Figure 23 also shows that during 2005 till 2008 crude oil prices were steadily increasing in line with demand, indicated by Baltic Dry Index. Another point worth mentioning is that worldwide oil price trend is similar to Brent benchmark. This can be explained because in 2011 70 %[38] of the total crude oil trade was directly or indirectly priced by Brent. However this is not the case for natural gas prices worldwide, because according International Energy Agency [41](IEA), natural gas in the United States trades at one-third of import prices of Europe and one-fifth of those to Japan, which is illustrated in figure 24.

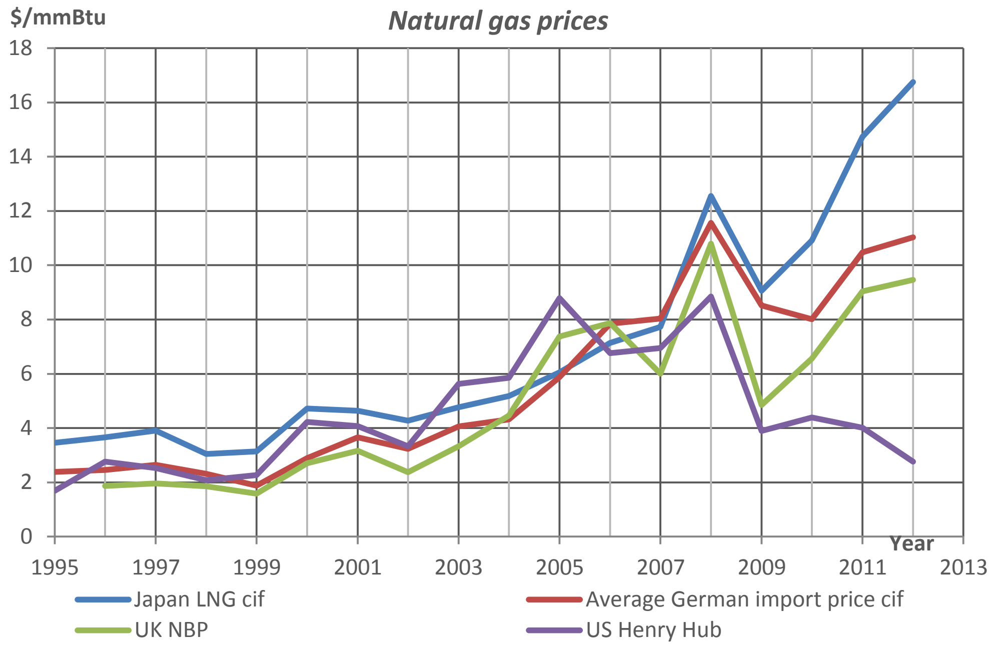



**FIGURE 24: PRICES OF NATURAL GAS (BP, 2013)**

The low price of natural gas in US is caused by the combination of increased production of shale gas[42] with limited 'demand'. This limited demand means the effect of the regulations of the US gas market which are described at the end of chapter 6.1.1. Due to these regulations it is difficult to export natural gas out of US, which limits 'demand'. However IEA expects that in 2020 US is changed from crude importer to exporter, changing the balance of oil/energy trade. This function shift is caused by the revolution of shale gas and the change in regulations which are expected to occur.

The steep increase in natural gas prices in Japan is caused by the aftermath of the Fukushima nuclear disaster in March 2011. Almost all of Japans nuclear power plants are

[40] (OPEC, 2012)
[41] (Agency, 2013)
[42] (US Energy Information Administration)

closed pending the investigation of Fukushima, causing a shift to alternative gas powered power plants and thus an increase in demand in natural gas. Another reason of the illustrated price difference is that there are different pricing mechanisms used as described earlier. US and, to a certain extent, European pricing is based on gas-on-gas markets. Japans pricing mechanism is still oil based[43].

## 6.3 VARIABLES

As previous figures illustrate, fuel prices are dependent of production cost, demands and availability. US shale gas production illustrates the effect of supply. Natural gas demand in Japan, after Fukushima, illustrates an effect of demand. These factors however also influence each other, because demand determines fuel availability. In case demand is low, availability will probably also be low and the other way around. Demand is also dependent of costs, if there are cheaper alternatives available demand for that particular fuel will be low. There is, obviously, also a global interdependency between crude oil demand and gas demand. Price benefits in favour of LNG might cause a shift to gas based source energy resulting in a reduced consumption of oil based fuels. Crude oil demand could decrease, which will lead to price reductions and so on.

Speculation can also been seen as variable which influences prices as the price change during the Arab Spring shows. However there is not much evidence to supports that statement according a study published by Centre for Economic Policy Research[44]. This study concluded that, based on existing evidence, speculation has in the long run no effect on the price. On short term however, speculation can have an effect, but this is mostly based on basic supply and demand economics. They stated that speculation is part of demand and consequently influences the price.

All these variables make the pricing mechanism complex and therefore it is next to impossible to make any solid prediction on future pricing. Rules and regulations complicate this even further. The development of these variables is explained in the next part of this chapter.

### 6.3.1 FUTURE DEMANDS

Multiple major oil and gas companies like ExxonMobil[45], Gazprom[46], Shell[47] and Statoil[48] expect that oil and natural gas demand will increase during the next 20-30 years, compared to 2010 levels. Annual growth of crude oil is expected to be just over 1 %, as shown in table 13, but predictions of annual growth for natural gas are in the range of 1.7 % according ExxonMobil[45] to 3.5 %, according Gazprom[46]. IEA describes same numbers in their world energy outlook reports. This increase in demand is mainly caused by economic growth in the World and not in the least by the ever growing global population.

There are different aspects that influence demand. Global growth increases demand and this can be defined as a constant. Another aspect can be a single event that influences oil

[43] (Miyazaki & Limam, 2013)
[44] (Kilian, Fattouh, & Mahadeva, 2012)
[45] ExxonMobil, 2012 Summary annual report
[46] Gazprom annual report 2012
[47] Shell sustainability report 2012
[48] Statoil annual report 2012

or LNG demand, like for instance a nuclear disaster which results in a shift from nuclear power plants to gas fuelled power plants. Effects of this unexpected change don't happen in one day, because alternative options have to be available. Influence on demand is therefore predictable on short notice; however it is unpredictable when such single event occurs in long term.

TABLE 13: GLOBAL OIL DEMAND 2011-2017 IN MILLION BARRELS PER DAY (IEA, 2012)

| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|---|---|---|---|---|---|---|---|
| Africa | 3.3 | 3.4 | 3.5 | 3.6 | 3.8 | 3.9 | 4 |
| Americas | 30.4 | 30.3 | 30.5 | 30.6 | 30.7 | 30.8 | 30.9 |
| Asia/Pacific | 28.4 | 29.2 | 29.5 | 30.1 | 30.9 | 31.6 | 32.3 |
| Europe | 15.1 | 14.7 | 14.5 | 14.5 | 14.4 | 14.4 | 14.3 |
| Former Soviet Union | 4.4 | 4.6 | 4.8 | 4.9 | 5.1 | 5.2 | 5.2 |
| Middle East | 7.4 | 7.6 | 7.8 | 8.1 | 8.4 | 8.7 | 9 |
| World | 89 | 89.8 | 90.6 | 91.8 | 93.2 | 94.5 | 95.7 |
| Annual Change (%) | 1 % | 0.9 % | 0.9 % | 1.4 % | 1.5 % | 1.4 % | 1.3 % |
| Annual Change (mb/d) | 0.9 | 0.8 | 0.8 | 1.2 | 1.3 | 1.3 | 1.2 |

The last influential aspect on demand is regulation. It takes time to develop new regulations so the effect can, up to a certain point, be predicted. However in case of the North Sea/Baltic Sulphur Emission Control Area (SECA,) there are multiple solutions to comply with these regulations and therefore multiple solutions in change of demand.

Looking closer at North Sea/Baltic SECA, there are more than 14000 ships sailing in that SECA[49]. These 14000 ships represent, in number of ships, 12% of the global fleet and 29% of the global fleet in terms of deadweight. Of these 14000, 2200 are permanent and 2700 operate more than 50% of their time in the SECA region. These figures are shown in table 14.

TABLE 14: NUMBER OF SHIPS IN SECA BALTIC[49]

| | Nr. ships | | dwt | |
|---|---|---|---|---|
| 100 % in SECA | 2,232 | 1.8 % | 6,952,936 | 0.5 % |
| 50 % - 99 % in SECA | 2,655 | 2.2 % | 27,872,994 | 1.9 % |
| 1 % - 49 % in SECA | 9,127 | 7.5 % | 378,241,695 | 26.4 % |
| **Total SECA** | **14,014** | **11.6 %** | **413,067,625** | **28.9 %** |
| 0 % in SECA | 106,969 | 88.4 % | 1,018,579,684 | 71.1 % |
| **Total** | **120,983** | **100 %** | **1,431,647,309** | **100 %** |

These ships consume around twelve million tonnes of fuel annually and with a fleet growth rate of 2 % consumption will grow to more than seventeen million tonnes in 2030[34]. Until 2015 ships are allowed to operate on fuel with a maximum sulphur content of 1 % and from 2015 this maximum is lowered to 0.1 %. This change will result in an increasing demand of fuels that can comply to this limit. In European ports however maximum sulphur content in fuel is already 0.1 %. In 2013 there are worldwide 34 ships, excluding LNG carriers and inland navigation ships, which use LNG for propulsion and for 2014 and 2015, 31 new ships are already planned[50]. With these stricter regulations in that SECA, demand for low sulphur fuel will increase and the question is if there will be enough low sulphur fuel available. Another question is what will happen with the supply of HFO in that area. If the demand drops, will it still be viable to supply HFO in those areas?

[49] (Danish Maritime Authority, North European LNG Infrastructure Project Appendix, 2012)
[50] (Burel, Taccani, & Zuliani, 2012)

### 6.3.2 FUTURE AVAILABILITY

Crude oil is available worldwide, but production of 'easy' oil is reducing. Most new oil reserves are in deep-water or in other frontier places, like the Arctic[51]. The prognosis is that oil supply will not decline in the next decade[52]. Oilfields that were not economically viable in the past are now producing oil due to a changed economic climate and thanks to technical innovations.

Availability of natural gas is globally growing. Looking for instance at Australia, natural gas reserves are enormous. More than 200 billion dollars' worth of LNG projects are under construction in Australia[53]. Shell has ordered a floating liquefied natural gas (FLNG) facility, which can annually provide more gas than annual gas demand of Hong Kong. FLNG will be used for developing large gas resources in the North of Australia[54]. Also other oil and gas companies like Petrobras are looking into FLNG.

Besides Australia, the United States are also an important player. As mentioned earlier, the US has not exported much gas due to regulations. In 2012[37] South Korea became a FTA and expectations are that they will import 'cheap' gas out of the US. Also the regulations are possible changing so that US can export more natural gas worldwide. In order to facilitate this increase in export, some LNG import terminals are refitted to become LNG export terminals[55].

The challenge with LNG is availability on small scale, so as bunkering fuels for ships. Availability of small scale LNG is growing rapidly, because LNG demand is growing. Looking at North Sea/Baltic SECA again, demand for high sulphur fuel will decrease as described earlier. The question is if this will affect the availability of high sulphur fuel in the SECA. Will it still be affordable to supply this type of fuel when demand is dropping? And on the other hand, will there be enough low sulphur fuel and LNG available in that SECA? According a study into LNG performed by PwC[52] small scale LNG is still in a market development phase, the beginning of an S-curve as shown in figure 25. In this phase the market adaption is still low, but this can rapidly increase in the next phase.

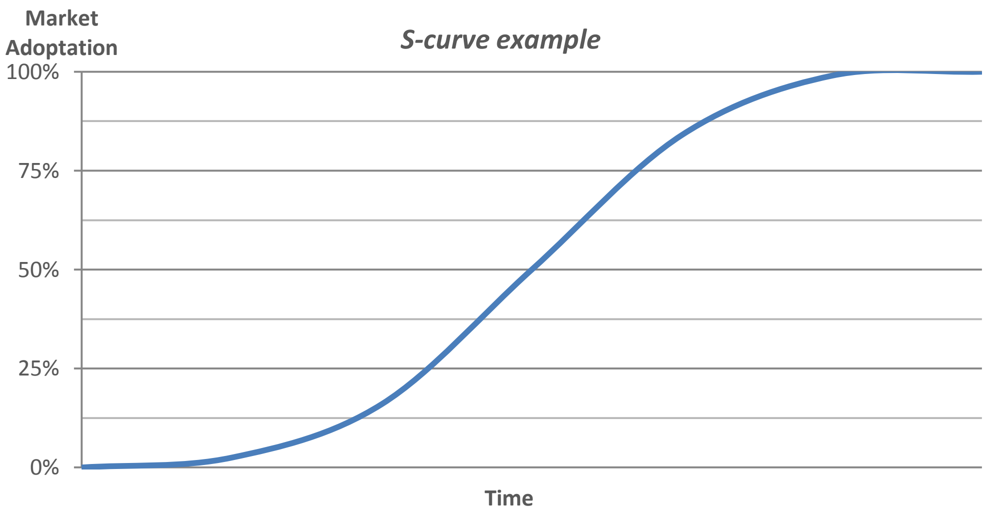



**FIGURE 25: EXAMPLE OF S-CURVE (ROGERS, 1962)**

[51] (Gautier, 2008)
[52] (PriceWaterhouseCooper, 2013)
[53] (Appea, 2013)
[54] (Shell)
[55] (Ratner, Fergusson, Parfomak, & Luther, 2013)

PwC expects that in the next couple of years small scale LNG will enter this next phase and supply of small scale LNG will rise significantly. The year in which this rise will start depends, according PwC, on policies, fuel alternatives, price difference between fuels and the growth of the transport sector.

### 6.3.3 FUTURE PRICE

The base price of the product is determined by the most expensive source/well. If the price of that well is too high, that particular well is not profitable and will not be in service. As mentioned in chapter 6.3.2, crude oil is produced in more difficult areas, which results in higher costs prices. Another part of price is determined by the supply and demand ratio in particular areas as shown above with the Fukushima example.

Looking at crude oil price for the next couple of years, expectation is that it will not increase much, due to the new supplies from Iraq and deep waters near Brazil. After these years the expectation is that prices will rise again due to the depletion/declining of "easy" accessible wells and the shift towards more difficult wells in deep water and arctic regions. The ratio between crude oil and natural gas is steady around 0.6 for the last couple of years, as figure 26 shows.

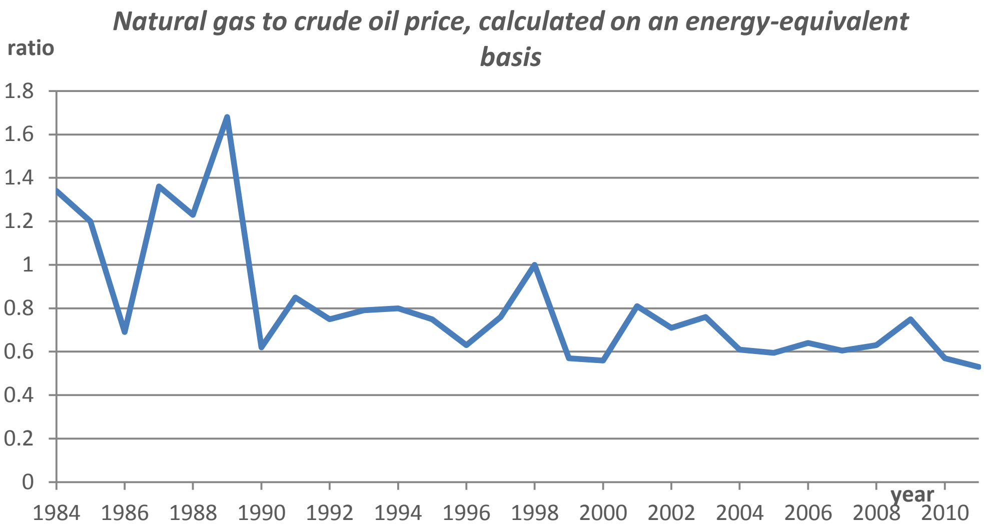



**FIGURE 26: NATURAL GAS VS. CRUDE OIL PRICE (PRICEWATERHOUSECOOPER, 2013)**

This ratio is expected to rise in the next couple of years, because natural gas prices are expected to rise, while crude oil remains around the same price level. Natural gas prices are expected to rise, due to increasing demand. When LNG supplies from, for example, Australia enters the market and oil price start to raise again the ratio will decrease.

This price increase of crude oil is globally as seen in the past, but for natural gas this will not be the case. As described earlier gas prices in Asia are indexed to oil prices in contrary to pricing mechanisms in the US and partly in Europe. The expectation is that, although more natural gas will be imported from the US, prices of natural gas in Asia remain high due to high demand. The production of large quantities of shale gas will cause prices in the US to remain low, compared to Asian prices. Price difference will decrease, because supply of natural gas will increase. When the expanded Panama channel will be opened in 2015 sailing time and sailings costs will be reduced for LNG carriers from the US to Asia.[56] Furthermore oil index pricing will eventually be discarded in Asia.

[56] (Arnsdorf, 2013)

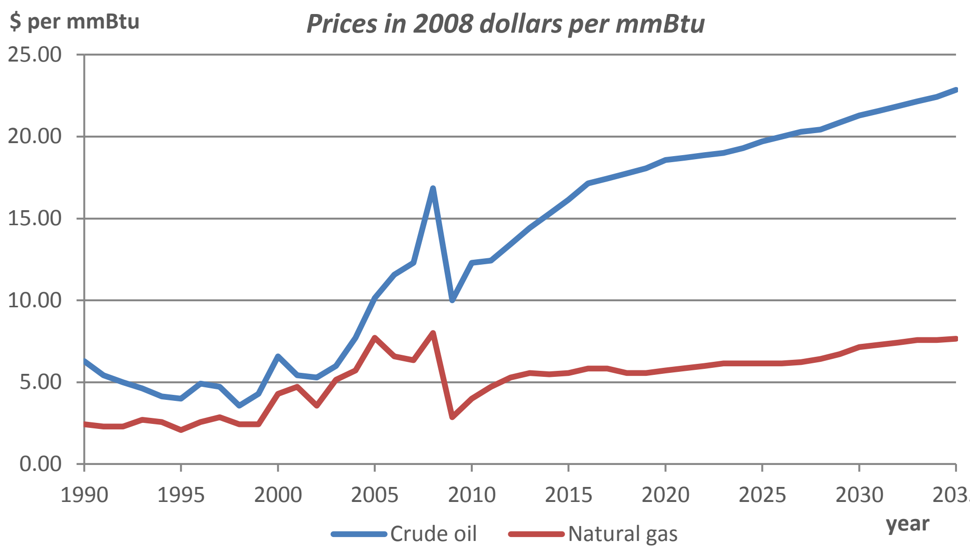
## 6.4 OTHER REPORTS

This thesis is not the first attempt to estimate future price trend of marine fuel. There are different studies into the future of fuel and these study results will be given in order of the year in which the studies were performed

### 6.4.1 GREENER SHIPPING IN THE BALTIC SEA BY DNV

In the summer of 2010 DNV published a study[57] into the environmental situation in the Baltic Sea. The conclusion of that study was that LNG fuel is a supreme solution to comply with the stringent regulation in the future. DNV expect that LNG trade will grow to become a large and flexible market, so availability of LNG is not going to be the limited growth factor. This study also included a small economic analysis and a prediction of future crude oil and natural gas prices until 2035. Figure 27 shows a graph of future prices and the prediction is that crude oil prices will increase more than natural gas.

FIGURE 27: PRICE PREDICTION OF CRUDE OIL AND NATURAL GAS (2010 DNV GREENER SHIP BALTIC)




In 2008 small scale LNG was sold for around $18 per mmBtu in comparison to LNG bought on the international market for around $8 per mmBtu. DNV expects that the difference of $10 per mmBtu will decrease due to bigger and more efficient liquefaction plants and efficient distribution of small scale LNG.

### 6.4.2 COSTS AND BENEFITS OF LNG AS SHIP FUEL FOR CONTAINER VESSELS BY GL AND MAN

In 2011 Germanischer Lloyd (GL) and MAN performed a joint study[58] into a container vessels fuelled by LNG. The objective of this study was to compare different technologies and determine benefits of these technologies. This study included a fuel price scenario to determine difference in costs for all technologies. The general assumption is that, due to increase in oil and gas production costs, fuel prices will also increase continuously. For LNG small-scale distribution cost, $4 per mmBtu, is assumed to be constant over time. The range of fuel price scenario is until 2030 and is illustrated in figure 28. This scenarios starts in 2010 which a HFO price of $650 per ton ($15.3 per mmBtu), $900 per ton MGO ($21.2 per mmBtu) and a LNG price of $13 per mmBtu which includes small scale distribution costs.

[57] (DNV, 2010)
[58] (Lyder Andersen, Clausen, & Samen, 2011)

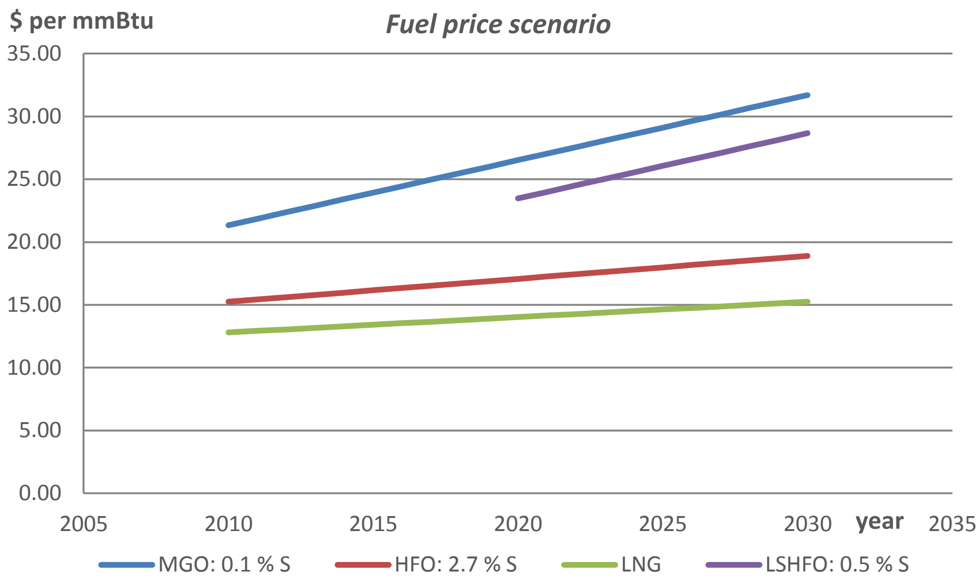



**FIGURE 28: FUEL PRICE SCENARIO - GL AND MAN 2011**

### 6.4.3 LNG FUELLED DEEP SEA SHIPPING BY LLOYDS REGISTER

Due to increasing focus on reducing emissions from shipping, Lloyds Register (LR) completed an outlook[59] up to 2025 for LNG fuelled ships. In this study three different scenarios were investigated; a base case, high case and low case scenario. The base case was assumed to be with current ECAs and a global sulphur limit of 0.5 % in bunker fuel in 2020. Furthermore it was forecasted that 653 LNG-fuelled ships are built upon 2025 and LNG bunker demand will reach 24 million tonnes by 2025. This is 1.5 % of global LNG production and 3.2 % of global HFO bunker consumption. The difference between scenarios is the number of forecasted LNG-fuelled ships and therefore different LNG bunker demand and different LNG bunker price. For base case scenarios, figure 29 shows predicted fuel prices.

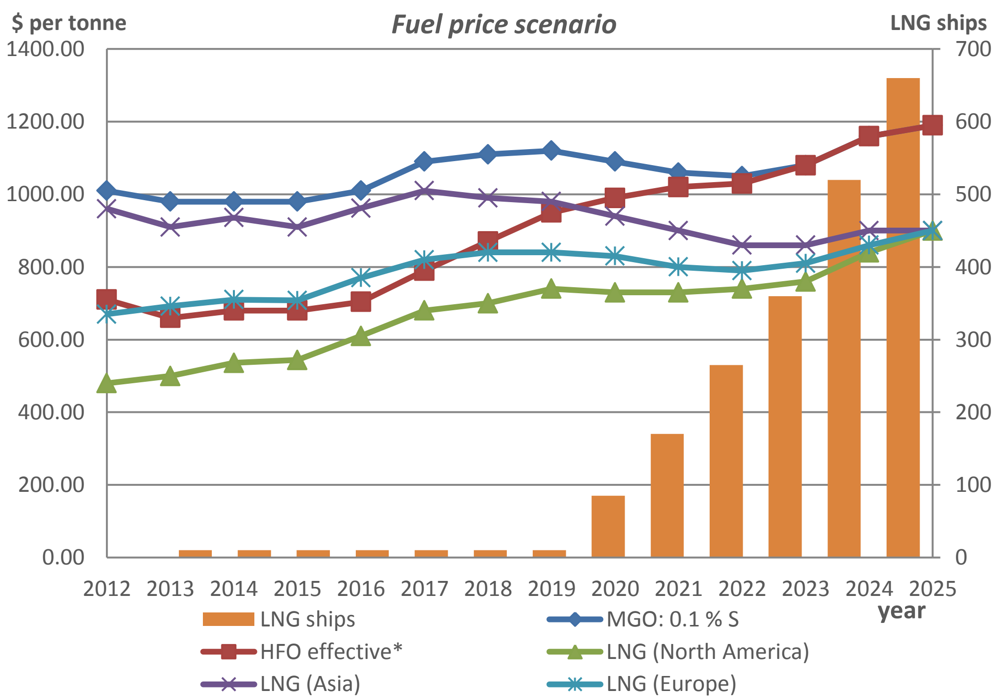



**FIGURE 29: LNG BUNKER PRICE FORECAST ACCORDING LR STUDY 2012**

[59] (Aagesen, Ajala, & Nicoll, 2012)

** "HFO Effective" is HFO with any variant of sulphur content higher than ECA or global limits at the given period*

Price difference between distillate fuels and LNG will be different for the three scenarios. In all scenarios, fuel prices are expected to converse to one price in 2025; meaning that there will not be price difference between, for example, LNG from North America or Europe. Also LNG is assumed to remain the cheaper fuel in all scenarios.

### 6.4.4 SHIPPING 2020 BY DNV

In 2010 DNV published a study into the Baltic Sea environmental situation as described in chapter 6.4.1 and in 2012 DNV published a report[60] into shipping in 2020. This report is based on predicted trends in the world economy and transport demand. Also marine regulations and technologies are mentioned. Four different scenarios, from low versus high economic growth and low versus high regulatory and stakeholder pressure, towards 2020 are defined which are shown in figure 30. DNV uses scenarios to explore effects of global trends in the shipping industry. The four chosen scenarios are in DNV's view likely developments.

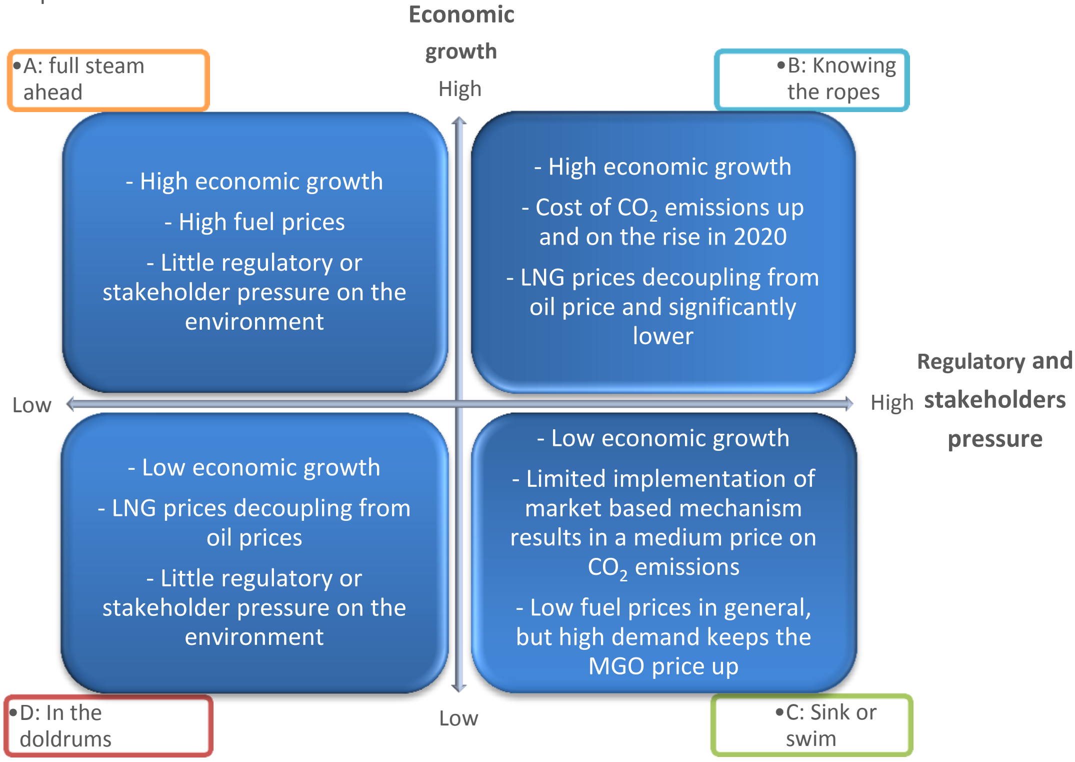



**FIGURE 30: FOUR FUTURE SCENARIOS MODELED ON ECONOMIC GROWTH AND REGULATORY AND STAKEHOLDERS PRESSURE**

Based on these scenarios DNV concluded the following; during the period 2012-2020 more than 10 % of new build ships will be gas powered. Furthermore, if LNG prices will be 30 % lower than HFO, LNG demand will increase with 13 %. Another finding was that marine distillate demand will increase from 30 million tonnes to 200-250 million tonnes annually in 2020, due to stricter regulations as mentioned earlier. Consumption of HFO will drop from 290 million tonnes to 80-110 million tonnes annually in 2020, if global sulphur limit comes into force in 2020, otherwise the drop will be in 2025. Figure 31, figure 32 and figure 33 show fuel price predictions based on OECD, IEA and EIA and are further developed by DNV according the outcome of different scenarios; more specific, figure 31 shows the HFO price projections from 2010 to 2035. For HFO and MGO the base price is the same for all outcomes. For LNG this is not the case, which will be explained on the next page.

[60] (Det Nørske Veritas AS, 2012)

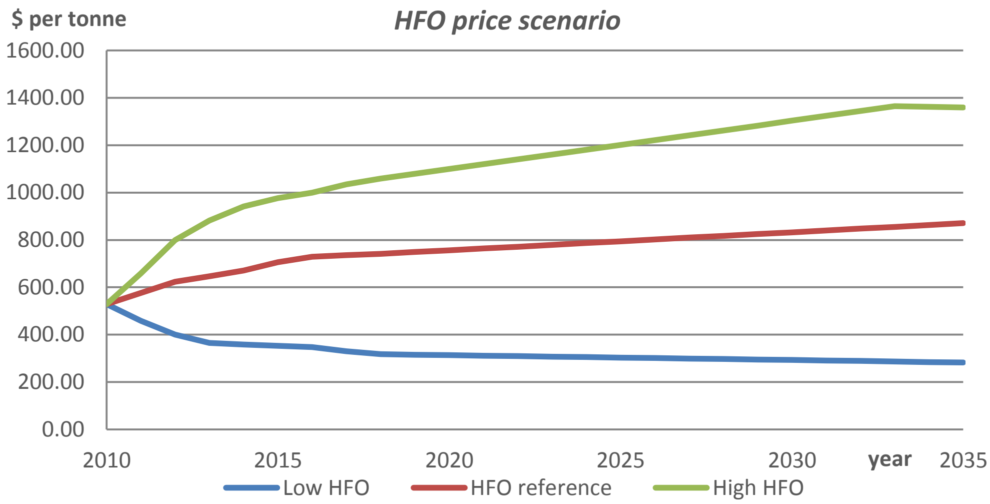



FIGURE 31: HFO PRICE PROJECTIONS 2010-2035 (REAL TERMS)

Figure 32 illustrates the MGO price projection from 2010 till 2035 for the three different scenarios.

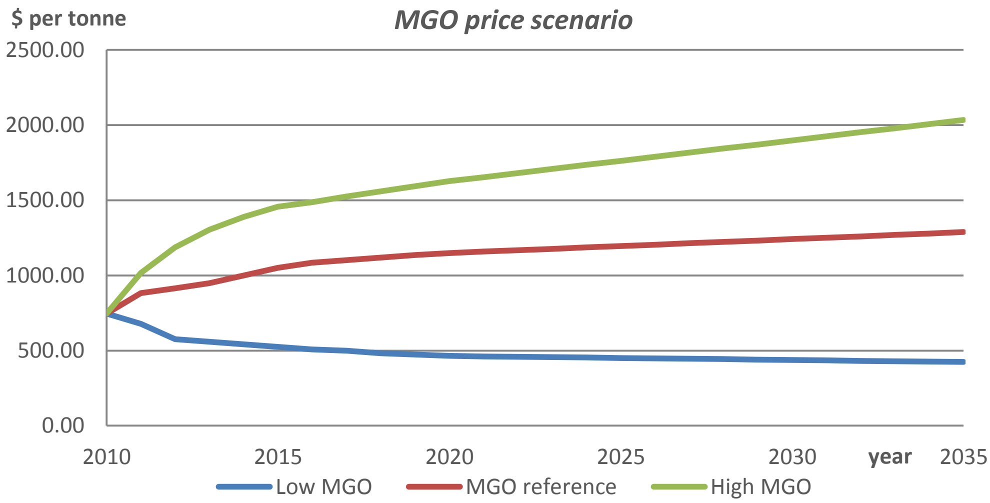



FIGURE 32: MGO PRICE PROJECTIONS 2010-2035 (REAL TERMS)

The LNG price projection for the period 2010 till 2035 is shown in figure 33. As described and show above, the base price for both HFO and MGO is the same. However as figure 33 show the base price for LNG is different for each outcome. This is caused by the difference in natural gas prices in North America, Europe and Asia as described in chapter 6.2, which are respectively Low LNG, reference LNG and high LNG.

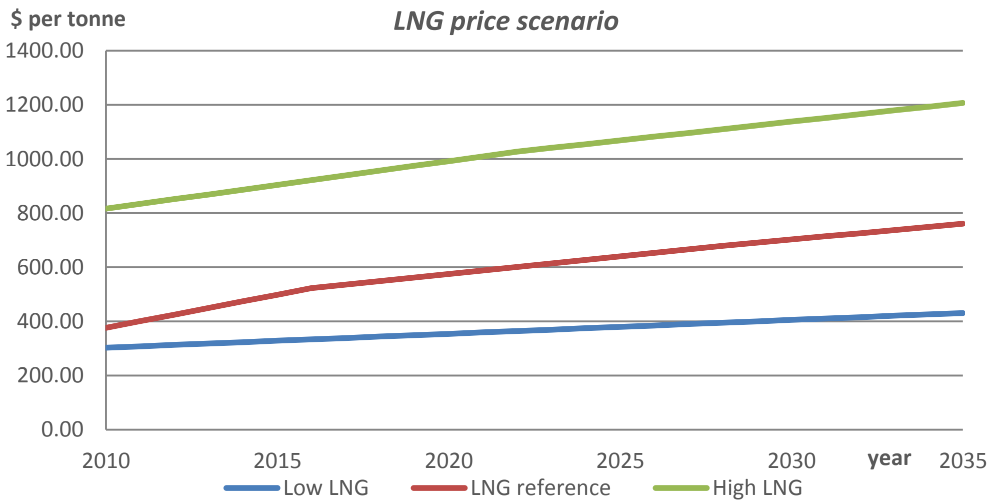



FIGURE 33: LNG PRICE PROJECTIONS 2010-2035 (REAL TERMS)

### 6.4.5 THE PRICE OF SULPHUR REDUCTIONS IN THE BALTIC SEA AND NORTH SEA SHIPPING BY BSR INNOSHIP

As part of Baltic Sea Region programme 2007-2013, BSR Innoship performed a study[61] to investigate the financial effect of MARPOL Annex VI regulation in the North Sea/Baltic SECA. There prediction is that price difference between HFO and MGO will increase in the future due to the assumption that crude oil prices as well as demand of middle distillates will continue to increase. Furthermore refineries are not likely to invest on production of middle distillates in the near future. In contrary to increase in middle distillate demand, HFO demand will decrease. Researchers couldn't answer the question if and when exhaust gas scrubbers penetrate the market. Figure 34 shows predicted fuel prices and these prices are basically a linear increase of prices with two small steps in 2015 and 2021 due to changing regulations.

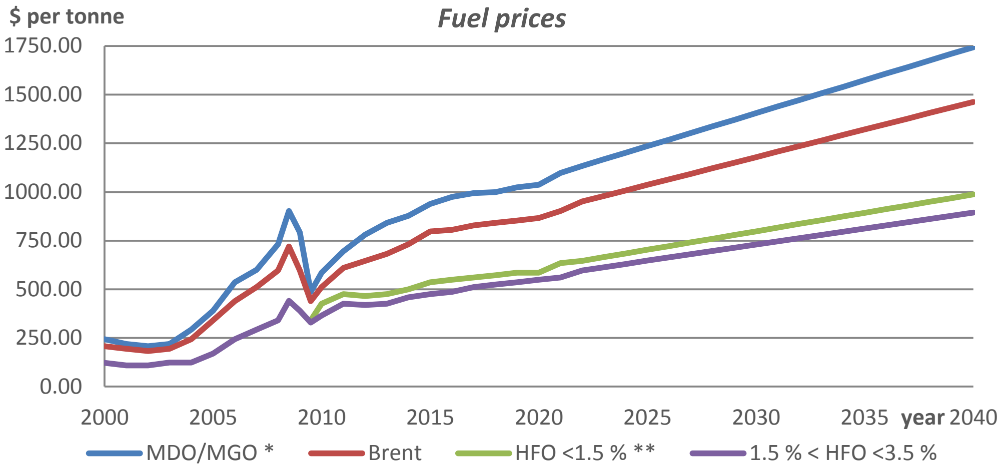



FIGURE 34: BSR INNOSHIP SHIP FUEL PRICES

### 6.4.6 ANNUAL WORLD ENERGY OUTLOOK

Besides above mentioned reports, US Energy Information Administration (EIA) publishes an annual world energy outlook[62] each year. This report is not only examining natural gas and crude oil, but also at other forms of sources like nuclear and coal. As earlier described *Shipping 2020 by DNV* study, EIA also works with scenarios. This can be seen in figure 35.

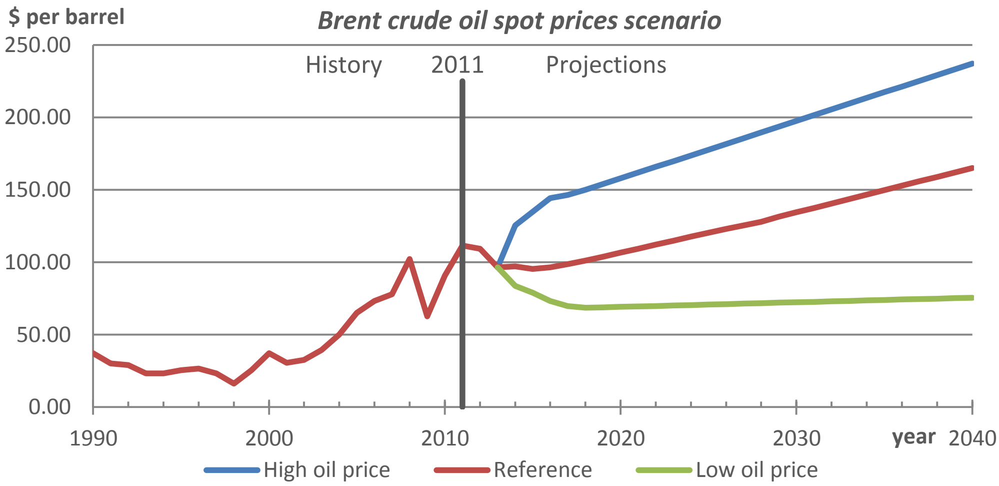


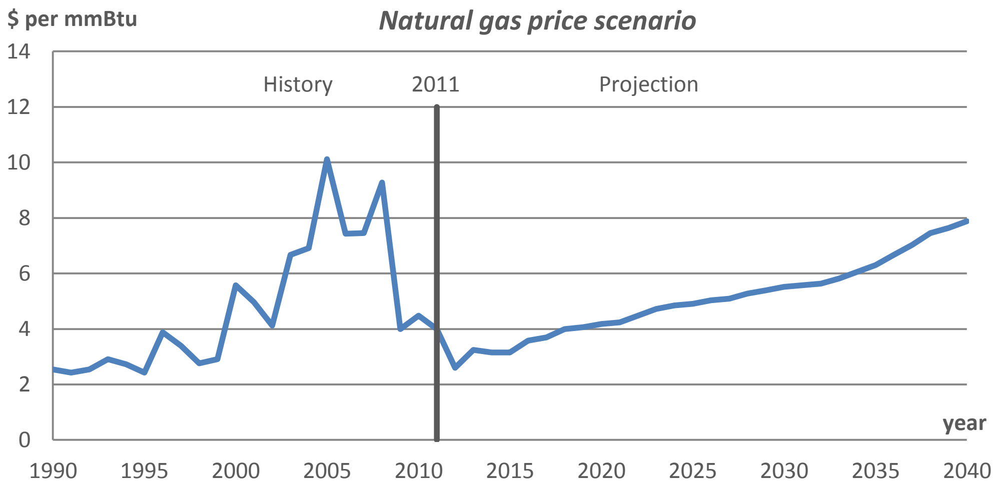

FIGURE 35: BRENT CRUDE OIL SPOT PRICES 1990 – 2040 (EIA, 2013)

[61] (Jalkanen, Kalli, & Stipa, 2013)
[62] (U.S. Energy Information Administration, 2013)
* *MDO price until 2010, after 2010 MGO price*
** *HFO with 1.5 % Sulphur until 2010-07, HFO with 1.0 % sulphur from then*

In this case a high and low oil price and reference scenario. All scenarios are based on a gradual increasing demand of crude oil and natural gas. EIA predicts an annual price increase of 1.3 % for Brent and 1.8 % for WTI crude oil. The base scenario suggests that Brent price declines to $96 per barrel in 2015 after which it increases to $163 per barrel in 2040; other scenario prices are indicated in figure 35.

Another difference is Non-OPEC oil production, because OPEC keeps in all scenarios production as low as possible to keep crude oil prices at a certain level. Figure 36 shows annual average Henry Hub spot prices which will increase in the future due to developing costs of new incremental production.

**FIGURE 36: ANNUAL HENRY HUB SPOT NATURAL GAS PRICES 1990 – 2040 (EIA, 2013)**




This occurs also for crude oil spot prices because 'easy' wells are depleting. Because the unit of natural gas is different than that of crude oil price, figure 37 shows the expected ratio between Brent and Henry Hub on an energy-equivalent basis. Keep in mind that the ratio in this figure is Brent vs. Henry hub, while figure 26 illustrates the ratio Henry hub vs. Brent.

**FIGURE 37: RATIO BRENT CRUDE OIL VS HENRY HUB PRICES 1990 – 2040 (EIA, 2013)**

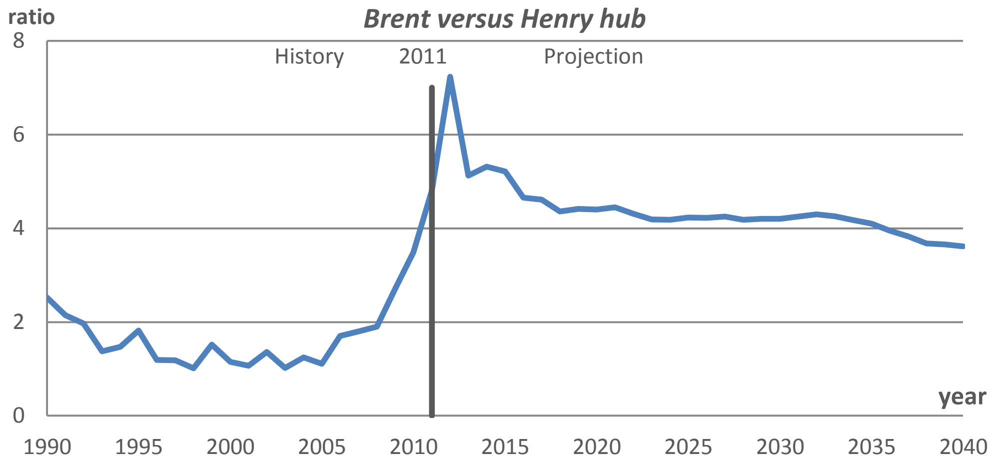



Figure 37 indicates that according EIA the prices of US based natural gas will increase more than crude oil prices. An explanation for this is that Henry Hub prices are relatively low and will increase with an average of 2.4 % each year as figure 36 shows; meaning prices will more than triple between 2011 and 2040. However this ratio is energy-equivalent based, which means that a ratio of 1 indicates that crude oil and natural gas costs the same in terms of energy content. This is not yet the case, so natural gas remains cheaper, but the gap is reduced.

This world energy outlook report provides a summary of future price prediction of different institutes. These institutes are IHS Global Insight Inc. (IHSGI), Energy Ventures Analysis Inc. (EVA), Interindustry Forecasting Project at the University of Maryland (INFORUM) and ICF international. IHSGI provides economic and financial information on industries and even countries. EVA is an energy consulting firm with more than 30 years of experience in the energy industry. IFC international is also a consultancy firm in the field of among other energy and environment. INFORUM is in general dedicated to understand the economic environment. All these institutes have many years of experience. Table 15 and table 16 show according the earlier mentioned institutes the different prediction for respectively natural gas and crude oil.

**Comparisons Henry Hub spot market price gas projections, 2025, 2035, and 2040 [$ per mmBtu]**

TABLE 15: COMPARISON HH PREDICTION IN $ PER MMBTU (EIA, 2013)

| | 2011 | 2025 | 2035 | 2040 |
|---|---|---|---|---|
| EIA - AEO2013 (Reference case) | 3.98 | 4.87 | 6.32 | 7.83 |
| IHSGI | - | 4.39 | 4.98 | 5.39 |
| EVA | - | 6.34 | 8 | - |
| ICF International | - | 5.02 | 6.21 | - |

Natural gas predictions, as shown in table 15, show the same trend. However predictions for crude oil prices, which are provided in table 16, are quite different.

**Comparisons of oil price projections, 2025, 2035, and 2040 [2011 $ per barrel]**

TABLE 16: COMPARISON OIL PRICE PREDICTIONS IN 2011 $ PER BARREL (EIA, 2013)

| | 2011 | | 2025 | | 2035 | | 2040 | |
|---|---|---|---|---|---|---|---|---|
| | WTI | Brent | WTI | Brent | WTI | Brent | WTI | Brent |
| EIA - AEO2013* | 94.86 | 111.26 | 115.36 | 117.36 | 143.41 | 145.41 | 160.68 | 162.68 |
| AEO2012* | 94.82 | - | 135.35 | - | 148.03 | - | - | - |
| EVA | - | - | - | 78.18 | - | 82.16 | - | 87.43 |
| IEA** | - | 107.6 | - | 135.7 | - | 145 | - | - |
| INFORUM | - | 111.26 | - | 136.77 | - | 149.55 | - | - |
| IHSGI | 94.88 | - | 93.05 | - | 86.25 | - | 81.2 | - |

* These prices are for the reference case
** These prices are from the current policies scenario and are an international average of crude oil import prices

One of these differences is that EVA expects a lower crude oil prices in comparison with the other institutes, because they expect an increase in natural gas demand. As a result EVA predicts that natural gas price increases more than the other predictions. Another interesting point is that IHSGI predicts that the price of WTI crude oil is reducing. IHSGI expects that Brent becomes an even greater benchmark for crude oil, due to limited supply of WTI. Also Brent will be used to price more crude oil in favour of WTI.

## 6.5 CHAPTER SUMMARY

As expected and as above described reports mentioned, future fuel price are hard to predict due to complex mechanisms. The general opinion is that prices will increase in the future which is the only similarity between all reports.

### CRUDE OIL

HFO and low sulphur fuel are distilled out of crude oil and price fluctuations of crude oil will be reflected in those fuels. The commonality of all consulted reports is that prices of crude oil are expected to rise. The reason for this price rise is twofold: The first reason is that World economies are recovering from the financial crisis and that transportation demand is growing. Because oil based fuels are still the most used fuel, this will increase the demand in crude oil and therefore price. The second reason is that OPEC has an incentive to restrict production[62] in order to maintain a certain price and ensure sustainable income in the long run. This incentive is visible in the limited supply growth and in case of more non-OPEC production, a reduction of OPEC production. This 'mechanism' can however not continuously be used by OPEC, because if production and therefore supply drops, income will also drop. Hence, prices are not expected to decrease drastically, because that would not be in favour of OPEC. Appendix I shows a list of OPEC countries.

### NATURAL GAS

Natural gas prices are not the same worldwide. Expectation is that different prices worldwide will converge toward each other and eventually prices will be roughly the same. US prices are expected to increase due to growing demand and loosening of strict export regulations. Prices in Asia will decrease, which is caused by rise in LNG supply from the US and Australia. Asian natural gas prices will also decrease because Asia will switch from oil based pricing to gas-on-gas market pricing mechanism. This will be reflected in the LNG price, because LNG is liquefied natural gas. In general LNG prices can rise due to growing demand or drop due to growing supply. It is expected that LNG demand will not drop.

## 6.6 USED SCENARIO

The basic pricing mechanisms and prediction of mayor players, like energy companies and institutes, are described above. With this knowledge future prices has to be predicted. To get a reasonable indication of different fuel price levels, different scenarios will be developed to reduce uncertainties of future prices.

There are some uncertainties which have to be taken into account. The first one is mentioned in chapter 6.2; one of the questions is what Japan will do with their power plants. After Fukushima, almost all nuclear power plants in Japan were shut down, but in summer of 2012 they put some plants back in operation to prevent a power failure[63]. Also Germany has plans to shut down all their nuclear power plants by 2022[64] and this "loss" of power has to be generated otherwise. This could influence natural gas demand and therefore LNG prices.

The second uncertainty is that it is unknown if ship owners will continue to sail on HFO with exhaust aftertreatment systems or switch to different fuels like low sulphur fuel or LNG in ECA zones. Due to $CO_2$ regulation, expectation is that ship owners tend to move to LNG as primary fuel, because LNG can comply with all regulations. This uncertainty influences demand in different fuels. If ship owners tend to scrubbers, HFO will still be used in ECA zones and demand for HFO will continue to increase. On the other hand when ship owners seek emission solution in LNG, HFO demand will be lower and LNG demand will increase. It also depends on the age of the vessel. As described in chapter 5.1.3 LNG is not favourable for retrofit, but scrubbers can be.

[63] (World Nuclear Association, 2013)
[64] (Evans, 2011)

As chapter 5.1.1 described, HFO is residue of the distillation unit when processing crude oil. Refineries which process sweet crude oil can produce more and/or cheaper low sulphur fuel than refineries that process sour crude oil. So the used process of a refinery has influence on the output composition. The question is what refineries will do when demand for HFO will decrease. Will they invest to produce more distillate fuels out of crude oil or will HFO prices drop? In case the answer is to produce more distillate fuels, what will happen to the price of low sulphur fuel? This could go either way. The demand for low sulphur fuel will increase due to stricter emission regulations and mandatory use of cleaner fuels. If the demand is higher than the increased supply, the price will rise. When this is not the case, prices could drop.

It is, however, assumed that fuel demand will rise, due to economic growth which causes fuel prices to rise as seen in the past. The level of increase will be different for oil based fuels and gas based fuels, which is influenced by ship owners in what they see as solution to reduce emissions.

Fuel prices in the port of Rotterdam on the 16th of January 2014 according bunkerworld.com[65] are used as reference price on which the base prices are based. These prices are shown in table 17.

TABLE 17: REFERENCE PRICES PORT OF ROTTERDAM ON 16/01/2014

| Reference prices port of Rotterdam on 16/01/2014 | | |
|---|---|---|
| IFO380 | $ 564.00 | $/mt |
| 0,1 % MGO | $ 873.50 | $/mt |
| LS380 (1 %) | $ 594.00 | $/mt |
| EN 590[66] | $ 1188.00 | $/mt |
| LNG[67] | $ 10.75 | mmBtu |

For LNG, prices are difficult to determine because they are not transparent. LNG prices are specified mostly in long term contracts and for small-scale LNG prices are unknown. The expectation is that demand for small-scale LNG is growing and more supply points will be build. This will reduce the distribution costs of LNG and therefore the difference between LNG and small-scale LNG prices. Another assumption is that in the future all LNG traders will use the same pricing mechanism as US is currently using, gas-on-gas mechanism and not oil based. LNG prices are given in dollars per mmBtu and to compare LNG prices with oil based fuels, mmBtu has to be converted into metric ton. The used conversion factor is 48.6, which results in a LNG price of $ 522.94 per mt.

According this knowledge, the following prices, as shown in table 18, are determined for this dissertation.

TABLE 18: SCENARIO PRICES IN DOLLARS PER MT

| | Low | Base | High |
|---|---|---|---|
| IFO380 | $ 423.00 | $ 564.00 | $ 705.00 |
| 0,1 % MGO | $ 655.13 | $ 873.50 | $ 1091.88 |
| LS380 (1 %) | $ 445.50 | $ 594.00 | $ 742.50 |
| EN 590 | $ 891.00 | $ 1188.00 | $ 1485.00 |
| LNG | $ 392.25 | $ 523.00 | $ 653.75 |

[65] (Bunkerworld Prices - Latest Prices - Rotterdam)
[66] (Quotation by Sakkocommercial.nl)
[67] (LNG Journal - Daily LNG News)

These prices are assumed according the following scenarios. There will be a base price and an increase and decrease of 25 % of that price. This represents respectively a base, high and low scenario. This deviation of 25 % gives an indication of the effect of price fluctuations on the results. For long term contracts, prices could be lower, but this is not taken into account.

With the different fuel prices determined, the next step is to choose which program will be used to perform the LCPA. This next step is described in chapter 7 and this chapter will describe how the program will be chosen and to which criteria the program has to comply.

# 7. LCPA PROGRAM

Almost all necessary information to perform an LCPA is described in previous chapters. However the most important part has yet to be chosen, which software program will be used. Will it be an existing LCA and/or LCC program or a program designed specifically to perform LCPA on ships? Some existing programs can only perform LCA, while others can perform both LCA and LCC. This chapter describes which program will be used and why that particular program is chosen. The overall performance of several programs will be mentioned and criteria will be determined in order to make an educated decision.

## 7.1 CRITERIA

The choice of which program to use will be based on different criteria. These criteria are weighted to determine the difference between the programs. To determine the effect of the weighting a small sensitivity study will be performed. This study will be described in chapter 7.1.2.

### 7.1.1 WEIGHTING

The defined criteria are weighted in order of importance, 1 for unimportant to 5 being critical as table 19 shows.

TABLE 19: WEIGHTING CRITERIA LEGEND

| Weighting criteria legend | |
|---|---|
| 1 | Unimportant |
| 2 | Slightly important |
| 3 | Important |
| 4 | Very important |
| 5 | Critical |

Based on that outcome the best suited program will be chosen. The following criteria are set to compare different programs.

- Adaptable: how adaptable is the program
- Easy to learn: how much time it takes to work with the program
- Efficient: is this program simple to use
- Price: is it affordable or expensive
- Reliable: is the program stable to work with
- Result: how accurate is the calculated result
- Shipping specific: is it specific for shipping industry or at least a big shipping related database
- Support: is there any support for this program in case of troubles

A short description of the meaning of these criteria and why they are chosen will be stated next.

#### ADAPTABLE

The program has to be adaptable to a certain level. All programs are developed with 2013 knowledge. In future this knowledge could change and thus program changes could be necessarily. When for instance in future regulations change it should be able to put these new regulations into the program. This criterion is weighed 2 out of 5, as this feature is not essential on short term.

### EASY TO LEARN

Multiple persons have to be able to work with this program. In order to reduce time spent learning to use this program, the program has to be easy to learn. Because it is related to time and money, this criterion is labelled important which is 3 out of 5.

### EFFICIENT

Efficient is also an indication of how simple this program is to use. The program will be used by different persons with different educational background, so the program has to be simple and understandable. A short description/manual is required, because long manuals will not be read which result in less use of the program and thus waste of money. One point that counts for all programs is that over time, when users get familiar with the program, they work more efficient.

Another point of efficient is that the program uses its resources efficient. This means that if the user changes a value in the program, the effect of this change is instantly visible; not that the user has to weight ages before a change is processed. This criterion is weighted 4 out of 5.

### PRICE

The program has to be affordable. Damen is a company who wants to make profit, so the investment of buying this program has to be meaningful. If the program is very expensive and does not improve service to a client, this program is not valuable. Therefore this criterion is weighted 4 out of 5. Notes concerning the prices that will be mentioned later and all these prices are excluding VAT.

### RELIABLE

The program has to be reliable and work stable. It's not allowed to malfunction, because that costs time. The weighting of support, in case malfunction occurs, is not related to this weighting criterion. This criterion is therefore weighted 4 out of 5.

### RESULT

This is the most important part of the program, because if the result is incorrect, the decision based on that result is also incorrect.  This criterion is critical and consequently weighted 5 out of 5.

### SPECIFIC FOR SHIPPING INDUSTRY

There are many LCA programs and in order to narrow the search, the program has to have affinity with shipping industry. The shipping industry is specific and not really comparable to most other forms of industry. The software must be able to cope with this specific industry. This criterion is weighted 1 out of 5, because it could also work when the program is not fully focussed on shipping.

### SUPPORT

In case there are problems with the program, support is needed.  The software is not used 100 % of the time, so some downtime is allowed. However problems have to be solved within days, so that possible answer to clients can be given and that it will not affect the image of Damen. Therefore this criterion is weighted 3 out of 5.

Table 20 shows the summary of the weighting criterion as described above. The main goal is that the program results are good, closely followed by efficient, price and reliable. In case a particular criterion is increased by one point, this will result in an increase of 3.85 % on the total weighting.

TABLE 20: CRITERIA WEIGHTING

| Criteria | Weighting | |
|---|---|---|
| | Amount | % |
| **Adaptable** | 2 | 7.7 % |
| **Easy to learn** | 3 | 11.5 % |
| **Efficient** | 4 | 15.4 % |
| **Price** | 4 | 15.4 % |
| **Reliable** | 4 | 15.4 % |
| **Result** | 5 | 19.2 % |
| **Shipping specific** | 1 | 3.8 % |
| **Support** | 3 | 11.5 % |

### 7.1.2 SENSITIVITY

To understand what the effects of these weighting are, a small sensitivity study is performed which will be described below. For all five weightings the impact of an increase or decrease of one is calculated. An example is shown in table 21.

TABLE 21: SENSITIVITY EXAMPLE FOR ORIGINAL WEIGHTING OF 1

| Criteria | Weighting | | Weighting | | Weighting | | Weighting | | Weighting | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | % | | % | | % | | % | | % |
| Adaptable | 2 | 7.7 % | 2 | 7.4 % | 2 | 7.1 % | 2 | 6.9 % | 2 | 6.7 % |
| Easy to learn | 3 | 11.5 % | 3 | 11.1 % | 3 | 10.7 % | 3 | 10.3 % | 3 | 10.0 % |
| Efficient | 4 | 15.4 % | 4 | 14.8 % | 4 | 14.3 % | 4 | 13.8 % | 4 | 13.3 % |
| Price | 4 | 15.4 % | 4 | 14.8 % | 4 | 14.3 % | 4 | 13.8 % | 4 | 13.3 % |
| Reliable | 4 | 15.4 % | 4 | 14.8 % | 4 | 14.3 % | 4 | 13.8 % | 4 | 13.3 % |
| Result | 5 | 19.2 % | 5 | 18.5 % | 5 | 17.9 % | 5 | 17.2 % | 5 | 16.7 % |
| ***Shipping specific*** | *1* | *3.8 %* | *2* | *7.4 %* | *3* | *10.7 %* | *4* | *13.8 %* | *5* | *16.7 %* |
| Support | 3 | 11.5 % | 3 | 11.1 % | 3 | 10.7 % | 3 | 10.3 % | 3 | 10.0 % |

This example shows the effect of a change in a criterion that was originally weighted one, in this case the shipping specific criterion. As table 21 shows, that particular criterion was affecting the total with only 3.8 % by a weighting of one; but this is increased to 7.4 % in case this criterion was weighted 2. This is an increase of 3.6 %. The next increased step however results in an increase on the overall effect of 3.3 %. The effective increase of weighting is thus reducing for each increasing step. Table 22 shows the results for all five weighting levels.

TABLE 22: SENSITIVITY RESULTS

| | 1 - 2 | 2 - 3 | 3 - 4 | 4 - 5 |
|---|---|---|---|---|
| **Original weighting = 1** | 3.6 % | 3.3 % | 3.1 % | 2.9 % |
| **Original weighting = 2** | 3.7 % | 3.4 % | 3.2 % | 3.0 % |
| **Original weighting = 3** | 3.8 % | 3.5 % | 3.3 % | 3.0 % |
| **Original weighting = 4** | 4.0 % | 3.7 % | 3.4 % | 3.1 % |
| **Original weighting = 5** | 4.2 % | 3.8 % | 3.5 % | 3.2 % |

The columns shows the steps from different weighting criteria, so 1 - 2 means the step from 1 to 2 in percent on the total weighting. In other words, if the weighting was increased from 1 to 2, the influence of, for example original weighting one on the overall results would be 3.6 %. And so for the change of one to four, the influence of that criterion on the overall results would be 3.6 + 3.3 + 3.1 = 9.9 %.

It can be seen that as described above, for all levels the effective increase of weighting is reducing for each increasing step. This can be explained because the total number of all weighting is higher and thus the increase by one is divided by a higher number, resulting in a lower effect. The average effect of one step on the total weighting is 3.4 %.

## 7.2 PROGRAMS

Keeping above described criteria in mind, the following programs are chosen to be evaluated; BESST LCPA, GaBi software and SimaPro. Lessons learned from evaluations of the former software tools were used to develop an excel-based program that will be evaluated with the same criteria at the end of this chapter to determine if it is worth to design/develop such program. The commercially available programs are chosen because they are either specific for the shipping industry, have a big database and/or are commonly used. All these programs can express environmental emissions in terms of global warming potential expressed in tonnes $CO_2$, eutrophication potential in tonnes $PO_4$ and acidification potential in tonnes $SO_2$. Furthermore these programs can perform LCC. In chapter 7.3 the best suited program to use for this thesis is selected. All programs will be rated on the criteria mentioned earlier this chapter. The rating system is from one to five, with one being poor and five being excellent. This rating is shown in table 23.

TABLE 23: RATING LEGEND

| Rating legend | |
|---|---|
| 1 | Poor |
| 2 | Fair |
| 3 | Average |
| 4 | Good |
| 5 | Excellent |

### 7.2.1 BESST LCPA VERSION 2.0.5

BESST is an abbreviation for Breakthrough in European Ship and Shipbuilding Technologies. It is the name of a project that was part of the Seventh Framework Programme (FP7) which started in September 2009 and ended 42 months later. FP7[68] is short for European Commission Seventh Framework Programme for Research and Technological Development. Framework programmes are used by the EU to support and fund research in Europe. BESST was initiated by EuroYards, a European Economic Interest Grouping which includes Damen Shipyard Group amongst other leading European Shipbuilding companies. This group was joined by 20 research institutes and universities, 5 classification societies and 31 industrial companies from 12 European countries. Figure 38 shows a timeline of the different framework programs.

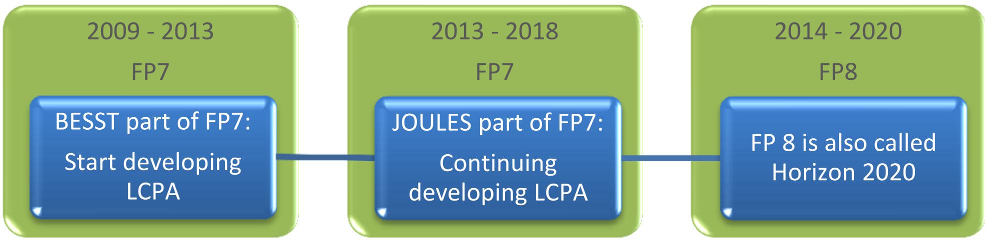



FIGURE 38: FRAMEWORK PROGRAMS TIMELINE

68 (European Commission FP7)

## JOINT OPERATION FOR ULTRA LOW EMISSION SHIPPING (JOULES)[69]

The JOULES project is a 'follow up' of BESST. This project started first of June 2013 and will last 48 months. As the name suggests, the goal will be to reduce energy consumption and air emissions, including $CO_2$, $NO_X$, $SO_X$ and PM, of European build ships significantly. The objective is to reduce ship emissions with 25 % in 2025 and at least 40 % by 2050 as compared to modern ships. JOULES consortium consists of eight shipyards, two towing tank institutes, eleven research institutes, thirteen technical suppliers, one software developer, two ship owners/operators and two classification societies, resulting in 39 partners from ten European countries. Damen Shipyard and Technical University Delft are participating in JOULES. This project will support the next project of the Eight Framework Programme called Towards a zero emission ship. This Eight Framework Programme is also called Horizon 2020.

## LIFE CYCLE PERFORMANCE ASSESSMENT

BESST primary goal was to increase competitiveness of ships build in Europe. This will be achieved by decreasing life cycle cost, reducing environmental impact of ships and continue to improve safety. The types of ships that were mainly focused on were passenger ships, ferries and mega-yachts. The end result of BESST is a LCPA tool. The version I have available is 2.0.5 while version 2.0.28 is already developed and on the market. Figure 39 shows an overview of the LCPA input screen, on the left side there is an input field of all components of the ship. On the top right there is an explorer to browse through different projects and bottom right there is a log.

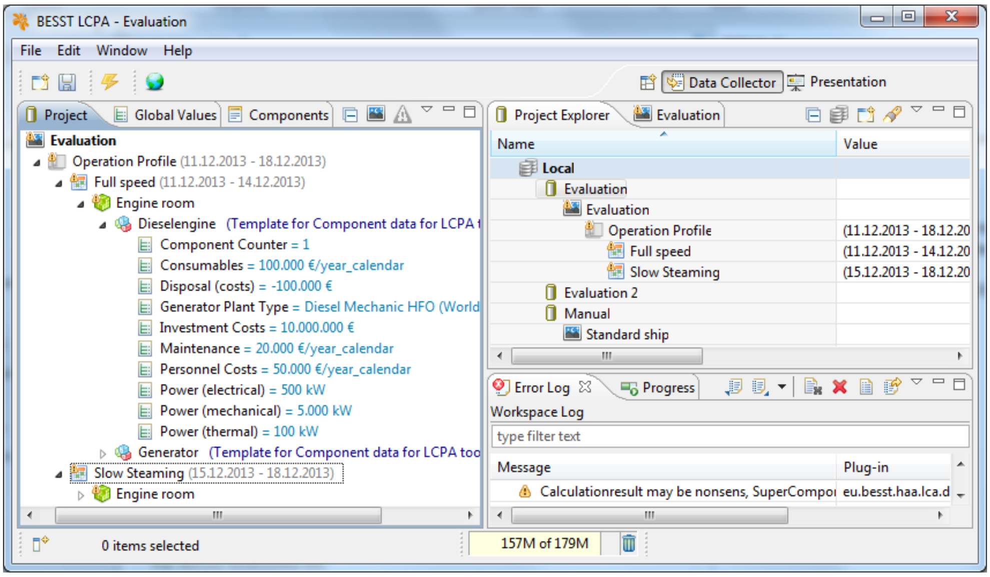



**FIGURE 39: BESST LCPA 2.0.5 OVERVIEW**

This tool is actually an extended life cycle costing tool. It is a LCC tool that also takes environmental emissions and some social aspect, like comfort, pleasure, safety and privacy into account. These social aspects can either be left empty or given a value between one, worst evaluation to ten, best evaluation. The average of all these number will give a total social score. The financial part is the most detailed. Multiple costs, like investment, personnel, maintenance and bunker costs can be taken into account. The result of LCC is given as net present value by a chosen discount rate.

[69] (JOULES, 2013)

### ADAPTABLE

BESST has several predefined global values and components; more can be added into the program. However other things are not adaptable. This could be changed in newer LCPA versions, but this is unknown. BESST LCPA scores for this criterion 3 out of 5.

### EASY TO LEARN

There is no manual available, so the working principle has to be figured out by the user. It takes some time, but eventually it is understandable what the influence of one change on the outcome is. The program is not complicated, it only takes time.  Because there is no manual and the user has to sort it out, this programs scores 2 out of 5.

### EFFICIENT

The accuracy of the calculations of this program can be set. Calculations are based on the phase which is defined by the user. This phase accuracy can be from hours up to years. When the phase accuracy is set to hours, it will calculate for each hour what the result will be. In case the phase accuracy is set to years, the program will calculated a complete year instead of every hour or day of that particular year. This accuracy has huge impact on the calculation time, which means that it depends on the accuracy how fast results are calculated. The difference between an accuracy of hours or years is minute's calculation time for a small model. This influences the efficiency, but the choice is up to the user.

This tool is simple to work with. As figure 40 illustrates the program is divided into a left and right side. The left side list the main components and by selecting such component, like engine room, a new window opens on the right side where more data can be filled in. This makes the program efficient to work with, because it reduces actions that have to be performed.  Because the user can determine the efficiency and the tool is easy to work with, BESST LCPA scores 5 out of 5.

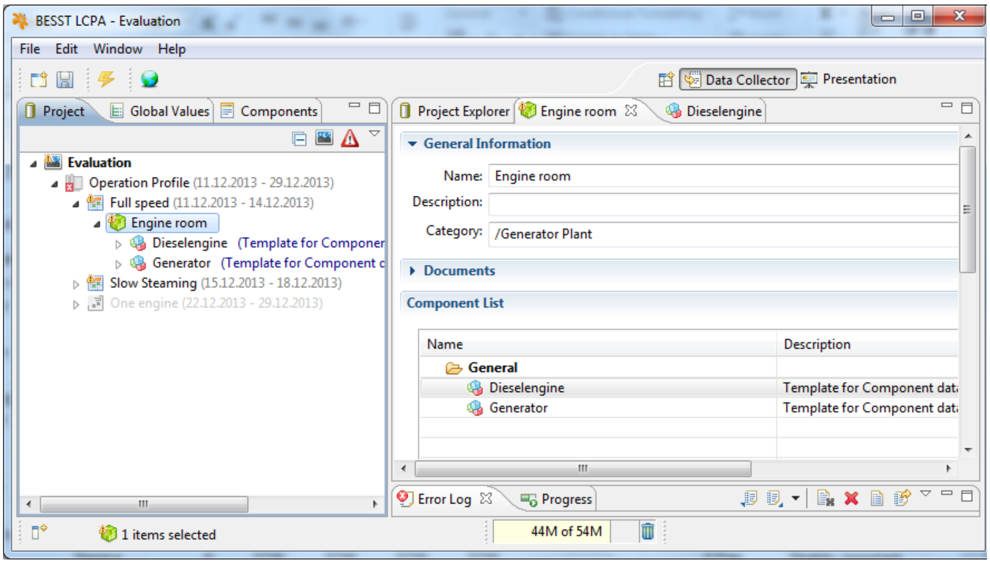



**FIGURE 40: BESST LCPA 2.0.5 DETAILED**

### PRICE

BESST software is far more expensive than the alternatives that are described later.  A company license costs an initial 32,000 euro and the yearly maintenance fee is 8,000 euro. Damen gets some discount, because Damen has participated in BESST, but this is not enough to be cheaper than the alternative. Because of this high costs, BESST scores 1 out of 5.

#### RELIABLE

This version of BESST is, in terms of stability, not reliable. During testing time, BESST crashed multiple times and sometimes the cause of the crash was unknown. It is expected that stability is better in future versions, but these future versions are not available as mentioned earlier. Due to the instability BESST scores 1 out of 5.

#### RESULT

The results are given in different graphs and there is a possibility to get all the results in one report with graphs, tables and input parameters. The result is given in a clear overview and also the quality of the result is good. Therefore this program is rated 5 out of 5.

#### SHIPPING SPECIFIC

As described earlier, BESST is specifically designed for shipping; however this LCPA version is in terms of environmental aspects only applicable to the operational phase of a ship and not the production or recycling phase. For the financial parts, these phases can be taken into account with the purchase price and the disposal price of the ship. This results in a score of 4 out of 5 for BESST. There are plans that the successor of this tool, which is being developed in the JOULES project, will incorporate the production and recycling phase of a ship.

#### SUPPORT

There are two LCPA workshops per year were new features are presented and further improvements can be discussed. There is online support, but this is only available after buying and registration of the program. It is all really restricted and therefore support of BESST scores 2 out of 5.

#### OVERALL

Overall BESST has the potential to be a good LCPA program specifically for shipping; unfortunately this program is clearly still in beta phase. Because there is no manual available, the learning curve is steep. Nevertheless, if the user understands the program it is, besides the instability, pleasant to work with. If these bugs are fixed in the most recent release the program would be ideal for LCA and LCC. The only drawback would be the price, because this is really high in comparison to other LCA programs and not justifiable. The overall score for this 2.0.5 version is 2.88 out of the maximum score of 5.

### 7.2.2 GABI SOFTWARE VERSION 6

GaBi software is a LCA engine which can work with both LCA and LCC. The program can make life cycle reports directly linked with the results of the analysis. GaBi can work with the complete cradle to grave cycle in terms of LCA and LCC according ISO 14040 & 14044. It is a very complete program with 4700 LCI datasets and latest LCA methodologies. Figure 41 displays an example of a life cycle of a steel paperclip in GaBi.

#### ADAPTABLE

Complex models can be built in GaBi and because data from 4700 datasets is available, adaptability is good; especially because these datasets are expending each year and these datasets are connected to the European reference Life-Cycle Database (ELCD). The only drawback is that the user is dependable of GaBi software in how up to date the data is which results in a score of 3 out of 5.

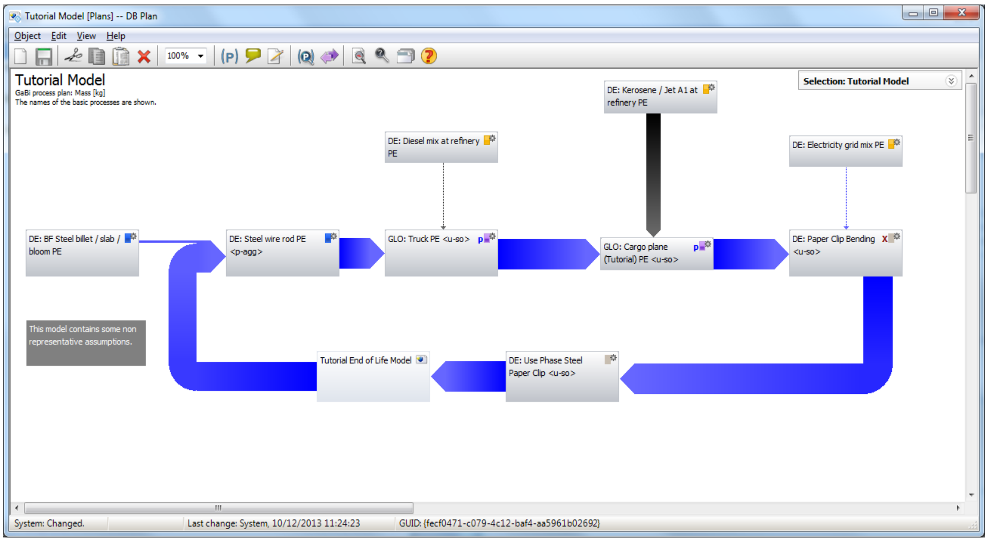



FIGURE 41: GABI VERSION 6 PAPERCLIP EXAMPLE

### EASY TO LEARN

GaBi has a complete learning center available on their website[70] on how to work with GaBi. This learning center is divided into two parts, an introduction to GaBi and scenario modelling for eco-design. The first part contains 21 chapters which is equivalent to about one hour of learning material. These chapters guide the user step by step through the software by setting up an LCA for steel paperclips. The second part also contains about one hour of learning material, related to how to make interactive reports in GaBi. Instead of watching these tutorials, it is possible to download a handbook with the same information. After this one or two hour, the user could start working with GaBi. Probably the user has to look back a few times, but most essential parts are explained. Because of the time it takes to learn the program, GaBi scores 4 out of 5.

### EFFICIENT

During the short time I used it, it was not working that efficient. Sometimes clicking twice with the mouse works, but other times I had to click with the right mouse pad, before the desired action was executed. This is frustrating and not easy to work with and therefore GaBi scores 2 out of 5.

### PRICE

The price of GaBi software could not be found on their website, so an email was sent to the sales department of GaBi. The response was that GaBi offers two license models for both software and database content. One license is a perpetual license with a price range for a full version of GaBi Software + prof. database from 9,000 euro. For a single database, prices range from 500 up to 4,500 euro. When a maintenance or service contract is wanted, that will costs around 25 % of license fees, which is 2,250 euro for the 9,000 euro license. So for the first two years GaBi software will cost 22,500 euro.

A temporary licence for one year cost 4,500 euro for both GaBi software and prof. database and costs for only databases are in range of 125 and 1,125 euro. In comparison to other software packages, this is a bit more expensive than SimaPro but much cheaper than BESST and therefore GaBi scores 2 out of 5.

[70] (GaBi 6 Learning Center)

#### RELIABLE

During the testing time, GaBi didn't crash or stopped working otherwise. This time frame however was short, so not a very good representative timespan, but in the same time frame BESST software crashed a lot. This is the reason that GaBi software scores 4 out of 5.

#### RESULT

As described earlier, GaBi has access to 4700 LCI databases and the latest LCA methodologies to use for calculations. Also the fact that numerous Fortune 500 companies use GaBi software is an indication that results are good. Because GaBi has access to many databases and is used by the biggest companies in the world results in a score of 5 out of 5.

#### SHIPPING SPECIFIC

GaBi software is not design specifically for shipping; however it has data of crude oil, LNG and ship materials like steel and aluminium in its databases. And data can be manually entered, but this is also possible in other LCA software. Because it has some shipping related information GaBi software scores 3 out of 5.

#### SUPPORT

GaBi support seems good. As mentioned earlier, I have contacted GaBi and within 15 minutes I got a response. There is also a possibility to live chat in case the user needs help. On their website there is a My GaBi service and support and GaBi offers different trainings. Another good thing is that a possible user can try GaBi software for free for 30 days. GaBi software scores on support 5 out of 5.

#### OVERALL

Overall GaBi software is used by big multinationals which indicates that it is a good program. It also has a huge amount of different possibilities and input methods. The GUI is pleasant to work with, better than SimaPro which appears to be outdated. The user can drag and drop flows or processes which is quite useful and it indicates when input is still needed. The iReport software that is incorporated in GaBi is useful to make report, without needing Word or another text program. There are however some drawbacks; the software focusses more on LCA than on LCC and GaBi is not specifically for shipping industry.  Gabi scores an overall score of 3.58 out of 5, which is better than the BESST LCPA software.

### 7.2.3 SIMAPRO VERSION 8

SimaPro is similar to GaBi software. It also provides LCA and LCC methods and is used worldwide. It can perform many different impact assessment methods. SimaPro is linked to Ecoinvent database version 3 which is their main database. SimaPro has different business licenses; compact, analyst and developer. Compact is for easy use, quick learning, so a kind of light version. Analyst has advanced features and is transparent and flexible, sufficient for normal users. Developer license is for consultant and industry association who develop tools for clients. In this comparison the business license analyst is chosen, because this is for the normal user and is most similar to the alternative software. Figure 42 illustrates a flow chart of a coffee maker in SimaPro version 8.

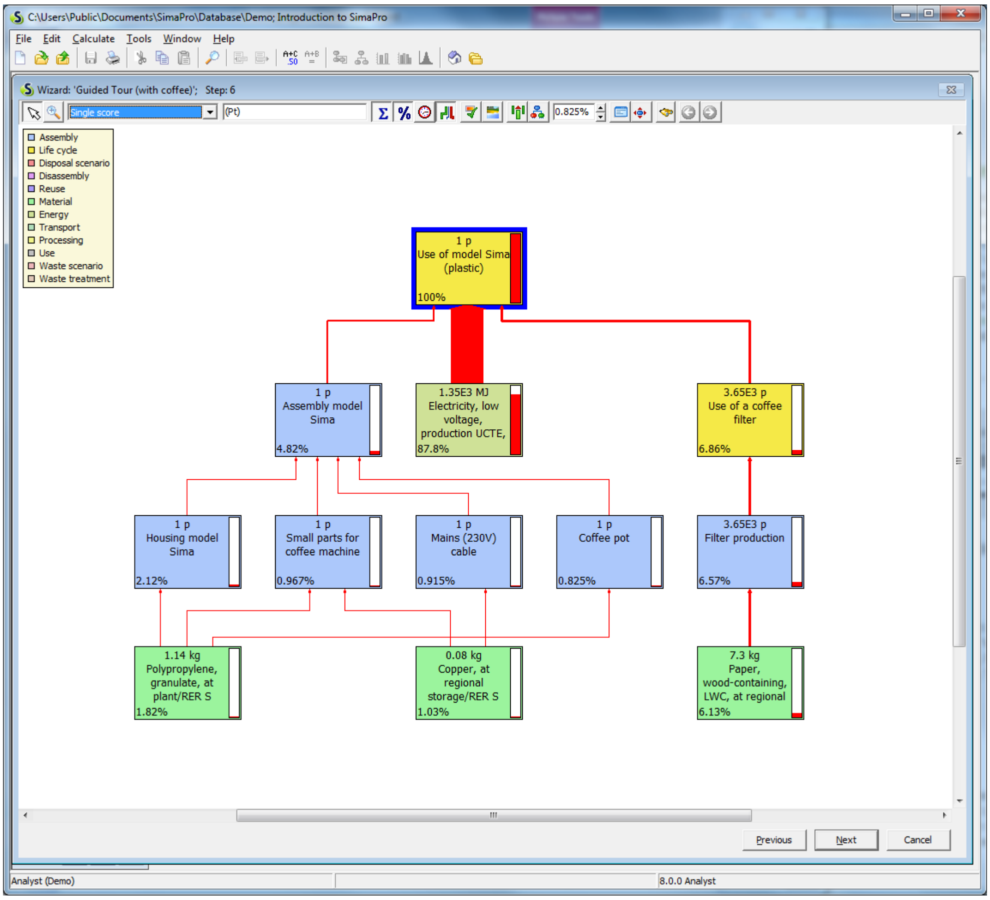



**FIGURE 42: SIMAPRO VERSION 8 OVERVIEW**

## ADAPTABLE

SimaPro has almost the same adaptability as described at GaBi. However, as described above, SimaPro has different licenses. Therefore there is a possibility to upgrade to a different license in order to adapt to other functions. Because of this advantage in relation to GaBi, SimaPro score one point higher, so 4 out of 5.

## EASY TO LEARN

SimaPro has two introduction ways; there is a guided tour about coffee which shows in about 30 minutes the most important features of SimaPro. The other way is a LCA Wizard Demo which shows various product stages in SimaPro. Furthermore there are additional files and manuals on SimaPro's website[71]. The guided tour shows indeed different features, but after this guided tour I was not able to start working with SimaPro, so SimaPro is not easy to learn, which results in SimaPro score 3 out of 5.

## EFFICIENT

After every change that is made, SimaPro changes/updates the database. How far this process is complete is indicated on the screen. For most simple changes it takes already a couple of seconds, even during the tutorial. This happens for all different licenses, even the compact one. This couple of seconds waiting time is annoying. Another irritating point is that if the user presses cancel during saving process, the complete work is gone and the user has to start all over again. These annoying and irritating points result in a score of 1 out of 5 for SimaPro.

[71] (SimaPro Downloads)

#### PRICE

The different licenses for SimaPro, which are mentioned in the beginning of chapter 7.2.3, are differently priced. The analyst business, which includes Ecoinvent 3 database license and first year service contract costs for indefinite use 8,800 euro. The service costs will be 1,710 euro per additional year. For the first two year SimaPro costs 19,310 euro.

A temporarily license for one year will cost 4,400 euro, which also includes service contract costs. In comparison to previous software packages, SimaPro is the cheapest for both perpetual as temporarily licenses. Therefore SimaPro scores 3 out of 5, because it is still a lot of money.

#### RELIABLE

As under criterion efficient is described, during a cancellation procedure, something went wrong and the complete work was lost. This is already taken into account, so it will not affect the score of this criterion. Like GaBi, the software didn't crashed or stopped working otherwise, but the time was short and not a very good representative. SimaPro scores the same as GaBi, which is 4 out of 5.

#### RESULT

The fact that SimaPro provide software in more than 80 countries indicates that SimaPro has many users. Also a lot of databases are used in the calculations, so the expectation is that the results will be good. Therefore SimaPro scores 5 out of 5.

#### SHIPPING SPECIFIC

For SimaPro it is the same as GaBi, it is not specifically designed for shipping, but has a big database and data can be entered manually. SimaPro scores the same as GaBi, which is 3 out of 5.

#### SUPPORT

On the website of SimaPro there is a support corner, which is divided into help center and FAQ. Furthermore there is a LCA learning Library, software installation and contact support. LCA Learning Library offers videos, slideshows, research report and more. This indicates that the support covers a lot. In contrary to GaBi there is no possibility to live chat with a helpdesk and therefore SimaPro scores 4 out of 5, one point less than GaBi.

#### OVERALL

Overall this tool is commonly used and this indicates that it is thoroughly tested and is expected to be reliable. The GUI could have been better, it is working but it would work more pleasant with a different/nicer GUI. It is nice that there are different licenses so the user can choose the one that fits best. However the learning curve of this program is steep and hopefully when the user is familiar with SimaPro it will be less irritating. Other drawbacks are the same as GaBi; it focusses more on LCA than on LCC and it is not specifically design for shipping. This results in an overall score of 3.42 out of 5.

## 7.3 SELECTING PROGRAM

In previous part three programs were analysed and rated to see which program is best suited to use for this dissertation. Table 24 shows an overview of the result of this rating.

TABLE 24: OVERVIEW RATING

| Criteria | Weighting | | BESST | | GaBi | | SimaPro | |
|---|---|---|---|---|---|---|---|---|
| | | % | Rating | Score | Rating | Score | Rating | Score |
| Adaptable | 2 | 7.7 % | 3 | 0.23 | 3 | 0.23 | 4 | 0.31 |
| Easy to learn | 3 | 11.5 % | 2 | 0.23 | 4 | 0.46 | 3 | 0.35 |
| Efficient | 4 | 15.4 % | 5 | 0.77 | 2 | 0.31 | 1 | 0.15 |
| Price | 4 | 15.4 % | 1 | 0.15 | 2 | 0.31 | 3 | 0.35 |
| Reliable | 4 | 15.4 % | 1 | 0.15 | 4 | 0.62 | 4 | 0.62 |
| Result | 5 | 19.2 % | 5 | 0.96 | 5 | 0.96 | 5 | 0.96 |
| Shipping specific | 1 | 3.8 % | 4 | 0.15 | 3 | 0.12 | 3 | 0.12 |
| Support | 3 | 11.5 % | 2 | 0.23 | 5 | 0.58 | 4 | 0.46 |
| **Total** | **26** | **100 %** | **23** | **2.88** | **28** | **3.58** | **27** | **3.42** |

GaBi has the highest rating, followed by SimaPro. BESST has the lowest rating, which is caused by high price and the unreliability. GaBi and SimaPro are used worldwide and are quite good. However these programs have drawbacks, because there are mainly focussed on LCA rather than both LCA and LCC. Furthermore they work not that efficient and the price is also high. On all other points these programs score averages or higher.

As mentioned earlier, the BESST LCPA version that was analysed was still a beta version with lots of bugs. The expectation is that newer versions are more robust and reliable to use. Another expectation is that the support will be better once the program is bought, as well as a manual or tutorial. In my opinion BESST has a high potential to be a good LCPA tool, however the price is way too high. Unfortunately I did not have the latest version to my disposal.

The program that will be used for this thesis will be of own design. The reason for this is that GaBi and SimaPro are just too complex to work with and are mainly focussed on LCA. Also the relatively high price is a barrier. BESST isn't used because the latest, more stable version is not available for this thesis and the beta version is too unstable. The development of the new program is described in the next part of this chapter.

## 7.4 NEW DESIGN

This chapter will be divided into two parts. The first part, 7.4.1, describes why this program will be better than above described programs. The second part, 7.4.2, will describe the programs development process and which choices are made during the development.

### 7.4.1 CRITERIA

LCA and LCC methods are based on formulas and Excel is commonly known to work with formulas. Therefore Excel will be used to develop the LCPA program, which will be further referred to as LCPA tool. Matlab could also have been used, but Matlab is more complex than Excel and thus more difficult to learn. According the earlier mentioned criteria it will be explained why an own design program is better than the alternatives.

#### ADAPTABLE

This tool will be developed in house and therefore source codes are known. This means that adjustments in the future are easy to incorporate. The only limitation is what Excel can or cannot do. Another advantage is that Damen already works with Excel for other purposes like power predictions. If all files are in Excel format, it is easier to combine those files when necessarily.

### EASY TO LEARN

Excel is familiar to most people so the program will not have a steep learning curve. Excel can deal with macros, but users can interpret those macros as black boxes. Data is going in and results are coming out, but what kinds of calculations are performed is unknown. The use of macros will be kept to a minimum. By not using macros, users can 'follow' what happens and is thus easier to understand. During the development a manual will be written in order to help user how to work with the LCPA tool. Furthermore it is tailor made to specific needs. Everything that will be in there has a purpose, so it will not have data which is irrelevant. This will simplify the learning process.

### EFFICIENT

This program will be efficient in two ways. First Excel will use a specific database with only relevant data; this keeps the database small. In comparison to other programs, which use databases with maybe 10 % relevant information, this saves times. This is possible by keeping everything simple and small. Another advantage of a small file is that this is not hardware intensive. The result will be that Excel works real time. This means that by changing one value, new results will be calculated immediately and are instantly visible.

Another point is that because it is developed from a user point of view, it is known what a logical order of input will be. This helps the program to be simple and so efficient to use.

### PRICE

This tool is, compared to other software prices, very cheap, because Excel is already purchased for other purposes. If we disregard this fact and assume that Excel still has to be bought, the price for Office 365 Enterprise E3, which contains Excel, but also Word, PowerPoint and Outlook, will be 19 euro per month[72].

Another point worth mentioning is that it takes time to develop this tool, which also costs money. This can be seen as investment costs and occur only once. Other costs could be the maintenance of the database; however most time will be in gathering the information for the database which will occur during the development. If, in the future, the database has to be updated, it will only change minor things, which won't costs much time and thus money.

### RELIABLE

Reliability is unknown in this phase. The program has to be built yet and therefore reliability can only be predicted, but Excel as a program is a stable platform. As long as all used formulas are incorporated into the excel tool and there are no links to other files which can result in delinking and therefore crashing of the program, it is expected that the program will be reliable.

### SHIPPING SPECIFIC

Excel itself is not specifically for ships; nevertheless this program will be developed for ships. The database will have different ships equipment and can cope with different operational profiles.

72 (Office 365 Enterprise E3, 2014)

#### SUPPORT

There will be no support for this developed program, because it is an own design. Therefore it has to be reliable as indicated above. This program however is designed in excel and there is enough support for excel.

#### OVERALL

Overall this tool will combine the advantages of the alternatives, without the drawbacks. The only drawback is that it takes time to develop, but once it is finished it will work better than the other programs.

### 7.4.2 PROGRAM DEVELOPMENT

As mentioned this program will be developed in excel. The main goal is to keep it simple. This will be achieved by working with a single input sheet and one sheet with all results. Examples of this result sheet will be shown in the next chapter during the performing of LCPA. All calculations and other things will be on different sheets. This keeps the program simple to learn and use. It also helps during the development stage that different calculations are performed on different sheets to keep a nice overview.

This program will be able to compare up to four different configurations. For all these different configurations there is a general part in which the sailing profile is defined. The sailing profile is assumed the same for all different configurations which makes it possible to compare the different configurations to each other. Besides the sailing profile, the fuel consumption is important for this program. The fuel consumption is based on installed power in combination with the sailing profile. For each sailing mode, the fuel consumption is calculated with the following formula, equation 20:

**EQUATION 20: CALCULATE FUEL CONSUMPTION**

$$\dot{m}fuel = Engine\ power * specific\ fuel\ consumption\ \ \left[{}^{kg}/_{h}\right]$$

This fuel consumption is per engine, so it has to be multiplied by the number of engines that are operating. Based on this fuel consumption the fuel costs and emissions for respectively the financial and the environmental result are calculated. Because LCA and LCC are two methods, the description of the development of this program is also divided into two parts; an environmental part and financial part.

#### ENVIRONMENTAL ASPECTS

For emissions calculations, fuel consumption is critical. Damen has already some excel files available which calculates fuel consumption. These files will be used as example to calculate fuel consumption. These fuel calculations are based on the sailing profile of the ship and the installed equipment.

As explained in chapters 4.1.1 and 4.1.3, the amount of $CO_2$ and $SO_2$ emission is directly linked to the amount of burned fuel and the concentration of respectively carbon and sulphur in the used fuel. $SO_2$ is calculated with the following formula, equation 21, with ṁfuel being the amount of consumed fuel.

**EQUATION 21: CALCULATE $SO_2$ EMISSIONS**

$$SO_2 = \dot{m}fuel * sulphur\ content * \frac{64.06}{32.07}\ [t]$$

$\frac{64.06}{32.07}$ is the emission ratio of sulphur in $SO_2$. The formula for $CO_2$ emission is similar as shown in equation 22.

**EQUATION 22: CALCULATE $CO_2$ EMISSIONS**

$$CO_2 = \dot{m}fuel * carbon\ content * \frac{44.01}{12.01}\ [t]$$

In this formula the carbon content times $\frac{44.01}{12.01}$ calculates the CF value. The general values of CF are given in table 25.

**TABLE 25: CF VALUES FOR DIFFERENT FUELS**

| | CF | |
|---|---|---|
| HFO | 3.1144 | ISO 8217 Grades RME Through RMK |
| LFO | 3.151 | ISO 8217 Grades RMA through RMD |
| MDO | 3.206 | ISO 8217 Grades DMB |
| MGO | 3.206 | ISO 8217 Grades DMA |
| LNG | +/- 2.75 | Depending on LNG origin |

For LNG the value depends on the LNG composition. If there is more methane in it, the value will be lower and vice versa. Just as $CO_2$ and $SO_2$, the emission of methane is calculated as amount of methane slip times the fuel flow.

The calculations for $NO_X$ and PM are unfortunately not as simple as the calculation of $CO_2$ and $SO_2$ emission, due to the complex reactions that take place inside the engine. The emission is different for each engine. However all engines has to comply with the MARPOL as stated in chapter 4.2.1.

There has been some research into $NO_X$ emission and the first published[73] result was by Lloyds Register in 1995. The results of this research are shown in table 26.

**TABLE 26: LLOYDS REGISTER AVERAGE EMISSION FACTORS (LLOYDS, 1995)**

| | $NO_X$ slow speed | $NO_X$ medium speed | CO2 | $SO_2$ | PM Fuel oil | PM Gas oil |
|---|---|---|---|---|---|---|
| g/kg fuel | 87 | 57 | 3170 | 20*S % | 7.6 | 1.2 |
| g/kWh | 17 | 12 | 660 | 4.2*S % | 1.5 | 0.2 |

Lloyds defined slow speed engines as all engines below 300 rpm. The origin of this data is an analysis of around 280 measurements of 56 different engines on 50 different vessels build between 1963 and 1990. More details are shown in appendix J. As this appendix shows the engines are quite old. Newer engines are assumed to emits less PM and $NO_X$.

Another conclusion of the Lloyds study was that there seems to be a correlation between the sulphur content in the fuel and the amount of PM that is emitted. Lloyds developed the following formula, equation 23, to calculate the PM in kg per ton fuel.

**EQUATION 23: PM FORMULA (LLOYDS, 1995)**

$$PM = 0.855 * e^{0.745*S} \left[\frac{kg}{ton} fuel\right]$$

S = per cent of sulphur in fuel

In 2012[74] a fifth order polynomial was derived from this formula. This polynomial is shown equation 24:

**EQUATION 24: PM POLYNOMIAL (ANDERSEN, 2012)**

$$PM = 0.1014S^5 - 0.6056S^4 + 1.3819S^3 - 0.7783S^2 + 0.4023S + 1.1 \left[\frac{kg}{ton} fuel\right]$$

S = per cent of sulphur in fuel

[73] (Lloyds Register Engineering Services, 1995)
[74] (Andersen, 2012)

This formula calculates a lower PM emission between sulphur contents from 0.5 % till 3 %. This is consistent with the assumption that newer engines emit less $NO_X$ and PM. However it seems that for lower sulphur content, the results is more accurate than for higher (more than 3 %) sulphur content[74] . This is assumed to be caused by the facts that fuels with more than 3 % sulphur are in general more dirty than fuels with less sulphur content. As explained in chapter 4.1.4, PM are not solely caused by sulphur but also by other incombustible parts of the fuel which are more present in fuels with higher sulphur content.

In 2000 EPA performed an analysis[75] of commercial marine vessel emissions and fuel consumption data. This research was an analysis of four other reports, including above described Lloyds report. Table 27 shows the results of the regression analysis that was performed on the data. For particulate matters R squared is 0.95, but this is based on only 31 measurements.

TABLE 27: RESULTS REGRESSION ANALYSIS OF DIFFERENT REPORTS ON EMISSIONS (EPA, 2000)

**Analyses of commercial marine vessels emissions and fuel consumption data [g/kWh]**

| Statistical Parameter | PM* | $NO_X$* | $SO_2$ | $CO_2$* |
|---|---|---|---|---|
| Exponent (x) | 1.5 | 1.5 | n/a | 1 |
| Intercept (b) | 0.2551 | 10.4496 | -0.4792 | 648.6 |
| Intercept t-stat | 7.78 | 24.154 | -1.124 | 33.957 |
| Significant intercept t? | Yes | Yes | No | Yes |
| Coefficient (a) | 0.0059 | 0.1255 | 2.3735 | 44.1 |
| Coefficient t-stat | 23.143 | 19.391 | 28.924 | 23.374 |
| Significant coefficient t? | Yes | Yes | Yes | Yes |
| $r^2$ | 0.95 | 0.57 | 0.78 | 0.65 |
| F-stat | 536 | 376 | 837 | 546 |
| Significant F-stat? | Yes | Yes | Yes | Yes |
| Observations | 31 | 291 | 239 | 291 |
| *Emission rate [g/kWh] = | $a * (\text{fractional load})^{-x} + b$ | | | |

In 2009 another assessment[76] was performed as part of the European sixth framework program ATTICA. The results of this research are shown in table 28. The results of Endresen et al. are divided into residual fuel and distillate fuel. All other results are average values for each emission. The values of all studies are roughly the same and the explanation for this is that these values are also average values.

TABLE 28: SUMMARY EMISSION FACTORS OF DIFFERENT STUDIES (EYRING, ET AL., 2009)

| Study | EF ($CO_2$) | EF ($NO_X$) | EF ($SO_2$) | EF (PM) |
|---|---|---|---|---|
| Lloyds (1995) | 3170 | 77 | 40 | 5.5 |
| ENTEC (2005) | 3190 | 67.9 | 52.8 | 5.19 |
| Corbett and Köhler (2003) | 3178 | 79 | 47 | 6 |
| Endresen et al. (2003) | 3170 | 87[a] / 57[b] | 54[c] / 10[d] | 7.6[a] / 1.2[b] |
| Eyring et al. (2005) | 2905 | 76 | 43 | 6 |

*All values given in [g/kg fuel]*
*a = slow speed engine*
*b = medium and high speed engine*
*c = Residual fuel: 2.7 % sulphur*
*d = Distillate fuel: 0.5 % sulphur*

75 (Sierra Research, 2000)
76 (Eyring, et al., 2009)

In 2011 MARIN published a report[77] regarding the emissions on the Netherlands Continental Shelf and the port areas of the Western Scheldt, Rotterdam, Amsterdam and the Ems. To calculate emissions a study into emission factors was performed and table 29 shows the factors that were calculated by TNO[78].

**TABLE 29: EMISSION FACTORS ACCORDING MARIN (TAK & COTTELEER, 2011)**

| Engine | rpm | PM | $CO_2$ | $NO_X$ | $SO_X$ | S % |
|---|---|---|---|---|---|---|
| Slow speed | < 500 | 0.8 | 533 | * | 5 | 1.5 % |
| Slow speed | < 500 | 0.3 | 529 | * | 2.7 | 0.8 % |
| Medium/High speed | > 500 | 0.7 | 580 | * | 5.5 | 1.5 % |
| Medium/High speed | > 500 | 0.3 | 576 | * | 2.9 | 0.8 % |

*All values are given in [g/kWh]*
*Values are based on 85 % MCR*
** NOX is 0.85 of Tier limits*

The provided values in table 29 are based on 85 % of its maximum continuous rating power (MCR). However engines emit relatively higher levels of PM and $NO_X$ emissions when run in light condition. Engines work less efficient in low loading condition. To correct for this higher emission levels, correction factors are calculated and these values are shown in table 30.

**TABLE 30: EMISSION CORRECTION FACTORS (TAK & COTTELEER, 2011)**

| % of MCR | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
|---|---|---|---|---|---|---|---|---|---|
| PM | 1.63 | 1.32 | 1.19 | 1.12 | 1.08 | 1.05 | 1.03 | 1.01 | 1.01 |
| $NO_X$ | 1.34 | 1.17 | 1.10 | 1.06 | 1.04 | 1.03 | 1.02 | 1.01 | 1.00 |

As visible only correction factors for less than 50 % MCR are provided. This is because there are no correction factors necessarily when engines run above 50 % MCR.

The PM values in table 29 are lower than in table 26 which can be explained partly by more efficient engines and cleaner fuel over time, respectively 2009 vs. 1995. This is also caused by the engines that are investigated. The calculations for the PM values in table 29 are based on engines from 2000 and later, while the values of table 26 are based on engine from 1973 till 1993.

Above described reports illustrates that it is, in contrary to $CO_2$ and $SO_X$, hard to define a general formula or value to calculate the $NO_X$ and PM emission. However when the engine manufacturer cannot provide emission data, a consensus has to be found to determine emission. For PM equation 24 is used to calculate the emissions. This calculated result could however deviate from its actual emission, but because the formula will be used for all configurations, the calculation error will be the same for all emissions. Furthermore the resulting emissions are used to compare the different configuration and less to determine the amount of PM that is emitted during the lifetime of the ship.

For the $NO_X$ emissions, the assumption is that these will be around the Tier limits. This is because there is a trade-off between specific fuel consumption and $NO_X$ emission, the so-called diesel dilemma as illustrated in figure 43. If $NO_X$ emissions are reduced, the fuel consumption rises. The same effect occurs the other way around. When in future better values or formulas are determined, these new data can be easily inputted into the model, because these values are stated on a single sheet. The calculated $NO_X$ and PM emissions are corrected according the most recent data as provided in the MARIN[77] report.

[77] (Tak & Cotteleer, 2011)
[78] (Gon & Hulskotte, 2009)

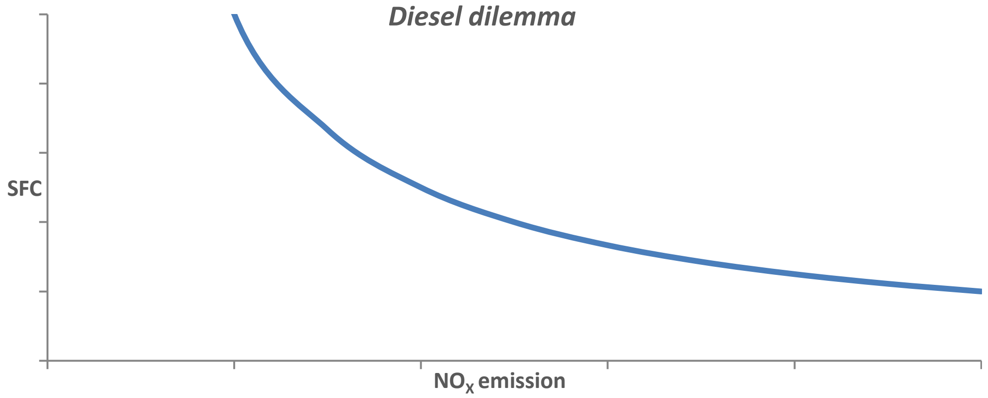



FIGURE 43: DIESEL DILEMMA

In case the emission is above the limit, exhaust gas treatment systems has to be installed. These EGTS reduced the emissions of $NO_X$, PM and $SO_X$. The percentages of reduction are stated in chapter 5.3; for PM reduction, an average percentage of 80 % is taken. These EGTS consumes power which results in higher engine power and thus more emissions and costs. The way these costs and other financial aspects of these EGTS are taken into account will be explained further this chapter.

### FINANCIAL ASPECTS

As explained in chapter 3.2, LCC is based on NPV and the formula to calculate NPV is given in equation 1. The NPV is based on the costs and revenues of the ship. The effect of depreciation on the taxes is not taken into account. This effect will be explained shortly with the following example. The difference between revenues and costs are the earnings of a company. A certain percentage of these earnings have to be paid as taxes. When the depreciation is also subtracted from these earnings, the amount of taxes that have to be paid will be lower. This results in a higher income and thus a higher NPV.

In case the discount ratio is unknown, the internal rate of return will be used as indicator of the financial results. The costs are divided in acquisition and sustainable costs as figure 8 showed. All costs are calculated per year. Furthermore, some prices are given in dollars, but the model gives the results in euros. To converge from dollars to euros an exchange rate 1:1.3616, so 1 euro is worth 1.3616 dollar, is used.

The acquisition costs are the capital expenditures (CAPEX) When a loan is necessary to acquirer the ship, the payback period and the amount of interest can be filled in. With this data the annual costs of that loan are calculated.

The sustainable costs, also referred to as operational expenditures (OPEX) that are taken into account are the following.

- Bunker costs
- Manning costs
- Maintenance costs
- Insurance costs
- Classification costs
- Port tariffs
- Unforeseen costs

The bunker costs can be subdivided in fuel costs, other consumables like lubrication oil and costs that are caused by exhaust gas treatment system like sodium hydroxide consumption in scrubbers. Fuel costs are directly related to the consumed fuel times the price of that fuel. The other consumables are taken as percentage of the fuel costs, because lubrication oil is related to the running time of an engine, which is related to the fuel costs. The used percentages in this model are shown in table 31. LNG is a cleaner fuel than the other fuels which result in lower lubrication oil consumption[79]. In contrary to LNG, HFO is a dirty fuel which results in higher lubrication oil consumption.

**TABLE 31: CONSUMABLES COSTS AS % OF FUEL COSTS**

| Fuel | LNG | EN 590 | MGO | HFO | LSF |
|---|---|---|---|---|---|
| % of fuel for consumables costs | 5 % | 10 % | 10 % | 15 % | 10 % |

For the exhaust gas treatment systems costs can be divided into acquisition costs when purchasing the system and the sustainable costs as described above.

The sustainable costs contain the costs for the used fuel, like NaOH in scrubbers and urea as used in SCR systems. Also the cost of disposal of the sludge is included. Appendix F shows the energy consumption of the EGTS. This consumption is added to the fuel consumption in order to incorporate the impact of EGTS.

### *SELECTIVE CATALYTIC REDUCTION*

The investment costs of an SCR are between 40 and 80 euros per kW[31]. Other estimations are that SCR investment costs are between 30 and 50 euros per kW, with operating costs ranging between 5 and 8 euro per MWh[80]. The investment price used in the model is 50 euro per kW with operating costs of 6.5 euro per MWh. Other reoccurring costs are the replacement of the catalyst element which has a life time of 4 to 6 years. The costs of a new element are around 10 euro per kW[81]. The increased power consumption for the pomp is set to one per cent of the engine power.

### *SCRUBBERS*

The investment costs for scrubbers differ between the different types. Open loop scrubbers are simpler than closed loop or hybrid systems. Based on data from Wärtsilä[81] this model uses the following investment prices for the different types of scrubbers as shown in table 32.

**TABLE 32: PRICE OF DIFFERENT SCRUBBERS**

| Scrubber | Investment price [€ / kW] |
|---|---|
| Open loop | 150 |
| Closed loop | 200 |
| Hybrid | 250 |

Wärtsilä has developed a formula to calculate the NaOH consumption. This is related to the amount of sulphur in the fuel which has to be cleaned and the total engine power.

**EQUATION 25: NAOH CONSUMPTION (WÄRTSILÄ, 2013)**

$$NaOH = 0.0057 * sulphur\ content * engine\ power\ \left[{}^{l}/_{h}\right]$$

With this formula the NaOH consumption can be calculated and this consumption has to be transferred in costs by multiplying it with the price of NaOH. This price is assumed[82] to be $ 375 per tonnes. The density of NaOH is 1.52 t/m$^3$, which results in a NaOH price of € 0.24 per kWh per percentage sulphur content. By multiplying this number with the actual sulphur content in the fuel and the used kWh, the urea costs can be calculated. The costs

[79] (Rolls-Royce, 2013)
[80] (Panasiuk & Lebedevas, 2013)
[81] (Wärtsilä Environmental Technologies, 2013)
[82] (ICIS, 2014)

for a hybrid scrubber are assumed to be half, because the assumption is that a hybrid scrubber works half the time in open loop and the other half time in closed loop configuration. As described in chapter 5.3.2 open loop scrubbers uses sea water for scrubber instead of NaOH. Another operational cost is the disposal of sludge that comes out of the scrubber. According Wärtsilä[81] this is around 0.2 g/kWh. The costs of this sludge is around 200 euro[83], which results in additional costs of 0.00004 € per kWh.

The assumed additional costs for EGTS are shown in table 33. When SCR is combined with one of the scrubbers, the costs are added to each other in order to calculate the costs associated with a combined EGTS.

TABLE 33: ADDITIONAL COSTS OF EXHAUST GAS TREATMENT SYSTEMS

| Installation | Investment [ € ] | Additional costs [€ / kWh] |
|---|---|---|
| SCR | 50 | 0.0065 |
| Open loop scrubber | 150 | 0.00004 |
| Closed loop scrubber | 200 | 0.24 * % S + 0.00004 |
| Hybrid scrubber | 250 | 0.12 * % S + 0.00004 |

The maintenance costs are taken as a fixed amount, but can be taken from the engines database as a schedule provided by the manufacturer. Some owners deviate from this schedule by postponing the maintenance in the expectations to save money. This delay in maintenance increases the risk of malfunction and could result in extra costs. This trade-off between maintenance costs and risk of operational time loss is not taken into account.

The manning costs are the total costs of the crew, so including crew training. All other costs are self-explanatory. All the sustainable costs are considered to increase linear over time with a given increasing rate. This rate can be different between the different configurations, because it could happen that for instance the fuel price of LNG is expected to increase more than the HOF fuel price.

### OTHER DATA

All other relevant data that is used in the program like fuel composition, conversion factors used conversion for sailing profile is given in appendix K. Also the costs of NaOH and sludge of scrubbers is given in that appendix.

## 7.5 CHAPTER CONCLUSION

In the beginning of this chapter it was mentioned that almost all data required to perform LCPA was available, only the software to perform the assessment had to be chosen. This chapter explained which program was chosen and why. Because an own designed tool was developed, this was also described in this chapter.  The next chapter will describe the analyses because all required data is available.

[83] (Hamworthy Krystallon, 2010)

# 8. PERFORMING LCPA

The previous chapter provided the last data that was needed to perform the LCPA, which this chapter will describe. This chapter is divided into three parts. First the ship that will be analysed will be described after which the different configurations will be described. In the third and last part the LCPA will be performed.

## 8.1 SHIP TYPE

As mentioned in the title and chapter 2 the ship that will be analysed is the Damen Fast Ferry 3007, also known as *"Damen Waterbus"*. The information of this ship will be divided into general information, machinery propulsion and sailing profile.

### 8.1.1 GENERAL INFORMATION

This DFF3007 is a 31 meters long aluminium catamaran with a beam of almost 8 meters which can transport up to 130 passengers (80 seated and 50 standing) and 50 bicycles; more information is given in table 34. The general arrangement is given shown in appendix L.

TABLE 34: GENERAL INFORMATION DFF3007 (DAMEN)

| | | | |
|---|---|---|---|
| **Yard number** | | | 538201, 538202, 538203 |
| **Type** | | | DFF 3007 |
| **Length over all** | | | 31.30 m |
| **Beam over all** | | | 7.70 m |
| **Depth** | | | 2.49 m |
| **Cruising Speed** | | | 21 knots |
| **Capacity** | Passengers | Seated | 80 |
| | | Standing | 50 |
| | | Wheelchairs | 2 |
| | Bicycles | | 40 |
| **Machinery** | | | |
| **Maximum power** | | | 366 kW |
| **Maximum rpm** | | | 2300 rpm |
| **Maximum speed** | | | 22 knots |

The DFF 3007 is equipped with two Caterpillar C12 main engines with C-rating and a maximum rpm of 2300. This results in maximum power per engine of 366 kW. These engines are connected to twin disc MGX 5114A gearboxes which are connected to two fixed pitch propellers. The top speed of the ship is 22 knots. Appendix M shows the complete datasheet of the DFF 3007.

This ship is, together with sister ships, operating as a public transport liner in the Rotterdam – Dordrecht area, more specifically public transport line 20. A timetable of the trip is given in appendix N. The sailing profile will be explained in chapter 8.1.2.

### 8.1.2 SAILING PROFILE

The sailing profile which will be described in this part of the chapter is based on one trip. By multiplying this one trip times the percentage of sailing time in a certain period, the total sailing profile is calculated for that particular period. This one trip is, as described earlier, the route of public transport liner 20, which sails between Rotterdam and

Dordrecht. The time table of this line is provided in appendix N and based on this time table, table 35 provides a summary.

TABLE 35: WATERBUS SAILING TIMES (WATERBUS,2014)

| | Winter (October – March) | | | Summer (April – September) | | |
|---|---|---|---|---|---|---|
| | Weekdays | Saturday | Sunday | Weekdays | Saturday | Sunday |
| **First** | 06:35 | 07:00 | 10:00 | 06:35 | 07:00 | 10:00 |
| **Last** | 20:58 | 20:58 | 19:58 | 21:58 | 21:58 | 20:28 |
| **Sailing time** | 14:23 | 13:58 | 09:58 | 15:23 | 14:58 | 10:28 |
| **% / day** | 60% | 58% | 42% | 64% | 62% | 44% |
| **Average % / day** | 57% | | | 61% | | |

As this table indicates, there are two different sailing periods. There are less sailing trips in the winter than in the summer. During the winter period the ship is 57 % of the day operational and in the summer this is 61 %. The winter period is from October until the end of March and the summer period are the other months. So half of the time the ship is sailing according the winter schedule and half of the time according summer schedule. This results in an average sailing percentage of 59 % each day. Another assumption is that the ship is sailing 95 % of all days per year. The other 5 % days is used for maintenance.

To determine the sailing profile during one single trip, measurements are performed during operations of the ship. These measurements are performed with a GPS receiver which recorded the ships track. Also visual data was acquired by looking at the engine speed and engine rpm. In case the ship reduced speed, notes were made of the reason why there was a change in speed. During the measurements a brief interview with the captain was conducted. The captain explained the rules and which things the captain has to keep in mind while sailing the ship. So at which point there is for instance a speed limitation. All these measurements are performed on the 15th of November 2013 on board waterbus *"De Schie"*.

Figure 44 illustrates the route that the ship is sailing.


FIGURE 44: PLOT OF SAILING PROFILE (BACKGROUND GOOGLE MAPS, 2014)

As the legend shows, the different colours indicate the sailing speed of the ship. In this figure the seven stops are illustrated with dark dots; the starting point in Rotterdam, followed by five intermediate stops and the endpoint in Dordrecht. The particular route shown in figure 44 is measured during the second run, from Dordrecht back to Rotterdam.

Measurements are performed during six trips, so three roundtrips on board the ship. The results of these measurements are shown in figure 45.

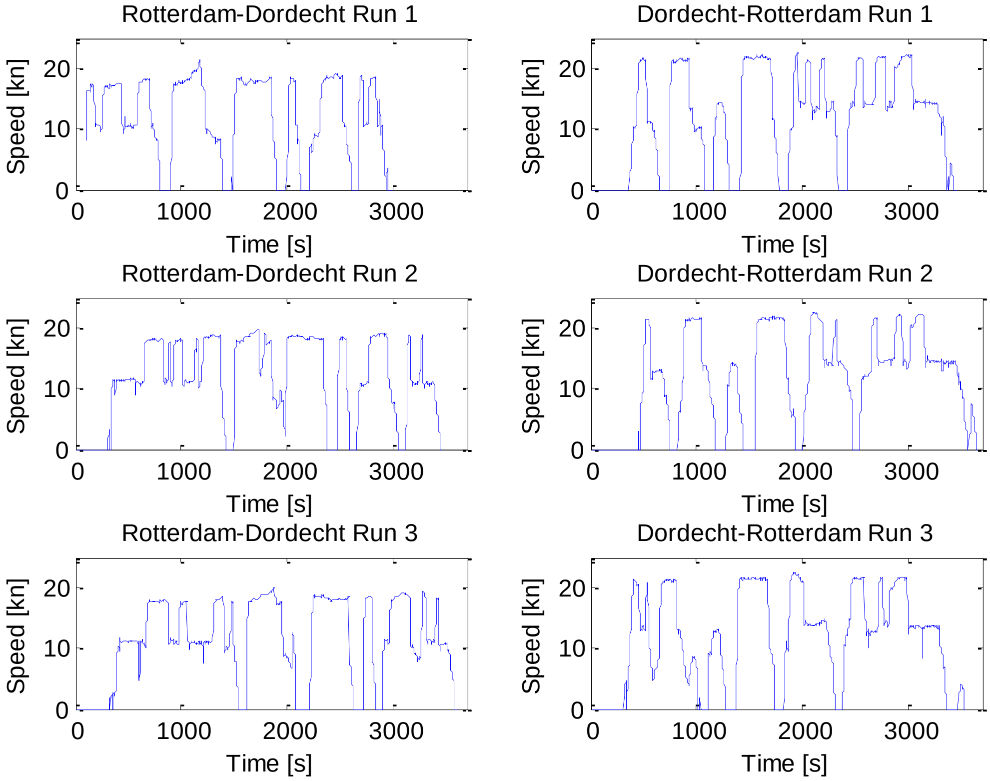



**FIGURE 45: OVERVIEW MEASUREMENTS, SPEED VS. TIME.**

This figure shows the time versus speed on the respectively x and y axes. Unfortunately, during the first run from Rotterdam to Dordrecht, there were some troubles with the measuring equipment which causes the measurement to start during the trip instead of at the beginning. The first couple of minutes are not registered, which can be seen at the top left plot where the run ends before 3000 seconds. During all the other five trips, no problems occur. These plots also show that at the beginning of each run, the ship is waiting at the quay. This time varies a bit due to the sailing schedule.

As figure 45 shows, the measurements are quite consistent. In each run the intermediate stops are visible. Also when the ship sailed past a stop because there were no passengers to transfer, this is visible in the figure. This can be seen when comparing the plots of the second and third Rotterdam – Dordrecht run with each other. These are the two bottom left plots. As visible there is a drop in speed in the second run around 3050 seconds, which is caused by stop of the ship. This drop in speed is not visible in the third run, because the ship sailed past this stop in the third run.

There is one more thing worth mentioning. The speed on the trips from Dordrecht to Rotterdam was higher than the other way, due to current. So at the same rpm, the achieved speed was higher. This is visible in figure 46. This figure is a histogram of the plots as shown in figure 45. On the horizontal axe the speed is given in steps of 1 knots and the vertical axe shows the percentage of time the ship was sailing that that particular speed.

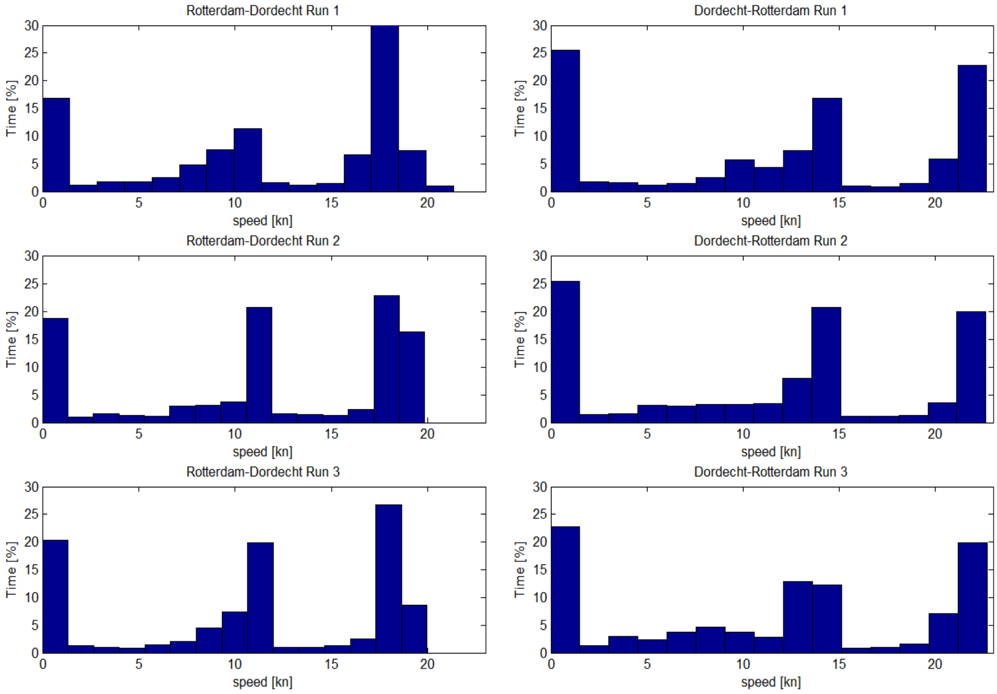



FIGURE 46: HISTOGRAM OF SPEED VS % TIME

The data shown in figure 46 can be divided into four modes:

- Moored, when ship is below 2 knots at stop
- Reduced speed, when ship is sailing at around 12 knots (between 10 and 14 knots)
- Full speed, when ship is sailing at more than 18 knots
- Acceleration or deceleration. This can further be sub-divided in:
    - Accelerating to full speed, from zero or half speed
    - Accelerating or decelerating to half speed, from zero or full speed
    - Decelerating to stop, from full or half speed.

During the accelerating or decelerating part the engines power is not changed gradually, but the final engine power is set. For instance when the ship has to accelerate to full speed, the captain gives full power instead of increasing the throttle step by step. In other words the engine speed in this acceleration/deceleration mode corresponds to the engines speed of respectively moored, reduced speed of full speed mode.

When the ship is about to moor at a stop, the engine rpm is reduced to 700, so the ship is not put into reverse in order to decelerate. When the ship is sailing in reduced speed mode, the engine rpm is between 1200 and 1400 rpm, depending on the reduced speed. An average of 1300 rpm and a speed of 12 knots is used. The last mode is the full speed mode, when the engine speed is 2200 rpm. These speed and rpm assumptions are stated in table 36.

These defined groups are used to determine how much time, in percentage, the ships sails at that particular speed. This is shown in figure 47 for all six trips. There is one side note, because as mentioned earlier the measurements of the first started a couple of minutes after the departure, so during the trip. The first minutes when the ship was sailing at reduced speed are not registered and therefor the distribution is odd, indicating far more full speed in favour of reduced speed.

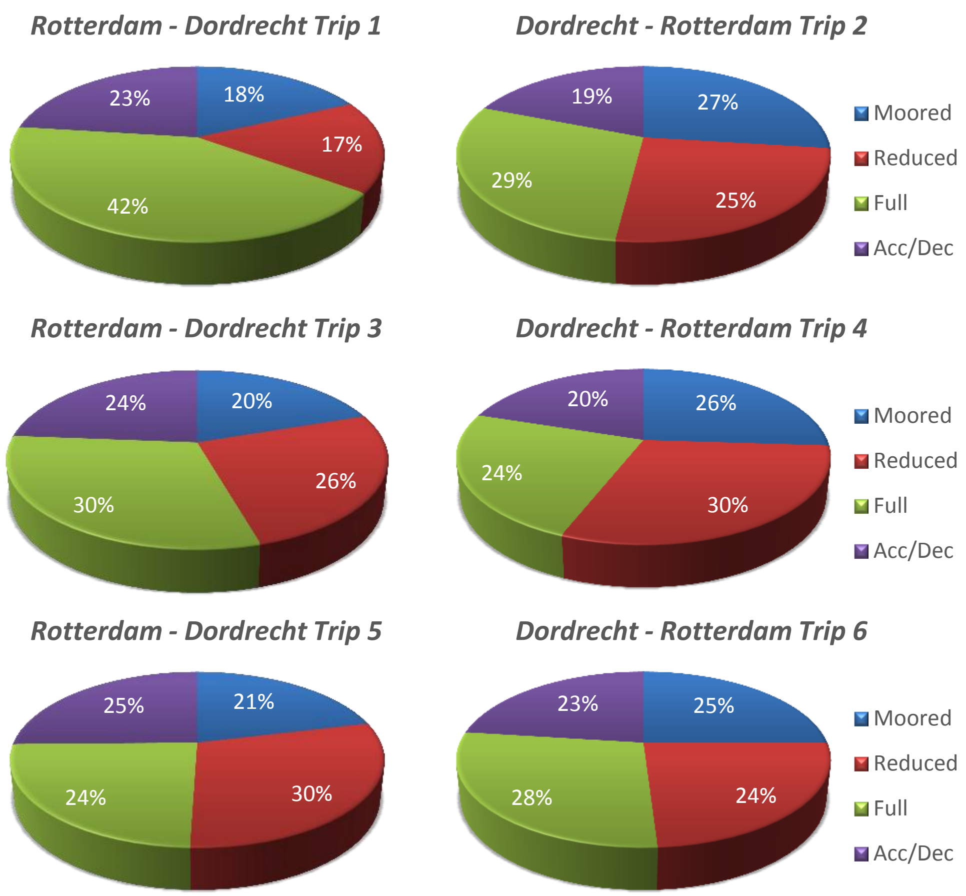



FIGURE 47: SPEED AS PERCENTAGE OF TIME

The first trip is only used as comparison to the other trips. All calculations are based on data from the second to the sixth trip. Combining this data gives the following speed distribution as shown in figure 48.

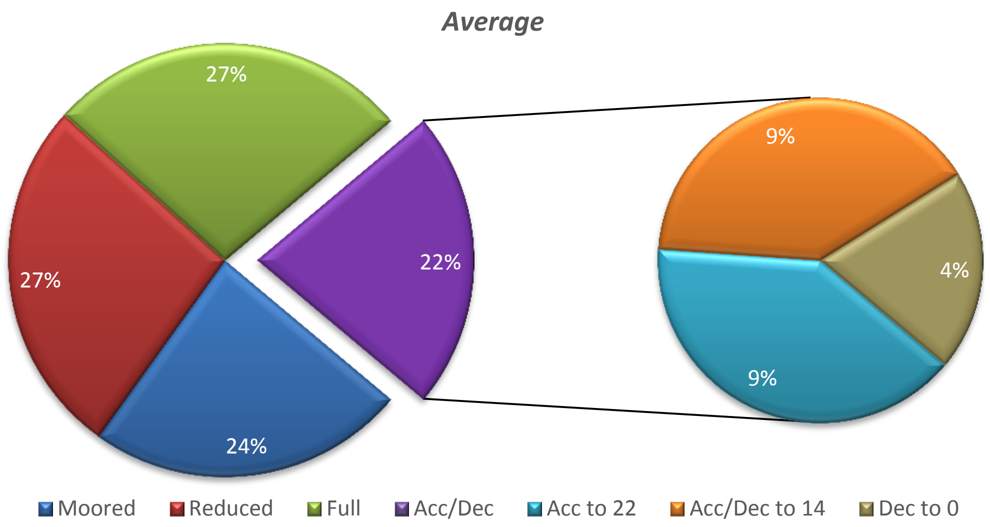



FIGURE 48: AVERAGE DISTRIBUTION OF SPEED

For this figure, the acceleration and deceleration mode is subdivided into a second pie chart. This average sub division is similar to the sub division of each individual trip. Table 36 states the following values that are used for each operational mode; speed, rpm, time in percentage and the specific fuel consumption of the engine in grams per kWh.

The data shown in table 36 are measured during the winter schedule. During the summer period, it is expected that more passengers uses the waterbus for transportation, which will increase mooring time per stop. This will however not result in a shift of time in the operational mode, because the ship will have less waiting/spare time at each end stop.

TABLE 36: USED DATA FOR ALL OPERATIONAL MODES

| | Speed [kn] | Rpm | Time [%] | SFC [g/kWh] |
|---|---|---|---|---|
| **Moored** | 0 | 700 | 23.8 | 263 |
| **Reduced speed** | +/- 12 | 1200-1400 | 26.8 | 221 |
| **Full speed** | >18 | 2200 | 27.2 | 207 |
| **Acceleration / Deceleration*** | 0 -> 12 & 18+ | 700 -> 1300 & 2200 | 22.2 | |
| *Accelerate to full speed* | *22* | *2200* | *8.8* | *207* |
| *Accelerate/Decelerate to reduced speed* | *12* | *1300* | *8.8* | *221* |
| *Decelerate to stop* | *0* | *700* | *4.4* | *263* |

** Sub divided into three modes which are shown in Italic*

Figure 44 illustrated only one trip, but this can be seen as general sailing profile for these public liners. In general the ship sails, when allowed, at a maximum speed of 40 km/h (= 21.6 knots). This maximum speed of 40 km/h is chosen due to regulations. These regulations state that a ship with only one captain on the bridge is allowed to sail at a maximum speed of 40 km/h. If the ship sails faster than 40 km/h it requires two, instead of just one, captain present on the bridge. This costs more money and therefore it is decided to sail with a maximum speed of 40 km/h.

There are also some speed restrictions on the ships route. From the starting point to around 2 km further up the river, the crossing with '*Koningshaven*', the ship is not allowed to sail faster than 20 km/h (=10.8 knots). This is visible by the green/yellow colour in the top left corner of figure 44. Also, due to the wash that this ship generates, it has to reduce its speed quite often to not disturb other (working) ships which are moored at the quay or which are dredging. This reduction is done by reducing engine rpm from 2200 to around 1300 rpm which results in a speed reduction from 40 km/h to around 20 km/h.

The captain pointed out that due to the tight time schedule he sails as fast as possible, also if it is only for five seconds; every second counts. This can be explained because there are only two minutes spare between each trip. The ships arrive at xx:58 and departures again at xx:00. The acceleration steepness from moored position, so 700 rpm to full speed, 2200 rpm is roughly the same as for reduced speed, 1400 rpm to full speed. This is illustrated in figure 49. This indication is roughly, because timing was done in seconds instead of milliseconds. This could influence the formula, but the general trend is visible.

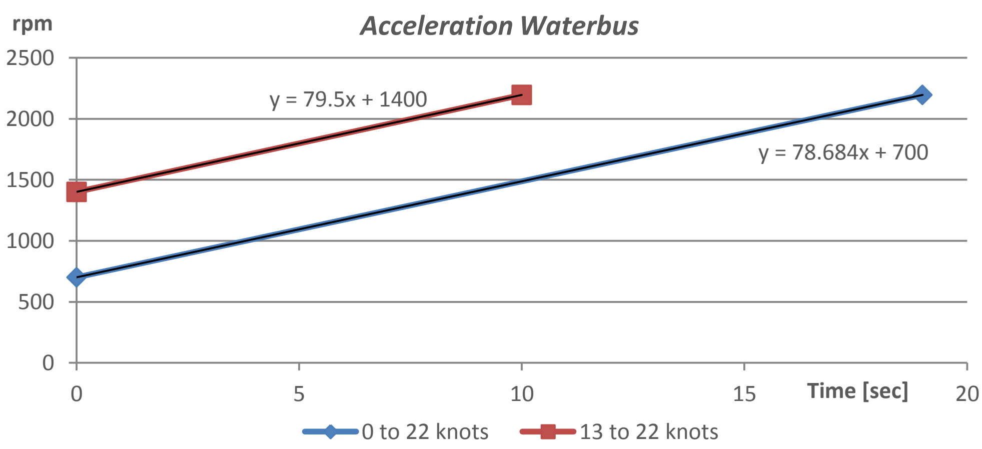



FIGURE 49: ACCELERATION "*DE SCHIE*"

## 8.2 CONFIGURATIONS

The sailing profile is known, so the next step is to describe the different configurations that will be analysed. First the current configuration, which is used as point of reference, will be described. After this reference, three alternative configurations will be stated. These alternatives must comply with the same requirements as the reference. This means a cruising speed of 21 knots and a passenger/cargo capacity as stated in table 34. The efficiency of the different engines is taken into account by the amount of power needed to reach the particular speed as mentioned in the sailing profile.

### 8.2.1 REFERENCE CASE WITH FUEL EN 590

As described in chapter 8.1.1, the DDF 3007 is equipped with two Caterpillar C12 engines which produce a total of 732 kW on 2300 rpm. The ships sails on EN 590 fuel which is similar to the diesel that is used in cars. This fuel contains only 0.001 % sulphur and the carbon content correspondents to 85.90 % of $CO_2$ as shown in appendix K.

### 8.2.2 LNG INSTALLATION

As mentioned in chapter 5.1.3 LNG requires more space than the fuel in the reference case. In order to keep the same passenger capacity the assumption is that more material is needed for this ship. This results in a higher price for the ship. Also the use of LNG engines makes the acquisition price higher. In comparison to oil based ships, LNG ships are assumed to be 15 to 25 % more expensive. This is dependent on the size of the ship and thus the influence of the LNG tanks on the dimensions and arrangement of the ship. Also the type of engine, dual fuel or complete gas, influences the price.

Unfortunately there was insufficient data of LNG engines with the required power available. The assumption is that the installed engine is a lean burn gas engine, so not a dual fuel engine. To compensate for the energy density difference between diesel oil and LNG, the fuel consumption for LNG is assumed to be 16 % lower. This is calculated by comparing the lower heating value* of LNG of around 49.109 kJ/kg to 42.700 kJ/kg, the lower heating value of diesel oil.

### 8.2.3 LOW SULPHUR FUEL

The fuel used in the reference case is ultra-low sulphur fuel with around 0.001 % of sulphur in the fuel. This alternative is powered with low sulphur fuel, with a sulphur content of around 0.1 %. This amount is still relatively low, but this fuel is cheaper than the fuel used in the reference case. By taking this fuel into account, the effect of low sulphur fuel in comparison to ultra-low sulphur fuel can be investigated. The same two engines as in the reference case are used in this case.

### 8.2.4 HFO + HYBRID SCRUBBER

This ship is an inland ship and has to sail on EN 590 fuel, but HFO is taken into consideration to see the influence of “dirty” fuel with exhaust gas treatment systems. The advantage of HFO is that it is a cheaper full, but requires more equipment, which costs more money, to comply with the emission regulations. In order to comply with the SECA

** Lower heating value: Heating value defines the amount of heat that is released during the combustion of a certain amount of fuel given in energy per substance like kJ/kg. The lower heating value defines the same, but with the assumption that all water vapour leaves the combustion without being condensed.*

rules a scrubber has to be installed. A hybrid scrubber is chosen to be flexible. Because Tier III is not applicable yet, this ship doesn't have to install a SCR on board in order to comply with the $NO_X$ emissions. The use of scrubbers results in higher running costs. Also for this case the same engines as used in the reference case are installed.

# 8.3 LCPA

## 8.3.1 GOAL AND SCOPE DEFINITION

There are three goals that LCPA has to clarify. The first goal is to compare different ship configurations as described in chapter 8.2. This will provide information on which configuration has the lowest emission output and/or is the cheapest in terms of net present value. This assessment is performed with current fuel prices as provided in table 17.

The second goal is to see what the influence of fuel prices is on the financial result. To achieve this goal, multiple LCPA will be performed with different fuel prices as described in chapter 6.6. The different fuel prices influence only the IRR and NPV, not the emissions. The second assessment will be based on results of the first assessment which was performed for the first goal. The fuel price of the configuration which have the lowest, so the worst, NPV in the first assessment will be decreased to 75 %. After that the fuel price in the case with the second worst financial result will be reduced and so on until all four fuels are 75 % of the base price. The next step is to increase the fuel price of the configuration with the highest NPV. In case that one scenario has already the worst IRR and NPV with the fuel price at 100 %, it makes no sense to see what the effect of that fuel price of 125 % will be. This results in a maximum of eight different assessments. For all these assessments the fuel price of all four fuels is increased with one percent.

This is one way to investigate the effect of fuel prices on the financial results. Another view on impact of the financial aspects is to change the increase in fuel price. The reports that are mentioned in chapter 6.3.1 predicts that oil prices will increase with around 1 %, while the increase of natural gas prices could be up to 3.5 % per year. To indicate the influence of this difference in increase, an assessment will be performed with these expected different price increase, so 1 % for oil and 3.5 % for natural gas.

This previous goal focusses only on the financial aspects and this third goal will focus on a combination of financial and environmental aspects. The sailing profile of this ship is within a SECA and thus stricter rules apply. To indicate the impact of a SECA, an assessment will be performed for configurations using the same fuel, without and with EGTS to comply with the tier II rules. This will show the influence of an EGTS on the outcome of the LCPA.

### BOUNDARIES

The boundaries that are taken into account are defined as which cycle is analysed. For this assessment only the operational/use phase of the ship is taken into account. This decision is based on three arguments. The first argument is that several studies[84],[85],[86],[87],[88],[89] shows

[84] (Ellingsen, Fet, & Aanondsen, 2002)
[85] (Guttormsdóttir, 2009)
[86] (Bengtsson, Life Cycle Assessment of Present and future marine fuels, 2011)

that the emission impact of both the phases extraction of raw materials and production are much less than the operational phase of the ship. This is the case for both materials as well as the fuels in this thesis. For example the impact that was calculated with an environmental life cycle assessment between LNG and HFO as marine fuel showed that LNG has a lower global warming potential than HFO[87]. The global warming potential of LNG was 127 versus 130.13 g $CO_{2\text{-eq}}$ / ton km of HFO. Respectively 88 and 99 g $CO_{2\text{-eq}}$ / ton km were caused in the operational phase. The complete global warming potential for each phase is shown in figure 50.

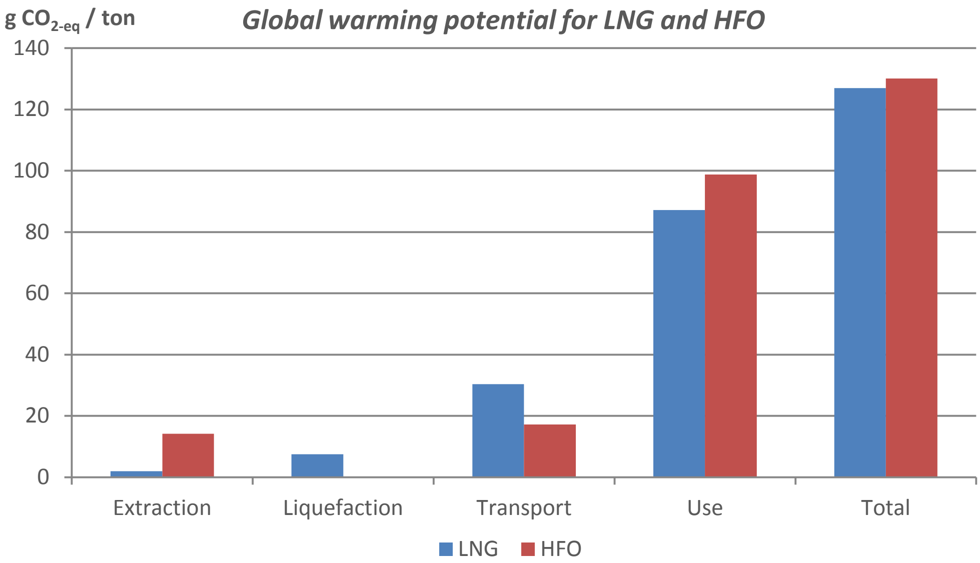



**FIGURE 50: COMPARISON GWP FOR LNG AND HFO (LAUGEN, 2013)**

The data shown in the example in figure 50 is based on LNG transported from Melkøya, in the North of Norway near Hammerfest, to Rotterdam. The HFO distilled from North Sea crude oil and transported from the West coast of Norway to Rotterdam. The fuels are used in a Ro-Pax ferry operating between Rotterdam and Hull.

In case bio fuels are also taken into account, the manufacturing phase has in comparison to the burning of bio fuels a significant influence due to the required area to grow the vegetables for bio fuels.

Another reason to only include the operational phase is that, for Damen, it is next to impossible to achieve all the required data for an assessment of the production and extraction phase. This is based on the experience that Damen has with the inventory of hazardous materials by suppliers.

The last argument is that this LCPA is a comparison between different configurations of the same ship, the DFF 3007. The base is that, independent of the configuration, the capacity of the ship remains the same, so it can carry the required amount of passengers and bicycles in each configuration. Therefore the difference between the configurations will be different machinery and maybe for LNG a slightly larger ship to accommodate the required LNG tanks. These "minor" adjustments and the knowledge that the production phase has less impact on the total environmental impact makes that on the total result

[87] (Laugen, 2013)
[88] (Bengtsson, Andersson, & Fridell, Life cycle assessment of marine fuels, 2011)
[89] (Hou, 2011)

the effect of the production phase will be negligible. This is not worth the time it required to achieve all data for a negligible effect on the result.

The different types of used material are taken into account by the installed power. An aluminium ship is lighter than a steel ship of the same size, thus requires less power. With less power the emissions will also be lower.

The recycling part is also not taken into account, because it is unknown what a client will do with his ships. A residual value for the ship is however taken into account. Furthermore, Damen is using the green passport which is described in chapter 4.2.6 which will reduce the emission of hazardous materials to a certain extent.

#### EFFECTS

The environmental effects that will be taken into account are already described in chapter 4.1; these are the air emissions $CO_2$, $NO_X$, $SO_X$, PM and $CH_4$ as shown in table 4. These emissions have local effect on human health, regional and global effects, but this is not quantified further. Instead the following environmental effects, global warming acidification and eutrophication potential as stated in chapter 3.1.3 are used in the impact assessment. For the eutrophication potential, only the terrestrial effects are taken into account, so which air emissions eventually come into contact with water and result in eutrophication. Another effect that is taken into account is the particulate matter. This is done by calculating the amount of PM. For this thesis it is not the case but for instance when bio fuels made from crops are taken into consideration, indicator like land usage has to be considered as an environmental impact effect.

Accidental spills where, in case of LNG, large amount of $CH_4$ are emitted are not covered as emission. The prediction of these spills is quite hard, because happily they occur rarely. Safety systems are in place to reduce the change of such spill. In case a spill does occur, there is a difference in effect. For instance oil based fuels floats on the water resulting that sea life is covered in these fuels. LNG on the other hand vaporizes and turns back into natural gas which is dissolved in the air. The water or ground it was spilled is not affected by the spill, not even by the low temperatures.

#### FUNCTIONAL UNIT

The definition of the functional unit depends on the goal of the assessment. If ships with different capacities will be compared to each other the functional unit will be different than for ships with the same capacity but different engines are assessed. For this assessment the ships' capacity will be the same, but the engines will be different for each configuration.

For this assessment the functional unit will be given in the amount of a particular emission in tonnes per year. The assumption is that the same amount of passengers and bicycles are transported, so this will not influence the functional unit. For the financial aspects, the results will be given in euros per year.

### 8.3.2 INVENTORY ANALYSIS

The previous part defined the operation phase as the only phase that will be taken into account. For this phase all the in- and outputs has to be defined. The input is the sailing profile as described in chapter 8.1.2. The sailing profile defines the required energy that has to be provided by the engine. The second input is thus the type of engine that is installed. The different engine configurations are described in chapter 8.2. These engines produce emissions which are an output in the model. If these engines are fitted with an EGTS the emissions are reduced, but other waste could occur like sludge from the scrubbers. Furthermore these engines consume fuel which has to be bought and thus money is a flow that has to be taken into account. Besides fuel, there are more costs associated with operating a ship, for instance the crew. All the other costs that have to be taken into account are stated in chapter 7.4.2, section *financial aspects*. After the operational phase is ended, the ship continues to the next phase, which is the recycling. In case the ship has still some rest value this is also taken into account. The recycling phase is not directly taken into account as mentioned above. Figure 51 illustrates all the flows.

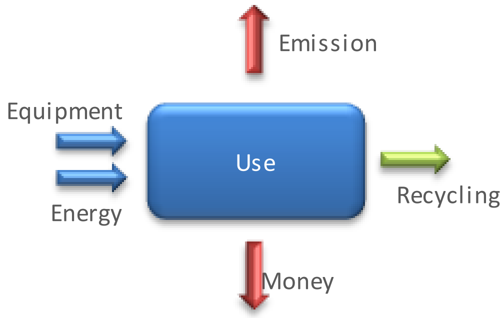



**FIGURE 51: INVENTORY ANALYSIS**

The money flow is different for each configuration because each configuration uses a different fuel with different price. However the rest of the costs are assumed to remain the same in each assessment. Also the percentage increase each year is constant and set to 1 %. An overview of the costs are shown and explained below.

The price of a DFF 3007 in the configuration as it is currently sailing is around 2.500.000 euro. A similar ship with the same capacity but with LNG as fuel is 20 % more expensive. For MGO and HFO as fuel, the price is assumed to remain the same. However in order to comply with the rules, the ship with HFO as fuel has to have a scrubber installed what results in an increase in price of 132.500 euro. The residual value of the complete ship is assumed to be 25 %. These are the initial costs of the ship. This has to be financed and the assumption is that the ship is financed with 30 % equity and for the remaining 70 % a loan is taken against 5 % interest for the next 10 years.

There are also annual costs as described earlier. Maintenance costs are taken as yearly amount instead of according a maintenance schedule according the engine manufacturer. The maintenance cost for LNG engines is lower than for diesel engines because the fuel is cleaner. The assumption is that this is a reduction of 25 % compared to the reference case[90]. For HFO it is the other way around, because this is a dirty fuel which requires more maintenance. Also the scrubbers' requires maintenance, which result in higher maintenance costs with the combination HFO + scrubber. For this case an increase of 25 % is assumed.

The manning cost also includes training and operating a ship with LNG as fuel requires more training. These costs for the ship with scrubbers are also assumed to be higher, because of the training to work with scrubbers. The insurance costs are a fixed percentage, in this case an assumption of 2 %[91], of the price of the ship. All other costs are assumed to be the same for all ships. It could be argued that the revenues for a LNG ship

[90] (LNG24, 2014)
[91] Damen

could be higher, because it sails on cleaner fuel, but this is not taken into account to reduce the number of variables in the assessment. An overview of the used costs in all the assessments is provided below in table 37.

TABLE 37: USED COSTS IN LCPA

| | Reference EN 590 | LNG | MGO | HFO + hybrid Scrubber |
|---|---|---|---|---|
| Acquisition costs [ € ] | | | | |
| Investment costs € | 2,500,000 | 3,000,000 | 2,500,000 | 2,682,500 |
| Loan for financing (70%) | 1,750,000 | 2,100,000 | 1,750,000 | 1,877,750 |
| Sustaining costs [€ per year] | | | | |
| Maintenance | 25,000 | 18,750 | 25,000 | 31,250 |
| Manning | 200,000 | 220,000 | 200,000 | 210,000 |
| Insurance | 50,000 | 60,000 | 50,000 | 54,380 |
| Classification | 1,500 | 1,500 | 1,500 | 1,500 |
| Unforeseen | 25,000 | 25,000 | 25,000 | 25,000 |
| Revenues | 775,000 | 775,000 | 775,000 | 775,000 |

### 8.3.3 IMPACT ASSESSMENT

Chapter 8.3.1 stated that the following environmental effects or KPI's are taken into account; global warming potential, the acidification potential, eutrophication potential and PM emission.

With all the emissions calculated, they can be expressed in the earlier mentioned indicators by multiplying it with the corresponding number shown in tables in appendix A. The effects are expressed over 100 years, so $CH_4$ is 25 times as bad as $CO_2$ in terms of greenhouse effect.

For the financial effects everything is given in euros. The input could be in a different unit as long as an exchange rate is used. All the money flows are related to the net present value with an assumed discount rate of 3.0 %.

So the six KPI's in which the results are expressed will be global warming, acidification and eutrophication potential as well as PM emission representing the environmental effects and net present value and internal rate of return as financial effects.

### 8.3.4 INTERPRETATION

The results of all assessments will be presented in the next chapter. However assumptions are made in the assessment that influences the result. These assumptions are divided into effect on the financial outcome and as effect on the environmental result.

The environmental aspects are not expressed in human, local and global effects. The amount of potential can be compared to each other and the area where the ship operates has to be taken into account. For instance if the ship is sailing on the ocean, far away from populated areas, the emission of $SO_X$ is less important than in a high populated area like near ports. This has to be interpreted by the reviewer. Also the importance of the different emissions has to be weighted by the reviewer.

In 2013 ship owner do not have to pay for their emissions, unless if they sail in Norway as explained in chapter 4.2.4. Chapter 4.2.5 stated that in the future this could be the case for more areas and/or emissions. This is not taken into account in this assessment, but could affect the outcome of the financial result in the future. An obvious results is that the configuration with the lowest emission will be least influenced by emission pricing mechanisms. The effect will be more interesting on the effect of using EGTS to reduce emissions and therefore extra costs.

As explained the financial result is given as net present value or at least as internal rate of return. The liquidity of the owner is not taken into account and the owner has to be aware of this. Also the maintenance costs are taken as percentage instead of schedules costs according the engines manufacturer. The decision of the owner to sail longer and ignore the schedule in order to try and save money on maintenance is not taken into account. To deal with unforeseeable costs, some money to cover this expense is taken into account; however this amount can be too high or too low.

The sensitivity of this assessment is hard to quantify. The assessment looks at 20 years into the future and a lot can change in 20 years. The effect of changing fuel prices is taken into account and also the increase of costs is covered. In case the input of costs is given in euro's the possible change in exchange rate will not affect the result. However if the input is given in for instance dollars, the exchange rate will influence the financial results. This is however not taken into account.

The effect of EGTS on emissions is given as parameter, so this effect is known. The financial effect of EGTS is determined by looking at the same configuration, consuming the same fuel, with or without an EGTS to see what the effect on NPV and IRR will be.

The emissions of $NO_X$ and PM are estimations, because it is hard to capture the emissions into one formula. To get more accurate results, the engine manufacturer has to provide numbers to calculate the emissions. If these numbers are not given, the results are less accurate.

# 9. RESULTS

In the previous chapter the LCPA was performed for the DFF 3007 sailing as a public liner between Rotterdam and Dordrecht. This chapter will provide the results of all these ten LCPA. The results have to be interpreted while keeping chapter 8.3.4 in mind. However these results can be used to compare the different ship configurations with each other to see which is better in terms of financial and environmental aspects. This chapter is divided into three parts, corresponding the three goals as described in chapter 8.3.1.

The KPI results will be given in a spider diagram with six axes. Four axes represent the environmental impact in terms of global warming potential, acidification potential, eutrophication potential and particulate matters. The other two axes represent the financial results in terms of net present value and internal rate of return. The reference case is always the blue line in the diagram. The legend of each diagram shows the used fuel and in case an EGTS is installed, also the installed EGTS. The LCPA results in numbers and diagrams for each KPI result are shown in appendix O.

The spider diagram shows the percentage change of each alternative configuration related to the reference case. This means that the reference case is always 0 %. The other cases are higher or lower than 0 % indicating respectively a worse or better result. In other words, when for example the GWP of case two is negative, this means that case two has a better, which means lower, GWP than the reference case. And if the GWP is worse and therefor higher, it is illustrated with a positive GWP. The following example, shown in table 38, illustrates the value of percentage change.

TABLE 38: EXAMPLE PERCENTAGE RESULTS OF LCPA

| | Old | New | Change [%] |
|---|---|---|---|
| **Example 1** | 750.00 | 600.00 | -20.0 % |
| **Example 2** | 400.00 | 0.04 | -100.0 % |
| **Example 3** | -200.00 | 800.00 | 500.0 % |

This table shows three different examples to indicate the effect of difference between old and new values and the results on the percentage of change.

Each LCPA results will be described in an own section. An overview of all LCPA and the used fuel prices is shown in table 39. The last (10th) LCPA has a different reference case, because this LCPA has as goal to compare different EGTS with each other.

TABLE 39: USED FUEL PRICES ($ /MT) IN EACH LCPA

| LCPA | Reference: EN 590 | LNG | MGO | HFO + hybrid scrubber |
|---|---|---|---|---|
| **1** | 1188.08 | 523.00 | 873.50 | 564.00 |
| **2** | **891.06** | 523.00 | 873.50 | 564.00 |
| **3** | 891.06 | 523.00 | **655.13** | 564.00 |
| **4** | 891.06 | 523.00 | 655.13 | **423.00** |
| **5** | 891.06 | **392.25** | 655.13 | 423.00 |
| **6** | 1188.08 | **653.75** | 873.50 | 564.00 |
| **7** | 1188.08 | 653.75 | **1091.88** | 564.00 |
| **8** | 1188.08 | 653.75 | 1091.88 | **705.00** |
| **9*** | 1188.08 | **523.00*** | 873.50 | 564.00 |
| ** LNG price increases with 3.5 % each year instead of only 1 % each year.* | | | | |
| | **Reference HFO** | **HFO + SCR** | **HFO + Hybrid scrubber** | **HFO + SCR + Hybrid scrubber** |
| **10** | 564.00 | 564.00 | 564.00 | 564.00 |

It seems that the first and ninth LCPA are the same, which in terms of used fuel prices in the first year, is correct. However the ninth LCPA has a different increase for LNG and for the oil based fuels in comparison to the first eight LCPA. For the first eight LCPA the assumption is that fuel prices for both oil based fuels as well as LNG is increase with one percent per year. In the ninth LCPA, LNG prices increase with 3.5 % each year. As mentioned earlier, the last LCPA is different than the other nine LCPA, because that LCPA has the same fuel price in all cases, but different installed EGTS.

The costs that are used for each LCPA are stated in table 37 and table 39. For the tenth LCPA however the used fuel in each configuration is HFO with a corresponding price of 564 dollar per metric ton. Table 40 summarizes all the other data which is assumed in all LCPA, unless otherwise indicated.

TABLE 40: SUMMARY OF USED DATA LCPA'S

| General | | Operational profile | | Loan | |
|---|---|---|---|---|---|
| Increase rate per year* | 1.0 % | Sailing time [years] | 20 | % of new price | 70.0 % |
| Discount | 3.0 % | % sailing per day | 59 % | Residual ship value | 25.0 % |
| LNG methane slip | 2.0 % | % sailing a year | 95 % | Duration [years] | 10 |
| *All costs are increased each year with this rate unless stated otherwise* | | | | Interest | 5.0 % |

## 9.1 GOAL COMPARISON

As described in chapter 8.3.1 the goal is to compare the different configurations with each other in terms of environmental and financial impact. For this goal, only one LCPA has to be performed of which the results will be described next. This first LCPA also indicates if it could be viable to invest in a more expensive ship which sails on cheaper fuel which compensates the higher purchase price.

### 9.1.1 FIRST LCPA: ALL BASE PRICES

This result of this first LCPA will be described and explained into more detail. All other LCPA results are more summarizes of which all results are provided in the appendix O on page 182.

The results of the first LCPA are provided in table 41. This data is shown graphically in figure 54.

TABLE 41: RESULT FIRST LCPA, ALL BASE PRICE

| | Reference | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|
| | EN 590 | LNG | MGO | HFO & Hybrid scrubber |
| Fuel | EN 590 | LNG | MGO | HFO |
| Fuel price [$ / mt] | $ 1,188.08 | $ 523.00 | $ 873.50 | $ 564.00 |
| EGTS | None | None | None | Hybrid scrubber |
| *LCA result* | | | | |
| GWP [t $CO_{2\,eq}$ / year] | 774.238 | 668.667 | 788.659 | 773.404 |
| AP [t $SO_{2\,eq}$ / year] | 3.366 | 0.336 | 3.852 | 3.708 |
| EP [t $PO_{4\,eq}$ / year] | 0.624 | 0.062 | 0.624 | 0.624 |
| PM [t PM / year] | 0.381 | 0.000 | 0.393 | 1.021 |
| LCC *result* | | | | |
| NPV | - € 224,650 | € 1,059,599 | € 789,356 | € 985,602 |
| IRR | 2.38 % | 5.36 % | 5.11 % | 5.45 % |

As this table shows LNG has the best score for all environmental KPI, which means that LNG has the lowest emission potential. The high score of LNG on the environmental KPI can be explained because LNG is a "clean" fuel as explained in chapter 5.1.3. Despite the methane slip of two percent which is taken into account, the GWP of LNG is still the lowest. Engine manufacturers expect that this methane slip can be reduced more in the future, which has a positive impact on the GWP of LNG. In contrary to the environmental results, the financial KPI of LNG is not the highest score. LNG has the highest score on NPV, but HFO has a slightly higher IRR. HFO has an IRR of 5.45 % and the IRR of LNG is 5.36 %. The reason why LNG scores the highest NPV, but not IRR, is illustrated in figure 52.

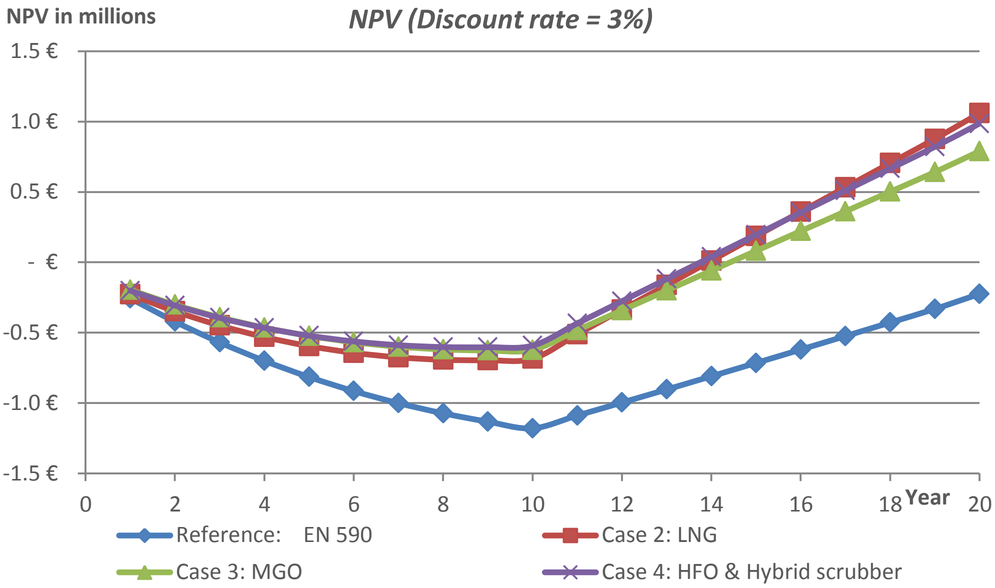



**FIGURE 52: NPV FIRST LCPA, ALL BASE PRICES**

In this figure it can be seen that in the first ten years, the NPV of LNG is lower than the NPV of HFO. This is caused by the higher CAPEX of LNG because the investment costs are higher. This is compensated in the following ten years, when the loan is paid off and the effect of the lower fuel prices can be seen. The OPEX, shown in figure 53, are, due to low LNG price, lower than the alternative configurations, but the advantages are only visible after these ten years.

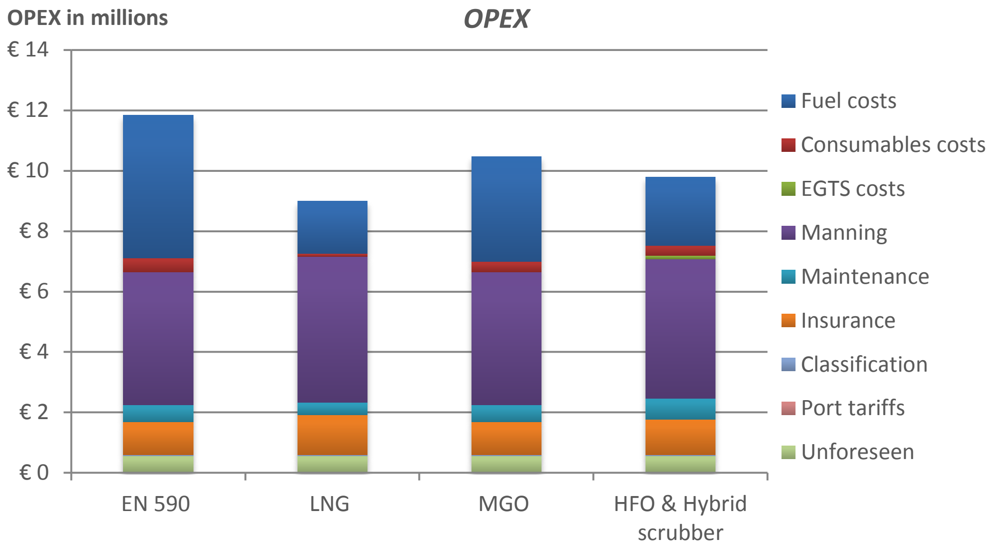



**FIGURE 53: OPEX FIRST LCPA, ALL BASE PRICES**

Figure 53 illustrates that there is a significant difference in fuel costs between the different configurations. LNG has, as expected, the lowest fuel costs, while EN 590 has the highest fuel costs. For EN 590 this is almost 44 % of the total OPEX, while for LNG the bunker costs are "only" 20.3 %. The manning costs are also an important part of the OPEX. Also visible are the EGTS costs for the configuration with the scrubber.

Focussing on the reference case, this case doesn't set a high score on all criteria, as shown in figure 54. The reason for this financial low score is because the fuel is the most expensive one of all four fuels. This indicates that in this particular case it is valuable to invest in a more expensive ship. In terms of environmental effect it scores similar to the other oil based fuels. For GWP this is caused by the similar carbon content of all oil based fuels. The low sulphur content of EN 590 results in a low AP score. Even the scrubber can't reduce to such low sulphur emissions for the high sulphur levels in HFO.

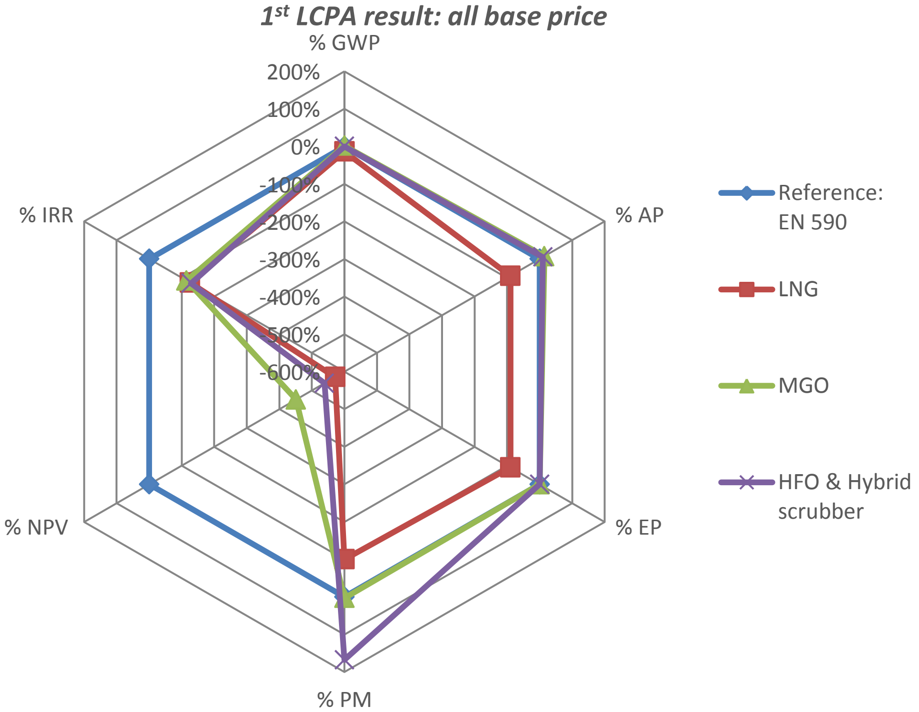



**FIGURE 54: RESULTS FIRST LCPA, ALL BASE PRICES**

This first LCPA shows that LNG has the best score for almost all KPI. Only for the IRR, the HFO case has a slightly higher IRR, but this is only 0.09 %. Therefore in this particular assessment the overall best solution is to use LNG as fuel.

## 9.2 GOAL: FINANCIAL EFFECTS

This second part provides the results of changes that influence the financial result. The emissions are not affected by this change in fuel price so these can be ignored. That will be described in chapter 9.3. As described in chapter 9.1.1 the following LCPA results will be more summarized. All results are provided in appendix O.

### 9.2.1 SECOND LCPA: LOWER EN 590 PRICE

Based on the result of the first LCPA, which is described above, the price of the reference fuel, EN 590, is reduced to 75 % to see if this results in a better financial score for the reference configuration in comparison to the other configurations. This reduction of 25 % corresponds to a decrease of more than 200 euro (around 300 dollars). All other costs are unchanged. Figure 55 shows the results of this change and appendix O on page 185 provide more data.

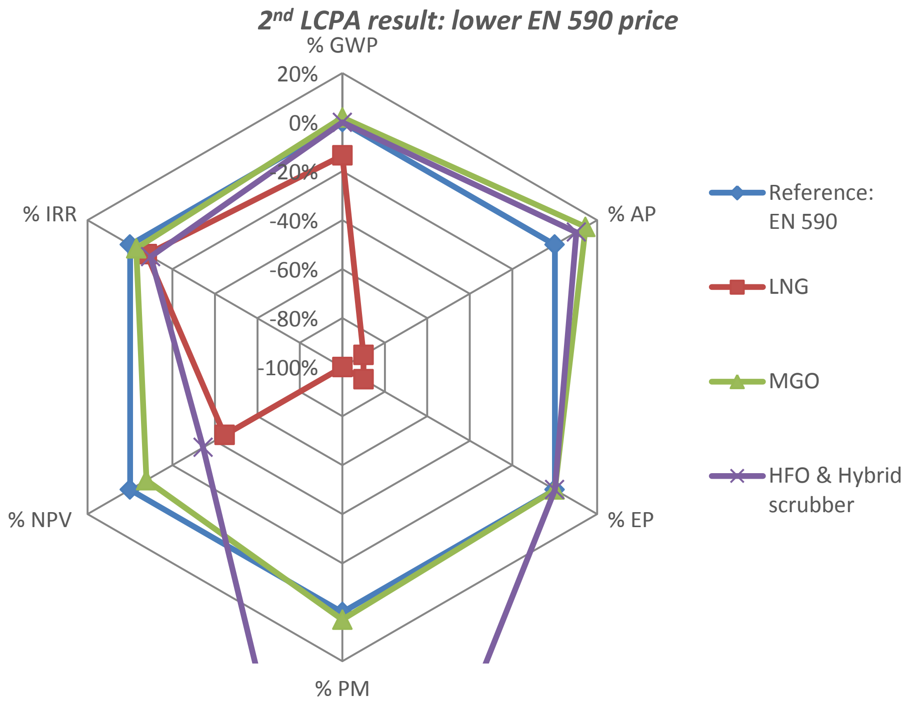



**FIGURE 55: RESULT SECOND LCPA, LOWER EN 590 PRICE**

The PM result for HFO is not visible in the figure, but as stated earlier, this remains the same as the first LCPA and not relevant for the following LCPA results. As expected the financial results increased for the reference, but both the NPV and IRR remains the lowest of all four configurations. The NPV increased from minus 224.650 euro to more than 732.750 euro caused by the decrease in fuel prices of around 215 euro. This is an increase of more than 957.400 euro. The IRR more than doubled with 2.58 % to 4.96 %.

### 9.2.2 THIRD LCPA: LOWER MGO PRICE

Previous LCPA showed a significant NPV increase of more than 400 % with a decreasing fuel price of around 215 euro. Based on the results of the second LCPA, MGO has the lowest NPV and IRR of the three alternative configurations. This third LCPA shows, in figure 56, the results of a lower MGO fuel. All data is provided in appendix O on page 188.

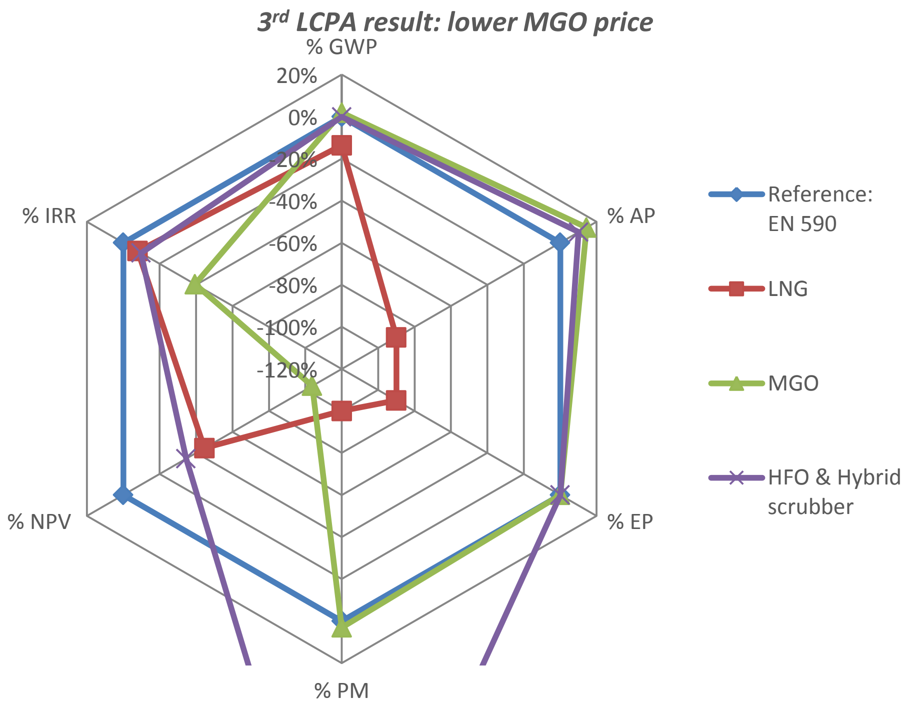



**FIGURE 56: RESULT THIRD LCPA, LOWER MGO PRICE**

This decrease in fuel price of a bit over 160 euro results in a NPV increase of more than 703.900 to a NPV of more than 1.493.200. This NPV increase is less than the increase in the second LCPA. This is caused by the lower price reduction of 215 euro versus 160 euro in respectively the second and this LCPA. The IRR increased with more than 1.8 % to a total of 6.92 %, which is the highest for all four cases in this third assessment.

### 9.2.3 FOURTH LCPA: LOWER HFO PRICE

As the result of the third LCPA shows, LNG has in comparison to HFO a lower IRR, while HFO has a lower NPV than LNG. As described in chapter 8.3.1, the fuel price of the case with the lowest NPV will be lowered and that is in this case HFO. The new HFO fuel price will be just over 310 euro, which is a reduction of around 100 euro. The result of this reduction is shown in figure 57. Appendix O on page 191 shows more data.

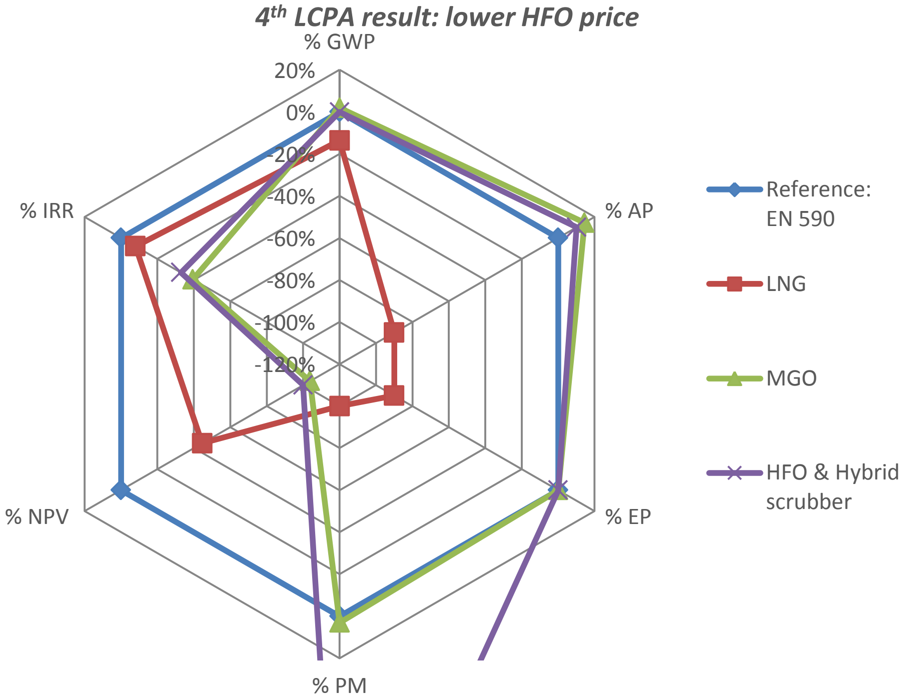



**FIGURE 57: RESULT FOURTH LCPA, LOWER HFO PRICE**

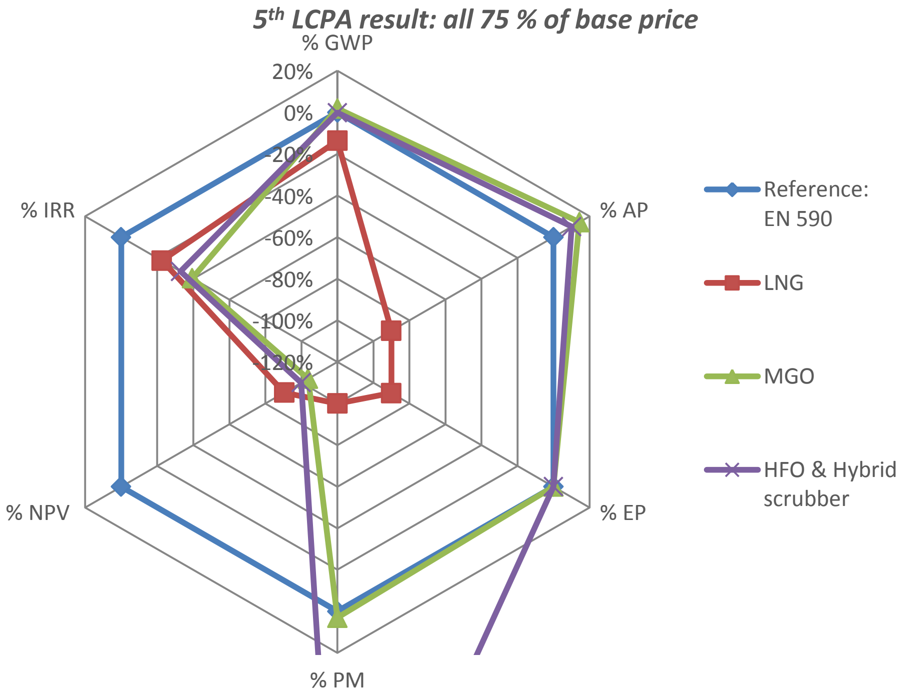
The first LCPA with all fuel prices at 100 % of the base price showed that HFO achieved a higher score for both NPV and IRR than the MGO configuration did. In this fourth LCPA both the price for MGO as HFO are lowered with 25 % to 75 % of the base price and the expectation is that HFO still has the highest financial KPI. However as this fourth LCPA shows, MGO has a higher NPV as well as a higher IRR. The explanation for this result is that the fuel price reduction causes the OPEX to be around 6.7 % (651.143 on 9.790.629 euro) lower for HFO and around 9.1 % (955.539 on 10.460.887 euro) lower for MGO. The effect of the fuel price decrease resulted in a higher percentage OPEX reduction and thus a greater impact on the NPV and IRR. The fuel price reduction to 310 euro results in a NPV of almost 480.000 to more than 1.465.200 euro. The IRR increased with only 1.15 % to 6.60 %, which is as mentioned earlier lower than the IRR of MGO (6.92 %).

### 9.2.4 FIFTH LCPA: ALL FUEL PRICES ARE 75 % OF BASE PRICE

In the second, third and fourth LCPA, the prices of respectively EN 590, MGO and HFO are already reduced, so for this fifth LCPA the LNG price will be reduced with almost 100 euro to 288 euro. Because all fuels prices of each configuration are reduced to 75 % of the base price as stated in table 18 this fifth LCPA can be compared to the first LCPA. So this fifth

LCPA will show if this fifth result is similar to the result of the first LCPA. There will probably be some differences as the result in chapter 9.2.4 indicates. In the first LCPA, LNG had the highest NPV and almost the highest IRR as visible in table 41. Figure 58 shows that this is not the case anymore when all fuel prices are 75 % of the base price. All results of this fifth LCPA are provided in appendix O on page 194. The LNG price decreased with almost 100 euro to around 290 euro which resulted in a NPV increase of more than 366.200 euro. The IRR increased to more than 6.0 %.

**FIGURE 58: RESULT FIFTH LCPA, ALL 75 % OF BASE PRICE**




As this figure illustrates both NPV and IRR of LNG are lower than the financial KPI of both MGO and HFO. This could also be explained by the change in OPEX as mentioned earlier. Due to the fuel price decrease, the OPEX for the LNG configuration reduced with 5.1 % (456.474 on 8.987.577 euro). This is even lower than the earlier mentioned 6.7 % reduction for HFO. The reason why the reduction of bunker costs has a smaller influence on the total OPEX is illustrated in figure 53. The bunker costs are for the LNG configuration only 20 % of the OPEX, while for MGO it is almost 44 %.

Compared to the first LCPA the different between the reference and the alternative configurations became smaller. This is caused by the fact that EN 590 has the highest fuel price. Therefore a reduction in the fuel price has a great impact on the financial results of the assessment. The higher the base fuel price is, the higher the effect of a reduction on both NPV as well as IRR.

### 9.2.5 SIXTH LCPA: HIGHER LNG PRICE

Previous chapter 9.2.1 until 9.2.4 provided LCPA results with lower fuel prices than the base price as stated in table 18. This next part describes the LCPA results with higher fuel prices than the base price. Looking at the outcome of the first LCPA again, LNG had the highest NPV but HFO had the highest IRR. As was done in chapter 9.2.3 the configuration with the highest NPV will be assessed, which means that this sixth LCPA will show the effect of a LNG price increase of 25 %. Figure 59 shows that they both remain higher than the reference configuration. The results of this assessment are shown in appendix O on page 197.

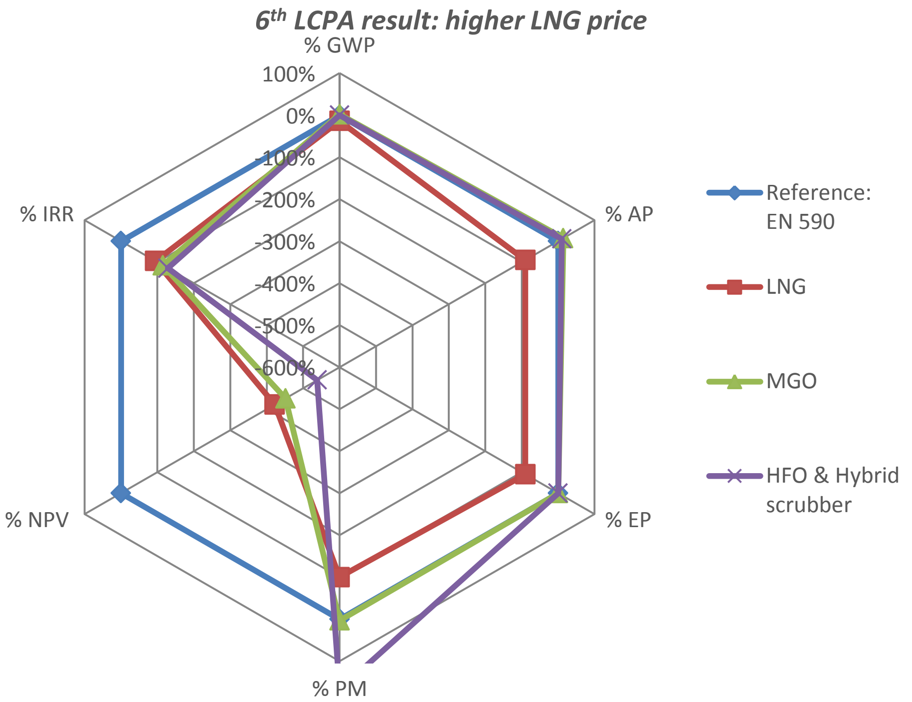



**FIGURE 59: RESULT SIXTH LCPA, HIGHER LNG PRICE**

This LCPA shows that a fuel price increase of almost 100 euro results in a NPV decrease of 336.260 euro. This is the same amount as the NPV increase in chapter 9.2.3. For the IRR there is a slight difference of 0.01 %, between the increase and decrease (0.72 % versus 0.73 %). An explanation for this difference will be given in chapter 9.2.8.

### 9.2.6 SEVENTH LCPA: HIGHER HFO PRICE

As mentioned in chapter 9.2.5 this LCPA will indicate the effect of a 25 % higher HFO price. This increase of more than 100 euro to a HFO price of more than 515 euro causes the NPV and IRR of HFO to drop below the NPV and IRR of LNG as illustrated in figure 60.

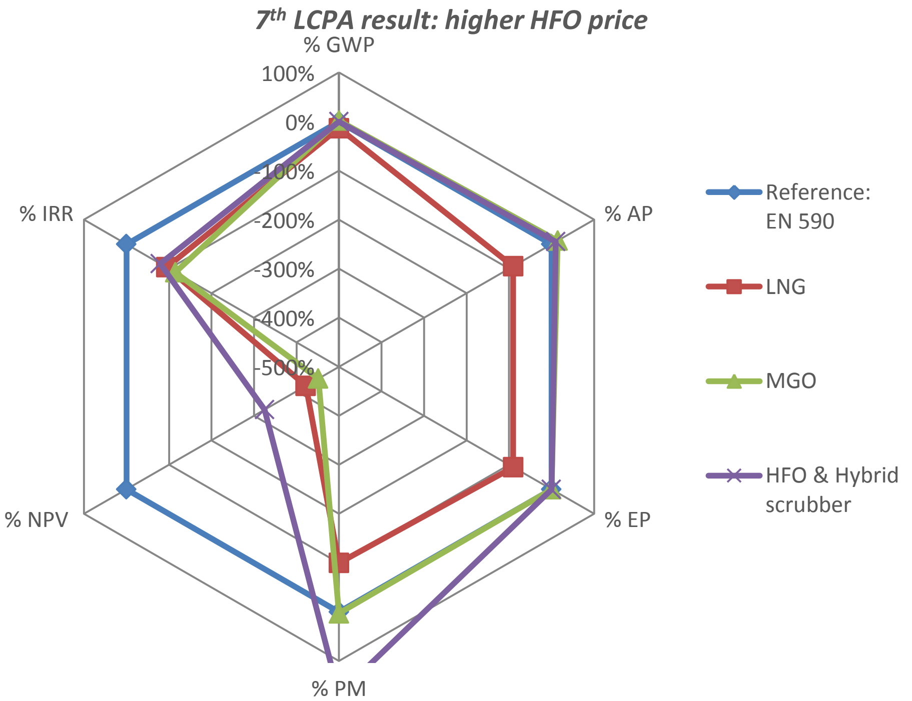



**FIGURE 60: RESULT SEVENTH LCPA, HIGHER HFO PRICE**

Just like the outcome of the previous (sixth) LCPA, the change in NPV is the same as in chapter 9.2.3 where the price of HFO was decreased with 25 %. The change in IRR is almost the same, but just as the LNG price there is a slight difference. In this case a difference of 0.03 %. Like all the other LCPA results, the results of this seventh LCPA are provided in appendix O on page 200.

### 9.2.7 EIGHT LCPA: HIGHER MGO PRICE

With the prices of both LNG and HFO increased to 125 % in chapters 9.2.5 and 9.2.6, MGO has the highest IRR and NPV. This next LCPA will show the influence of a higher MGO price. This 160 euro price increase results in a price which is around 70 euro less than the reference case with EN 590 fuel. The IRR, although reduced with 1.88 % to 3.23 % is still higher than the IRR of the reference case which is 2.38 %. This is illustrated in figure 61.

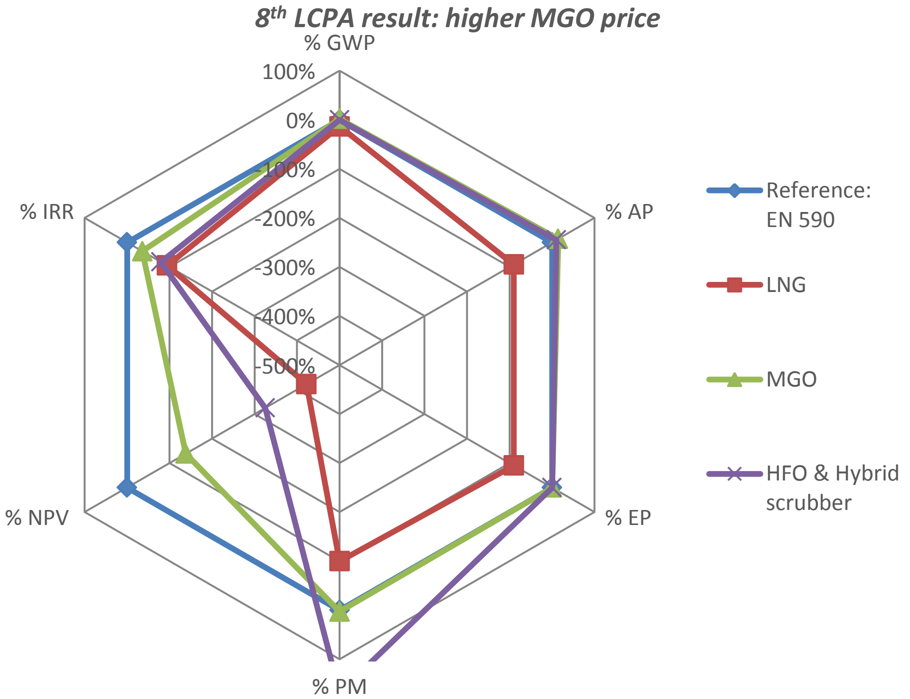



FIGURE 61: RESULT EIGHTH LCPA, HIGHER MGO PRICE

The NPV is almost zero, but remains still higher than the NPV of the reference case. The difference between both the LNG as the HFO case and this, MGO, case is become bigger. A similar phenomenon was seen in chapter 9.2.4. A price increase has a higher impact on configurations with a higher base price. Because almost all fuel price increases, LNG scores the best on all KPI as can be seen in figure 61 and in appendix O on page 203. The reason for this is that LNG had already the best score on almost all KPI as the first LCPA showed. Furthermore, as mentioned earlier, the impact of a price increase is higher when the base price was already higher and the price of HFO is higher than the LNG price.

### 9.2.8 SUMMARY SECOND GOAL

As the results of the eight LCPA shows and figure 61 illustrates, it is not necessary to see the influence of an increase of EN 590 fuel price, because EN 590 still has the lowest IRR and NPV. The results of a 25 % higher price of EN 590 will only results in an even lower NPV and IRR.

The second to eight LCPA results showed the following results, which are summarized in table 42 and table 43. Table 42 only shows the effect of fuel price change on NPV for the second to fifth LCPA. The results for the sixth till eighth are not shown because these are the same as the results that are shown. As these tables shown and as concluded earlier this chapter, the NPV and IRR are mostly influenced both in amount and percentages by the cases with high fuel prices.

TABLE 42: OVERVIEW EFFECT FUEL PRICE CHANGE ON NPV

| LCPA | Fuel | Base price | Δ price | Base NPV | Δ NPV | % Δ NPV | % per Δ price |
|---|---|---|---|---|---|---|---|
| 2nd | EN 590 | € 873 | € 218 | € -224,650 | € 957,409 | -426.2 % | 1.95 |
| 3rd | MGO | € 642 | € 160 | € 789,356 | € 703,908 | 89.2 % | 0.56 |
| 4th | HFO | € 414 | € 104 | € 985,602 | € 479,671 | 48.7 % | 0.47 |
| 5th | LNG | € 384 | € 96 | € 1,059,599 | € 336,266 | 31.7 % | 0.33 |

As mentioned above, the effect on the NPV change is the same for a fuel price increase and decrease. Dividing the change in fuel price by the effect on NPV, the answer for these assessments is around 0.50 %. This means that for each euro that the fuel price is changed the NPV will change with 0.50 %. With much higher NPV's the percentage per price difference will be lower. For LNG this percentage is slightly lower, around 0.33 %, because LNG has a higher CAPEX. For EN 590 the percentage is around 1.95 %. The reason why this percentage is not in line with the other results is that the NPV of the reference case is relative small.

TABLE 43: OVERVIEW EFFECT FUEL PRICE CHANGE ON IRR

| LCPA | Fuel | Base price | Δ price | Base IRR | Δ IRR | % Δ IRR | % per Δ price |
|---|---|---|---|---|---|---|---|
| 2nd | EN 590 | € 873 | € 218 | 2.38 % | 2.58 % | 108.6 % | 0.50 |
| 3rd | MGO | € 642 | € 160 | 5.11 % | 1.81 % | 35.4 % | 0.22 |
| 4th | HFO | € 414 | € 104 | 5.45 % | 1.15 % | 21.1 % | 0.20 |
| 5th | LNG | € 384 | € 96 | 5.36 % | 0.72 % | 13.5 % | 0.14 |
| 6th | LNG | € 384 | € 96 | 5.36 % | 0.73 % | 13.7 % | 0.14 |
| 7th | HFO | € 414 | € 104 | 5.45 % | 1.17 % | 21.6 % | 0.21 |
| 8th | MGO | € 642 | € 160 | 5.11 % | 1.88 % | 36.7 % | 0.23 |

As table 43 shows there is a difference on the IRR if the fuel price is increased or decreased with the same percentage. This is caused by the different in OPEX. Chapter 3.2.1 described the time value of money and the IRR indicates the discount ratio for which NPV is equal to zero. The reason why this has not the same difference, while the fuel price is changed with the same percentage is caused by the different in steepness of the curve, visible in figure 62.

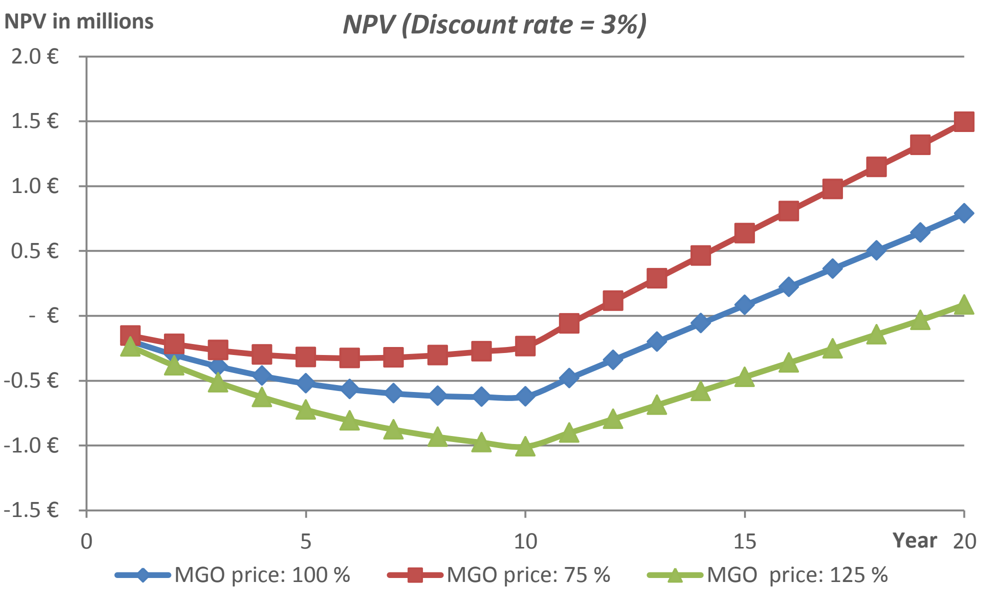



FIGURE 62: NPV FOR THREE DIFFERENT MGO FUEL PRICES

Due to this difference in steepness, the NPV has the same percentage of deviation, but a difference in IRR. In general, when the fuel price is changed with one euro, the IRR will change by around 0.20 %. This number act similar as the result for the NPV; the percentage per change in fuel price will be lower for higher IRR.

### 9.2.9 NINTH LCPA: HIGHER PRICE INCREASE OF LNG

As reports mentioned in chapter 6.3.1, the expectation is that oil based fuel prices will increase with around 1 % each year, while the increase of natural gas prices could be up to 3.5 % per year. This ninth LCPA shows the influence of that different increase in fuel price over the years.

The extra bunker costs of LNG will increase with 494,436 euro to a total of 2,233,385 over the life time of the ship; this is an increase of 28.4 % as provided in appendix O on page 206. As figure 63 illustrates, the NPV and IRR of LNG are lower than both the alternatives HFO and MGO. LNG remains much higher than the reference case. The PM result of the HFO configuration is not visible in the figure, but this value is just as in the previous LCPA in this chapter 9.2 not relevant.

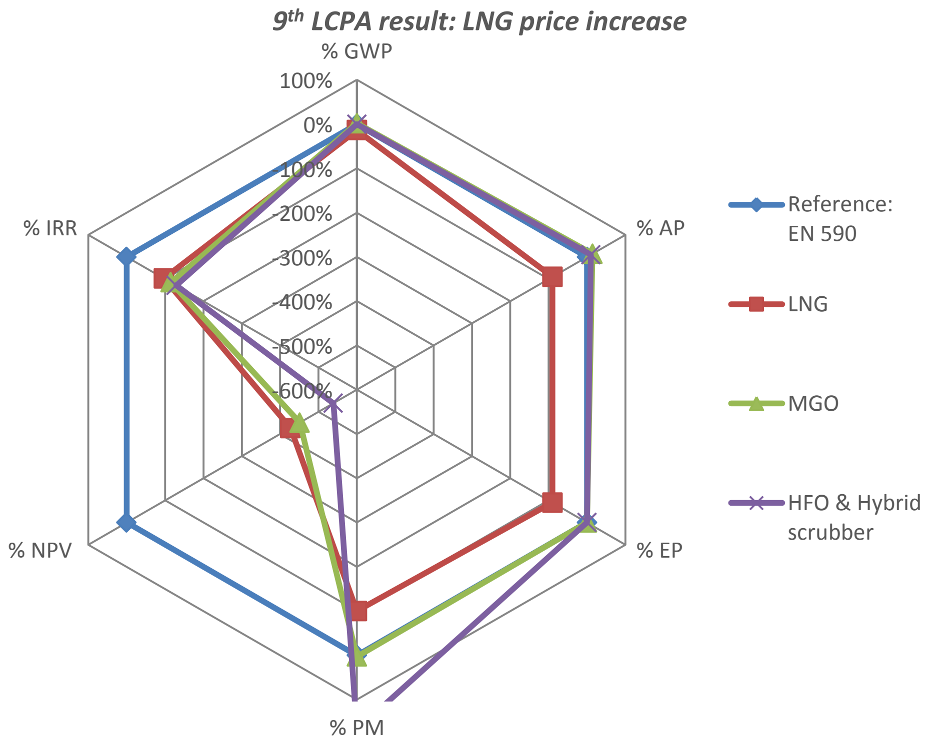



**FIGURE 63: RESULT NINTH LCPA, LNG PRICE INCREASE**

Comparing the financial outcome of this LCPA to the outcome of the sixth LCPA, described in chapter 9.2.5, where the LNG price was increasing to 125 % of the base price, the results are almost the same. The difference in NPV is almost 11,000 euro and for the IRR the difference is smaller than 0.1 %. So the effect of a LNG price increase of 25 % or an annual price increase of 3.5 % is similar. As shown above, a price increase of 3.5 % annually results over 20 years in a fuel costs increase of 28.4 %, which explains why the result of this annual increase is similar to a LNG price increase of 25 %.

Chapter 9.2 focussed on the financial aspects of the LCPA. It showed that the effect of a yearly increase of 3.5 % is similar to a fuel price increase of 25 %, the difference in fuel costs is 3.4 %. This chapter showed furthermore that the impact of a price increase is higher when the base fuel price was already higher than the reference base fuel price.

## 9.3 GOAL: EXHAUST GAS TREATMENT SYSTEM EFFECTS

Chapter 9.2 focussed only on the financial aspects but this chapter will investigate both the environmental and financial aspects. The analysed ship is sailing in a SECA thus stricter rules are applicable. The impact of a SECA will be illustrated in this chapter. This will be shown by performing an assessment for the ship sailing on the same fuel, HFO, only with different exhaust gas treatment systems. The reference configuration in this LCPA is the ship sailing on HFO without any EGTS. The second case is the same ship with a selective catalytic reduction installed and only a scrubber is installed in the third case. The last case has both a scrubber and SCR installed to reduce $NO_X$, $SO_X$ and PM. This assessment shows what kind of influence an EGTS on the results of a LCPA has.

### 9.3.1 TENTH LCPA: ALL HFO WITH FOUR DIFFERENT EGTS

This LCPA is focussed on a combination between financial and environmental KPI's. The reference is a ship sailing on HFO. The alternatives are the same ship with different EGTS installed on board to see what the impact of each EGTS is. The differences are the investment costs of the EGTS and the sustainable costs of these EGTS. There is furthermore a difference in manning costs, because the crew has to work with these EGTS and therefore requires training. The assumption is that for a SCR and scrubber, the costs are the same, but for a combination of these two, the costs are 5000 euro more. Also the maintenance of the EGTS results in extra costs and is thus taken into account. The maintenance costs of a scrubber are already mentioned chapter 8.3.2 and the maintenance costs for a SCR are assumed to be 10 %[32] more. A combination of a scrubber and a SCR are assumed to costs 35 % extra than without these EGTS.

Figure 64 shows the results and as expected, the reference case without any EGTS has the highest NPV and IRR. This is caused by no additional costs that are caused by the EGTS.

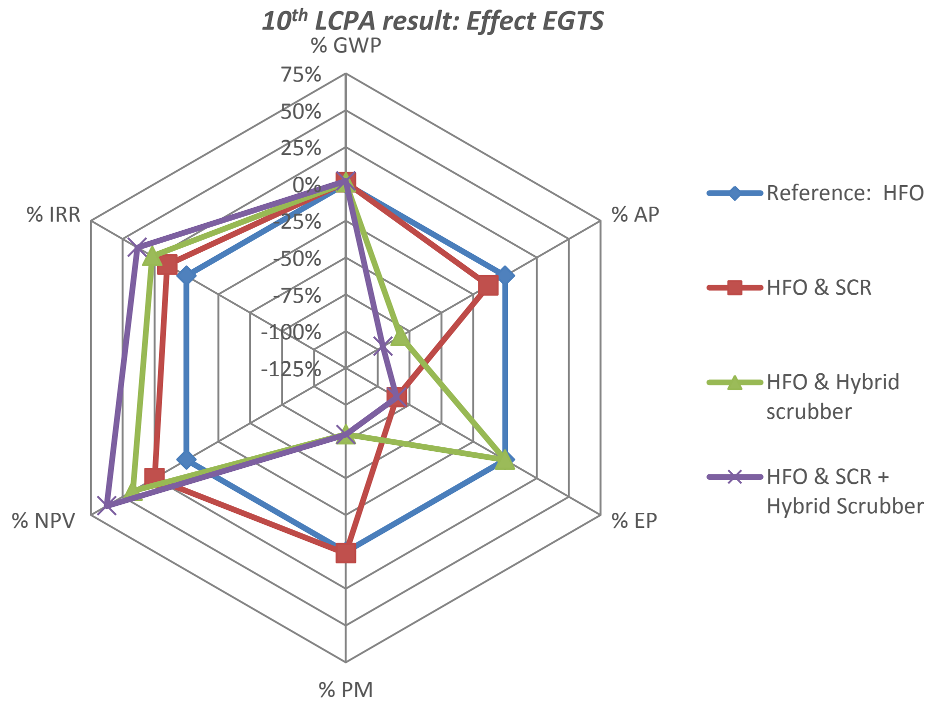



**FIGURE 64: RESULT TENTH LCPA, EFFECT EGTS**

However for the environmental KPI's this results in the lowest score, because most emissions are emitted. The configuration with the combined EGTS of SCR and scrubbers has the highest score on almost all the environmental KPI's because the least emission is emitted. Only the configuration with only the hybrid scrubber installed emits less PM. This is caused by the additional power required for the EGTS. This resulted in more fuel combustion and thus more PM emission. This combined EGTS has consequently also the worst NPV and IRR. More data can be found in appendix O on page 209.

The EGTS are not reducing $CO_2$ emissions, but in facts increasing $CO_2$ emissions caused by additional consumed fuel. Table 44 shows the emission reduction per year for each EGTS. When the value is negative, it means that it produces more than the reference. This table also shows the additional costs in comparison of having no EGTS installed on board.

TABLE 44: ADDITIONAL COSTS FOR REDUCED EMISSIONS

| | EGTS | None | SCR | Hybrid scrubber | SCR + Hybrid scrubber |
|---|---|---|---|---|---|
| Reduced GWP | t $CO_{2\ eq}$ / year | 0.0 | -7.661 | -7.278 | -14.939 |
| Reduced AP | t $SO_{2\ eq}$ / year | 0.0 | 2.685 | 16.854 | 19.707 |
| Reduced EP | t $PO_{4\ eq}$ / year | 0.0 | 0.530 | 0.000 | 0.530 |
| Reduced PM | t PM / year | 0.0 | -0.051 | 4.037 | 4.027 |
| Additional costs | € / year | € - | € 25,004 | € 28,592 | € 48,225 |

This table shows that there is a trade of between additional costs and reduced emissions. It is up to the owner which reduction is worth the extra money.

## 9.4 CHAPTER CONCLUSION

This chapter provided the results of all LCPA performed to answer three goals. The first goal is to see if this method could be used to compare different configurations on board the same ship in terms of environmental and financial impact. As explained in chapter 9.1 this is possible. This chapter also shows that, although the ship is more expensive, it is advisable to invest in that ship, because lower fuel prices compensate the high investment. This can be seen in figure 52, where in this particular assessment the NPV of LNG is increasing more than that of the other configurations.

The life time for this assessment was 20 years, but if the lifetime was different, the result would also change. A longer lifetime would be, in terms of financial motivation, in favour of a LNG configurations while a shorter lifetime would be in favour of the configuration were the ship sails on HFO with a hybrid scrubber to comply with the regulations.

Another conclusion is that, if/when in the future ship owners have to pay for their emissions, ships that emit fewer emissions are in favour; in this case ships sailing on LNG. One effect is that the price difference between for instance HFO and LNG could be bigger, while the TCO of LNG remains lower.

The second goal focusses on the effect of changing fuel prices on the financial result. The result of the second until the eighth LCPA is that the effect on the financial KPI is higher if the fuel price is higher. This conclusion is also applicable to the effect of the difference in long term contract prices or spot rates which are used for the assessment. In all these assessments the spot fuel rates are used instead of the long term contracts. In case long term contract prices were to be used, the prices could be lower, resulting in a lower impact of a change in fuel price on the NPV and IRR. Examples of the effects of lower fuel prices are described in chapter 9.2.4.

Another financial related matter is that over a period of 20 years there is almost no difference in financial result between a base price increase of 25 % with an annual price increase of 1 % compared to the base price with an annual price increase of 3.5 %. A combination of this financial matter and the previous one, where the financial results of higher fuel prices are affected more by a price change than lower fuel prices, applies to a change in exchange rate between the euro and the US dollar. In all assessments this is assumed to be the same. The fuel prices are set in dollars, while the result is given in euro. If the exchange rate increases, the fuel price in euro will be lower.

The last goal, which is described in chapter 9.3, investigated the effect of EGTS on both the environmental and financial result. This goal is assessed because the used data for the EGTS is based on bigger installations than those that are assumed to be installed on board the DFF 3007. The actual price per kW could be higher, which would influence the results of the tenth LCPA in the way that the additional costs would be higher. However this third goal shows that this tool can provide what the additional costs of an EGTS are in order to reduce certain emissions.

All these LCPA are performed on a DFF 3007, which is an aluminium catamaran. The next chapter will evaluate this method and described if this method can be used on another ship type that Damen has in its portfolio

# 10. EVALUATION LCPA

The previous chapter described the results of all LCPA that are performed on the DFF 3007 in chapter 8. This chapter will evaluate the LCPA and this is done in two parts. The first part will describe whether the tool is applicable to other types of ships and the second part describes discussion points that have to be taken into account while working with this tool. These discussion points are related to the assumptions.

## 10.1 APPLICABILITY

All these LCPA are performed on a 30 meters long aluminium catamaran. Damen has more types of ships in its portfolio; ranging from tug and workboats, ferries, fast crew suppliers and platform support vessels for offshore structures, to naval ships. Chapter 9 showed that a ferry is suitable to perform a LCPA on with the designed software tool, but is the program also capable to assess other ship types?

As described in chapter 3.1.1 a life cycle assessment can have different goals. One goal is to compare multiple ships with each other while another goal could be to determine which step of the life cycle has the highest impact. This developed LCPA software tool can be used to compare different ship configurations to a reference configuration. The base has to be the same. It cannot be used to compare different ships of the same type for instance a 100m cargo ship with a 50m cargo ship.

Furthermore this designed LCPA tool is based on the operational profile. This operational profile in combination with the installed engines is the reason why this LCPA tool is applicable to different types of ships. For example tugs can be analysed with this tool because the main purpose, the bollard pull, is taken into account with the installed engine. The installed engines determine the amount of bollard pull that can be achieved. A tug has a different sailing profile with much time spent on low engine power. At low engine power the efficiency is lower and thus more emissions are produced. This can be taken into account with the tool as well.

In terms of applicability the conclusion is that this tool can be used to analyse other ship types as long as the operational sailing profile and the installed engines are known. Another advantage for Damen is that because it is developed in Excel, it could be combined with other Excel files that the Research Department is currently using. The file is kept simple and no macros are used, so it is easy to learn and it does not require specific computer software to run smoothly.

## 10.2 DISCUSSION

As stated above the tool is based on assumptions, which are described in chapter 8.3.4. These assumptions influence the result and therefore have to be taken into account while working with this tool.

The assumption that influences the environmental result will be discussed first. The accuracy of the $NO_X$ and PM calculations is questionable. This is because there is not enough knowledge about the forming of these emissions as described in chapter 7.4.2. Chapter 4.1 mentioned some causes, but there are no models to predict what actually happens inside a combustion chamber when fuel is ignited. This makes it difficult to determine a formula which accurately calculates the formed emissions. Engine manufacturers are continuing to investigate those processes. For this dissertation the assumption is that due to otherwise higher fuel consumptions, the $NO_X$ emissions are just inside the limits of the regulations. The PM emission calculation is related to the sulphur content of the fuel, but sulphur is not solely responsible for all PM that are emitted, as explained in chapter 4.1.4.

Another assumption is that the impact of the emissions is expressed in different potentials. This does not say anything about the regional impact or the impact on the human health. This potential only indicates the quantity of the different emissions. For this dissertation all four ship configurations sail on the same route, so the impact of each emission is the same. Only the quantity counts and this is taken into account.

The assumptions that influence the financial results are mostly investigated with the different LCPA. However it is important to remember that the price development of the different fuels is hard to predict and have a great impact on the financial outcome. For example, a scenario were the fuel price of a particular fuel increase the first couple of years with 1 percent and the other years, due to less demand, with 4 % is not investigated. This “sudden” increase within a couple of years could have a great impact on which fuel to choose and if an EGTS in combination with cheaper, dirtier fuel suddenly becomes more attractive.

Also the influence of the discount rate is not taken into account; in all LCPA the same discount rate is used. Chapter 3.2.1 showed the influence of a used discount rate on the result. A higher discount rate is in favour of configurations which have lower capital costs in the beginning.

# 11. CONCLUSION AND RECOMMENDATION

Based on chapters 9 and 10, this chapter states the conclusion of this thesis. Also some small recommendations are provided which can be taken into consideration in a follow-up study.

## 11.1 CONCLUSION

Based on the results of this dissertation, the following conclusions are drawn. Life cycle assessment and life cycle costing could be usable method for Damen. Incorporated in the LCPA software program it has some advantages but it also has some drawbacks. It depends on which goal Damen wants to achieve. When the goal is to determine the environmental and financial impact of different configurations of the same ship, this program is ideal to indicate those differences. It provides a quick indicator of the environmental and financial effects of a ship. However when different ship types or different ship sizes of the same type are compared, this program is not suitable. In order to be able to compare different ship sizes with each other, the program has to be edited that more phases, like the building phase, can be taken into account. Gathering information for this building phase is time consuming and not worth the effort.

Another goal that can be achieved and is useful for Damen is that it could determine the effect of EGTS. This shows if it is viable to sell a ship with a higher price, due to EGTS, because this saves money when operating the ship. Or in general, this program provides information on which decision leads to the lowest costs or lowest emissions.

As the first LCPA showed, it is justifiable to sell a more expensive ship which sails on LNG, because, due to the lower bunker costs, the total costs of ownership of the ship are lower. Another advantage of sailing on LNG is that the ship emits less harmful emissions in comparison to a “conventional” ship sailing on diesel oil.

This program can be used for all ship types, as long as the installed engines and the operational profile is known. The effect of used materials is taken into account in the amount of installed power.

## 11.2 RECOMMENDATIONS

These conclusions are based on a couple of assumptions which are stated in chapter 8.3.4. Because some of these assumptions are questionable, as explained in chapter 10.2, there are some recommendations. One of the recommendations is to investigate further the calculations for both $NO_X$ and PM emissions. Another recommendation is to examine the development in fuels in general. For this dissertation, among others, biofuel was not investigated. Also the use of hybrid technologies like batteries or shore power is not looked into. These “new” technologies can be used to reduce the amount of emission. When data of how much emission can be reduced by using these systems is known, it can easily be implemented into the program.

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# APPENDICES CONTENT

# APPENDIX A: GWP, AP AND EP

**Global Warming Potential (GWP)**

| Name | Formula | GWP [ton $CO_2$/ton fuel] 2007 |
|---|---|---|
| **Carbon Dioxide** | $CO_2$ | 1 |
| **Methane** | $CH_4$ | 25 |
| **Nitrous Oxide** | $N_2O$ | 298 |
| **Sulphur hexafluoride** | $SF_6$ | 22800 |
| **HFC-23** | $CHF_3$ | 14800 |
| **HFC-32** | $CH_2F_2$ | 675 |
| **HFC-125** | $CHF_2CF_3$ | 3500 |
| **HFC-134a** | $CH_2FCF_3$ | 1430 |
| **HFC-143a** | $CH_3CF_3$ | 4470 |
| **HFC-152a** | $CH_3CHF_2$ | 124 |
| **HFC-227ea** | $CF_3CHFCF_3$ | 3220 |
| **HCF-236fa** | $CF_3CH_2CF_3$ | 9810 |
| **PFC-14** | $CF_4$ | 7390 |
| **PFC-116** | $C_2F_6$ | 12200 |
| **PFC-3-1-10** | $C_4F_{10}$ | 8830 |
| **PFC-5-1-14** | $C_6F_{14}$ | 9300 |
| ***Source:*** | *IPCC Fourth Assessment Report, 2007* | |

**Acidification Potential (AP)**

| Name | CAS number | AP [kg $SO_2$/kg] |
|---|---|---|
| **Ammonia** | 7664-41-7 | 1,88 |
| **Hydrogen Chloride** | 7664-01-0 | 0,88 |
| **Hydrogen Fluoride** | 7664-39-3 | 1,6 |
| **Hydrogen sulphide** | 7783-06-4 | 1,88 |
| **Nitric acid** | 7697-37-2 | 0,51 |
| **Nitrogen dioxide** | 10102-44-0 | 0,7 |
| **Nitrogen monoxide** | 10102-43-9 | 1,07 |
| **Nitrogen oxides** | 10102-44-0 | 0,7 |
| **Phosphoric acid** | 7664-38-2 | 0,98 |
| **Sulphur dioxide** | 7446-09-5 | 1 |
| **Sulphur trioxide** | 7446-11-9 | 0,8 |
| **Sulphuric acid** | 7664-93-9 | 0,65 |

**$PO_4$ equivalence factors of various substances**

| Nutrient [1kg] | $PO_4$ equivalence factor [kg] |
|---|---|
| **Nitrogen oxides ($NO_X$, air)** | 0,13 |
| **Total nitrogen (water)** | 0,42 |
| **Total phosphorous (water)** | 3,07 |
| **Chemical $O_2$ demand (COD)** | 0,022 |
| **$NH_3$** | 0,35 |
| **$NH_4$+** | 0,33 |
| **$NO_3$-** | 0,095 |
| **$NO_2$-** | 0,13 |

***Source: Equivalence factors suggested by CML (University of Leiden, 1992) are generally used in LCA***

# APPENDIX B: MARPOL ANNEX VI USEFUL SECTIONS

## CHAPTER I: GENERAL

### REGULATION 1: *APPLICATION*

### REGULATION 2: *DEFINITIONS*

For the purpose of this Annex:

1. *Annex* means Annex VI to the International Convention for the Prevention of Pollution from Ships 1973 (MARPOL), as modified by the Protocol of 1978 relating thereto, and as modified by the Protocol of 1997, as amended by the Organization, provided that such amendments are adopted and brought into force in accordance with the provisions of article 16 of the present Convention.
2. A similar stage of construction means the stage at which:

2.1 construction identifiable with a specific ship begins; and

2.2 assembly of that ship has commenced comprising at least 50 tons or one per cent of the estimated mass of all structural material, whichever is less.

3. *Anniversary date* means the day and the month of each year which will correspond to the date of expiry of the International Air Pollution Prevention Certificate.
4. *Auxiliary control device* means a system, function, or control strategy installed on a marine diesel engine that is used to protect the engine and/or its ancillary equipment against operating conditions that could result in damage or failure, or that is used to facilitate the starting of the engine. An auxiliary control device may also be a strategy or measure that has been satisfactorily demonstrated not to be a defeat device.
5. *Continuous feeding* is defined as the process whereby waste is fed into a combustion chamber without human assistance while the incinerator is in normal operating conditions with the combustion chamber operative temperature between 850°C and 1,200°C.
6. *Defeat device* means a device which measures, senses, or responds to operating variables (*e.g.*, engine speed, temperature, intake pressure or any other parameter) for the purpose of activating, modulating, delaying or deactivating the operation of any component or the function of the emission control system such that the effectiveness of the emission control system is reduced under conditions encountered during normal operation, unless the use of such a device is substantially included in the applied emission certification test procedures.
7. *Emission* means any release of substances, subject to control by this Annex, from ships into the atmosphere or sea.
8. *Emission Control Area* means an area where the adoption of special mandatory measures for emissions from ships is required to prevent, reduce and control air pollution from $NO_X$ or $SO_X$ and particulate matter or all three types of emissions and their attendant adverse impacts on human health and the environment. Emission Control Areas shall include those listed in, or designated under, regulations 13 and 14 of this Annex.

9. *Fuel oil* means any fuel delivered to and intended for combustion purposes for propulsion or operation on board a ship, including distillate and residual fuels.
10. *Gross tonnage* means the gross tonnage calculated in accordance with the tonnage measurement regulations contained in Annex I to the International Convention on Tonnage Measurements of Ships, 1969 or any successor Convention.
11. *Installations* in relation to regulation 12 of this Annex means the installation of systems, equipment including portable fire-extinguishing units, insulation, or other material on a ship, but excludes the repair or recharge of previously installed systems, equipment, insulation, or other material, or the recharge of portable fire-extinguishing units.
12. *Installed* means a marine diesel engine that is or is intended to be fitted on a ship, including a portable auxiliary marine diesel engine, only if its fuelling, cooling, or exhaust system is an integral part of the ship. A fuelling system is considered integral to the ship only if it is permanently affixed to the ship. This definition includes a marine diesel engine that is used to supplement or augment the installed power capacity of the ship and is intended to be an integral part of the ship.
13. *Irrational emission control strategy* means 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.
14. *Marine diesel engine* means any reciprocating internal combustion engine operating on liquid or dual fuel, to which regulation 13 of this Annex applies, including booster/compound systems if applied.
15. *$NO_X$ Technical Code* means the Technical Code on Control of Emission of Nitrogen Oxides from Marine Diesel Engines adopted by resolution 2 of the 1997 MARPOL Conference, as amended by the Organization, provided that such amendments are adopted and brought into force in accordance with the provisions of article 16 of the present Convention.
16. *Ozone depleting substances* means controlled substances defined in paragraph (4) of article 1 of the Montreal Protocol on Substances that Deplete the Ozone Layer, 1987, listed in Annexes A, B, C or E to the said Protocol in force at the time of application or interpretation of this Annex.

Ozone depleting substances that may be found on board ship include, but are not limited to:

Halon 1211 Bromochlorodifluoromethane

Halon 1301 Bromotrifluoromethane

Halon 2402 1, 2-Dibromo -1, 1, 2, 2-tetraflouroethane (also known as Halon 114B2)

CFC-11 Trichlorofluoromethane

CFC-12 Dichlorodifluoromethane

CFC-113 1, 1, 2 – Trichloro – 1, 2, 2 – trifluoroethane

CFC-114 1, 2 – Dichloro –1, 1, 2, 2 – tetrafluoroethane

CFC-115 Chloropentafluoroethane

17. *Shipboard incineration* means the incineration of wastes or other matter on board a ship, if such wastes or other matter were generated during the normal operation of that ship
18. *Shipboard incinerator* means a shipboard facility designed for the primary purpose of incineration.
19. *Ships constructed* means ships the keels of which are laid or which are at a similar stage of construction.
20. *Sludge oil* means sludge from the fuel oil or lubricating oil separators, waste lubricating oil from main or auxiliary machinery, or waste oil from bilge water separators, oil filtering equipment or drip trays.
21. *Tanker* in relation to regulation 15 means an oil tanker as defined in regulation 1 of Annex I or a chemical tanker as defined in regulation 1 of Annex II of the present Convention
22. *Existing ship* means a ship which is not a new ship.
23. *New ship* means a ship:

23.1 for which the building contract is placed on or after 1 January 2013; or

23.2 in the absence of a building contract, the keel of which is laid or which is at a similar stage of construction on or after 1 July 2013; or

23.3 the delivery of which is on or after 1 July 2015.

24. *Major Conversion* means in relation to chapter 4 a conversion of a ship:

24.1 which substantially alters the dimensions, carrying capacity or engine power of the ship; or

24.2 which changes the type of the ship; or

24.3 the intent of which in the opinion of the Administration is substantially to prolong the life of the ship; or

24.4 which otherwise so alters the ship that, if it were a new ship, it would become subject to relevant provisions of the present Convention not applicable to it as an existing ship; or

24.5 which substantially alters the energy efficiency of the ship and includes any modifications that could cause the ship to exceed the applicable required EEDI as set out in regulation 21.

25. *Bulk carrier* means a ship which is intended primarily to carry dry cargo in bulk, including such types as ore carriers as defined in SOLAS chapter XII, regulation 1, but excluding combination carriers.
26. *Gas carrier* means a cargo ship constructed or adapted and used for the carriage in bulk of any liquefied gas.
27. *Tanker* in relation to chapter 4 means an oil tanker as defined in MARPOL Annex I, regulation 1 or a chemical tanker or an NLS tanker as defined in MARPOL Annex II, regulation 1.
28. *Container ship* means a ship designed exclusively for the carriage of containers in holds and on deck.
29. *General cargo ship* means a ship with a multi-deck or single deck hull designed primarily for the carriage of general cargo. This definition excludes specialized dry cargo ships, which are not included in the

calculation of reference lines for general cargo ships, namely livestock carrier, barge carrier, heavy load carrier, yacht carrier, nuclear fuel carrier.

30. *Refrigerated cargo carrier* means a ship designed exclusively for the carriage of refrigerated cargoes in holds.
31. *Combination carrier* means a ship designed to load 100% deadweight with both liquid and dry cargo in bulk.
32. *Passenger ship* means a ship which carries more than 12 passengers.
33. *Ro-Ro cargo ship (vehicle carrier)* means a multi deck roll-on-roll-off cargo ship designed for the carriage of empty cars and trucks.
34. *Ro-Ro cargo ship* means a ship designed for the carriage of roll-on-roll-off cargo transportation units.
35. *Ro-Ro passenger ship* means a passenger ship with roll-on-roll-off cargo spaces.
36. *Attained EEDI* is the EEDI value achieved by an individual ship in accordance with regulation 20 of chapter 4.
37. *Required EEDI* is the maximum value of attained EEDI that is allowed by regulation 21 of chapter 4 for the specific ship type and size.

## REGULATION 3: EXCEPTIONS AND EXEMPTIONS

**General**

38. Regulations of this annex shall not apply to:

    1.1 any emission necessary for the purpose of securing the safety of a ship or saving life at sea; or

    1.2 any emission resulting from damage to a ship or its equipment:

    1.2.1 provided that all reasonable precautions have been taken after the occurrence of the damage or discovery of the emission for the purpose of preventing or minimizing the emission; and

    1.2.2 except if the owner or the master acted either with the intent to cause damage, or recklessly and with knowledge that damage would probably result.

**Trials for Ship Emission Reduction and Control Technology Research**

2. The Administration of a Party may, in co-operation with other Administrations as appropriate, issue an exemption from specific provisions of this Annex for a ship to conduct trials for the development of ship emission reduction and control technologies and engine design programmes. Such an exemption shall only be provided if the applications of specific provisions of the Annex or the revised $NO_X$ Technical Code 2008 could impede research into the development of such technologies or programmes. A permit for such an exemption shall only be provided to the minimum number of ships necessary and be subject to the following provisions:

    2.1 for marine diesel engines with a per cylinder displacement up to 30 litres, the duration of the sea trial shall not exceed 18 months. If additional time is required, a permitting Administration or Administrations may permit a renewal for one additional 18-month period; or

    2.2 for marine diesel engines with a per cylinder displacement at or above 30 litres, the duration of the ship trial shall not exceed 5 years and shall require a progress review by the permitting Administration or Administrations at each intermediate survey. A permit may be withdrawn based on this review if the testing has not adhered to the conditions of the permit or if it is determined that the technology or programme is not likely to produce effective results in the reduction and control of ship emissions. If the reviewing Administration or Administrations determine that additional time is required to conduct a test of a particular technology or programme, a permit may be renewed for an additional time period not to exceed five years.

**Emissions from Sea-bed Mineral Activities**

3. Emissions directly arising from the exploration, exploitation and associated offshore processing of sea-bed mineral resources are, consistent with article 2(3)(b)(ii) of the present Convention, exempt from the provisions of this Annex. Such emissions include the following:
   - 3.1 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;
   - 3.2 the release of gases and volatile compounds entrained in drilling fluids and cuttings;
   - 3.3 emissions associated solely and directly with the treatment, handling, or storage of sea-bed minerals; and
   - 3.4 emissions from marine diesel engines that are solely dedicated to the exploration, exploitation and associated offshore processing of sea-bed mineral resources.

### REGULATION 4: *EQUIVALENTS*

## CHAPTER II: SURVEY, CERTIFICATION AND MEANS OF CONTROL

### REGULATION 5: *SURVEYS*
### REGULATION 6: ISSUE OR ENDORSEMENT OF A CERTIFICATES
### REGULATION 7: ISSUE OF A CERTIFICATE BY ANOTHER PARTY
### REGULATION 8: FORM OF CERTIFICATES
### REGULATION 9: DURATION AND VALIDITY OF CERTIFICATES
### REGULATION 10: PORT STATE CONTROL ON OPERATION REQUIREMENTS
### REGULATION 11: DETECTION OF VIOLATIONS AND ENFORCEMENT

## CHAPTER III: REQUIREMENTS FOR CONTROL OF EMISSIONS FROM SHIPS

### REGULATION 12: OZONE DEPLETING SUBSTANCES

1. This regulation does not apply to permanently sealed equipment where there are no refrigerant charging connections or potentially removable components containing ozone depleting substances.
2. Subject to the provisions of regulation 3.1, any deliberate emissions of ozone depleting substances shall be prohibited. Deliberate emissions include emissions occurring in the course of maintaining, servicing, repairing or disposing of systems or equipment, except that deliberate emissions do not include minimal releases associated with the recapture or recycling of an ozone depleting substance. Emissions arising from leaks of an ozone depleting substance, whether or not the leaks are deliberate, may be regulated by Parties.
   - 3.1 Installations which contain ozone depleting substances, other than hydro-chlorofluorocarbons, shall be prohibited:
     - 3.1.1 on ships constructed on or after 19 May 2005; or
     - 3.1.2 in the case of ships constructed before 19 May 2005, which have a contractual delivery date of the equipment to the ship on or after 19 May 2005 or, in the absence of a contractual delivery date, the actual delivery of the equipment to the ship on or after 19 May 2005
   - 3.2 Installations which contain hydro-chlorofluorocarbons shall be prohibited:
     - 3.2.1 on ships constructed on or after 1 January 2020; or
     - 3.2.2 in the case of ships constructed before 1 January 2020, which have a contractual delivery date of the equipment to the ship on or after 1 January 2020 or, in the absence of a contractual delivery date, the actual delivery of the equipment to the ship on or after 1 January 2020.
4. The substances referred to in this regulation, and equipment containing such substances, shall be delivered to appropriate reception facilities when removed from ships.
5. Each ship subject to regulation 6.1 shall maintain a list of equipment containing ozone depleting substances.
6. Each ship subject to regulation 6.1 which has rechargeable systems that contain ozone depleting substances shall maintain an Ozone Depleting Substances Record Book. This Record Book may form part of an existing log-book or electronic recording system as approved by the Administration.
7. Entries in the Ozone Depleting Substances Record Book shall be recorded in terms of mass (kg) of substance and shall be completed without delay on each occasion, in respect of the following:
   - 7.1 recharge, full or partial, of equipment containing ozone depleting substances;
   - 7.2 repair or maintenance of equipment containing ozone depleting substances;
   - 7.3 discharge of ozone depleting substances to the atmosphere:
     - 7.3.1 deliberate; and
     - 7.3.2 non-deliberate;
   - 7.4 discharge of ozone depleting substances to land-based reception facilities; and
   - 7.5 supply of ozone depleting substances to the ship.

### REGULATION 13: NITROGEN OXIDES ($NO_X$)

**Application**

1.1 This regulation shall apply to:

1.1.1 each marine diesel engine with a power output of more than 130 kW installed on a ship; and

1.1.2 each marine diesel engine with a power output of more than 130 kW which undergoes a major conversion on or after 1 January 2000 except when demonstrated to the satisfaction of the Administration that such engine is an identical replacement to the engine which it is replacing and is otherwise not covered under paragraph 1.1.1 of this regulation.

1.2 This regulation does not apply to:

1.2.1 a marine diesel engine intended to be used solely for emergencies, or solely to power any device or equipment intended to be used solely for emergencies on the ship on which it is installed, or a marine diesel engine installed in lifeboats intended to be used solely for emergencies; and

1.2.2 a marine diesel engine installed on a ship solely engaged in voyages within waters subject to the sovereignty or jurisdiction of the State the flag of which the ship is entitled to fly, provided that such engine is subject to an alternative $NO_X$ control measure established by the Administration.

1.3 Notwithstanding the provisions of subparagraph 1.1 of this paragraph, the Administration may provide an exclusion from the application of this regulation for any marine diesel engine which is installed on a ship constructed, or for any marine diesel engine which undergoes a major conversion, before 19 May 2005, provided that the ship on which the engine is installed is solely engaged in voyages to ports or offshore terminals within the State the flag of which the ship is entitled to fly.

**Major Conversion**

2.1 For the purpose of this regulation, major conversion means a modification on or after 1 January 2000 of a marine diesel engine that has not already been certified to the standards set forth in paragraph 3, 4, or 5.1.1 of this regulation where:

2.1.1 the engine is replaced by a marine diesel engine or an additional marine diesel engine is installed, or

2.1.2 any substantial modification, as defined in the revised $NO_X$ Technical Code 2008, is made to the engine, or

2.1.3 the maximum continuous rating of the engine is increased by more than 10% compared to the maximum continuous rating of the original certification of the engine.

2.2 For a major conversion involving the replacement of a marine diesel engine with a non- identical marine diesel engine or the installation of an additional marine diesel engine, the standards in this regulation in force at the time of the replacement or addition of the engine shall apply. On or after 1 January 2016, in the case of replacement engines only, if it is not possible for such a replacement engine to meet the standards set forth in paragraph 5.1.1 of this regulation (Tier III), then that replacement engine shall meet the standards set forth in paragraph 4 of this regulation (Tier II). Guidelines are to be developed by the Organization to set forth the criteria of when it is not possible for a replacement engine to meet the standards in subparagraph 5.1.1 of this regulation.

2.3 A marine diesel engine referred to in paragraph 2.1.2 or 2.1.3 shall meet the following standards:

2.3.1 for ships constructed prior to 1 January 2000, the standards set forth in paragraph 3 of this regulation shall apply; and

2.3.2 for ships constructed on or after 1 January 2000, the standards in force at the time the ship was constructed shall apply.

**Tier I**

3. Subject to regulation 3 of this Annex, the operation of a marine diesel engine which is installed on a ship constructed on or after 1 January 2000 and prior to 1 January 2011 is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of NO2) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute):

3.1 17.0 g/kWh when n is less than 130 rpm;

3.2 $45 \cdot n^{(-0.2)}$ g/kWh when n is 130 or more but less than 2,000 rpm;

3.3 9.8 g/kWh when n is 2,000 rpm or more.

**Tier II**

4. Subject to regulation 3 of this Annex, the operation of a marine diesel engine which is installed on a ship constructed on or after 1 January 2011 is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of NO2) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute)

4.1 14.4 g/kWh when n is less than 130 rpm;

4.2 $44 \cdot n^{(-0.23)}$ g/kWh when n is 130 or more but less than 2,000 rpm;

4.3 7.7 g/kWh when n is 2,000 rpm or more.

**Tier III**

5.1 Subject to regulation 3 of this Annex, the operation of a marine diesel engine which is installed on a ship constructed on or after 1 January 2016:

5.1.1 is prohibited except when the emission of nitrogen oxides (calculated as the total weighted emission of NO2) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute):

5.1.1.1 3.4 g/kWh when n is less than 130 rpm;

5.1.1.2 $9 \cdot n^{(-0.2)}$ g/kWh when n is 130 or more but less than 2,000 rpm; and

5.1.1.3 2.0 g/kWh when n is 2,000 rpm or more;

5.1.2 is subject to the standards set forth in subparagraph 5.1.1 of this paragraph when the ship is operating in an Emission Control Area designated under paragraph 6 of this regulation; and

5.1.3 is subject to the standards set forth in paragraph 4 of this regulation when the ship is operating outside of an Emission Control Area designated under paragraph 6 of this regulation.

5.2 Subject to the review set forth in paragraph 10 of this regulation, the standards set forth in paragraph 5.1.1 of this regulation shall not apply to:

5.2.1 a marine diesel engine installed on a ship with a length (L), as defined in regulation 1.19 of Annex I to the present Convention, less than 24 metres when it has been specifically designed, and is used solely, for recreational purposes; or

5.2.2 a marine diesel engine installed on a ship with a combined nameplate diesel engine propulsion power of less than 750 kW if it is demonstrated, to the satisfaction of the Administration, that the ship cannot comply with the standards set forth in paragraph 5.1.1 of this regulation because of design or construction limitations of the ship.

**Emission Control Area**

6. For the purpose of this regulation, an Emission Control Area shall be any sea area, including any port area, designated by the Organization in accordance with the criteria and procedures set forth in appendix III to this Annex.

**Marine Diesel Engines Installed on a Ship Constructed Prior to 1 January 2000**

7.1 Notwithstanding paragraph 1.1.1 of this regulation, a marine diesel engine with a power output of more than 5,000 kW and a per cylinder displacement at or above 90 litres installed on a ship constructed on or after 1 January 1990 but prior to 1 January 2000 shall comply with the emission limits set forth in subparagraph 7.4 of this paragraph, provided that an Approved Method for that engine has been certified by an Administration of a Party and notification of such certification has been submitted to the Organization by the certifying Administration. Compliance with this paragraph shall be demonstrated through one of the following:

7.1.1 installation of the certified Approved Method, as confirmed by a survey using the verification procedure specified in the Approved Method File, including appropriate notation on the ship's International Air Pollution Prevention Certificate of the presence of the Approved Method; or

7.1.2 certification of the engine confirming that it operates within the limits set forth in paragraph 3, 4, or 5.1.1 of this regulation and an appropriate notation of the engine certification on the ship's International Air Pollution Prevention Certificate.

7.2 Subparagraph 7.1 shall apply no later than the first renewal survey that occurs 12 months or more after deposit of the notification in subparagraph 7.1. If a ship-owner of a ship on which an Approved Method is to be installed can demonstrate to the satisfaction of the Administration that the Approved Method was not commercially available despite best efforts to obtain it, then that Approved Method shall be installed on the ship no later than the next annual survey of that ship which falls after the Approved Method is commercially available.

7.3 With regard to a ship with a marine diesel engine with a power output of more than 5,000 kW and a per cylinder displacement at or above 90 litres installed on a ship constructed on or after 1 January 1990 but prior to 1 January 2000, the International Air Pollution Prevention Certificate shall, for a marine diesel engine to which paragraph 7.1 of this regulation applies, indicate that either an Approved Method has been applied pursuant to paragraph 7.1.1 of this regulation or the engine has been certified pursuant to paragraph 7.1.2 of this regulation or that an Approved Method does not yet exist or is not yet commercially available as described in subparagraph 7.2 of this regulation.

7.4 Subject to regulation 3 of this Annex, the operation of a marine diesel engine described in subparagraph 7.1 is prohibited, except when the emission of nitrogen oxides (calculated as the total weighted emission of NO2) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute):

7.4.1 17.0 g/kWh when n is less than 130 rpm;

7.4.2 $45 \cdot n^{(-0.2)}$ g/kWh when n is 130 or more but less than 2,000 rpm; and

7.4.3 9.8 g/kWh when n is 2,000 rpm or more.

7.5 Certification of an Approved Method shall be in accordance with chapter 7 of the revised $NO_X$ Technical Code 2008 and shall include verification:

7.5.1 by the designer of the base marine diesel engine to which the Approved Method applies that the calculated effect of the Approved Method will not decrease engine rating by more than 1.0%, increase fuel consumption by more than 2.0% as measured according to the appropriate test cycle set forth in the revised $NO_X$ Technical Code 2008, or adversely affect engine durability or reliability; and

7.5.2 that the cost of the Approved Method is not excessive, which is determined by a comparison of the amount of $NO_X$ reduced by the Approved Method to achieve the standard set forth in subparagraph 7.4 of this paragraph and the cost of purchasing and installing such Approved Method**.

**Certification**

8. The revised $NO_X$ Technical Code 2008 shall be applied in the certification, testing, and measurement procedures for the standards set forth in this regulation.

9. The procedures for determining $NO_X$ emissions set out in the revised $NO_X$ Technical Code 2008 are intended to be representative of the normal operation of the engine. Defeat devices and irrational emission control strategies undermine this intention and shall not be allowed. This regulation shall not prevent the use of auxiliary control devices that are used to protect the engine and/or its ancillary

** The cost of an Approved Method shall not exceed 375 Special Drawing Rights/metric ton $NO_X$ calculated in accordance with the Cost-Effectiveness formula:

$$Ce = \frac{Cost\ of\ Approved\ Method \cdot 10^6}{P(kW) \cdot 0.768 \cdot 6000(\frac{hours}{year}) \cdot 5(years) \cdot ?NO_X(\frac{g}{kWh})}$$

equipment against operating conditions that could result in damage or failure or that are used to facilitate the starting of the engine.

**Review**

10. Beginning in 2012 and completed no later than 2013, the Organization shall review the status of the technological development s to implement the standards set forth in paragraph 5.1.1 of this regulation and shall, if proven necessary, adjust the time periods set forth in that subparagraph.

## REGULATION 14: SULPHUR OXIDES ($SO_X$) AND PARTICULATE MATTER

**General Requirements**

1. The sulphur content of any fuel oil used on board ships shall not exceed the following limits:
   1.1 4.50% m/m prior to 1 January 2012;
   1.2 3.50% m/m on and after 1 January 2012; and
   1.3 0.50% m/m on and after 1 January 2020.
2. The worldwide average sulphur content of residual fuel oil supplied for use on board ships shall be monitored taking into account guidelines developed by the Organization.[92]

**Requirements within Emission Control Areas**

3. For the purpose of this regulation, Emission Control Areas shall include:
   3.1 the Baltic Sea area as defined in regulation 1.11.2 of Annex I, the North Sea as defined in regulation 5(1)(f) of Annex V; and
   3.2 any other sea area, including port areas, designated by the Organization in accordance with criteria and procedures set forth in appendix III to this Annex.
4. While ships are operating within an Emission Control Area, the sulphur content of fuel oil used on board ships shall not exceed the following limits:
   4.1 1.50% m/m prior to 1 July 2010;
   4.2 1.00% m/m on and after 1 July 2010; and
   4.3 0.10% m/m on and after 1 January 2015.
5. The sulphur content of fuel oil referred to in paragraph 1 and paragraph 4 of this regulation shall be documented by its supplier as required by regulation 18 of this Annex.
6. Those ships using separate fuel oils to comply with paragraph 4 of this regulation and entering or leaving an Emission Control Area set forth in paragraph 3 of this regulation shall carry a written procedure showing how the fuel oil change-over is to be done, allowing sufficient time for the fuel oil service system to be fully flushed of all fuel oils exceeding the applicable sulphur content specified in paragraph 4 of this regulation prior to entry into an Emission Control Area. The volume of low sulphur fuel oils in each tank as well as the date, time, and position of the ship when any fuel-oil-change-over operation is completed prior to the entry into an Emission Control Area or commenced after exit from such an area, shall be recorded in such log-book as prescribed by the Administration.

[92] MEPC.82(43), "Guidelines for Monitoring the World-wide Average Sulphur Content of Residual Fuel Oils Supplied for Use On Board Ships".

7. During the first twelve months immediately following an amendment designating a specific Emission Control Area under paragraph 3.2 of this regulation, ships operating in that Emission Control Area are exempt from the requirements in paragraphs 4 and 6 of this regulation and from the requirements of paragraph 5 of this regulation insofar as they relate to paragraph 4 of this regulation.

**Review Provision**

8. A review of the standard set forth in subparagraph 1.3 of this regulation shall be completed by 2018 to determine the availability of fuel oil to comply with the fuel oil standard set forth in that paragraph and shall take into account the following elements:
   - 8.1 the global market supply and demand for fuel oil to comply with paragraph 1.3 of this regulation that exist at the time that the review is conducted;
   - 8.2 an analysis of the trends in fuel oil markets; and
   - 8.3 any other relevant issue.
9. The Organization shall establish a group of experts, comprising of representatives with the appropriate expertise in the fuel oil market and appropriate maritime, environmental, scientific, and legal expertise, to conduct the review referred to in paragraph 8 of this regulation. The group of experts shall develop the appropriate information to inform the decision to be taken by the Parties.
10. The Parties, based on the information developed by the group of experts, may decide whether it is possible for ships to comply with the date in paragraph 1.3 of this regulation. If a decision is taken that it is not possible for ships to comply, then the standard in that subparagraph shall become effective on 1 January 2025.

### REGULATION 15: VOLATILE ORGANIC COMPOUNDS (VOCS)
### REGULATION 16: SHIPBOARD INCINERATION
### REGULATION 17: RECEPTION FACILITIES
### REGULATION 18: FUEL OIL AVAILABILITY AND QUALITY

## CHAPTER IV: REGULATIONS ON ENERGY EFFICIENCY FOR SHIPS

### REGULATION 19: *APPLICATION*

1.1 This chapter shall apply to all ships of 400 gross tonnage and above.

1.2 The provisions of this chapter shall not apply to:

1.2.1 ships solely engaged in voyages within waters subject to the sovereignty or jurisdiction of the State the flag of which the ship is entitled to fly. However, each Party should ensure, by the adoption of appropriate measures, that such ships are constructed and act in a manner consistent with chapter 4, so far as is reasonable and practicable.

1.3 Regulation 20 and regulation 21 shall not apply to ships which have diesel-electric propulsion, turbine propulsion or hybrid propulsion systems.

1.4 Notwithstanding the provisions of paragraph 1 of this regulation, the Administration may waive the requirement for a ship of 400 gross tonnage and above from complying with regulation 20 and regulation 21.

1.5 The provision of paragraph 4 of this regulation shall not apply to ships of 400 gross tonnage and above:

1.5.1 for which the building contract is placed on or after 1 January 2017; or

1.5.2 in the absence of a building contract, the keel of which is laid or which is at a similar stage of construction on or after 1 July 2017; or

1.5.3 the delivery of which is on or after 1 July 2019; or

1.5.4 in cases of a major conversion of a new or existing ship, as defined in regulation 2.24, on or after 1 January 2017, and in which regulation 5.4.2 and regulation 5.4.3 of chapter 2 apply.

The Administration of a Party to the present Convention which allows application of paragraph 4, or suspends, withdraws or declines the application of that paragraph, to a ship entitled to fly its flag shall forthwith communicate to the Organization for circulation to the Parties to the present Protocol particulars thereof, for their information.

### REGULATION 20: ATTAINED ENERGY EFFICIENCY DESIGN INDEX (ATTAINED EEDI)

1. The attained EEDI shall be calculated for:
   1.1 each new ship;
   1.2 each new ship which has undergone a major conversion; and
   1.3 each new or existing ship which has undergone a major conversion, that is so extensive that the ship is regarded by the Administration as a newly constructed ship.

   which falls into one or more of the categories in regulations 2.25 to 2.35. The attained EEDI shall be specific to each ship and shall indicate the estimated performance of the ship in terms of energy efficiency, and be accompanied by the EEDI technical file that contains the information necessary for the calculation of the attained EEDI and that shows the process of calculation. The attained EEDI shall be verified, based on the EEDI technical file, either by the Administration or by any

2. The attained EEDI shall be calculated taking into account guidelines developed by the Organization.

### REGULATION 21: *REQUIRED EEDI*

1. For each:
   1.1 each new ship;
   1.2 each new ship which has undergone a major conversion; and
   1.3 new or existing ship which has undergone a major conversion that is so extensive that the ship is regarded by the Administration as a newly constructed ship.which falls into one of the categories defined in regulation 2.25 to 2.31 and to which this chapter is applicable, the attained EEDI shall be as follows:

$$Attained\ EEDI\ \leq \left(Required\ EEDI = \frac{1-\mathrm{x}}{100} \cdot Reference\ line\ value\right)$$

   where X is the reduction factor specified in Table 1 for the required EEDI compared to the EEDI Reference line.

2. For each new and existing ship that has undergone a major conversion which is so extensive that the ship is regarded by the Administration as a newly constructed ship, the attained EEDI shall be calculated and meet the requirement of paragraph

21.1 with the reduction factor applicable corresponding to the ship type and size of the converted ship at the date of the contract of the conversion, or in the absence of a contract, the commencement date of the conversion.

**TABLE 1: REDUCTION FACTORS (IN PERCENTAGE) FOR THE EEDI RELATIVE TO THE EEDI**

| Ship Type | Size [DWT] | Phase 0: 1 Jan '13 – 31 Dec '14 | Phase 1: 1 Jan '15 – 31 Dec '19 | Phase 2: 1 Jan '20 – 31 Dec '24 | Phase 3: 1 Jan '25 and onwards |
|---|---|---|---|---|---|
| Bulk carrier | ≥ 20.000 | 0 | 10 | 20 | 30 |
| | 10.000 – 20.000 | n/a | 0 – 10* | 0 – 20* | 0 – 30* |
| Gas carrier | ≥ 10.000 | 0 | 10 | 20 | 30 |
| | 2.000 – 10.000 | n/a | 0 – 10* | 0 – 20* | 0 – 30* |
| Tanker | ≥ 20.000 | 0 | 10 | 20 | 30 |
| | 4.000 – 20.000 | n/a | 0 – 10* | 0 – 20* | 0 – 30* |
| Container ship | ≥ 15.000 | 0 | 10 | 20 | 30 |
| | 10.000 – 15.000 | n/a | 0 – 10* | 0 – 20* | 0 – 30* |
| General Cargo ships | ≥ 15.000 | 0 | 10 | 15 | 30 |
| | 3.000 –15.000 | n/a | 0 – 10* | 0 – 15* | 0 – 30* |
| Refrigerated cargo carrier | ≥ 5.000 | 0 | 10 | 15 | 30 |
| | 3.000 – 5.000 | n/a | 0 – 10* | 0 – 15* | 0 – 30* |
| Combination carrier | ≥ 20.000 | 0 | 10 | 20 | 30 |
| | 4.000 – 20.000 | n/a | 0 – 10* | 0 – 20* | 0 – 30* |

** Reduction factor to be linearly interpolated between the two values dependent upon vessel size. The lower value of the reduction factor is to be applied to the smaller ship size.*
*N/A means that no required EEDI applies.*

3. The reference line values shall be calculated as follows:
   Reference line value= A·B^(-C)
   Where A, B and C are parameters given in table 2.

**TABLE 2: PARAMETERS FOR DETERMINATION OF REFERENCE VALUES FOR THE DIFFERENT SHIP TYPES**

| Ship type defined in regulations 2 | A | B | C |
|---|---|---|---|
| 2.25 Bulk carrier | 961.79 | DWT of the ship | 0.477 |
| 2.26 Gas carrier | 1120.00 | DWT of the ship | 0.456 |
| 2.27 Tanker | 1218.80 | DWT of the ship | 0.488 |
| 2.28 Container ship | 174.22 | DWT of the ship | 0.201 |
| 2.29 General cargo ship | 107.48 | DWT of the ship | 0.216 |
| 2.30 Refrigerated cargo carrier | 227.01 | DWT of the ship | 0.244 |
| 2.31 Combination carrier | 1219.00 | DWT of the ship | 0.488 |

4. If the design of a ship allows it to fall into more than one of the above ship type definitions, the required EEDI for the ship shall be the most stringent (the lowest) required EEDI.
5. For each ship to which this regulation applies, the installed propulsion power shall not be less than the propulsion power needed to maintain the manoeuvrability of the ship under adverse conditions as defined in the guidelines to be developed by the Organization.
6. At the beginning of Phase 1 and at the midpoint of Phase 2, the Organization shall review the status of technological developments and, if proven necessary, amend the time periods, the EEDI reference line parameters for relevant ship types and reduction rates set out in this regulation.

### Regulation 22: Ship Energy Efficiency Management Plan (SEEMP)

1. Each ship shall keep on board a ship specific Ship Energy Efficiency Management Plan (SEEMP). This may form part of the ship's Safety Management System (SMS).
2. The SEEMP shall be developed taking into account guidelines adopted by the Organization.

### Regulation 23: Promotion of technical co-operation and transfer of technology relating to the improvement of energy efficiency ships

1. Administrations shall, in co-operation with the Organization and other international bodies, promote and provide, as appropriate, support directly or through the Organization to States, especially developing States, that request technical assistance.
2. The Administration of a Party shall co-operate actively with other Parties, subject to its national laws, regulations and policies, to promote the development and transfer of technology and exchange of information to States which request technical assistance, particularly developing States, in respect of the implementation of measures to fulfil the requirements of chapter 4 of this annex, in particular regulations 19.4 to 19.6.

# APPENDIX C: DIRECTIVE 2012/33/EU

I

(Legislative acts)

## DIRECTIVES

DIRECTIVE 2012/33/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 21 November 2012

amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels

THE EUROPEAN PARLIAMENT AND THE COUNCIL OF THE EUROPEAN UNION,

Having regard to the Treaty on the Functioning of the European Union, and in particular Article 192(1) thereof,

Having regard to the proposal from the European Commission,

After transmission of the draft legislative act to the national parliaments,

Having regard to the opinion of the European Economic and Social Committee,

After consulting the Committee of the Regions,

Acting in accordance with the ordinary legislative procedure,

Whereas:

(1) The environmental policy of the Union, as set out in the action programmes on the environment, and in particular in the Sixth Environmental Action Programme adopted by Decision No 1600/2002/EC of the European Parliament and of the Council, has as one of its objectives to achieve levels of air quality that do not give rise to significant negative impacts on and risks to human health and the environment.

(2) Article 191(2) of the Treaty on the Functioning of the European Union (TFEU) provides that Union policy on the environment is to aim at a high level of protection, taking into account the diversity of situations in the various regions of the Union.

(3) Council Directive 1999/32/EC of 26 April 1999 relating to a reduction in the sulphur content of certain liquid fuels lays down the maximum permitted sulphur content of heavy fuel oil, gas oil, marine gas oil and marine diesel oil used in the Union.

(4) Emissions from shipping due to the combustion of marine fuels with a high sulphur content contribute to air pollution in the form of sulphur dioxide and particulate matter, which harm human health and the environment and contribute to acid deposition. Without the measures set out in this Directive, emissions from shipping would soon have been higher than emissions from all land-based sources.

(5) Air pollution caused by ships at berth is a major concern for many harbour cities when it comes to their efforts to meet the Union's air quality limit values.

(6) Member States should encourage the use of shore-side electricity, as the electricity for present-day ships is usually provided by auxiliary engines.

(7) Under Directive 1999/32/EC, the Commission is to report to the European Parliament and the Council on the implementation of that Directive and may submit with its report proposals for amending it, in particular as regards the reduction of sulphur limits for marine fuel in $SO_X$ Emission Control Areas (SECAs), in accordance with the work of the International Maritime Organisation (IMO).

(8) In 2008, the IMO adopted a resolution to amend Annex VI of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL), containing regulations for the prevention of air pollution from ships. The revised Annex VI to MARPOL entered into force on 1 July 2010.

(9) The revised Annex VI to MARPOL introduces, inter alia, stricter sulphur limits for marine fuel in SECAs (1,00 % as of 1 July 2010 and 0,10 % as of 1 January 2015) as well as in sea areas outside SECAs (3,50 % as of 1 January 2012 and, in principle, 0,50 % as of 1 January 2020). Most Member States are obliged, in accordance with their international commitments, to require ships to use fuel with a maximum sulphur content of 1,00 % in SECAs as of 1 July 2010. In order to ensure coherence with international law as well as to secure proper enforcement of new globally established sulphur standards in the Union, Directive 1999/32/EC should be aligned with the revised Annex VI to MARPOL. In order to ensure a minimum quality of fuel used by ships either for fuel-based or technology-based compliance, marine fuel the sulphur content of which exceeds the general standard of 3,50 % by mass should not be allowed for use in the Union, except for fuels supplied to ships using emission abatement methods operating in closed mode.

(10) Amendments to Annex VI to MARPOL regarding SECAs are possible under IMO procedures. In the event that further changes, including exemptions, are introduced with regard to the application of SECA limits in Annex VI to MARPOL, the Commission should consider any such changes and, where appropriate, without delay make the necessary proposal in accordance with the TFEU to fully align Directive 1999/32/EC with the IMO rules regarding SECAs.

(11) The introduction of any new emission control areas should be subject to the IMO process under Annex VI to MARPOL and should be underpinned by a well- founded case based on environmental and economic grounds and supported by scientific data.

(12) In accordance with regulation 18 of the revised Annex VI to MARPOL, Member States should endeavour to ensure the availability of marine fuels which comply with this Directive.

(13) In view of the global dimension of environmental politics and shipping emissions, ambitious emission standards should be set at a global level.

(14) Passenger ships operate mostly in ports or close to coastal areas and their impacts on human health and the environment are significant. In order to improve air quality around ports and coasts, those ships are required to use marine fuel with a maximum sulphur content of 1,50 % until stricter sulphur standards apply to all ships in territorial seas, exclusive economic zones and pollution control zones of Member States.

(15) In accordance with Article 193 TFEU, this Directive should not prevent any Member State from maintaining or introducing more stringent protective measures in order to encourage early implementation with respect to the maximum sulphur content of marine fuels, for instance using emission abatement methods outside SECAs.

(16) In order to facilitate the transition to new engine technologies with the potential for significant further emission reductions in the maritime sector, the Commission should further explore opportunities to enable and encourage the uptake of gas-powered engines in ships.

(17) Proper enforcement of the obligations with regard to the sulphur content of marine fuels is necessary in order to achieve the aims of Directive 1999/32/EC. The experience from the implementation of Directive 1999/32/EC has shown that there is a need for a stronger monitoring and enforcement regime in order to ensure the proper implementation of that Directive. To that end, it is necessary that Member States ensure sufficiently frequent and accurate sampling of marine fuel placed on the market or used on board ship as well as regular verification of ships' log books and bunker delivery notes. It is also necessary for Member States to establish a system of effective, proportionate and dissuasive penalties for non-compliance with the provisions of Directive 1999/32/EC. In order to ensure more transparency of information, it is also appropriate to provide that the register of local suppliers of marine fuel be made publicly available.

(18) Reporting by Member States under Directive 1999/32/EC has proved insufficient for the purpose of verification of compliance with that Directive due to the lack of harmonised and sufficiently precise provisions on the content and the format of the Member States' reports. Therefore, more detailed indications as regards the content and the format of the report are necessary to ensure more harmonised reporting.

(19) Following the adoption of Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control), which recasts the Union legislation on industrial emissions, it is necessary to amend the provisions of Directive 1999/32/EC relating to maximum sulphur content of heavy fuel oil accordingly.

(20) Complying with the low sulphur limits for marine fuels, particularly in SECAs, can result in a significant increase in the price of such fuels, at least in the short term, and can have a negative effect on the competitiveness of short sea shipping in comparison with other transport modes, as well as on the competitiveness of the industries in the countries bordering SECAs. Suitable solutions are necessary in order to reduce compliance costs for the affected industries, such as allowing for alternative, more cost-effective methods of compliance than fuel-based compliance and providing support, where necessary. The Commission will, based inter alia on reports from Member States, closely monitor the impacts of the shipping sector's compliance with the new fuel quality standards, particularly with respect to possible modal shift from sea to land-based transport and will, if appropriate, propose proper measures to counteract such a trend.

(21) Limiting modal shift from sea to land-based transport is important given that an increasing share of goods being transported by road would in many cases run counter to the Union's climate change objectives and increase congestion.

(22) The costs of the new requirements to reduce sulphur dioxide emissions could result in modal shift from sea to land-based transport and could have negative effects on the competitiveness of the industries. The Commission should make full use of instruments such as Marco Polo and the trans-European transport network to provide targeted assistance so as to minimise the risk of modal shift. Member States may consider it necessary to provide support to operators affected by this Directive in accordance with the applicable State aid rules.

(23) In accordance with existing guidelines on State aid for environmental protection, and without prejudice to future changes thereto, Member States may provide State aid in favour of operators affected by this Directive, including aid for retrofitting operations of existing vessels, if such aid measures are deemed to be compatible with the internal market in accordance with Articles 107 and 108 TFEU, in particular in light of the applicable guidelines on State aid for environmental protection. In this context, the Commission may take into account that the use of some emission abatement methods go beyond the requirements of this Directive by reducing not only the sulphur dioxide emissions but also other emissions.

(24) Access to emission abatement methods should be facilitated. Those methods can provide emission reductions at least equivalent to, or even greater than, those achievable using low sulphur fuel, provided that they have no significant negative impacts on the environment, such as marine ecosystems, and that they are developed subject to appropriate approval and control mechanisms. The already known alternative methods, such as the use of on-board exhaust gas cleaning systems, the mixture of fuel and liquefied natural gas (LNG) or the use of biofuels should be recognised in the Union. It is important to promote the testing and development of new emission abatement methods in order, among

other reasons, to limit modal shift from sea to land-based transport.

(25) Emission abatement methods hold the potential for significant emission reductions. The Commission should therefore promote the testing and development of these technologies, inter alia by considering the establishment of a co-financed joint programme with industry, based on principles from similar programmes, such as the Clean Sky Programme.

(26) The Commission, in cooperation with Member States and stakeholders, should further develop measures identified in the Commission's staff working paper of 16 September 2011 entitled 'Pollutant emission reduction from maritime transport and the sustainable waterborne transport toolbox'.

(27) Alternative emission abatement methods such as some types of scrubbers could generate waste that should be handled properly and not be discharged into the sea. Pending the revision of Directive 2000/59/EC of the European Parliament and of the Council of 27 November 2000 on port reception facilities for ship-generated waste and cargo residues, Member States should ensure, in accordance with their international commitments, the availability of port reception facilities adequate to meet the needs of ships using exhaust gas cleaning systems. In the revision of Directive 2000/59/EC, the Commission should consider the inclusion of waste from exhaust gas cleaning systems under the principle of no special fee applying to port fees for ship-generated waste provided for in that Directive.

(28) The Commission should, as part of its air quality policy review in 2013, consider the possibility of reducing air pollution, including in the territorial seas of Member States.

(29) Effective, proportionate and dissuasive penalties are important for the implementation of Directive 1999/32/EC. Member States should include in those penalties fines calculated in such a way as to ensure that the fines at least deprive those responsible of the economic benefits derived from their infringement and that those fines gradually increase for repeated infringements. Member States should notify the provisions on penalties to the Commission.

(30) The power to adopt acts in accordance with Article 290 TFEU should be delegated to the Commission in respect of the amendment of the equivalent emission values for and the criteria for the use of emission abatement methods in order to adapt the provisions of Directive 1999/32/EC to scientific and technical progress and in such a way as to ensure strict consistency with the relevant instruments of the IMO and in respect of the amendment of points 1, 2, 3, 3a, 3b and 4 of Article 2, point (b) of Article 6(1a) and Article 6(2) of Directive 1999/32/EC in order to adapt the provisions of that Directive to scientific and technical progress. It is of particular importance that the Commission carry out appropriate consultations during its preparatory work, including at expert level. The Commission, when preparing and drawing up delegated acts, should ensure a simultaneous, timely and

appropriate transmission of relevant documents to the European Parliament and to the Council.

(31) In order to ensure uniform conditions for the implementation of Directive 1999/32/EC, implementing powers should be conferred on the Commission. Those powers should be exercised in accordance with Regulation (EU) No 182/2011 of the European Parliament and of the Council of 16 February 2011 laying down the rules and general principles concerning mechanisms for control by Member States of the Commission's exercise of implementing powers.

(32) It is appropriate for the Committee on Safe Seas and the Prevention of Pollution from Ships established by Regulation (EC) No 2099/2002 of the European Parliament and of the Council of 5 November 2002 establishing a Committee on Safe Seas and the Prevention of Pollution from Ships (COSS) to assist the Commission in the approval of the emission abatement methods which are not covered by Council Directive 96/98/EC of 20 December 1996 on marine equipment.

(33) In accordance with the Joint Political Declaration of 28 September 2011 of Member States and the Commission on explanatory documents, Member States have undertaken to accompany, in justified cases, the notification of their transposition measures with one or more documents explaining the relationship between the components of a directive and the corresponding parts of national transposition instruments. With regard to this Directive, the legislator considers the transmission of such documents to be justified.

(34) Directive 1999/32/EC should therefore be amended accordingly,

HAVE ADOPTED THIS DIRECTIVE:

Article 1

**Amendments to Directive 1999/32/EC**

Directive 1999/32/EC is amended as follows:

(1) **in Article 1(2),** point (h) is replaced by the following:

(h) without prejudice to Article 3a, fuels used on board vessels employing emission abatement methods in accordance with Articles 4c and 4e.;

(2) **Article 2** is amended as follows:

(a) points 1 and 2 are replaced by the following:

(1) heavy fuel oil means:

— any petroleum-derived liquid fuel, excluding marine fuel, falling within CN code 2710 19 51 to 2710 19 68, 2710 20 31, 2710 20 35, 2710 20 39, or

— any petroleum-derived liquid fuel, other than gas oil as defined in points 2 and 3, which, by reason of its distillation limits, falls within the category of heavy oils intended for use as fuel and of which less than 65 % by volume (including losses) distils at 250 °C by the ASTM D86 method. If the distillation cannot be determined by the ASTM D86 method, the petroleum product is likewise categorised as a heavy fuel oil;

(2) gas oil means:

— any petroleum-derived liquid fuel, excluding marine fuel, falling within CN code 2710 19 25, 2710

19 29, 2710 19 47, 2710 19 48, 2710 20 17 or 2710 20 19, or

— any petroleum-derived liquid fuel, excluding marine fuel, of which less than 65 % by volume (including losses) distils at 250 °C and of which at least 85 % by volume (including losses) distils at 350 °C by the ASTM D86 method.

Diesel fuels as defined in point 2 of Article 2 of Directive 98/70/EC of the European Parliament and of the Council of 13 October 1998 relating to the quality of petrol and diesel fuels (*) are excluded from this definition. Fuels used in non-road mobile machinery and agricultural tractors are also excluded from this definition;

(b) points 3a and 3b are replaced by the following:

(3a) marine diesel oil means any marine fuel as defined for DMB grade in Table I of ISO 8217 with the exception of the reference to the sulphur content;

(3b) marine gas oil means any marine fuel as defined for DMX, DMA and DMZ grades in Table I of ISO 8217 with the exception of the reference to the sulphur content;

(c) point 3m is replaced by the following:

'(3m) emission abatement method means any fitting, material, appliance or apparatus to be fitted in a ship or other procedure, alternative fuel, or compliance method, used as an alternative to low sulphur marine fuel meeting the requirements set out in this Directive, that is verifiable, quantifiable and enforceable;

(3) **Article 3** is amended as follows:

(a) paragraphs 1 and 2 are replaced by the following:

1. Member States shall ensure that heavy fuel oils are not used within their territory if their sulphur content exceeds 1 % by mass.

2. Until 31 December 2015, subject to appropriate monitoring of emissions by competent authorities, paragraph 1 shall not apply to heavy fuel oils used:

(a) in combustion plants which fall within the scope of Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants, which are subject to Article 4(1) or (2) or Article 4(3)(a) of that Directive and which comply with the emission limits for sulphur dioxide for such plants as set out in that Directive;

(b) in combustion plants which fall within the scope of Directive 2001/80/EC, which are subject to Article 4(3)(b) and Article 4(6) of that Directive and the monthly average sulphur dioxide emissions of which do not exceed 1 700 mg/Nm 3 at an oxygen content in the flue gas of 3 % by volume on a dry basis;

(c) in combustion plants which do not fall under points (a) or (b), and the monthly average sulphur dioxide emissions of which do not exceed 1 700 mg/Nm 3 at an oxygen content in the flue gas of 3 % by volume on a dry basis;

(d) for combustion in refineries, where the monthly average of emissions of sulphur dioxide averaged over all combustion plants in the refinery, irrespective of the type of fuel or fuel combination used, but excluding plants which fall under points (a) and (b), gas turbines and gas engines, do not exceed 1 700 mg/Nm 3 at an oxygen content in the flue gas of 3 % by volume on a dry basis.

3. As from 1 January 2016, subject to appropriate monitoring of emissions by competent authorities, paragraph 1 shall not apply to heavy fuel oils used:

(a) in combustion plants which fall within the scope of Chapter III of Directive 2010/75/EU of the European Parliament and of the Council (**), and which comply with the emission limits for sulphur dioxide for such plants as set out in Annex V to that Directive or, where those emission limit values are not applicable according to that Directive, for which the monthly average sulphur dioxide emissions do not exceed 1 700 mg/Nm 3 at an oxygen content in the flue gas of 3 % by volume on a dry basis;

(b) in combustion plants which do not fall under point (a), and the monthly average sulphur dioxide emissions of which do not exceed 1 700 mg/Nm 3 at an oxygen content in the flue gas of 3 % by volume on a dry basis;

(c) for combustion in refineries, where the monthly average of emissions of sulphur dioxide averaged over all combustion plants in the refinery, irrespective of the type of fuel or fuel combination used, but excluding plants falling under point (a), gas turbines and gas engines, do not exceed 1 700 mg/Nm 3 at an oxygen content in the flue gas of 3 % by volume on a dry basis.

Member States shall take the necessary measures to ensure that no combustion plant using heavy fuel oil with a sulphur concentration greater than that referred to in paragraph 1 is operated without a permit issued by a competent authority, which specifies the emission limits.

(b) paragraph 3 is deleted;

(4) the following Article is inserted:

'Article 3a **Maximum sulphur content in marine fuel**

Member States shall ensure that marine fuels are not used within their territory if their sulphur content exceeds 3,50 % by mass, except for fuels supplied to ships using emission abatement methods subject to Article 4c operating in closed mode.';

(5) in Article 4, paragraph 1 is replaced by the following:

1. Member States shall ensure that gas oils are not used within their territory if their sulphur content exceeds 0,10 % by mass.

(6) **Article 4a** is amended as follows:

(a) the title is replaced by the following:

'Maximum sulphur content of marine fuels used in territorial seas, exclusive economic zones and pollution control zones of Member States, including $SO_X$ Emission Control Areas and by passenger ships operating on regular services to or from Union ports';

(b) paragraph 1 is replaced by the following:

'1. Member States shall take all necessary measures to ensure that marine fuels are not used in the areas of their territorial seas, exclusive economic zones and pollution control zones falling within $SO_X$ Emission Control Areas if the sulphur content of those fuels by mass exceeds:

(a) 1,00 % until 31 December 2014;
(b) 0,10 % as from 1 January 2015.

This paragraph shall apply to all vessels of all flags, including vessels whose journey began outside the Union. The Commission shall have due regard to any future changes to the requirements pursuant to Annex VI to MARPOL applicable within $SO_X$ Emission Control Areas, and, where appropriate, without undue delay make any relevant proposals with a view to amending this Directive accordingly.

(c) the following paragraph is inserted:

1a. Member States shall take all necessary measures to ensure that marine fuels are not used in the areas of their territorial seas, exclusive economic zones and pollution control zones if the sulphur content of those fuels by mass exceeds:

(a) 3,50 % as from 18 June 2014;
(b) 0,50 % as from 1 January 2020.

This paragraph shall apply to all vessels of all flags, including vessels whose journey began outside of the Union, without prejudice to paragraphs 1 and 4 of this Article and Article 4b.

(d) paragraphs 4, 5, 6 and 7 are replaced by the following:

'4. Member States shall take all necessary measures to ensure that marine fuels are not used in their territorial seas, exclusive economic zones and pollution control zones falling outside $SO_X$ Emission Control Areas by passenger ships operating on regular services to or from any Union port if the sulphur content of those fuels exceeds 1,50 % by mass until 1 January 2020.

Member States shall be responsible for the enforcement of this requirement at least in respect of vessels flying their flag and vessels of all flags while in their ports.

5. Member States shall require the correct completion of ships' logbooks, including fuel-changeover operations.

5a. Member States shall endeavour to ensure the availability of marine fuels which comply with this Directive and inform the Commission of the availability of such marine fuels in its ports and terminals

5b. If a ship is found by a Member State not to be in compliance with the standards for marine fuels which comply with this Directive, the competent authority of the Member State is entitled to require the ship to:

(a) present a record of the actions taken to attempt to achieve compliance; and
(b) provide evidence that it attempted to purchase marine fuel which complies with this Directive in accordance with its

voyage plan and, if it was not made available where planned, that attempts were made to locate alternative sources for such marine fuel and that, despite best efforts to obtain marine fuel which complies with this Directive, no such marine fuel was made available for purchase.

The ship shall not be required to deviate from its intended voyage or to delay unduly the voyage in order to achieve compliance.

If a ship provides the information referred to in the first subparagraph, the Member State concerned shall take into account all relevant circumstances and the evidence presented to determine the appropriate action to take, including not taking control measures.

A ship shall notify its flag State, and the competent authority of the relevant port of destination, when it cannot purchase marine fuel which complies with this Directive.

A port State shall notify the Commission when a ship has presented evidence of the non-availability of marine fuels which comply with this Directive.

6. Member States shall, in accordance with regulation 18 of Annex VI to MARPOL:
   (a) maintain a publicly available register of local suppliers of marine fuel;
   (b) ensure that the sulphur content of all marine fuels sold in their territory is documented by the supplier on a bunker delivery note, accompanied by a sealed sample signed by the representative of the receiving ship;
   (c) take action against marine fuel suppliers that have been found to deliver fuel that does not comply with the specification stated on the bunker delivery note;
   (d) ensure that remedial action is taken to bring any non-compliant marine fuel discovered into compliance.

7. Member States shall ensure that marine diesel oils are not placed on the market in their territory if the sulphur content of those marine diesel oils exceeds 1,50 % by mass.

(e) paragraph 8 is deleted;

(7) Articles 4b and 4c are replaced by the following:

Article 4b: **Maximum sulphur content of marine fuels used by ships at berth in Union ports**

1. Member States shall take all necessary measures to ensure that ships at berth in Union ports do not use marine fuels with a sulphur content exceeding 0,10 % by mass, allowing sufficient time for the crew to complete any necessary fuel-changeover operation as soon as possible after arrival at berth and as late as possible before departure.
   Member States shall require the time of any fuel- changeover operation to be recorded in ships' logbooks.
2. Paragraph 1 shall not apply:

(a) whenever, according to published timetables, ships are due to be at berth for less than two hours;
(b) to ships which switch off all engines and use shore- side electricity while at berth in ports.

3. Member States shall ensure that marine gas oils are not placed on the market in their territory if the sulphur content of those marine gas oils exceeds 0,10 % by mass.

Article 4c: **Emission abatement methods**

1. Member States shall allow the use of emission abatement methods by ships of all flags in their ports, territorial seas, exclusive economic zones and pollution control zones, as an alternative to using marine fuels that meet the requirements of Articles 4a and 4b, subject to paragraphs 2 and 3 of this Article.
2. Ships using the emission abatement methods referred to in paragraph 1 shall continuously achieve reductions of sulphur dioxide emissions that are at least equivalent to the reductions that would be achieved by using marine fuels that meet the requirements of Articles 4a and 4b. Equivalent emission values shall be determined in accordance with Annex I.

2a. Member States shall, as an alternative solution for reducing emissions, encourage the use of onshore power supply systems by docked vessels.

3. The emission abatement methods referred to in paragraph 1 shall comply with the criteria specified in the instruments referred to in Annex II.
4. Where justified in the light of scientific and technical progress regarding alternative emission abatement methods and in such a way as to ensure strict consistency with the relevant instruments and standards adopted by the IMO, the Commission shall:
   (a) be empowered to adopt delegated acts in accordance with Article 9a amending Annexes I and II;
   (b) adopt implementing acts laying down the detailed requirements for monitoring of emissions, where appropriate. Those implementing acts shall be adopted in accordance with the examination procedure referred to in Article 9(2).

(8) the following Articles are inserted:

Article 4d: **Approval of emission abatement methods for use on board ships flying the flag of a Member State**

1. Emission abatement methods falling within the scope of Council Directive 96/98/EC shall be approved in accordance with that Directive.
2. Emission abatement methods not covered by paragraph 1 of this Article shall be approved in accordance with the procedure referred to in Article 3(2) of Regulation (EC) No 2099/2002 of the European Parliament and of the Council of 5 November 2002 establishing a Committee on Safe Seas and the Prevention of Pollution from Ships (COSS), taking into account:
   (a) guidelines developed by the IMO;

(b) the results of any trials conducted under Article 4e;
(c) effects on the environment, including achievable emission reductions, and impacts on ecosystems in enclosed ports, harbours and estuaries; and
(d) the feasibility of monitoring and verification.

Article 4e: **Trials of new emission abatement methods**

Member States may, in cooperation with other Member States, as appropriate, approve trials of ship emission abatement methods on vessels flying their flag, or in sea areas within their jurisdiction. During those trials, the use of marine fuels meeting the requirements of Articles 4a and 4b shall not be mandatory, provided that all of the following conditions are fulfilled:

(a) the Commission and any port State concerned are notified in writing at least six months before trials begin;
(b) permits for trials do not exceed 18 months in duration;
(c) all ships involved install tamper-proof equipment for the continuous monitoring of funnel gas emissions and use it throughout the trial period;
(d) all ships involved achieve emission reductions which are at least equivalent to those which would be achieved through the sulphur limits for fuels specified in this Directive;
(e) there are proper waste management systems in place for any waste generated by the emission abatement methods throughout the trial period;
(f) there is an assessment of impacts on the marine environment, particularly ecosystems in enclosed ports, harbours and estuaries throughout the trial period; and
(g) full results are provided to the Commission, and made publicly available, within six months of the end of the trials.

Article 4f: **Financial measures**

Member States may adopt financial measures in favour of operators affected by this Directive where such financial measures are in accordance with State aid rules applicable and to be adopted in this area.

(9) Article 6 is replaced by the following:

Article 6: **Sampling and analysis**

1. Member States shall take all necessary measures to check by sampling that the sulphur content of fuels used complies with Articles 3, 3a, 4, 4a and 4b. The sampling shall commence on the date on which the relevant limit for maximum sulphur content in the fuel comes into force. It shall be carried out periodically with sufficient frequency and quantities in such a way that the samples are representative of the fuel examined, and in the case of marine fuel, of the fuel being used by vessels while in relevant sea areas and ports. The samples shall be analysed without undue delay.

1a. The following means of sampling, analysis and inspection of marine fuel shall be used:

(a) inspection of ships' log books and bunker delivery notes;

and, as appropriate the following means of sampling and analysis;

(b) sampling of the marine fuel for on-board combustion while being delivered to ships, in accordance with the Guidelines for the sampling of fuel oil for determination of compliance with the revised MARPOL Annex VI adopted on 17 July 2009 by Resolution 182(59) of the Marine Environment Protection Committee (MEPC) of the IMO, and analysis of its sulphur content; or

(c) sampling and analysis of the sulphur content of marine fuel for on-board combustion contained in tanks, where technically and economically feasible, and in sealed bunker samples on board ships.

1b. The Commission shall be empowered to adopt implementing acts concerning:

(a) the frequency of sampling;
(b) the sampling methods;
(c) the definition of a sample representative of the fuel examined.

Those implementing acts shall be adopted in accordance with the examination procedure referred to in Article 9(2).

2. The reference method adopted for determining the sulphur content shall be ISO method 8754 (2003) or PrEN ISO 14596 (2007).
In order to determine whether marine fuel delivered to and used on board ships is compliant with the sulphur limits required by Articles 3a, 4, 4a and 4b the fuel verification procedure set out in Appendix VI to Annex VI to MARPOL shall be used.

(10) **Article 7** is amended as follows:

(a) paragraph 1 is replaced by the following:

1. Each year by 30 June, Member States shall, on the basis of the results of the sampling, analysis and inspections carried out in accordance with Article 6, submit a report to the Commission on the compliance with the sulphur standards set out in this Directive for the preceding year.

On the basis of the reports received in accordance with the first subparagraph of this paragraph and the notifications regarding the non-availability of marine fuel which complies with this Directive submitted by Member States in accordance with the fifth subparagraph of Article 4a(5b), the Commission shall, within 12 months from the date referred to in the first subparagraph of this paragraph, draw up and publish a report on the implementation of this Directive. The Commission shall evaluate the need for further strengthening the relevant provisions of this Directive and make any appropriate legislative proposals to that effect.';

(b) the following paragraph is inserted:

1a. The Commission may adopt implementing acts concerning the information to be included in the report and the format of the report. Those implementing acts shall be adopted in accordance with the examination procedure referred to in Article 9(2).

(c) paragraphs 2 and 3 are replaced by the following:

2. By 31 December 2013 the Commission shall submit a report to the European Parliament and to the Council which shall be accompanied, if appropriate, by legislative proposals. The Commission shall consider in its report the potential for reducing air pollution taking into account, inter alia: annual reports submitted in accordance with paragraphs 1 and 1a; observed air quality and acidification; fuel costs;

potential economic impact and observed modal shift; and progress in reducing emissions from ships.

3. The Commission shall, in cooperation with Member States and stakeholders, by 31 December 2012, develop appropriate measures, including those identified in the Commission's staff working paper of 16 September 2011 entitled "Pollutant emission reduction from maritime transport and the sustainable waterborne transport toolbox" promoting compliance with the environmental standards of this Directive, and minimising the possible negative impacts.

(d) paragraph 4 is replaced by the following:

4. The Commission shall be empowered to adopt delegated acts in accordance with Article 9a concerning the adaptations of Article 2, points 1, 2, 3, 3a, 3b and 4, point (b) of Article 6(1a) and Article 6(2) to scientific and technical progress. Such adaptations shall not result in any direct changes to the scope of this Directive or to sulphur limits for fuels specified in this Directive.

(11) Article 8 is deleted;

(12) Article 9 is replaced by the following:

Article 9: **Committee procedure**

1. The Commission shall be assisted by a committee. That committee shall be a committee within the meaning of Regulation (EU) No 182/2011 of the European Parliament and of the Council of 16 February 2011 laying down the rules and general principles concerning mechanisms for control by Member States of the Commission's exercise of implementing powers.
2. Where reference is made to this paragraph, Article 5 of Regulation (EU) No 182/2011 shall apply.
   Where the committee delivers no opinion, the Commission shall not adopt the draft implementing act and the third subparagraph of Article 5(4) of Regulation (EU) No 182/2011 shall apply.

(13) the following Article is inserted:

Article 9a**: Exercise of the delegation**

1. The power to adopt delegated acts is conferred on the Commission subject to the conditions laid down in this Article.
2. The power to adopt delegated acts referred to in Article 4c(4) and Article 7(4) shall be conferred on the Commission for a period of five years from 17 December 2012. The Commission shall draw up a report in respect of the delegation of power not later than nine months before the end of the five-year period. The delegation of power shall be tacitly extended for periods of an identical duration, unless the European Parliament or the Council opposes such extension not later than three months before the end of each period.
3. The delegation of power referred to in Article 4c(4) and Article 7(4) may be revoked at any time by the European Parliament or by the Council. A decision to revoke shall put an end to the delegation of the powers specified in that decision. It shall take effect the day following the publication of the decision in the Official Journal of the European Union or at a later date specified therein. It shall not affect the validity of any delegated acts already in force.
4. As soon as it adopts a delegated act, the Commission shall notify it

simultaneously to the European Parliament and to the Council.

5. A delegated act adopted pursuant to Article 4c(4) and Article 7(4) shall enter into force only if no objection has been expressed either by the European Parliament or the Council within a period of three months of notification of that act to the European Parliament and the Council or if, before the expiry of that period, the European Parliament and the Council have both informed the Commission that they will not object. That period shall be extended by three months at the initiative of the European Parliament or of the Council.

(14) Article 11 is replaced by the following:

Article 11: **Penalties**

1. Member States shall determine the penalties applicable to breaches of the national provisions adopted pursuant to this Directive.
2. The penalties determined must be effective, proportionate and dissuasive and may include fines calculated in such a way as to ensure that the fines at least deprive those responsible of the economic benefits derived from their infringement and that those fines gradually increase for repeated infringements.

(15) the Annex to Directive 1999/32/EC is replaced by the Annex to this Directive.

Article 2

**Transposition**

1. Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with this Directive by 18 June 2014. They shall forthwith communicate to the Commission the text of those provisions.

   When Member States adopt those provisions, they shall contain a reference to this Directive or be accompanied by such a reference on the occasion of their official publication. The methods of making such reference shall be laid down by Member States.

2. Member States shall communicate to the Commission the text of the main provisions of national law which they adopt in the field covered by this Directive.

Article 3

**Entry into force**

This Directive shall enter into force on the twentieth day following that of its publication in the Official Journal of the European Union.

Article 4

**Addressees**

This Directive is addressed to the Member States.

Done at Strasbourg, 21 November 2012.

For the European Parliament: The President M. SCHULZ

For the Council: The President A. D. MAVROYIANNIS

# ANNEX

## ANNEX I

### EQUIVALENT EMISSION VALUES FOR EMISSION ABATEMENT METHODS AS REFERRED TO IN ARTICLE 4c(2)

Marine fuel sulphur limits referred to in Articles 4a and 4b and regulations 14.1 and 14.4 of Annex VI to MARPOL and corresponding emission values referred to in Article 4c(2):

| Marine fuel Sulphur Content (% m/m) | Ratio Emission $SO_2$ (ppm)/$CO_2$(% v/v) |
|---|---|
| 3.50 | 151.7 |
| 1.50 | 65.0 |
| 1.00 | 43.3 |
| 0.50 | 21.7 |
| 0.10 | 4.3 |

Note:

- The use of the Ratio Emissions limits is only applicable when using petroleum based Distillate or Residual Fuel Oils.
- In justified cases where the CO 2 concentration is reduced by the exhaust gas cleaning (EGC) unit, the CO 2 concentration may be measured at the EGC unit inlet, provided that the correctness of such a methodology can be clearly demonstrated.

## ANNEX II

### CRITERIA FOR THE USE OF EMISSION ABATEMENT METHODS REFERRED TO IN ARTICLE 4c(3)

The emission abatement methods referred to in Article 4c shall comply at least with the criteria specified in the following instruments, as applicable:

| Emission abatement method | Criteria for use |
|---|---|
| Mixture of marine fuel and boil-off gas | Commission Decision 2010/769/EU of 13 December 2010 on the establishment of criteria for the use by liquefied natural gas carriers of technological methods as an alternative to using low sulphur marine fuels meeting the requirements of Article 4b of Council Directive 1999/32/EC relating to a reduction in the sulphur content of certain liquid fuels as amended by Directive 2005/33/EC of the European Parliament and of the Council on the sulphur content of marine fuels ( 1 ). |
| Exhaust gas cleaning systems | Resolution MEPC.184(59) adopted on 17 July 2009 "Wash water resulting from exhaust gas cleaning systems which make use of chemicals, additives, preparations and relevant chemical created in situ", referred to in point 10.1.6.1 of Resolution MEPC.184(59), shall not be discharged into the sea, including enclosed ports, harbours and estuaries, unless it is demonstrated by the ship operator that such wash water discharge has no significant negative impacts on and do not pose risks to human health and the environment. If the chemical used is caustic soda it is sufficient that the washwater meets the criteria set out in Resolution MEPC.184(59) and its pH does not exceed 8,0. |
| Biofuels | Use of biofuels as defined in Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources ( 2 ) that comply with the relevant CEN and ISO standards. The mixtures of biofuels and marine fuels shall comply with the sulphur standards set out in Article 3a, Article 4a(1), (1a) and (4) and Article 4b of this Directive. |

# APPENDIX D: CALIFORNIA AIR RESOURCES BOARD

## BARCLAYS OFFICIAL CALIFORNIA CODE OF REGULATIONS

TITLE: 13: MOTOR VEHICLES
DIVISION 3: AIR RESOURCES BOARD
CHAPTER 5.1: STANDARDS FOR FUELS NON-VEHICULAR SOURCES
PARAGRAPH 2299.2: FUEL SULFUR AND OTHER OPERATIONAL REQUIREMENTS FOR OCEAN-GOING VESSELS WITHIN CALIFORNIA WATERS AND 24 NAUTICAL MILES OF THE CALIFORNIA BASELINE.

### (A) PURPOSE

The purpose of this section is to require the use of low sulfur marine distillate fuels in order to reduce emissions of particulate matter (PM), diesel particulate matter, nitrogen oxides, and sulfur oxides from the use of auxiliary diesel and diesel-electric engines, main propulsion diesel engines, and auxiliary boilers on ocean-going vessels within any of the waters subject to this regulation ( "Regulated California Waters").

### (B) PURPOSE

2. Except as provided in subsection (c), this section applies to any person who owns, operates, charters, rents, or leases any ocean-going vessel that operates in any of the Regulated California Waters, which include all of the following:
   a) all California internal waters;
   b) all California estuarine waters;
   c) all California ports, roadsteads, and terminal facilities (collectively "ports");
   d) all waters within 3 nautical miles of the California baseline, starting at the California-Oregon border and ending at the California-Mexico border at the Pacific Ocean, inclusive;
   e) all waters within 12 nautical miles of the California baseline, starting at the California-Oregon border and ending at the California-Mexico border at the Pacific Ocean, inclusive; and
   f) all waters within 24 nautical miles of the California baseline, starting at the California-Oregon border and ending at the California-Mexico border at the Pacific Ocean, inclusive, except for the region within the area defined by 34.8 degrees North, 121.14 degrees West, thence to 34.46 degrees North, 120.82 degrees West, thence to 34.36 degrees North, 120.82 degrees West, thence to 34.29 degrees North, 120.99 degrees West, and following the boundary 24 nautical miles from the California baseline from 34.29 degrees North, 120.99 degrees West to 34.8 degrees North, 121.14 degrees West.
3. Except as provided in subsection (c), this section applies to ocean-going vessels that are flagged in, registered in, entitled to fly the flag of, or otherwise operating under the authority of the United States ( "U.S.-flagged") or any other country ( "foreign-flagged").
4. Nothing in this section shall be construed to amend, repeal, modify, or change in any way any applicable U.S. Coast Guard requirements. Any person subject to this section shall be responsible for ensuring compliance with both U.S. Coast Guard regulations and the requirements of this section, including but not limited to, obtaining any necessary approvals, exemptions, or orders from the U.S. Coast Guard.

### (C) EXEMPTIONS

1. The requirements of this section do not apply to ocean-going vessel voyages that are comprised of continuous and expeditious navigation through any Regulated California Waters for the purpose of traversing such bodies of water without entering California internal or estuarine waters or calling at a port, roadstead, or terminal facility. “Continuous and expeditious navigation” includes stopping and anchoring only to the extent such stopping and anchoring are required by the U.S. Coast Guard; rendered necessary by force majeure or distress; or made for the purpose of rendering assistance to persons, ships, or aircraft in danger or distress. This exemption does not apply to the passage of an ocean-going vessel that engages in any of the prejudicial activities specified in United Nations Convention on the Law of the Seas (UNCLOS) 1982, Article 19, subpart 2. Further, notwithstanding any Coast Guard mandated stops or stops due to force majeure or the rendering of assistance, this exemption does not apply to a vessel that was otherwise scheduled or intended to enter California internal or estuarine waters or call at a port, roadstead or terminal facility.
2. The requirements of this section do not apply to emergency generators.
3. The requirements of this section do not apply to auxiliary engines, main engines or auxiliary boilers onboard ocean-going vessels owned or operated by any branch of local, state, or federal government, or by a foreign government, when such vessels are operated within Regulated California Waters on government non-commercial service. However, such vessels are encouraged to act in a manner consistent, so far as is reasonable and practicable, with this section.
4. The requirements of this section do not apply to auxiliary engines, main engines, and auxiliary boilers while such engines and boilers are operating on alternative fuel in Regulated California Waters.
5. The requirements of this section, including the payment of Noncompliance Fees as provided in subsection (h), do not apply if the master reasonably and actually determines that compliance with this section would endanger the safety of the vessel, its crew, its cargo or its passengers because of severe weather conditions, equipment failure, fuel contamination, or other extraordinary reasons beyond the master's reasonable control. This exemption applies only as long as and to the extent necessary to secure the safety of the vessel, its crew, its cargo, or its passengers and provided that;
   a) the master takes all reasonable precautions after the conditions necessitating the exemption have ended to avoid or minimize repeated claims of exemption under this subsection;
   b) the master notifies the Executive Officer of a safety exemption claim within 24 hours after the end of each such episode (i.e., the period of time during which the emergency conditions exist that necessitate the safety exemption claim, as provided in paragraph (5) above); and
   c) the master submits to the Executive Officer, within 4 working days after the notification in paragraph (B) above, all documentation necessary to establish the conditions necessitating the safety exemption and the date(s), local time, and position of the vessel (longitude and latitude) in Regulated California Waters at the beginning and end of the time period during which a safety exemption is claimed under this subsection. All documentation required under this paragraph shall be provided in English.

6. Temporary Experimental or Research Exemption. As provided in this paragraph, the requirements of this section do not apply to vessels that have been granted a temporary experimental exemption by the Executive Officer for the duration of the approved exemption. A temporary experimental exemption may be granted by the Executive Officer for experimental purposes for up to three years with one extension for up to three additional years. The exemption will be limited in duration as specified by the Executive Officer in the Executive Order granting such an exemption or extension. All documentation and information submitted in support of an application for a temporary experimental exemption or extension shall be deemed non-confidential and available for public review under the Public Records Act.
   a) Pursuant to this paragraph, a person may operate an auxiliary engine, main engine or auxiliary boiler with fuel that does not meet the provisions of (e)(1), provided the person meets all of the following requirements:
      1. the person obtains written approval for this exemption or extension, in the form of an Executive Order from the Executive Officer, before the vessel enters Regulated California Waters;
      2. the person or master of the vessel takes all measures available to minimize emissions of diesel PM, $NO_X$, and $SO_X$ to the extent feasible during the period in which the temporary experimental exemption is in effect;
      3. the request for an exemption or extension is provided in writing, submitted to the Executive Officer at least 30 days before the vessel enters Regulated California Waters, and contains the following:
         a. specifications for the non-compliant fuel that the person is proposing to use pursuant to this paragraph, including but not limited to, sulfur content (expressed to the nearest tenth weight percent); whether the fuel meets ASTM specifications for marine diesel oil (MDO), marine gas oil (MGO), or some other fuel (identify which ASTM specifications the fuel meets, if any); and
         b. a clear and convincing demonstration that the use of the proposed non-compliant fuel will generate data as part of research that advances the state of knowledge of exhaust control technology or characterization of emissions. For purposes of this paragraph, the Executive Officer's determination that the person has provided a “clear and convincing demonstration” shall be based on whether the person's use of the proposed noncompliant fuel is an express part of a formal, executed research contract or project; a doctoral dissertation; or a master's thesis. A demonstration of the “state of knowledge” includes specific citations to scientific, academic, industry or regulatory literature existing or in progress at the time of the request;
         c. identification of the purpose, goals, and objectives of the project, measures taken to minimize emission of air contaminants, and testing procedures and testing schedules;
   b) A person with an exemption granted pursuant to this provision shall:
      1. bring the vessel into full compliance with the requirements of this section, including subsection (e)(1), prior to the expiration of the temporary experimental exemption as specified; and

2. provide a progress report annually from the date of the executive order, to the Executive Officer providing interim test data or other interim results, description of vessel modifications or retrofitting done as part of the projects or other information generated from the date of the prior progress report.
3. provide all official test data and all other results, data, or other information generated during the exemption period to the Executive Officer, in writing and final form, no more than 90 days after the expiration of the temporary experimental exemption or extension.

c) No modifications to the terms and conditions of an approved temporary experimental exemption shall be valid unless in writing and agreed to by both the Executive Officer and the person. Any variance, deviance, or nonconformance with the terms and conditions of an approved temporary experimental exemption or extension shall be deemed a separate violation of this section.

## (D) DEFINITIONS

For purposes of this section, the following definitions apply:

1. "Alternative fuel" means natural gas, propane, ethanol, methanol, hydrogen, electricity, or fuel cells. Alternative fuel also means any mixture that only contains these fuels.
2. "ASTM" means ASTM International.
3. "Auxiliary boiler" means any fuel-fired combustion equipment designed primarily to produce steam for uses other than propulsion, including, but not limited to, heating of residual fuel and liquid cargo, heating of water for crew and passengers, powering steam turbine discharge pumps, freshwater generation, and space heating of cabins. Exhaust gas economizers that exclusively use diesel engine exhaust as a heat source to produce steam are not auxiliary boilers.
4. "Auxiliary engine" means a diesel engine on an ocean-going vessel designed primarily to provide power for uses other than propulsion or emergencies, except that all diesel-electric engines shall be considered "auxiliary diesel engines" for purposes of this section.
5. "Baseline" means the mean lower low water line along the California coast, as shown on the following National Oceanic and Atmospheric Administration (NOAA) Nautical Charts as authored by the NOAA Office of Coast Survey, which are incorporated herein by reference:
   a) Chart 18600, Trinidad Head to Cape Blanco (January 2002);
   b) Chart 18620, Point Arena to Trinidad Head (June 2002);
   c) Chart 18640, San Francisco to Point Arena (August 2005);
   d) Chart 18680, Point Sur to San Francisco (June 2005);
   e) Chart 18700, Point Conception to Point Sur (July 2003);
   f) Chart 18720, Point Dume to Purisima Point (August 2008); and
   g) Chart 18740, San Diego to Santa Rosa Island (March 2007).
6. "Diesel Engine" means an internal combustion, compression-ignition (CI) engine with operating characteristics significantly similar to the theoretical diesel combustion cycle. The regulation of power by controlling fuel supply in lieu of a throttle is indicative of a compression ignition engine.

7. "Diesel Particulate Matter" means the particles found in the exhaust of diesel engines, which may agglomerate and adsorb other species to form structures of complex physical and chemical properties.
8. "Diesel-electric engine" means a diesel engine connected to a generator that is used as a source of electricity for propulsion or other uses.
9. "Emergency Generator" means a diesel-electric engine operated only during emergencies or to perform maintenance and testing necessary to ensure readiness for emergencies.
10. "Essential Modification" means the addition of new equipment, or the replacement of existing components with modified components, that can be demonstrated to be necessary to comply with this regulation. Essential modifications do not include:
    1. changes that are made for convenience or automation of fuel switching; or
    2. replacement of components that would be replaced in the absence of this regulation, based on measured component wear, visual inspection, or expected service life, even if accelerated due to the fuel requirements.

    Additional tankage is considered essential only if existing available tankage has less than the capacity required for a complete voyage within Regulated California Waters.
11. "Estuarine Waters" means an arm of the sea or ocean that extends inland to meet the mouth of a river.
12. "Executive Officer" means the executive officer of the Air Resources Board (ARB), or his or her designee.
13. "Hydrocarbon (HC)" means the sum of all hydrocarbon air pollutants.
14. "Internal Waters" means any navigable river or waterway within the State of California.
15. "IMO" means the International Maritime Organization.
16. "ISO" means the International Organization for Standardization.
17. "Main Engine" means a diesel engine on an ocean-going vessel designed primarily to provide propulsion, except that diesel-electric engines shall not be considered "main engines" for purposes of this section.
18. "Marine Diesel Oil (MDO)" means any fuel that meets all the specifications for DMB grades as defined in Table I of International Standard ISO 8217, as revised in 2005, which is incorporated herein by reference, or DMB grades as defined in Table I of International Standard ISO 8217, as revised on June 15, 2010, which is incorporated herein by reference.
19. "Marine Gas Oil (MGO)" means any fuel that meets all the specifications for DMX or DMA grades as defined in Table I of International Standard ISO 8217, as revised in 2005, which is incorporated herein by reference, or DMX, DMA, or DMZ grades as defined in Table I of International Standard ISO 8217, as revised on June 15, 2010, which is incorporated herein by reference.
20. "Master" means the person who operates a vessel or is otherwise in charge of the vessel's operations.
21. "Military Vessel" means any ship, boat, watercraft, or other contrivance used for any purpose on water, and owned or operated by the armed services.
22. "Nitrogen Oxides ($NO_X$)" means compounds of nitric oxide (NO), nitrogen dioxide ($NO_2$), and other oxides of nitrogen, which are typically created during combustion processes and are major contributors to smog formation and acid deposition.

23. "Non-Methane Hydrocarbons (NMHC)" means the sum of all hydrocarbon air pollutants except methane.
24. "Ocean-going Vessel (OGV)" means a commercial, government, or military vessel meeting any one of the following criteria:
    a) a non-tanker vessel greater than or equal to 400 feet in length overall (LOA) as defined in 50 CFR § 679.2, as adopted June 19, 1996;
    b) a non-tanker vessel greater than or equal to 10,000 gross tons (GT ITC) per the convention measurement (international system) as defined in 46 CFR 69.51-.61, as adopted September 12, 1989;
    c) a non-tanker vessel propelled by a marine compression ignition engine with a per-cylinder displacement of greater than or equal to 30 liters; or
    d) a tanker that meets any one of the criteria in subsections (A)-(C).

    For purposes of this section, "ocean-going vessel" does not include tugboats, towboats, or pushboats.
25. "Operate" means steering or otherwise running the vessel or its functions while the vessel is underway, moored, anchored, or at dock.
26. "Own" means having all the incidents of ownership, including the legal title, of a vessel whether or not that person lends, rents, or pledges the vessel; having or being entitled to the possession of a vessel as the purchaser under a conditional sale contract; or being the mortgagor of a vessel.
27. "Particulate Matter" means any airborne finely divided material, except uncombined water, which exists as a liquid or solid at standard conditions (e.g., dust, smoke, mist, fumes or smog).
28. "Person" includes all of the following:
    a) any person, firm, association, organization, partnership, business trust, corporation, limited liability company, or company;
    b) any state or local governmental agency or public district, or any officer or employee thereof;
    c) the United States or its agencies, to the extent authorized by federal law.
29. "Port Visit" means any of the following:
    a) each separate and distinct entry of a vessel into a port, roadstead, or terminal facility (collectively "port") in Regulated California Waters that results in the vessel stopping, docking, mooring, or otherwise dropping anchor (collectively "stopping") at the port. The "port visit" continues if the vessel moves to a different berth within the same port, but the "port visit" ends when the vessel leaves for or is otherwise moved to another port within the same bay or any other port;
    b) except as provided in paragraph (C) below, each separate and distinct entry of a vessel into an offshore location in Regulated California Waters away from a port that results in the vessel stopping at that offshore location (e.g., Catalina Island or off Monterey). The "port visit" ends when the vessel leaves for or is otherwise moved to a port or another offshore location; or
    c) each separate and distinct entry of a vessel into an offshore location in Regulated California Waters away from a port that results in the vessel stopping, followed by entry into that port, shall constitute one "port visit", provided the offshore stop was conducted solely because the port could not accept the vessel as scheduled due to reasons beyond the reasonable control of the vessel operator or master.

30. "Regulated California Waters" means all of the following:
    a) all California internal waters;
    b) all California estuarine waters;
    c) all California ports, roadsteads, and terminal facilities (collectively "ports");
    d) all waters within 3 nautical miles of the California baseline, starting at the California-Oregon border and ending at the California-Mexico border at the Pacific Ocean, inclusive;
    e) all waters within 12 nautical miles of the California baseline, starting at the California-Oregon border and ending at the California-Mexico border at the Pacific Ocean, inclusive; and
    f) all waters within 24 nautical miles of the California baseline, starting at the California-Oregon border and ending at the California-Mexico border at the Pacific Ocean, inclusive, except for the region within the area defined by 34.8 degrees North, 121.14 degrees West, thence to 34.46 degrees North, 120.82 degrees West, thence to 34.36 degrees North, 120.82 degrees West, thence to 34.29 degrees North, 120.99 degrees West, and following the boundary 24 nautical miles from the California baseline from 34.29 degrees North, 120.99 degrees West to 34.8 degrees North, 121.14 degrees West.
31. "Roadstead" means any facility that is used for the loading, unloading, and anchoring of ships.
32. "Steamship" means a self-propelled vessel in which the primary propulsion and electrical power are provided by steam boilers.
33. "Slow Speed Engine" means an engine with a rated speed of 150 revolutions per minute or less.
34. "Sulfur Oxides" means compounds of sulfur dioxide ($SO_2$), and other oxides of sulfur, which are typically created during combustion of sulfur containing fuels.
35. "Tanker" means a self-propelled vessel constructed or adapted primarily to carry, or that carries, oil or hazardous material in bulk as cargo or cargo residue.
36. "Two-stroke Engine" means an internal combustion engine which operates on a two stroke cycle where the cycle of operation completes in one revolution of the crankshaft.
37. "Vessel" means any tugboat, tanker, freighter, passenger ship, barge, or other boat, ship, or watercraft, except those used primarily for recreation and any of the following:
    a) a seaplane on the water;
    b) a watercraft specifically designed to operate on a permanently fixed course, the movement of which is restricted to a fixed track or arm to which the watercraft is attached or by which the watercraft is controlled.
38. "Voyage" means each separate and distinct journey that begins when a vessel reaches Regulated California Waters from a point beyond Regulated California Waters, includes at least one port visit, and ends when the vessel departs from Regulated California Waters.

## (D) OPERATIONAL REQUIREMENTS

1. Fuel Sulfur Content Limits.
    a) Auxiliary Diesel Engines:

1. Except as provided in subsections (c) and (h), beginning June 28, 2009, a person subject to this section shall operate any auxiliary diesel engine, while the vessel is operating in Regulated California Waters, with either marine gas oil (MGO), with a maximum of 1.5 percent sulfur by weight, or marine diesel oil (MDO), with a maximum of 0.5 percent sulfur by weight, rounded as specified in subsection (i)(3);
2. Except as provided in subsections (c) and (h), beginning August 1, 2012, a person subject to this section shall operate any auxiliary diesel engine, while the vessel is operating in Regulated California Waters, with either marine gas oil (MGO), with a maximum of 1.0 percent sulfur by weight, or marine diesel oil (MDO), with a maximum of 0.5 percent sulfur by weight, rounded as specified in subsection (i)(3);
3. Except as provided in subsections (c) and (h), beginning January 1, 2014, a person subject to this section shall operate any auxiliary diesel engine, while the vessel is operating in Regulated California Waters, with marine gas oil (MGO) with a maximum of 0.1% sulfur by weight or marine diesel oil (MDO) with a maximum of 0.1% sulfur by weight, rounded as specified in subsection (i)(3).

b) Main Engines and Auxiliary Boilers:

1. Except as provided in subsections (c) and (h), beginning July 1, 2009, a person subject to this section shall operate any main engine or auxiliary boiler, while the vessel is operating in Regulated California Waters, with either marine gas oil (MGO), with a maximum of 1.5 percent sulfur by weight, or marine diesel oil (MDO), with a maximum of 0.5 percent sulfur by weight, rounded as specified in subsection (i)(3);
2. Except as provided in subsections (c) and (h), beginning August 1, 2012, a person subject to this section shall operate any main engine or auxiliary boiler, while the vessel is operating in Regulated California Waters, with either marine gas oil (MGO), with a maximum of 1.0 percent sulfur by weight, or marine diesel oil (MDO), with a maximum of 0.5 percent sulfur by weight, rounded as specified in subsection (i)(3);
3. Except as provided in subsections (c) and (h), beginning January 1, 2014, a person subject to this section shall operate any main engine or auxiliary boiler, while the vessel is operating in Regulated California Waters, with marine gas oil (MGO) with a maximum of 0.1% sulfur by weight or marine diesel oil (MDO) with a maximum of 0.1% sulfur by weight, rounded as specified in subsection (i)(3).

2. Recordkeeping, Reporting, and Monitoring Requirements.

a) Recordkeeping.

Upon the effective date of this regulation, any person subject to this section shall retain and maintain records in English that contain the following information for at least three years following the date when the records were made:

1. The date, local time, and position (longitude and latitude) of the vessel for each entry into Regulated California Waters from waters outside Regulated California Waters, and each departure from Regulated California Waters to waters outside Regulated California Waters;
2. The date, local time, and position (longitude and latitude) of the vessel at the initiation and completion of any fuel switching procedures used to

comply with subsection (e)(1) prior to entry into Regulated California Waters from waters outside Regulated California Waters;

3. The date, local time, and position (longitude and latitude) of the vessel at the initiation and completion of any fuel switching procedures within Regulated California Waters; completion of fuel switching procedures occurs the moment all engines subject to this section have completely transitioned from operation on one fuel to another fuel;
4. The type of fuel used (e.g., marine gas oil, marine diesel oil or heavy fuel oil) in each auxiliary engine, main engine, and auxiliary boiler operated in Regulated California Waters; and
5. The types, amounts, and the actual percent by weight sulfur content of all fuels purchased for use on the vessel, as reported by the fuel supplier or a fuel testing firm.

b) Documentation of Fuel Switch Over Procedures.

Any person subject to this section that complies with the fuel sulfur content limits by switching fuels shall retain and maintain records in English on-board ship that contain the following information for auxiliary engines, main engines and auxiliary boilers:

1. A fuel system diagram that shows all storage, service, and mixing tanks, fuel handling, pumping, and processing equipment, valves, and associated piping. The diagram or other documentation shall list the fuel tank capacities and locations, and the nominal fuel consumption rate of the machinery at rated power;
2. Description of the fuel switch over procedure with detailed instructions and clear identification of responsibilities; and
3. The make, model, rated power, and serial numbers of all main engines, and auxiliary engines and make, model, rated output, and serial numbers of all auxiliary boilers subject to subsection (e)(1).

c) Reporting and Monitoring.

1. Any person subject to this section shall provide in writing the information specified in subsection (e)(2)(A) and (e)(2)(B) to the Executive Officer upon request, either within 24 hours or by a later date approved by the Executive Officer. To the extent the person already collects the information specified in subsections (e)(2)(A) and (e)(2)(B) in English to comply with other regulatory requirements or standard practices, the person may provide the requested information in a format consistent with those other regulatory requirements or standard practices.
2. Any person subject to this section shall provide to the Executive Officer upon request additional information the Executive Officer determines to be necessary to determine compliance with this section.
3. Any person subject to this section shall provide to the Executive Officer access to the vessel for the purpose of determining compliance with the this section, including but not limited to, access to and review of records and information required under subsections (e)(2)(A) and (e)(2)(B), and for the purpose of collecting fuel samples for testing and analysis.

## (F) VIOLATIONS

1. Any person who is subject to this section and commits a violation of any provision, criteria or requirement in this section is subject to the penalties, injunctive relief, and other remedies specified in Health and Safety Code, sections 39674-39675 and 42400 et seq.; other applicable sections in the Health and Safety Code; and other applicable provisions as provided under California law for each violation. Nothing in this section shall be construed to limit or otherwise affect any applicable penalties or other remedies available under Federal law.
2. Any failure to meet any provision, criteria or requirement in this section, including but not limited to the applicable fuel sulfur content limits; recordkeeping requirements; and Noncompliance Fee provision shall constitute a single, separate violation of this section for each hour that a person operates an ocean-going vessel in Regulated California Waters until such provision, criteria or requirement has been met.
3. Any person who is subject to this section is liable for meeting the requirements of this section, notwithstanding any contractual arrangement that person may have with any third-parties..

## (G) NONCOMPLIANCE FOR VESSELS BASED ON THE NEED FOR ESSENTIAL MODIFICATIONS

If a person cannot meet the requirements of subsection (e)(1) without essential modifications, as defined in subsection (d), the Executive Officer will grant the person an exemption in whole or in part to subsection (e)(1). For this provision to apply, the person shall meet all of the following criteria:

1. Notification Requirements.

For each voyage before the person's vessel enters Regulated California Waters from waters outside Regulated California Waters, a person who has demonstrated need under subsection (g)(2) must notify the Executive Officer that the person will not meet the requirements of subsection (e)(1) while operating within Regulated California Waters, but the person will instead meet the requirements of this subsection (g). If the Executive Officer has not received such notice and the person enters Regulated California Waters, the person will be in violation of this section.

2. Demonstration of Need.

At least 45 days prior to a vessel's first reliance on subsection (g) when entering Regulated California Waters, or at the earliest practicable date prior to entry into Regulated California Waters if first reliance on subsection (g) is less than 45 days after the effective date of this section, the person shall provide, in writing, the Executive Officer with an Essential Modification Report attested to under the penalty of perjury by the Chief Engineer of the person's vessel. The Executive Officer has 30 days to act on the Essential Modification Report. Additional information may be provided by the applicant or requested by the Executive officer after submittal of the original Essential Modification Report. The Executive Officer will have an additional 15 days to review the additional submittal and act on the amended Essential Modification Report. The Essential Modification Report shall, to the satisfaction of the Executive Officer:

a) identify the specific essential vessel modifications ( “essential modifications” as defined in subsection (d)) required to meet the requirements of subsection (e)(1);

b) demonstrate that modifications to the vessel are necessary to meet the requirements of subsection (e)(1); and

c) identify the maximum extent, with respect to trip distance or regulated equipment type, to which the vessel can meet the requirements of (e)(1) without essential modifications where feasible and safe for each of the auxiliary engines, main engines, and auxiliary boilers.

3. While the vessel is operating in Regulated California Waters, a person subject to this subsection shall:

a) operate each main engine meeting the requirements of (e)(1) to the extent identified in (g)(2)(C);

b) operate each auxiliary boiler meeting the requirements of (e)(1) to the extent identified in (g)(2)(C); and

c) operate each auxiliary engine meeting the requirements of (e)(1) to the extent identified in (g)(2)(C).

## (H) NONCOMPLIANCE FEE IN LIEU OF MEETING SUBSECTION (E)(1)

The Executive Officer may permit a person ( "person") to pay noncompliance fees ( "fees") in lieu of meeting the requirements of subsection (e)(1). Payment of the fees notwithstanding, all other provisions of this section shall continue to apply. No person shall be permitted to pay the fees unless the person meets the notification requirements in subsection (h)(1) and the requirements in either subsections (h)(2), (h)(3), or (h)(4), as specified below:

1. Notification Requirements.

Before the person's vessel enters Regulated California Waters from waters outside Regulated California Waters, the Executive Officer must receive notice that the person will not meet the requirements of subsection (e)(1) while operating within Regulated California Waters, but the person will instead meet the requirements of this subsection (h). If the Executive Officer has not received such notice and the person enters Regulated California Waters, the person will be in violation of this section and will not be permitted to pay the fees in lieu of meeting the requirements of subsection (e)(1).

2. Noncompliance for Reasons Beyond a Person's Reasonable Control.

Any person wishing to pay the fees under this subsection (h)(2) shall meet the following criteria:

a) Demonstration of Need.

The person shall, through adequate documentation, demonstrate to the Executive Officer's satisfaction that the person's noncompliance with the requirements of subsection (e)(1) is beyond the person's reasonable control. For the purposes of this paragraph, "beyond the person's reasonable control" applies only when one or more of the following sets of circumstances (1, 2, or 3) applies:

1. Unplanned Redirection.

This provision applies only when all of the following criteria are met:

a. after leaving the last port of call, the person's vessel was redirected from his/her original, officially logged, non-California destination to a California port, roadstead, or terminal facility (collectively "port"); and

b. the vessel does not contain a quantity of fuel sufficient for the auxiliary engines, main engines, and auxiliary boilers to meet the requirements of subsection (e)(1).

2. Inadequate Fuel Supply.
3. This provision applies only when all of the following criteria are met:
    a. the person made good faith efforts to acquire a quantity of fuel sufficient for the auxiliary engines, main engines, and auxiliary boilers to meet the requirements of subsection (e)(1); and
    b. the person was unable to acquire fuel sufficient for auxiliary engines, main engines, and auxiliary boilers to meet the requirements of subsection (e)(1).
4. Inadvertent Purchase of Defective Fuel.
   This provision applies only when all of the following criteria are met:
    a. based on the fuel supplier's certification of the fuel specifications, the person reasonably believed, and relied on such belief, that the fuel the person purchased on the route from the vessel's home port to California would enable the auxiliary engines, main engines, and auxiliary boilers to meet the requirements of subsection (e)(1);
    b. the person determined that the auxiliary engines, main engines, and auxiliary boilers in fact will not meet the requirements of subsection (e)(1) using any of the fuel purchased under paragraph 3.a; and
    c. the vessel is already on its way to California, and there are no other ports of call on the vessel's route where fuel can be purchased sufficient to meet the requirements of subsection (e)(1).

b) Payment of Fees.
   Upon meeting the requirements of paragraph (A) in this subsection (h)(2), the person shall pay the fees for every port visit, as specified in subsection (h)(5) below.

c) Executive Officer Review.
   For the purposes of verifying the demonstration of need as specified in paragraph (A) above, the Executive Officer may consider and rely on any facts or circumstances the Executive Officer believes are appropriate, including but not limited to: the fuel supplier's ability or failure to provide adequate fuel ordered by the person; any material misrepresentation by the fuel supplier concerning the fuel specifications; the reasonableness of the person's reliance on fuel suppliers with a history of supplying fuel inadequate for meeting the requirements of subsection (e)(1); and force majeure.

3. Noncompliance for Vessels to Be Taken Out of Service for Modifications.

If a person cannot meet the requirements of subsection (e)(1) without vessel modifications, and elects not to comply under section (g), and such modifications cannot be completed prior to the effective date of subsection (e)(1), the Executive Officer may permit the person to pay the fees as specified in this subsection. The vessel must be scheduled to complete the necessary modifications (e.g. during a dry dock operation) as soon as possible, but no later than December 31, 2014. For this provision to apply, the person shall meet all of the following criteria:

a) Demonstration of Need.

The person shall provide the Executive Officer a Compliance Report, signed by the Chief Engineer of the person's vessel, which:

1. identifies the specific vessel modifications ( "modifications") (e.g., installation of additional fuel tanks, fuel cooling systems) the person plans to use for meeting the requirements of subsection (e)(1);
2. identifies the specific date by which the modifications will be completed (i.e., while the vessel is in dry dock); and
3. demonstrates to the satisfaction of the Executive Officer that the modifications will be made at the earliest possible date (e.g., the vessel has been scheduled for the earliest available dry dock appointment).

b) Payment of Fees.
Upon meeting the requirements of paragraph (A) in this subsection (h)(3), the person shall pay the fees for every port visit, as specified in subsection (h)(5) below.

c) Proof of Modifications Actually Performed.
Within ten (10) business days after the scheduled or actual completion of the modifications, whichever occurs first, the person shall provide written certification to the Executive Officer that the modifications specified under this subsection (h)(3) have been completed. If the modifications have not been completed, the person shall certify which modifications have been completed, which have not, and the anticipated completion date for the remaining modifications. The notification requirement specified in this paragraph, the notification requirements in subsection (h)(1) above, and the fee provisions in subsection (h)(5) below shall apply until all the modifications have been completed.

4. Noncompliance Based on Infrequent Visits and Need for Vessel Modifications.

If a person cannot meet the requirements of subsection (e)(1) without modifications for the vessel at issue, and elects not to comply under section (g), and that vessel will make no more than two California voyages per calendar year, and no more than 4 California voyages after the effective date of the regulation, during the life of the vessel, the Executive Officer may permit the person to pay the fees as specified in this subsection. This provision terminates on December 31, 2014.

a) Demonstration of Need.

The person shall demonstrate to the satisfaction of the Executive Officer that modifications to the vessel are necessary to meet the requirements of subsection (e)(1), and that the vessel shall meet the visitation limits specified in this subsection (h)(4).

b) Payment of Fees.

Upon meeting the requirements of paragraph (A) above, the person shall pay the fees for every port visit as specified in subsection (h)(5) below.

5. Calculation and Payment of Fees
Fees will be calculated based on the number of port visits made by a person using fuel that does not comply with subsection (e)(1). For each port visit, the person who elects to pay the fees pursuant to this subsection (h) shall pay the applicable fees shown in

Table 1 prior to leaving the California port or by a later date approved by the Executive Officer. For persons that purchase fuels complying with subsection (e)(1) during their California port visit, and use these complying fuels during their port visit and upon departure, the fees specified in Table 1 shall be halved. The person shall deposit the fees in the port's Noncompliance Fee Settlement and Air Quality Mitigation Fund. If no such port fund exists, the person shall deposit the fees into the California Air Pollution Control Fund, as directed by the Executive Officer. Port visits shall be cumulative for all non-compliant port visits over the life of the vessel. For the purposes of this paragraph, any port visit where the non-compliance fee is waived shall not be included in the cumulative total.

a) Noncompliance Fee Schedule.

**Table 1: Noncompliance Fee Schedule, Per Vessel**

| *Port Visit* | *Per-Port Visit Fee* |
|---|---|
| **1st Port Visited** | $45,500 |
| **2nd Port Visited** | $45,500 |
| **3rd Port Visited** | $91,000 |
| **4th Port Visited** | $136,500 |
| **5th or more Port Visited** | $182,000 |

b) The fees shown in Table 1 shall be assessed by the Executive Officer at the time of the port visit. For the purposes of assessing fees under subsection (h), offshore anchorages made in conjunction with a port visit shall not be considered as a separate port visit.

c) For subsection (h)(2), beginning January 1, 2014, the fee will be waived once per vessel during each calendar year until December 31, 2014, when all of the following are met:

   1. a person acquires fuel and meets the requirements of subsection (e)(1) prior to leaving the first port visited during the voyage and meets the requirements of (e)(1) for the remainder of the voyage; and

   2. during any non-compliant portion of the voyage, a person operates each auxiliary engine, main engine, and auxiliary boiler with either marine gas oil (MGO), with a maximum of 1.0 percent sulfur by weight, or marine diesel oil (MDO), with a maximum of 0.5 percent sulfur by weight, rounded as specified in subsection (i)(3).

d) The Executive Officer may enter into enforceable agreements with each port that will receive the fees. The agreements shall require that the fees be used by the ports only to fund projects that will substantially reduce emissions of diesel PM, $NO_X$, and $SO_X$ from on-site sources, sources within 2 miles of port boundaries, or ocean-going vessels operated within the Regulated California Waters, except that the fees shall not be used to fund projects on vessels from which noncompliance fees were paid. Fees intended for ports that do not have such agreements at the time the fees are paid shall be deposited into the California Air Pollution Control Fund.

e) If for any reason the person is not notified by the Executive Officer of the assessed fee by the end of the port visit, the person shall nevertheless be responsible for payment of the appropriate fee as specified in this subsection (h) prior to leaving the California port or by a later date approved by the Executive Officer.

## (I) TEST METHODS

The following test methods or alternative test methods that are demonstrated to the written satisfaction of the Executive Officer to be equally or more accurate, shall be used to determine compliance with this section:

1. Test methods used to determine whether fuels meets the requirements of marine gas oil (DMA or DMX) or marine diesel oil (DMB), as specified in subsection (e)(1), shall be the methods specified in International Standard ISO 8217 (as revised in 2005), which is incorporated herein by reference.
2. The sulfur content of fuels shall be determined pursuant to International Standard ISO 8754 (as adopted in 2003), which is incorporated herein by reference.
3. For purposes of determining compliance with the specifications in (e)(1)(A), an observed value or a calculated value shall be rounded "to the nearest unit" in the last right-hand digit used in expressing the specification limit, in accordance with the rounding method of ASTM E 29-93a Standard Practice for Using Significant Digits in Test Data to Determine Conformance Specifications (published May 1993), which is incorporated herein by reference.

## (J) SUNSET, BASELINE, AND TEST METHOD REVIEW.

1. The requirements specified in subsection (e) shall cease to apply if the United States adopts and enforces requirements that will achieve emissions reductions within the Regulated California Waters that are equivalent to those achieved by this section. Equivalent requirements may be from IMO regulations that are adopted and enforced by the United States or may be contained in regulations that are initiated by the U.S. Environmental Protection Agency. Subsection (e) shall remain in effect under this subsection until the Executive Officer issues written findings that federal requirements are in place that will achieve equivalent emissions reductions within the Regulated California Waters and are being enforced within the Regulated California Waters.
2. The Executive Officer shall periodically review the California baseline determinations by the National Oceanic and Atmospheric Administration (NOAA) to determine if updates to the baseline charts incorporated by reference in this section are necessary. If modifications to the baseline charts are determined to be necessary, the Executive Officer shall conduct a public hearing as soon as practicable to amend this section accordingly.
3. The Executive Officer shall periodically review the test methods incorporated by reference in this section to determine if updates to the referenced methods are necessary. If updates to the test methods are determined to be necessary, the Executive Officer shall conduct a public hearing as soon as practicable to amend this section accordingly.

## (K) SEVERABILITY

Each part of this section shall be deemed severable, and in the event that any part of this section is held to be invalid, the remainder of this section shall continue in full

# APPENDIX E: PORT TARIFFS REDUCTIONS

## ENVIRONMENTALLY RELATED DUES IN THE PORT OF GOTHENBURG

In addition to port dues, environmentally related additional charges are mare, or deduction granted, for each call by a vessel.

### SULPHUR CHARGES

For vessels calling at the Port of Gothenburg, an extra charge is payable if the sulphur content of the fuel for the vessel's operation exceeds 0.2 per cent by weight according the following table.

| Sulphur content (per cent weight) | Charge / GT | Charge / GT after deduction |
|---|---|---|
| **0.00 – 0.20** | SEK 0.00 | |
| **0.21 – 0.50** | SEK 0.10 | 0.00 |
| **> 0.50** | SEK 0.20 | SEK 0.10* |

* On 1 April 2010 the sulphur emission charge was halved for all vessels categories from SEK 0.20 to SEK 0.10 GT. The deduction applies until 31 December 2013

### NITRIC OXIDE DISCOUNT

Ships that by various measures have reduced their nitric oxide emissions to less than 10 grams per kWh are given a reduction of the harbour dues as follows

| Emission level in grams of $NO_X$ / kWh | Reduction in SEK per unit of ship's gross tonnage (GT) |
|---|---|
| **6.0 – 9.9** | SEK 0.05 / GT |
| **2.0 – 5.9** | SEK 0.10 / GT |
| **0.0 – 1.9** | SEK 0.20 / GT |

## ENVIRONMENTALLY RELATED DUES IN THE PORT OF STOCKHOLM

The following tariffs are used in the port of Stockholm

| Normal tariff | Description | SEK | Unit |
|---|---|---|---|
| **Sulphur rebate*** | Sulphur content >0.2 but < 0.5 % | - 0.10 | GT |
| | Sulphur content ≤ 0.2 | - 0.20 | GT |
| **Nitric Oxide rebate**** | 5 g/kWh < Nitric Oxide content <10 g/kWh | - 0.15 | GT |
| | 1 g/kWh < Nitric Oxide content ≤ 5 g/kWh | - 0.25 | GT |
| | Nitric Oxide content ≤ 1 g/kWh | - 0.30 | GT |

* Vessels with a sulphur content in the fuel below 0.5 percent per weight will receive a discount provided that the Swedish Maritime Administration has issued a valid Sulphur Oxide Reduction Certificate in accordance with SJÖFS 1998:13. Notification of a Sulphur Oxide Reduction Certificate should be submitted to the Port and Traffic department (BTC) when reporting a vessel's first call into port.

**Vessels, which through different actions have reduced nitric oxide emissions to less than 10 grams per kilowatt hour, will be granted a reduction in harbour dues for vessels provided that the Swedish Maritime Administration has issued a valid Nitric Oxide Certificate in accordance with SJÖFS 1998:13. Notification of this Nitric Oxide Certificate should be submitted to the Port and Traffic department (BTC) when reporting a vessel's first call into port.

# ENVIRONMENTALLY RELATED DUES IN THE PORT OF MARIEHAMN

§ 7 ENVIRONMENTAL DIFFERENTIATION

In order to reduce air pollution caused by shipping, the following environmental differentiation is included in the rates;

Reduction granted on measures taken in order to reduce emissions of nitric oxides and sulphur dioxides from the ships:

1. For vessels with emissions of nitric oxides with the maximum level of 10 grams per kWh of the output of the vessel's all auxiliary and main engines at 75 per cent engine load, the harbour charge is reduced according to rectilinear scale so that the maximum level of 10 grams entitles to 1 per cent reduction and the level below 1 gram entitles to 8 per cent reduction on the rate. In calculation of the discount the percentage is given in two decimals.
2. A vessel using bunker oil with sulphur content up to the maximum of 0.5 percentage by weight only, is granted a 4 per cent discount, and those with the maximum of 0.1 percentage by weight are given a discount of 8 per cent.
3. Vessels with emissions of nitric oxides less than 1 gram per kWh of the power of the vessel's all engines, according to the above mentioned, and also using bunker oil with a sulphur content with the maximum of 0.5 percentage by weight are granted a bonus discount of 8 per cent.

Reductions concerning nitric oxide are only granted to vessels which can verify that they are continuously operated with equipment reducing the nitric oxide.

A precondition for the reduction concerning sulphur is that only bunker oil with the sulphur content less than 0.5 percentage of weight is stored in all bunker tanks of the vessel. When requested, the captain can verify that this is and has been the case by presenting verifications, bunker receipts etc, and can give her/his consent to the taking of specimens from all bunker tanks.

When the vessel submits a notification of its arrival at the port, in order to apply for a discount the vessel shall present a valid and by a maritime authority written certificate indicating the emission reduction. Regarding the nitric emission, the certificate shall include, apart from the nitric oxide emissions in gram $NO_X$ per kWh of the individual engines, a report on calculated weight average value for the vessel's total $NO_X$ emission in gram /kWh with one decimal at 75 per cent engine load for the total installed engine output. These reductions do not apply to charges for laying up

# APPENDIX F: SCRUBBERS

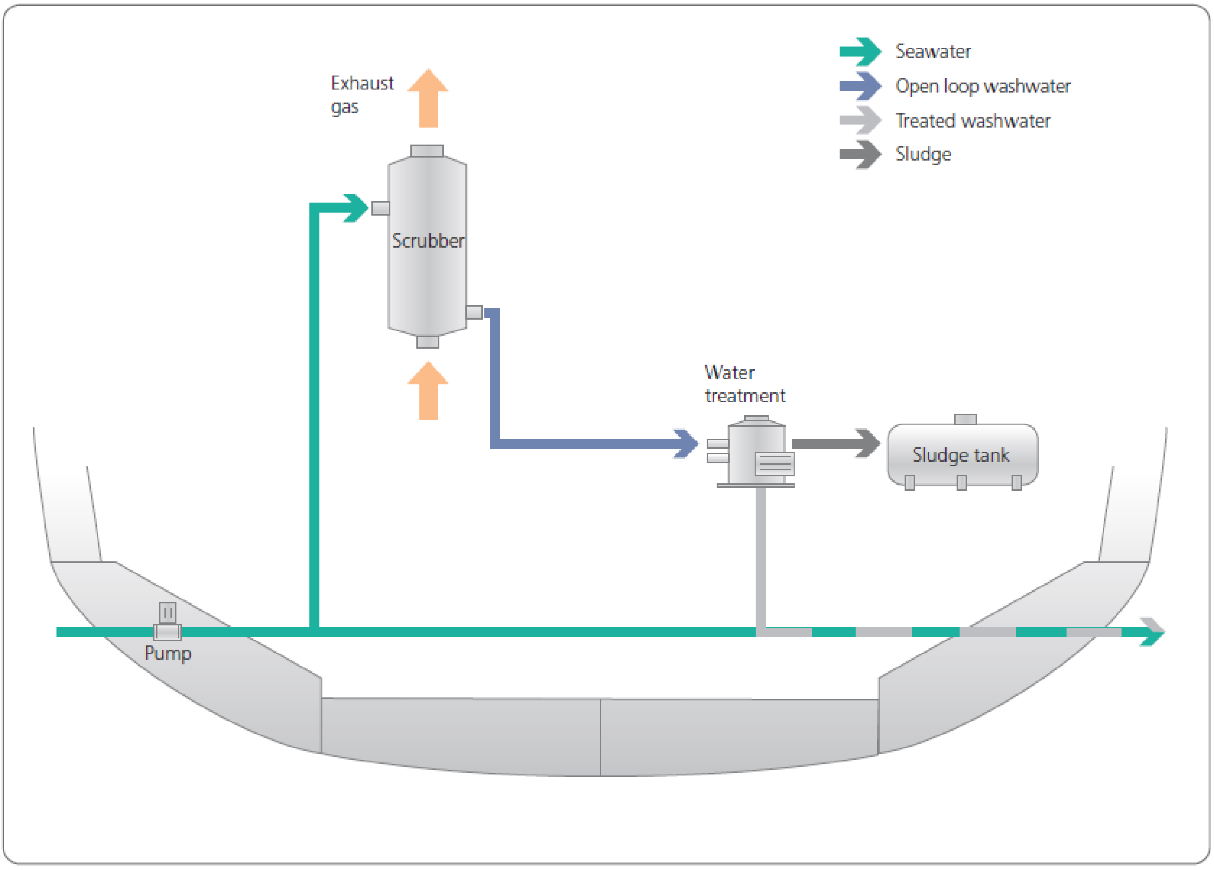



Figure 8: An open loop wet $SO_x$ scrubbing system

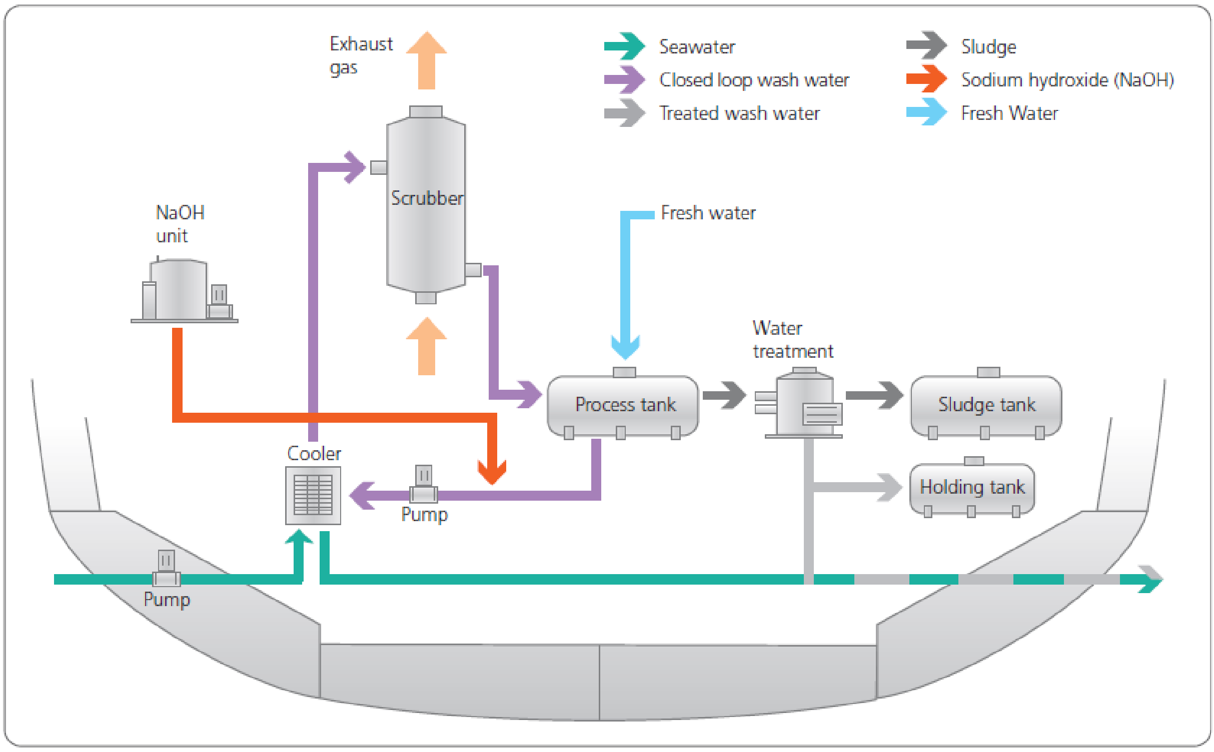



Figure 9: A closed loop wet $SO_x$ scrubbing system

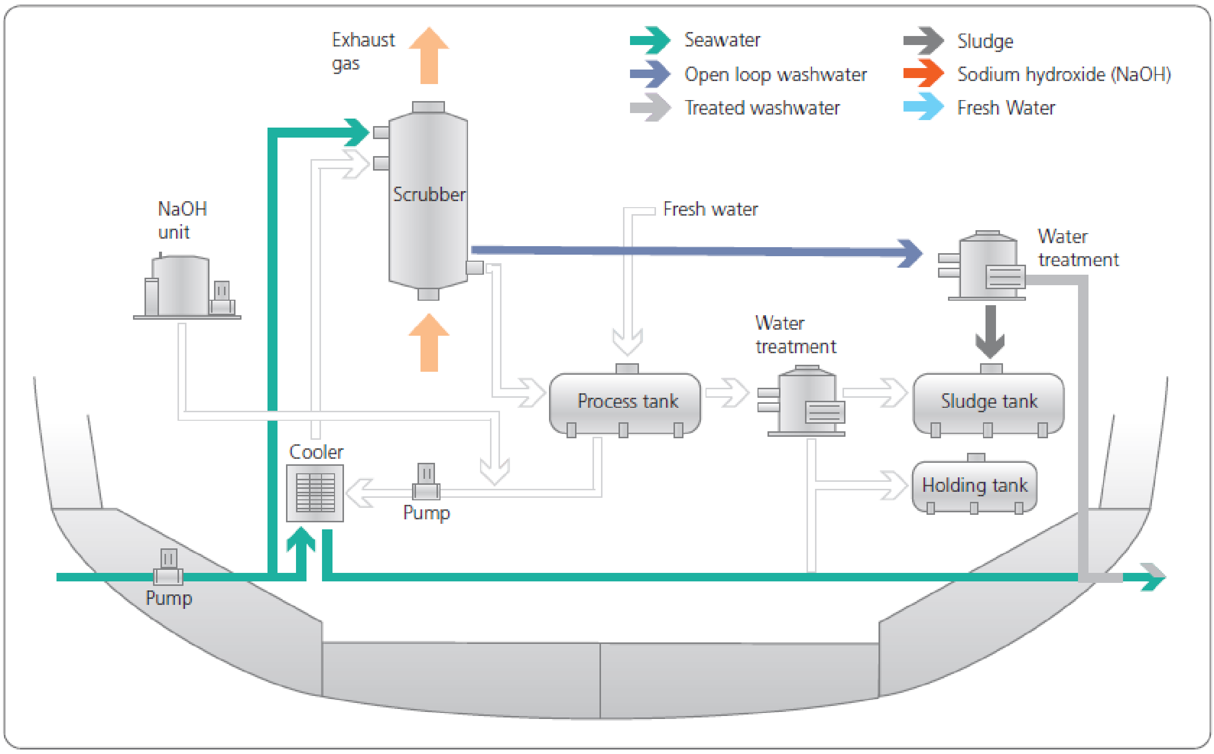



Figure 10a: A hybrid $SO_x$ scrubbing system, operating in open loop mode

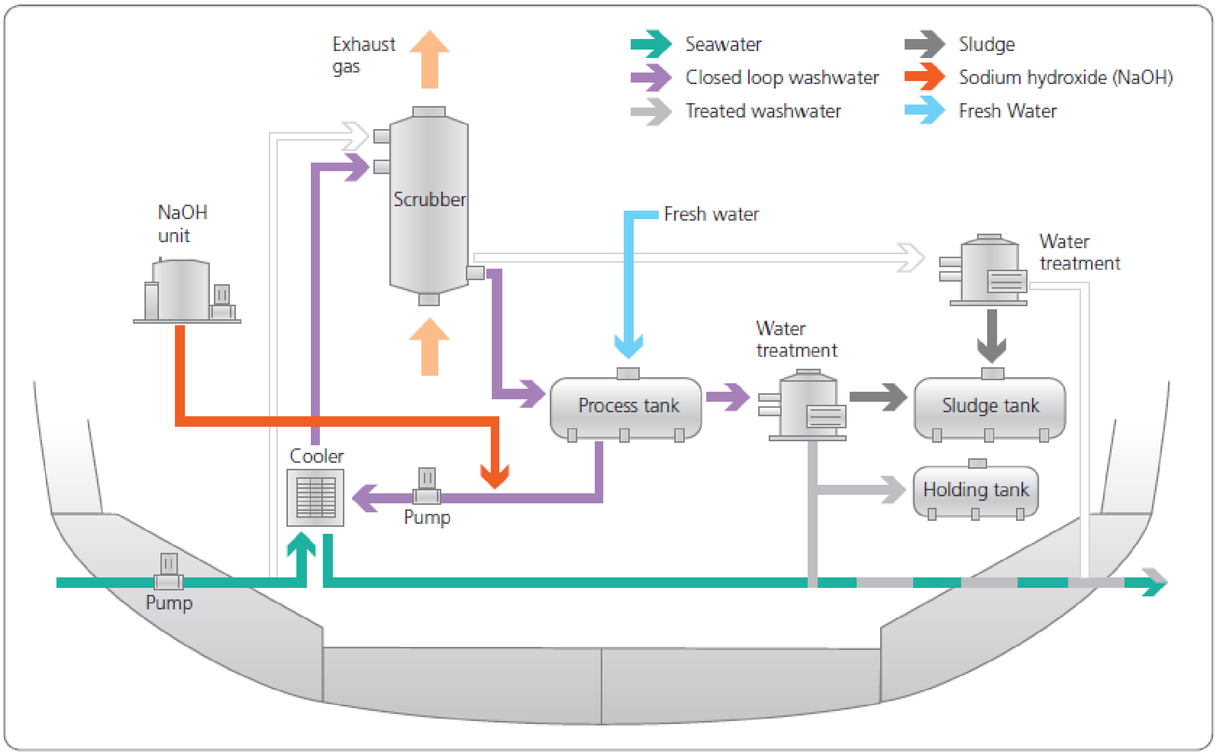
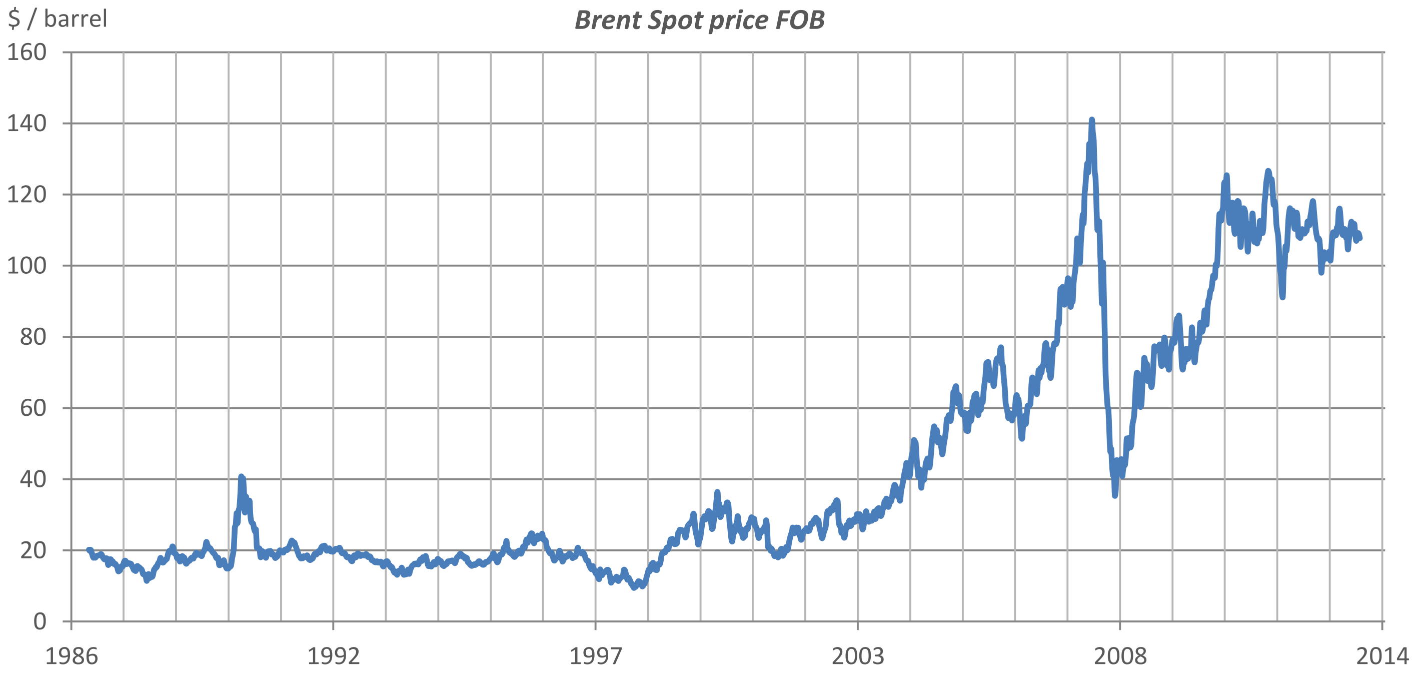



Figure 10b: A hybrid $SO_x$ scrubbing system, operating in closed loop mode

| | Wet scrubber, open loop | Wet scrubber, closed loop and hybrid | Dry scrubber |
|---|---|---|---|
| Main system components | •Scrubber | •Scrubber | •Absorber |
| | •Washwater piping | •Washwater piping | •Fresh granulate hopper |
| | •Washwater pumps | •Washwater pumps | •Used granulate hopper |
| | •Washwater treatment equipment | •Washwater processing tank | •Granulate transport system |
| | •Sludge handling equipment | •Washwater holding tank | •Additional granulate storage (new and used granules) |
| | | •Sodium hydroxide storage tank | |
| | | •Washwater treatment equipment | |
| | | •Sludge handling equipment | |
| Operation in fresh water | ✗ | ✓ | ✓ |
| Operation without discard at sea | No | For a limited time depending on the size of the washwater holding tank | yes |
| Weight Typical values for a 20MW SOX scrubber | 30-55t (Excluding washwater system and treatment equipment) | 30-55t (Excluding washwater system, treatment equipment, washwater processing tank and washwater holding tank) | ≈200t (Including granules stored adjacent to the absorber but excluding additional granulate storage) |
| Power consumption (% of max. scrubbed engine power) | 1-2% | 0,5-1% | 0,15-0,2% |
| Scrubbing chemical consumable | No consumale | Sodion hydroxide solution (≈6 l/MWh·%S) | Calcium hydroxide granules (≈10 kg/MWh·%S) |
| Compatibility with waste heat recovery system (WHRS) | Yes, provided the scrubber is installed after the WHRS | Yes, provided the scrubber is installed after the WHRS | Yes. Can be placed before or after the WHRS |
| Compatibility with SCR system | No, unless a reheater is fitted after the wet scrubber to raise the exhaust gas temperature | No, unless a reheater is fitted after the wet scrubber to raise the exhaust gas temperature | ✓ |
| Compatibility with EGR system | ✓ | ✓ | ✓ |
| Particulate matter removal | ✓ | ✓ | ✓ |

# APPENDIX G: FTA COUNTRIES

# APPENDIX H: BRENT SPOT PRICE FOB



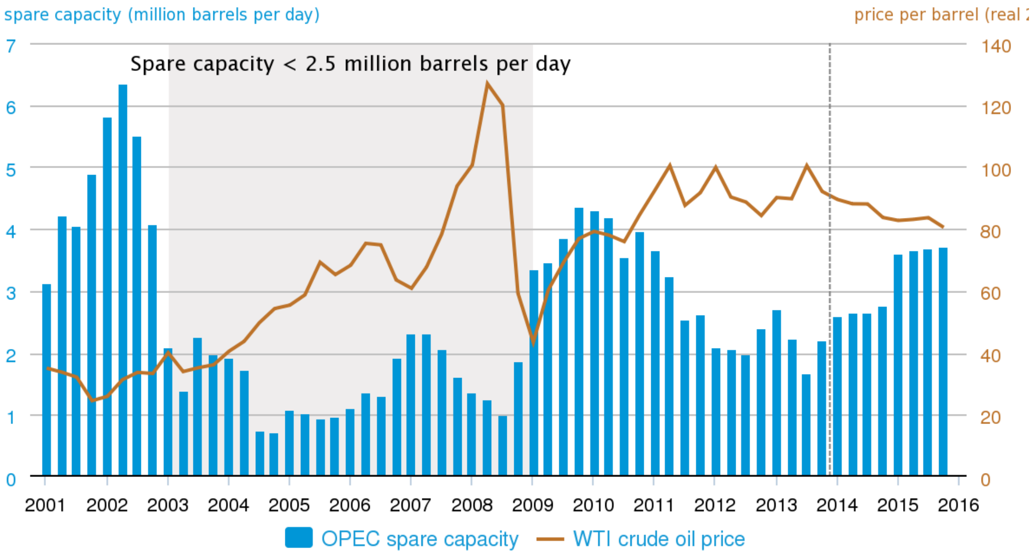
# APPENDIX I: OPEC COUNTRIES

| | |
|---|---|
| Algeria | (1969 - present) |
| Angola | (2007 - present) |
| Ecuador | (1973 - 1992 and 2007 - present) |
| Iran | (1960 - present) |
| Iraq | (1960 - present) |
| Kuwait | (1960 - present) |
| Libya | (1962 - present) |
| Nigeria | (1971 - present) |
| Qatar | (1961 - present) |
| Saudi Arabia | (1960 - present) |
| United Arab Emirates | (1967 - present) |
| Venezuela | (1960 - present) |

**Countries no longer members of OPEC:**

| | |
|---|---|
| Gabon | (1975 - 1994) |
| Indonesia | (1962 - 2008) |

**OPEC spare production capacity and WTI crude oil prices**




Source: U.S. Energy Information Administration, Thomson Reuters.
Updated: Monthly | Last Updated: 1/7/2014

# APPENDIX J : DETAIL OF LLOYDS REGISTER ENGINEERING SERVICES DATABASE

| Characteristic of database | no. | Comments |
|---|---|---|
| Number of vessels | 50 | Ages between 1963 - 1990 with deadweight of 80 - 172810 |
| Ro-Ro ferries | 14 | |
| Tanker | 11 | |
| Container | 3 | |
| Dredger | 6 | |
| Bulk carrier | 6 | |
| Tug | 8 | |
| Rhine barge | 1 | |
| Naval unit | 1 | |
| Number of engines included | 56 | |
| Slow speed | 15 | Range 5296 - 21634 kW |
| Medium speed | 41 | range 364 - 7700 kW |
| Number of fuels analyses | 48 | |
| HFO | 9 | |
| Intermediate FO | 2 | |
| Light FO | 19 | |
| Gas oil | 18 | |
| Number of emissions measurements | | |
| $NO_X$ | 280 | |
| $SO_2$ | 280 | |
| $CO_2$ | 280 | |
| PM, | 24 | |

# APPENDIX K: DATA USED IN MODEL

**Conversion factors**

| 1 unit of | = | to |
|---|---|---|
| 1 km = | 0.539957 | nm |
| 1 knots = | 1.852 | km/h |
| 1 mt = | 48.6 | mmBtu |
| 1 mmBtu = | 5.41 | boe |
| 1 € = | 1.3616 | $ |

**Sailingprofile**

| | days | .. in year |
|---|---|---|
| day | 1 | 365 |
| week | 7 | 52.14 |
| month | 30 | 12.17 |
| year | 365 | 1 |

ik

**NaOH**

| | | |
|---|---|---|
| Costs | 375 | $ / t |
| Density | 1.52 | t / m3 |

**Sludge**

| | | |
|---|---|---|
| Costs | 200 | € / t |

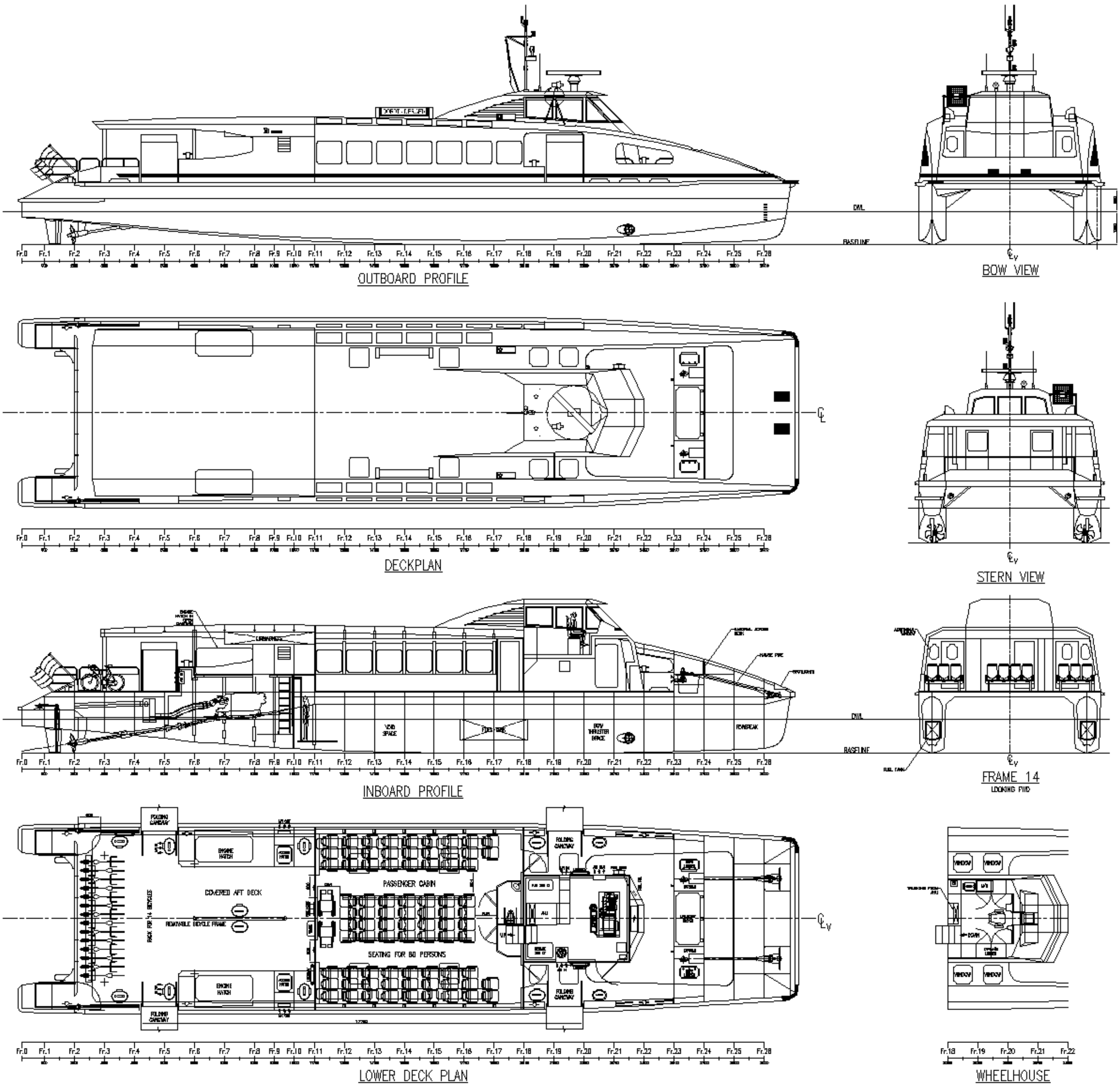
**Fuel data**

| | | LNG | EN 590 | MGO | HFO | LSF |
|---|---|---|---|---|---|---|
| Base price | $ / mt | $ 523.00 | $ 1,188.08 | $ 873.50 | $ 564.00 | $ 594.00 |
| % fuel for other consumables | | 5 % | 10% | 10% | 15% | 10% |
| CF | | 2.75 | 3.15 | 3.21 | 3.11 | 3.15 |
| LHV | kJ/kg | 49709 | 42780 | 42500 | 40500 | 41000 |
| Density | [kg/m3] | 452,48 | 839 | 860.00 | 983.60 | 840.00 |
| SFC correction | | 84 % | | | | |
| $NO_X$ correction | | 10 % | 100 % | 100 % | 100 % | 100 % |
| PM correction | | 0.01 % | 100 % | 100 % | 100 % | 100 % |
| Composition | $CO_2$ | 0.00 % | 85.9 % | 87.5 % | 85.0 % | 86.0 % |
| | S | 0.0000 % | 0.001 % | 0.10 % | 3.50 % | 1.00 % |
| | $CH_4$ | 94.00 % | | | | |
| | $C_2H_6$ | 4.70 % | | | | |
| | $C_3H_8$ | 0.80 % | | | | |
| | $C_4H_{10}$ | 0.20 % | | | | |
| | $C_5H_{12}$ | 0.00 % | | | | |
| | $N_2$ | 0.30 % | | | | |

**Aftertreatment system**

| Reduction | $CO_2$ | $SO_2$ | $NO_X$ | PM | Extra power | Investment | Extra costs per year | Other costs per | years | Sludge | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Installation** | % | % | % | % | % | € / kW | € / kWh | € / kW | | g/kWh | € / kWh |
| **None** | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0 | 0 | | 0 | 0.000 |
| **SCR** | 0.0 | 0.0 | 85.0 | 0.0 | 1.0 | 50 | 0.0065 | 10 | 5 | 0 | 0.000 |
| **Open loop scrubber** | 0.0 | 98.0 | 0.0 | 80.0 | 1.4 | 150 | 0 | 0 | | 0.2 | 0.000 |
| **Closed loop scrubber** | 0.0 | 98.0 | 0.0 | 80.0 | 0.5 | 200 | 0.2386 | 0 | | 0.2 | 0.000 |
| **Hybrid scrubber** | 0.0 | 98.0 | 0.0 | 80.0 | 1.0 | 250 | 0.1193 | 0 | | 0.2 | 0.000 |
| **SCR + Open loop Scrubber** | 0.0 | 98.0 | 85.0 | 80.0 | 2.4 | 200 | 0.0065 | 15 | 5 | 0.2 | 0.00004 |
| **SCR + Closed loop Scrubber** | 0.0 | 98.0 | 85.0 | 80.0 | 1.5 | 250 | 0.2451 | 15 | 5 | 0.2 | 0.000 |
| **SCR + Hybrid Scrubber** | 0.0 | 98.0 | 85.0 | 80.0 | 2.0 | 300 | 0.1258 | 15 | 5 | 0.2 | 0.000 |

# APPENDIX L: GENERAL ARRANGEMENT DFF 3007



# APPENDIX M: DATASHEET DFF 3007

## DAMEN WATER BUS® 3007
"VLIJ" & "SCHIE"

### GENERAL

| | |
|---|---|
| YARD NUMBER | 538201 and 538202 |
| DELIVERY DATE | 2004 / 2006 |
| HULL MATERIAL | Aluminium |
| SUPERSTRUCTURE | Aluminium |
| BASIC FUNCTIONS | Fast Passenger Ferry |
| CLASSIFICATION | Bureau Veritas<br>1 ✠ HULL, • MACH, Lightship / Fast Passenger Vessel, Sheltered Area |
| SAFETY | National authorities requirements for inland waters |
| FLAG | The Netherlands |
| OWNER | Waterbus B.V. |

### DIMENSIONS

| | |
|---|---|
| LENGTH O.A. | 31.30 m |
| BEAM O.A. | 7.70 m |
| DEPTH MOULDED | 2.49 m |
| DRAUGHT (HULL) | 1.41 m |

### TANK CAPACITIES

| | |
|---|---|
| FUEL | 2.00 $m^3$ |
| FRESH WATER | 0.22 $m^3$ |
| SEWAGE | 0.22 $m^3$ |

### PERFORMANCE

| | |
|---|---|
| SPEED AT 90% MCR | 21 kn. at 12 tonnes deadweight |
| WASH, MAXIMUM | 0.25 m (crest to through) at 35 m from vessel transit line |

### PROPULSION SYSTEM

| | |
|---|---|
| MAIN ENGINES | 2 x Caterpillar C 12 |
| TOTAL POWER | 732 bkW (980 bhp) at 2300 rpm |
| GEARBOXES | 2 x Twin Disc 5114A |
| PROPULSION | 2 x CuNiAl Fixed pitch propellers |

### AUXILIARY EQUIPMENT

| | |
|---|---|
| GENERATOR | 1 X 32 kWe |
| NETWORK | 400V / 230V AC, 3 phase , 50 Hz, 24V DC |

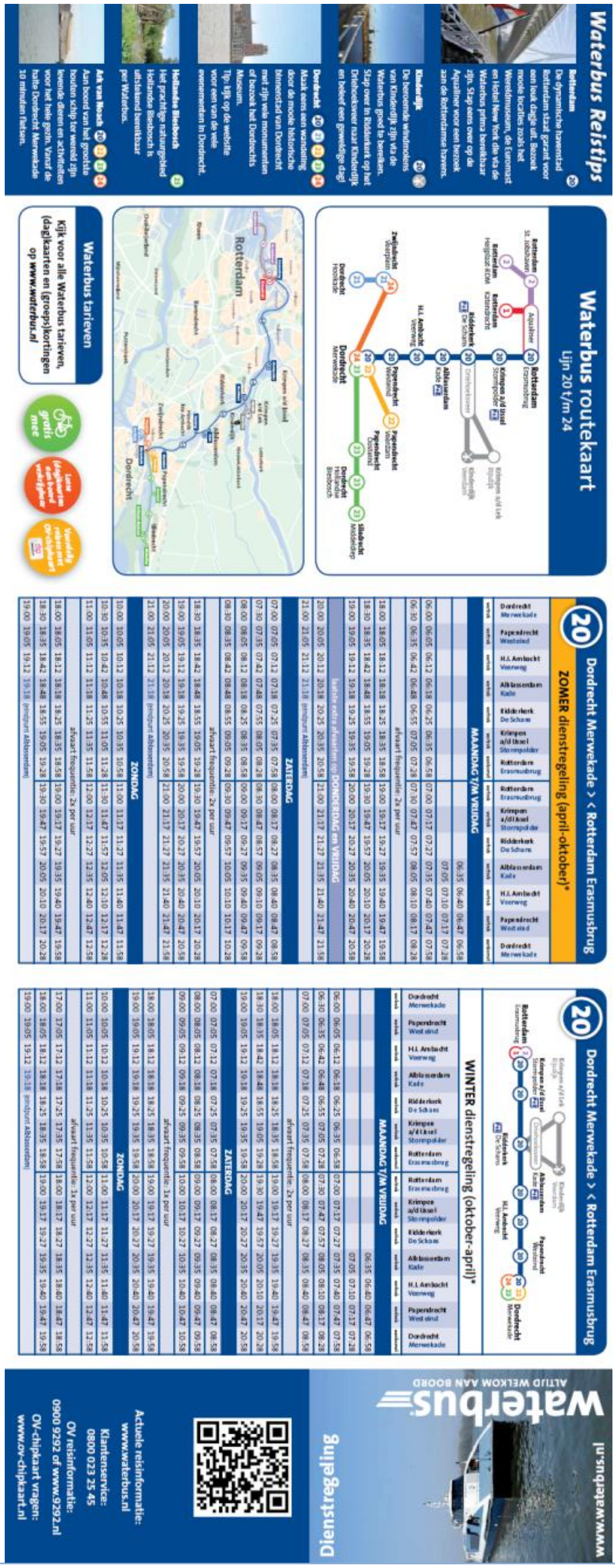
### ACCOMMODATION

| | |
|---|---|
| PASSENGERS | 130 (80 seated + 50 standing) |
| CARGO | 1.50 tonnes (bicycles, etc.) |
| TOILETS | 1 |
| CREW | 2 |
| HVAC | Ventilation and heating in passenger saloon, A/C in wheelhouse |

### NAUTICAL, SURVEILLANCE AND COMMUNICATION EQUIPMENT

| | |
|---|---|
| GPS | Koden KGP 913D |
| MAGNETIC COMPASS | Ritchie |
| RATE OF TURN INDICATOR | Turnmaster 40 |
| ECHO SOUNDER | Koden CVS 118 |
| RADAR | MK 6217 River Radar |
| VHF RADIO | RT 2048 AK |
| GSM | Nokia 810 with Car Kit |
| INTERCOM AND PA | Phonetech |

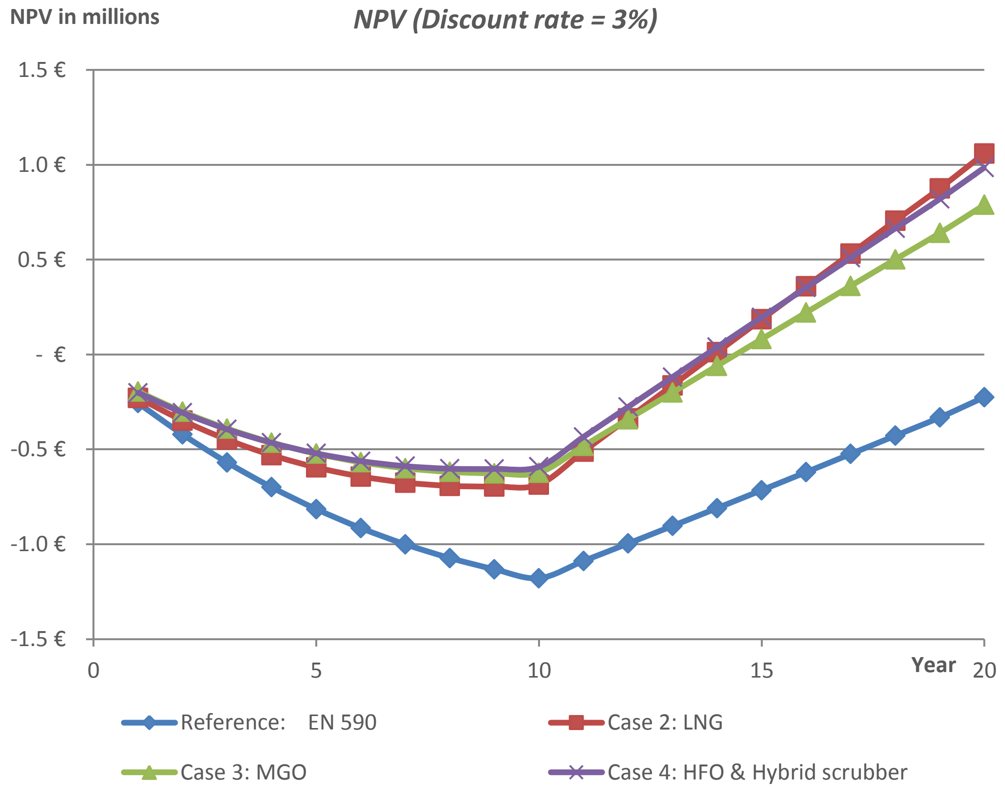
# APPENDIX N: TIMETABLE WATERBUS



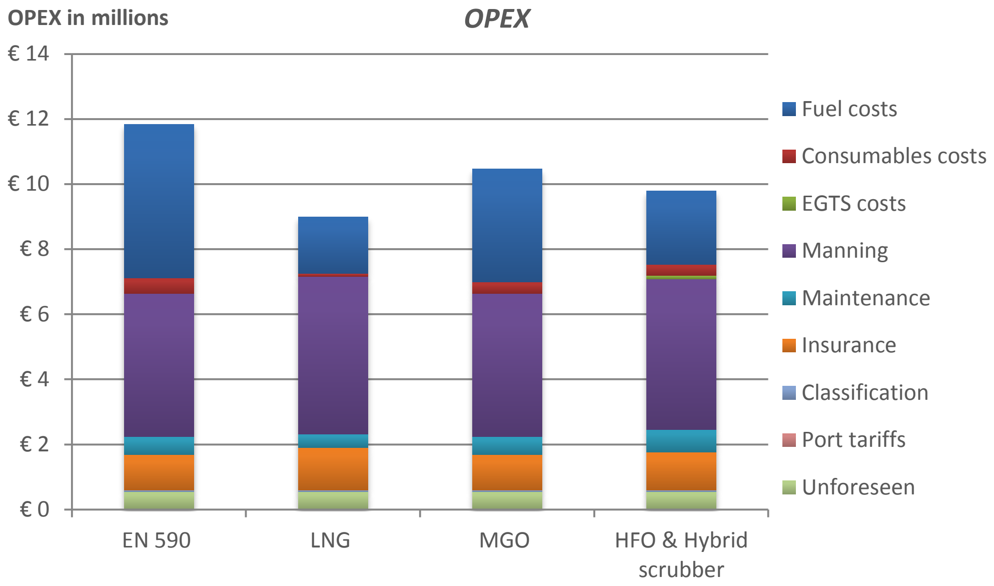
# APPENDIX O: LCPA RESULTS

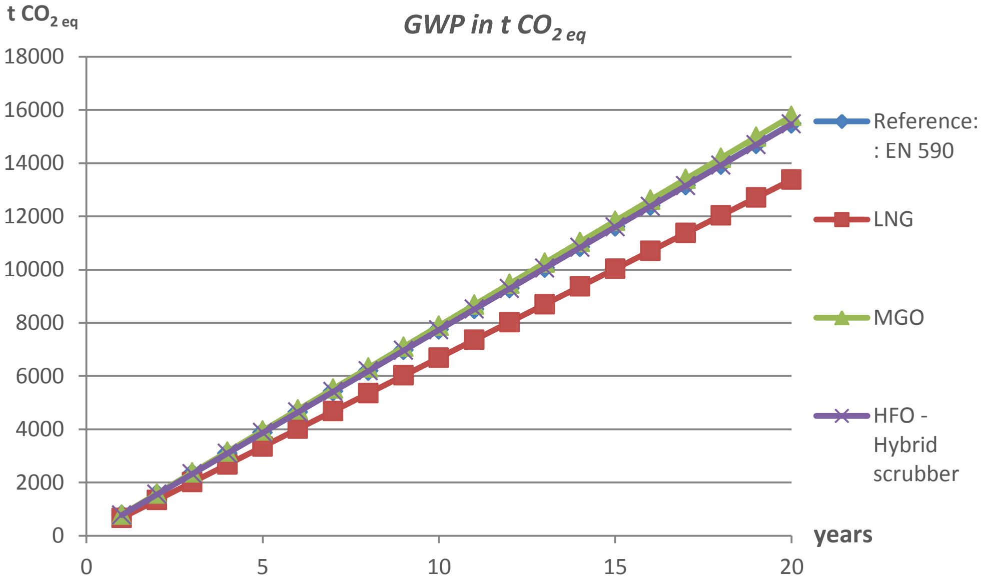
## FIRST LCPA: ALL BASE PRICES

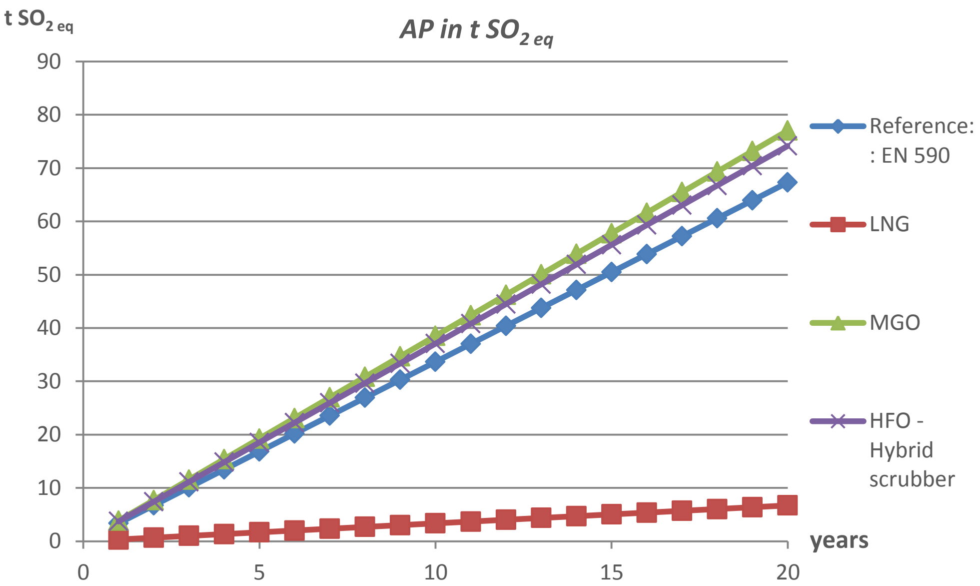
| | | Reference | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|---|
| | | EN 590 | LNG | MGO | HFO & Hybrid scrubber |
| **Fuel** | - | EN 590 | LNG | MGO | HFO |
| **Fuel price** | $ / mt | $ 1,188.08 | $ 523.00 | $ 873.50 | $ 564.00 |
| **EGTS** | - | None | None | None | Hybrid scrubber |
| | | **LCA result** | | | |
| **GWP** | t $CO_{2\ eq}$ / year | 774.238 | 668.667 | 788.659 | 773.404 |
| **AP** | t $SO_{2\ eq}$ / year | 3.366 | 0.336 | 3.852 | 3.708 |
| **EP** | t $PO_{4\ eq}$ / year | 0.624 | 0.062 | 0.624 | 0.624 |
| **PM** | t PM / year | 0.381 | 0.000 | 0.393 | 1.021 |
| | | **LCC result** | | | |
| **NPV** | | -€ 224,650 | € 1,059,599 | € 789,356 | € 985,602 |
| **IRR** | | 2.38 % | 5.36 % | 5.11 % | 5.45 % |
| | | **Deviation in percentages** | | | |
| **% GWP** | | 0% | -14 % | 2 % | 0 % |
| **% AP** | | 0% | -90 % | 14 % | 10 % |
| **% EP** | | 0% | -90 % | 0 % | 0 % |
| **% PM** | | 0% | -100 % | 3 % | 168 % |
| **% NPV** | | 0% | -572 % | -451 % | -539 % |
| **% IRR** | | 0% | -125 % | -115 % | -129 % |

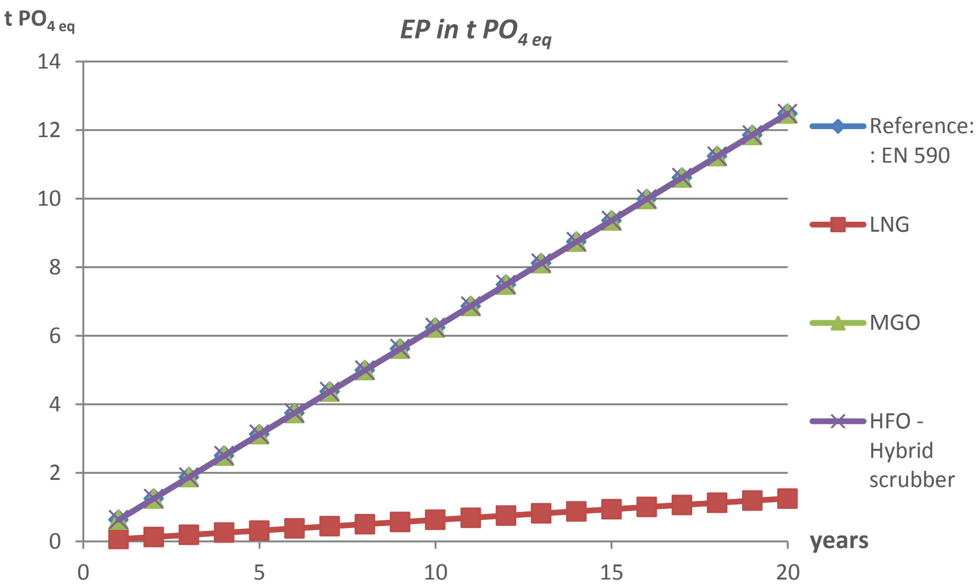


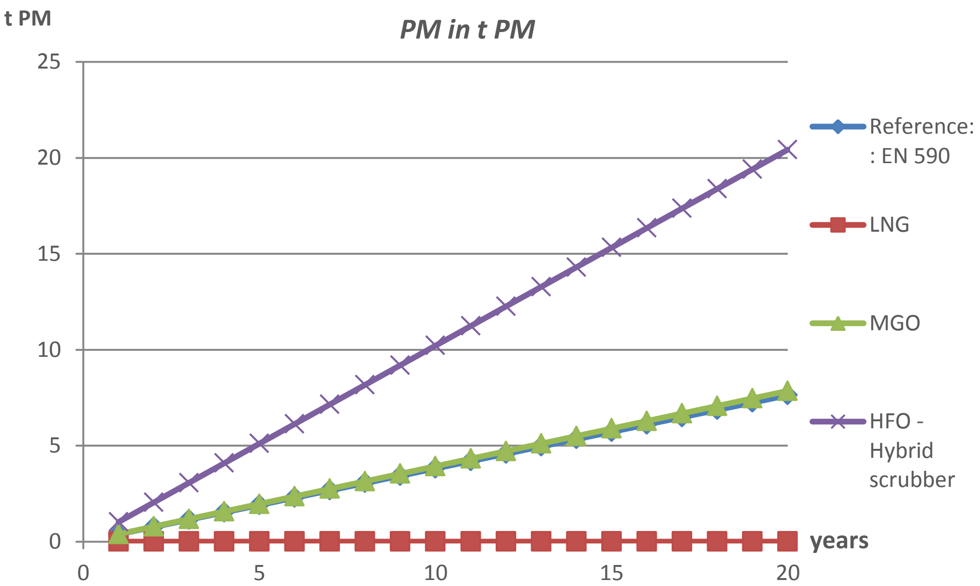
| | Reference: EN 590 | LNG | MGO | HFO & Hybrid scrubber |
|---|---|---|---|---|
| **Fuel costs** | € 4,726,044 | € 1,738,948 | € 3,474,688 | € 2,264,844 |
| **Consumables costs** | € 472,604 | € 86,947 | € 347,469 | € 339,727 |
| **EGTS costs** | € 0 | € 0 | € 0 | € 109,150 |
| **Manning** | € 4,403,801 | € 4,844,181 | € 4,403,801 | € 4,623,991 |
| **Maintenance** | € 550,475 | € 412,856 | € 550,475 | € 688,094 |
| **Insurance** | € 1,100,950 | € 1,321,140 | € 1,100,950 | € 1,181,320 |
| **Classification** | € 33,029 | € 33,029 | € 33,029 | € 33,029 |
| **Port tariffs** | € 0 | € 0 | € 0 | € 0 |
| **Unforeseen** | € 550,475 | € 550,475 | € 550,475 | € 550,475 |
| **OPEX** | € 11,837,379 | € 8,987,577 | € 10,460,887 | € 9,790,629 |



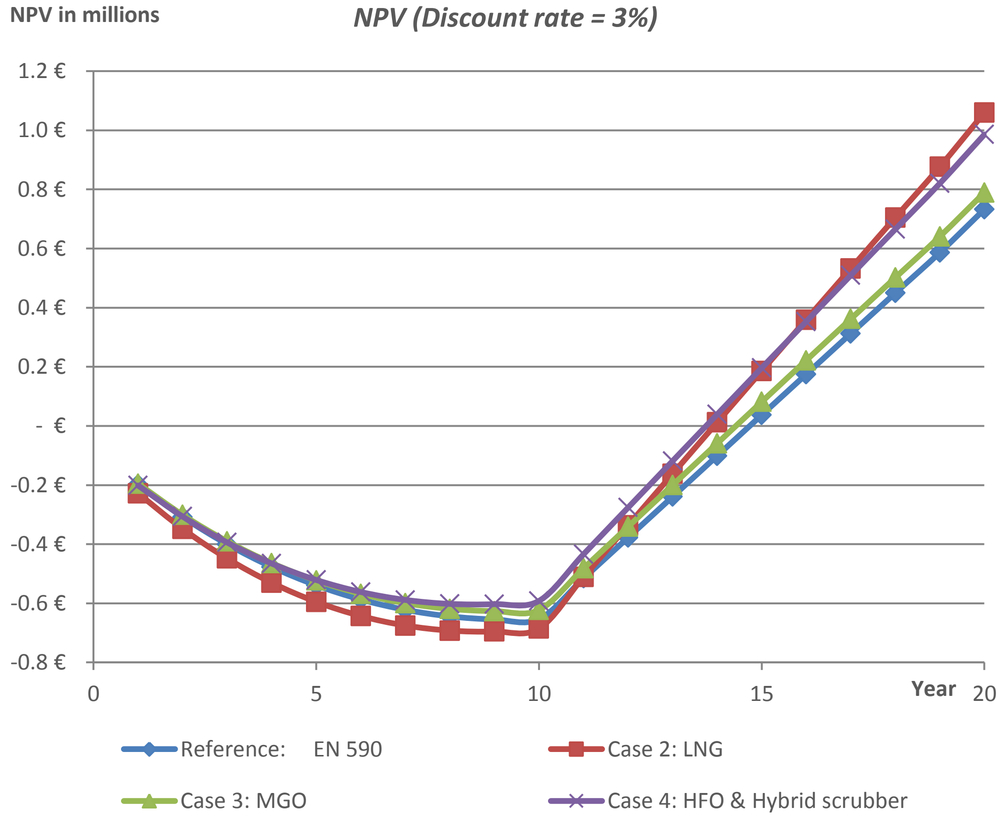

t $SO_{2\ eq}$
AP in t $SO_{2\ eq}$
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber


t $PO_{4\ eq}$
EP in t $PO_{4\ eq}$
14
12
10
8
6
4
2
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

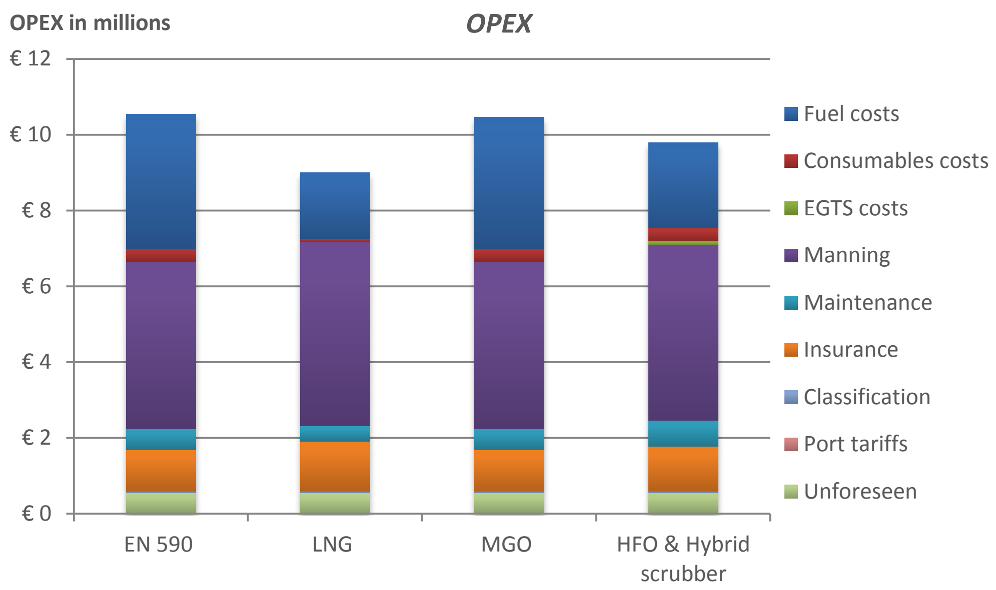

t PM
PM in t PM
25
20
15
10
5
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

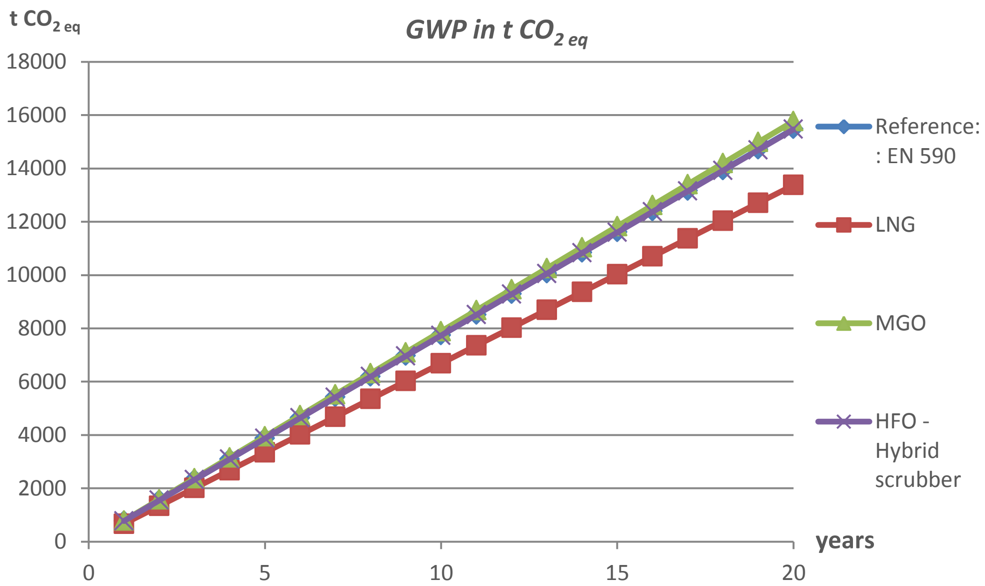
# SECOND LCPA: LOWER EN 590 PRICE

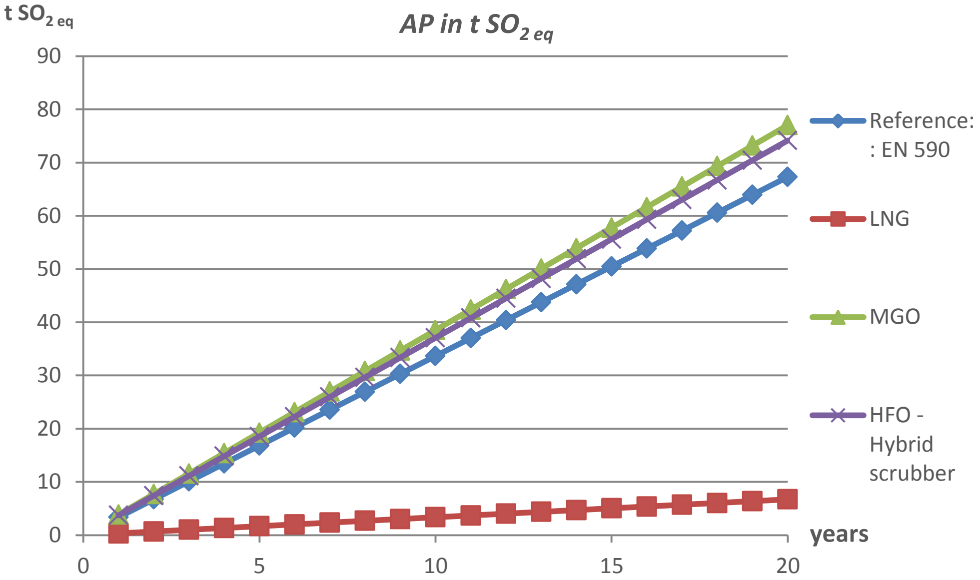
| | | *Reference* | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|---|
| | | *EN 590* | LNG | MGO | HFO & Hybrid scrubber |
| **Fuel** | - | *EN 590* | LNG | MGO | HFO |
| **Fuel price** | $ / mt | *$ 891.06* | $ 523.00 | $ 873.50 | $ 564.00 |
| **EGTS** | - | *None* | None | None | Hybrid scrubber |
| | | **LCA result** | | | |
| **GWP** | t $CO_{2\ eq}$ / year | *774.238* | 668.667 | 788.659 | 773.404 |
| **AP** | t $SO_{2\ eq}$ / year | *3.366* | 0.336 | 3.852 | 3.708 |
| **EP** | t $PO_{4\ eq}$ / year | *0.624* | 0.062 | 0.624 | 0.624 |
| **PM** | t PM / year | *0.381* | 0.000 | 0.393 | 1.021 |
| | | **LCC result** | | | |
| **NPV** | | *€ 732,759* | € 1,059,599 | € 789,356 | € 985,602 |
| **IRR** | | *4.96 %* | 5.36 % | 5.11 % | 5.45 % |
| | | **Deviation in percentage** | | | |
| **% GWP** | | *0%* | -14 % | 2 % | 0 % |
| **% AP** | | *0%* | -90 % | 14 % | 10 % |
| **% EP** | | *0%* | -90 % | 0 % | 0 % |
| **% PM** | | *0%* | -100 % | 3 % | 168 % |
| **% NPV** | | *0%* | -45 % | -8 % | -35 % |
| **% IRR** | | *0%* | -8 % | -3 % | -10 % |

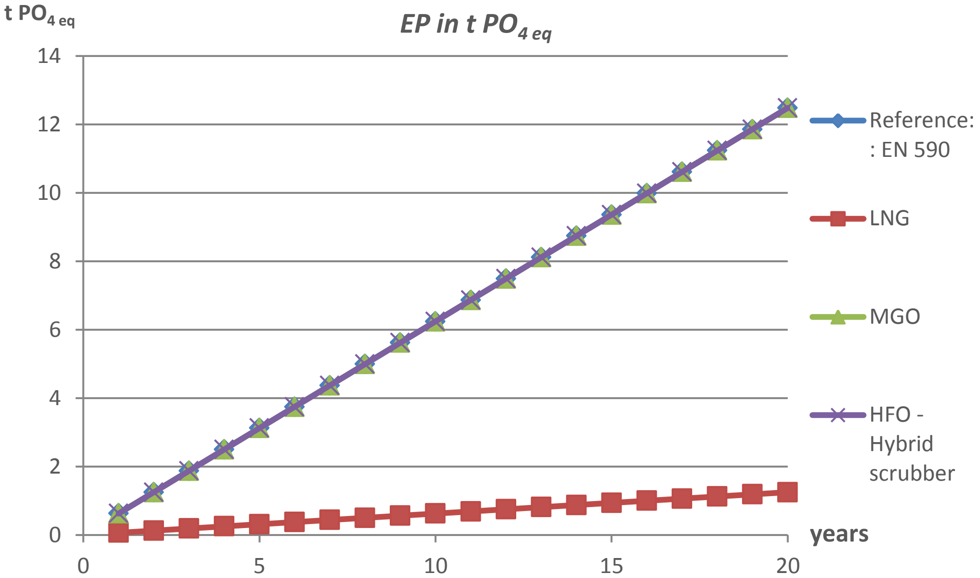


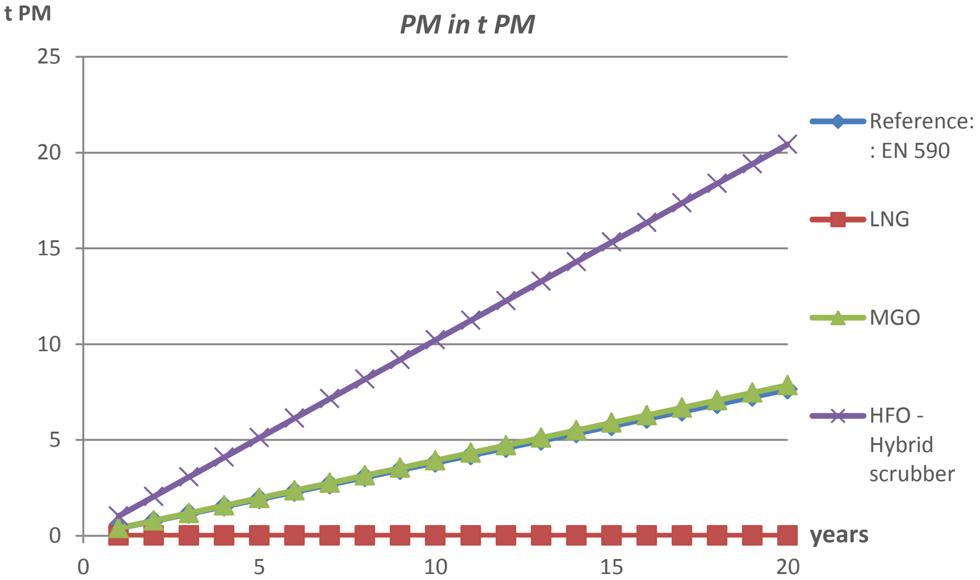
| | *Reference: EN 590* | LNG | MGO | HFO & Hybrid scrubber |
|---|---|---|---|---|
| **Fuel costs** | *€ 3,544,533* | € 1,738,948 | € 3,474,688 | € 2,264,844 |
| **Consumables costs** | *€ 354,453* | € 86,947 | € 347,469 | € 339,727 |
| **EGTS costs** | *€ 0* | € 0 | € 0 | € 109,150 |
| **Manning** | *€ 4,403,801* | € 4,844,181 | € 4,403,801 | € 4,623,991 |
| **Maintenance** | *€ 550,475* | € 412,856 | € 550,475 | € 688,094 |
| **Insurance** | *€ 1,100,950* | € 1,321,140 | € 1,100,950 | € 1,181,320 |
| **Classification** | *€ 33,029* | € 33,029 | € 33,029 | € 33,029 |
| **Port tariffs** | *€ 0* | € 0 | € 0 | € 0 |
| **Unforeseen** | *€ 550,475* | € 550,475 | € 550,475 | € 550,475 |
| **OPEX** | *€ 10,537,716* | € 8,987,577 | € 10,460,887 | € 9,790,629 |



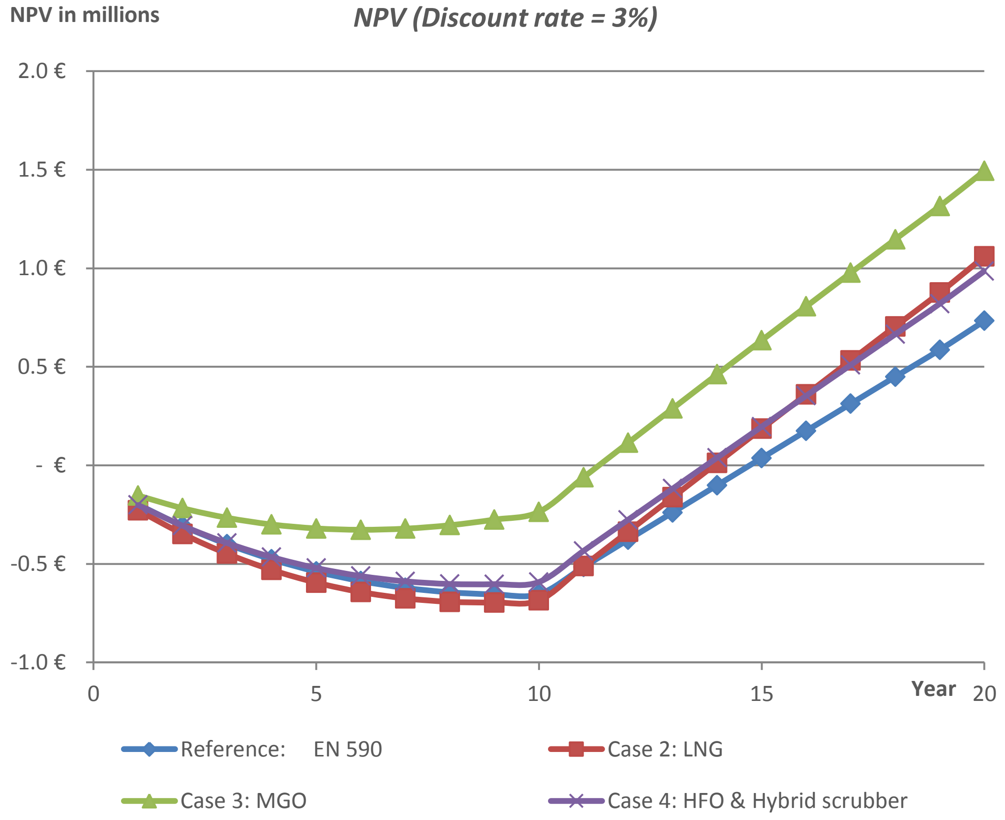

t $SO_{2\ eq}$
AP in t $SO_{2\ eq}$
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber


t $PO_{4\ eq}$
EP in t $PO_{4\ eq}$
14
12
10
8
6
4
2
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

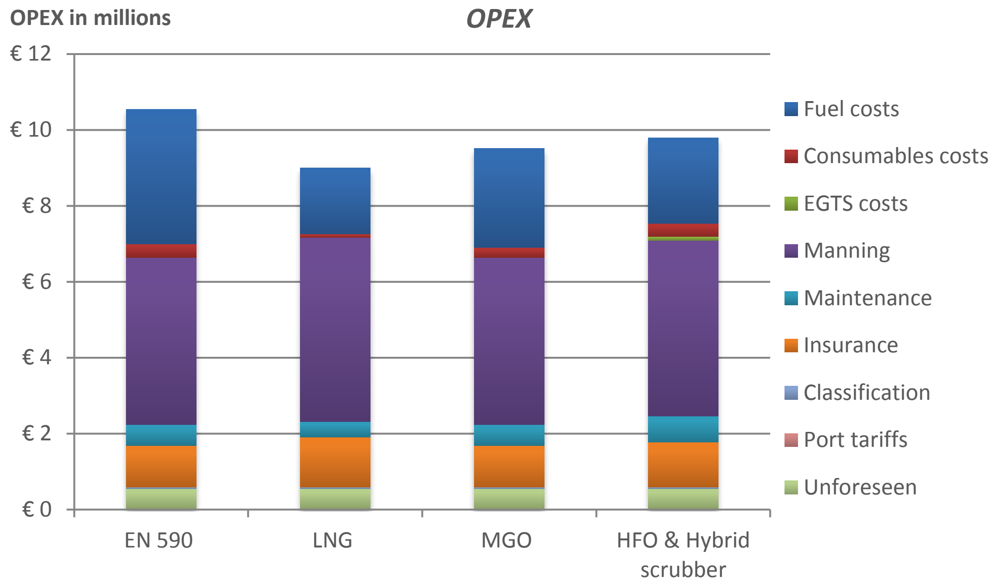

t PM
PM in t PM
25
20
15
10
5
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

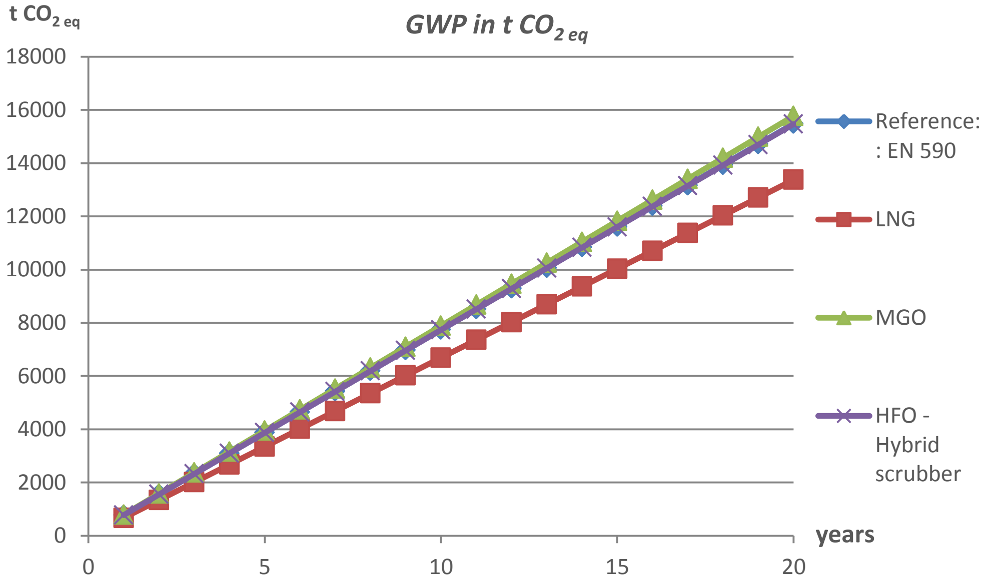
## THIRD LCPA: LOWER MGO PRICE

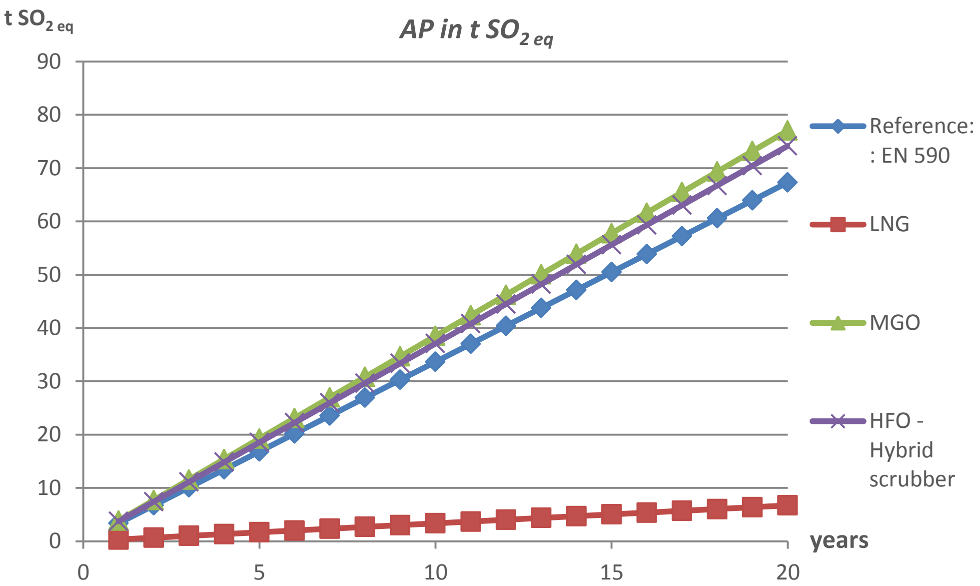
| | | Reference | Case 2 | *Case 3* | Case 4 |
|---|---|---|---|---|---|
| | | EN 590 | LNG | *MGO* | HFO & Hybrid scrubber |
| **Fuel** | - | EN 590 | LNG | *MGO* | HFO |
| **Fuel price** | $ / mt | $ 891.06 | $ 523.00 | *$ 655.13* | $ 564.00 |
| **EGTS** | - | None | None | *None* | Hybrid scrubber |
| | | **LCA result** | | | |
| **GWP** | t $CO_{2\ eq}$ / year | 774.238 | 668.667 | *788.659* | 773.404 |
| **AP** | t $SO_{2\ eq}$ / year | 3.366 | 0.336 | *3.852* | 3.708 |
| **EP** | t $PO_{4\ eq}$ / year | 0.624 | 0.062 | *0.624* | 0.624 |
| **PM** | t PM / year | 0.381 | 0.000 | *0.393* | 1.021 |
| | | **LCC result** | | | |
| **NPV** | | € 732,759 | € 1,059,599 | *€ 1,493,264* | € 985,602 |
| **IRR** | | 4.96 % | 5.36 % | *6.92 %* | 5.45 % |
| | | **Deviation in percentages** | | | |
| **% GWP** | | 0% | -14 % | *2 %* | 0 % |
| **% AP** | | 0% | -90 % | *14 %* | 10 % |
| **% EP** | | 0% | -90 % | *0 %* | 0 % |
| **% PM** | | 0% | -100 % | *3 %* | 168 % |
| **% NPV** | | 0% | -45 % | *-104 %* | -35 % |
| **% IRR** | | 0% | -8 % | *-39 %* | -10 % |

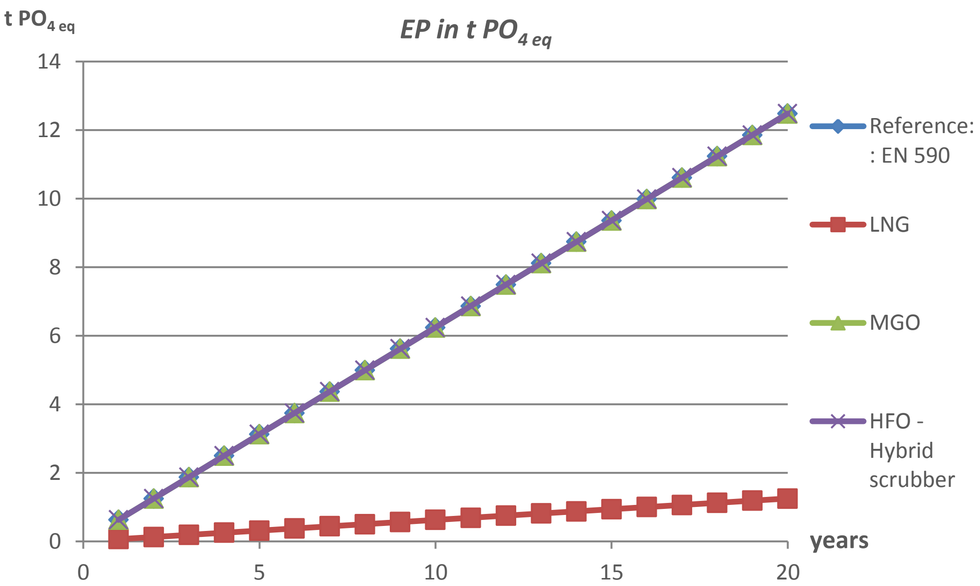


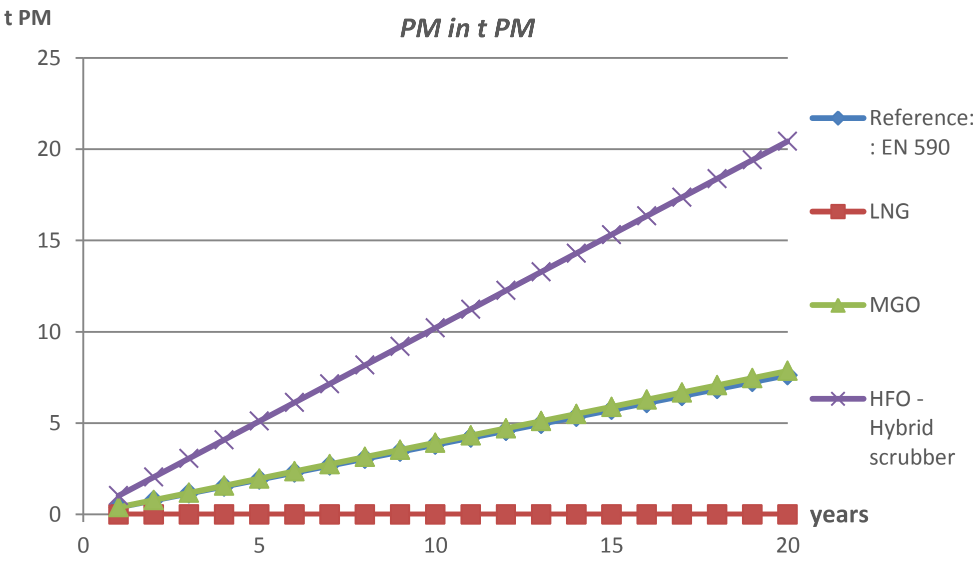
| | Reference: EN 590 | LNG | *MGO* | HFO & Hybrid scrubber |
|---|---|---|---|---|
| **Fuel costs** | € 3,544,533 | € 1,738,948 | *€ 2,606,016* | € 2,264,844 |
| **Consumables costs** | € 354,453 | € 86,947 | *€ 260,602* | € 339,727 |
| **EGTS costs** | € 0 | € 0 | *€ 0* | € 109,150 |
| **Manning** | € 4,403,801 | € 4,844,181 | *€ 4,403,801* | € 4,623,991 |
| **Maintenance** | € 550,475 | € 412,856 | *€ 550,475* | € 688,094 |
| **Insurance** | € 1,100,950 | € 1,321,140 | *€ 1,100,950* | € 1,181,320 |
| **Classification** | € 33,029 | € 33,029 | *€ 33,029* | € 33,029 |
| **Port tariffs** | € 0 | € 0 | *€ 0* | € 0 |
| **Unforeseen** | € 550,475 | € 550,475 | *€ 550,475* | € 550,475 |
| **OPEX** | € 10,537,716 | € 8,987,577 | *€ 9,505,348* | € 9,790,629 |



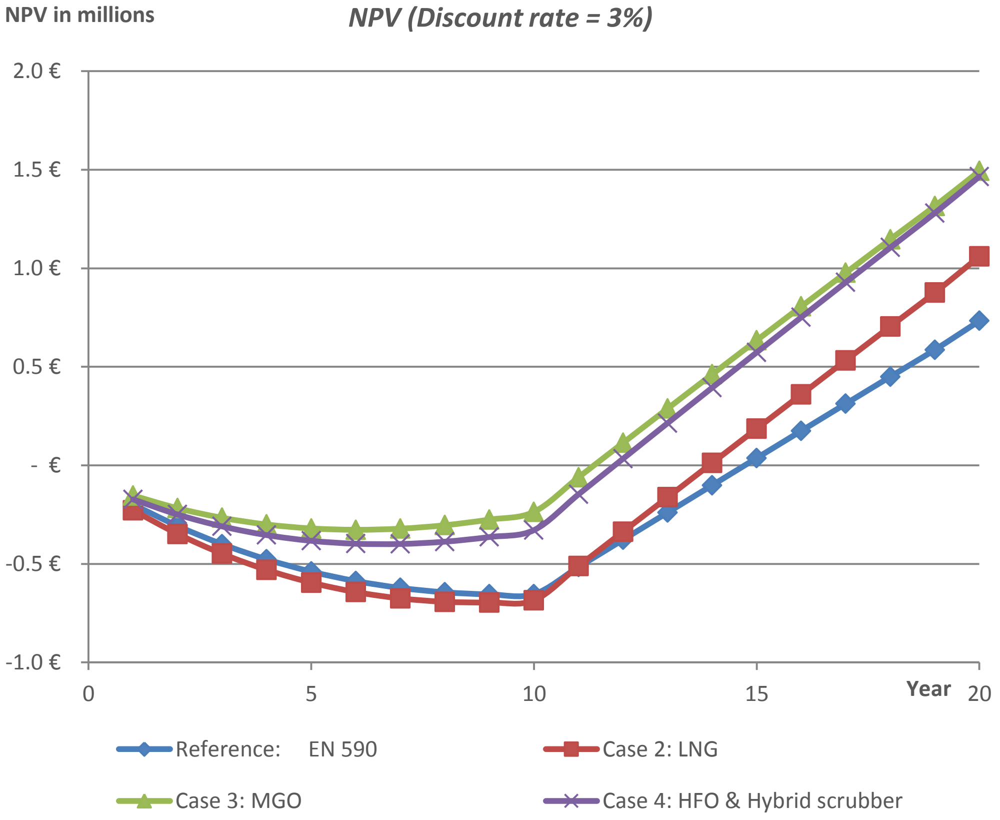

t $SO_{2\ eq}$
AP in t $SO_{2\ eq}$
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber


t $PO_{4\ eq}$
EP in t $PO_{4\ eq}$
14
12
10
8
6
4
2
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

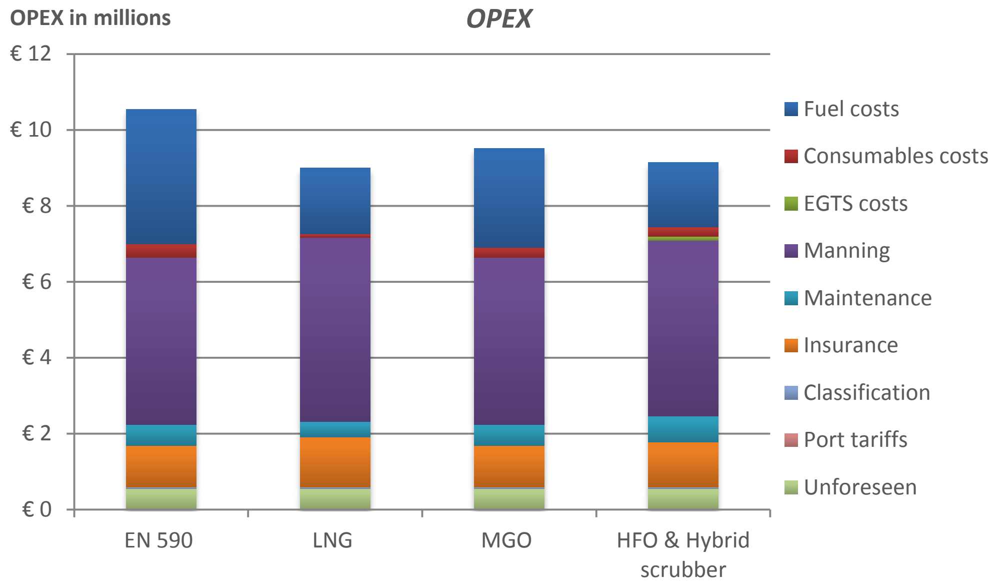

t PM
PM in t PM
25
20
15
10
5
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

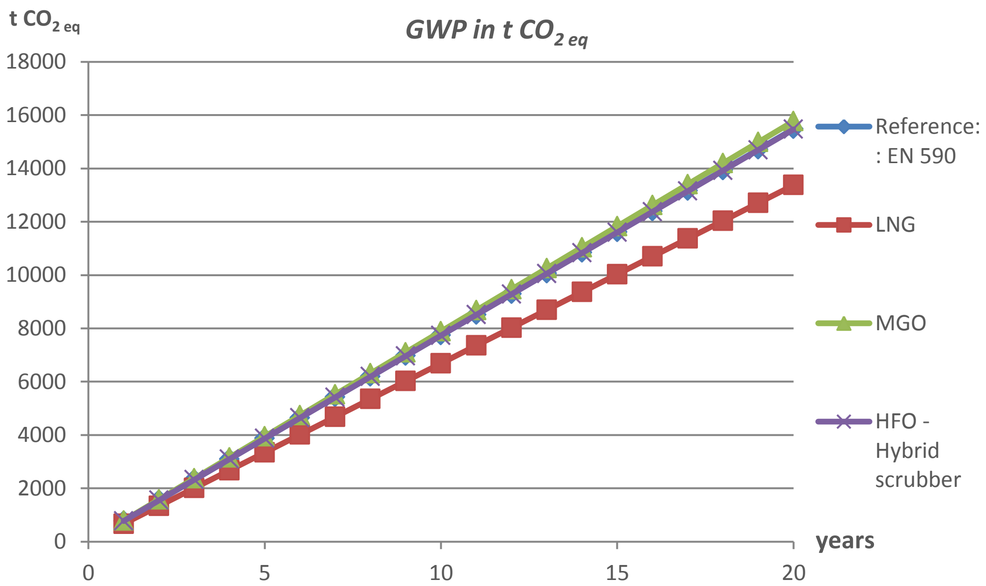
## FOURTH LCPA: LOWER HFO PRICE

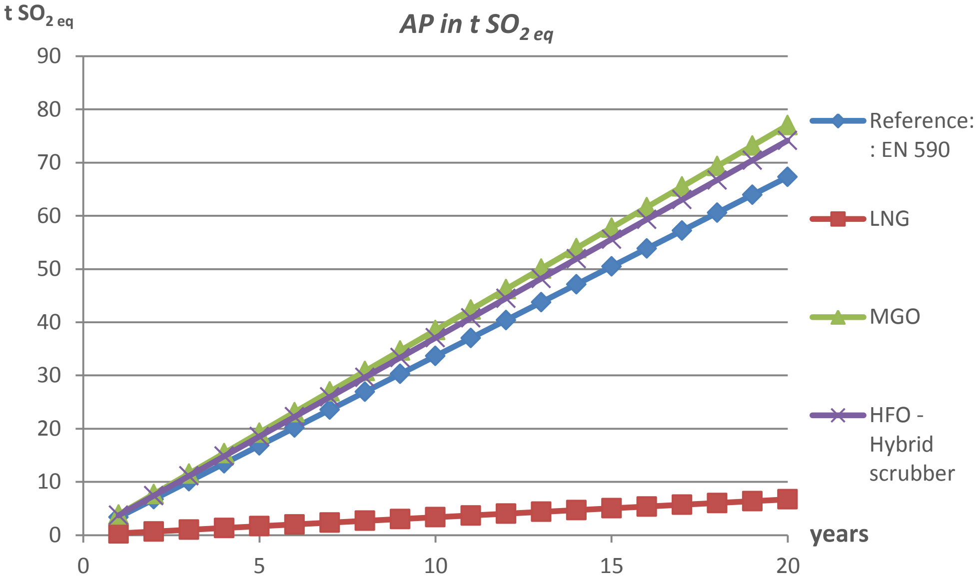
| | | Reference | Case 2 | Case 3 | *Case 4* |
|---|---|---|---|---|---|
| | | EN 590 | LNG | MGO | *HFO & Hybrid scrubber* |
| **Fuel** | - | EN 590 | LNG | MGO | *HFO* |
| **Fuel price** | $ / mt | $ 891.06 | $ 523.00 | $ 655.13 | *$ 423.00* |
| **EGTS** | - | None | None | None | *Hybrid scrubber* |
| | | **LCA result** | | | |
| **GWP** | t $CO_{2\ eq}$ / year | 774.238 | 668.667 | 788.659 | *773.404* |
| **AP** | t $SO_{2\ eq}$ / year | 3.366 | 0.336 | 3.852 | *3.708* |
| **EP** | t $PO_{4\ eq}$ / year | 0.624 | 0.062 | 0.624 | *0.624* |
| **PM** | t PM / year | 0.381 | 0.000 | 0.393 | *1.021* |
| | | **LCC result** | | | |
| **NPV** | | € 732,759 | € 1,059,599 | € 1,493,264 | *€ 1,465,273* |
| **IRR** | | 4.96 % | 5.36 % | 6.92 % | *6.60 %* |
| | | **Deviation in percentages** | | | |
| **% GWP** | | 0% | -14 % | 2 % | *0 %* |
| **% AP** | | 0% | -90 % | 14 % | *10 %* |
| **% EP** | | 0% | -90 % | 0 % | *0 %* |
| **% PM** | | 0% | -100 % | 3 % | *168 %* |
| **% NPV** | | 0% | -45 % | -104 % | *-100 %* |
| **% IRR** | | 0% | -8 % | -39 % | *-33 %* |

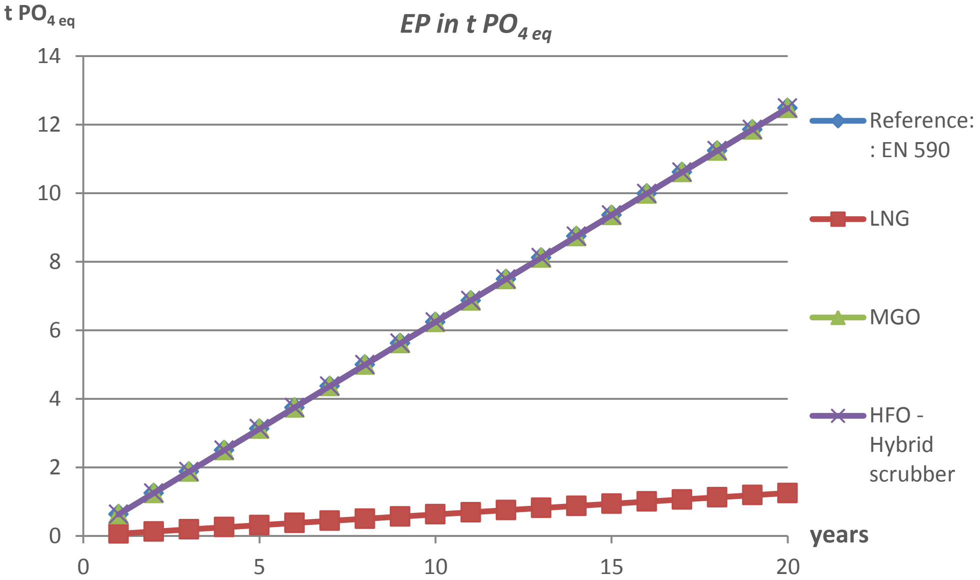


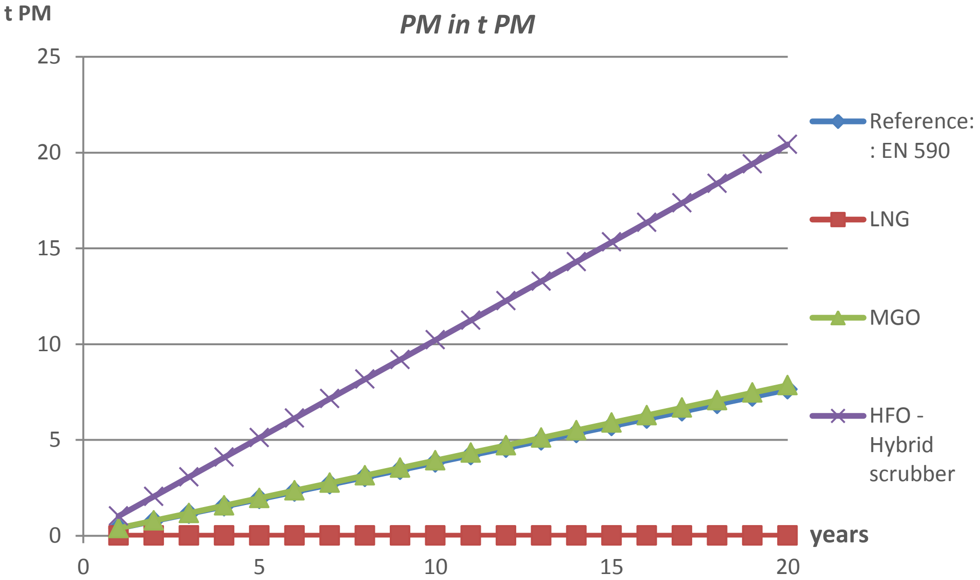
| | Reference: EN 590 | LNG | MGO | *HFO & Hybrid scrubber* |
|---|---|---|---|---|
| **Fuel costs** | € 3,544,533 | € 1,738,948 | € 2,606,016 | *€ 1,698,633* |
| **Consumables costs** | € 354,453 | € 86,947 | € 260,602 | *€ 254,795* |
| **EGTS costs** | € 0 | € 0 | € 0 | *€ 109,150* |
| **Manning** | € 4,403,801 | € 4,844,181 | € 4,403,801 | *€ 4,623,991* |
| **Maintenance** | € 550,475 | € 412,856 | € 550,475 | *€ 688,094* |
| **Insurance** | € 1,100,950 | € 1,321,140 | € 1,100,950 | *€ 1,181,320* |
| **Classification** | € 33,029 | € 33,029 | € 33,029 | *€ 33,029* |
| **Port tariffs** | € 0 | € 0 | € 0 | *€ 0* |
| **Unforeseen** | € 550,475 | € 550,475 | € 550,475 | *€ 550,475* |
| **OPEX** | € 10,537,716 | € 8,987,577 | € 9,505,348 | *€ 9,139,487* |



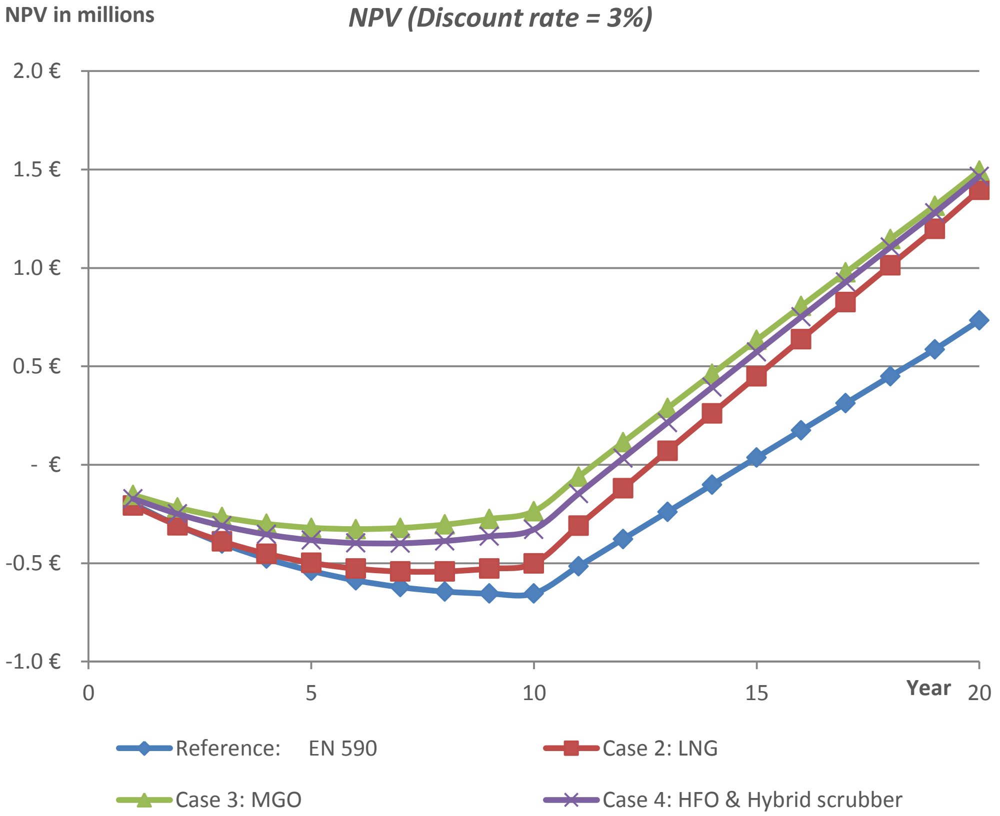

t SO2 eq
AP in t SO2 eq
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber


t PO4 eq
EP in t PO4 eq
14
12
10
8
6
4
2
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

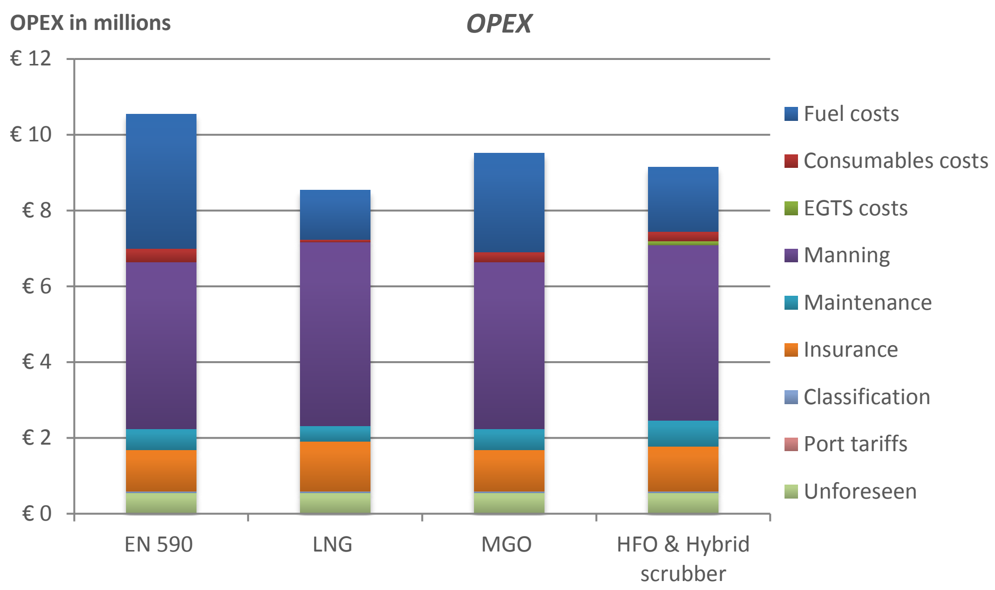

t PM
PM in t PM
25
20
15
10
5
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

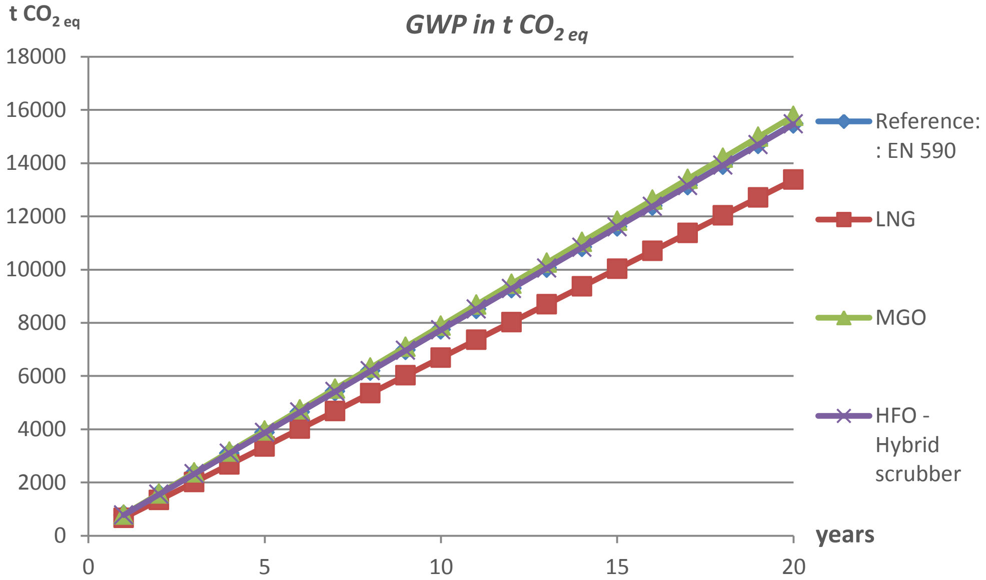
## FIFTH LCPA: ALL FUEL PRICES ARE 75 % OF BASE PRICE

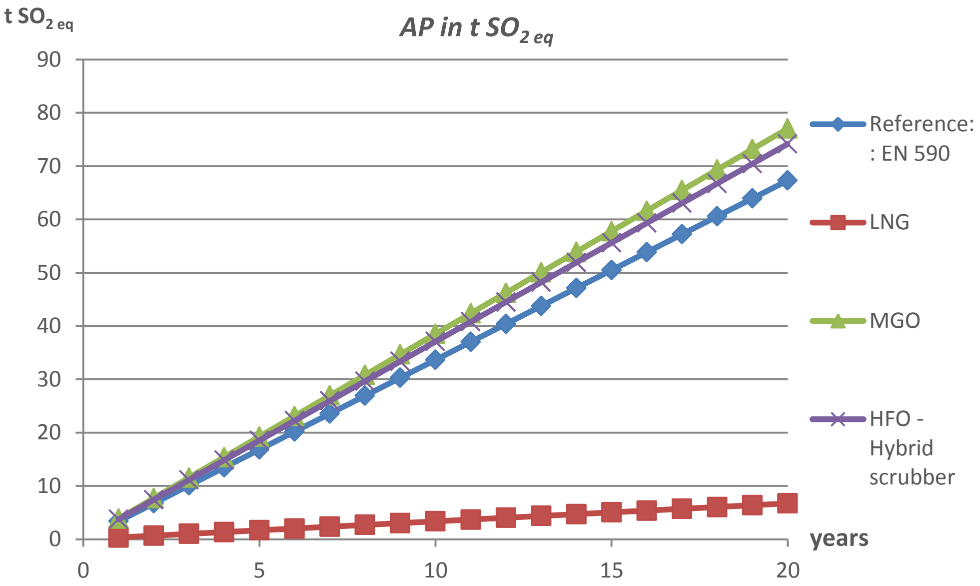
| | | Reference | *Case 2* | Case 3 | Case 4 |
|---|---|---|---|---|---|
| | | EN 590 | *LNG* | MGO | HFO & Hybrid scrubber |
| **Fuel** | - | EN 590 | *LNG* | MGO | HFO |
| **Fuel price** | $ / mt | $ 891.06 | *$ 392.25* | $ 655.13 | $ 423.00 |
| **EGTS** | - | None | *None* | None | Hybrid scrubber |
| | | **LCA result** | | | |
| **GWP** | t $CO_{2\ eq}$ / year | 774.238 | *668.667* | 788.659 | 773.404 |
| **AP** | t $SO_{2\ eq}$ / year | 3.366 | *0.336* | 3.852 | 3.708 |
| **EP** | t $PO_{4\ eq}$ / year | 0.624 | *0.062* | 0.624 | 0.624 |
| **PM** | t PM / year | 0.381 | *0.000* | 0.393 | 1.021 |
| | | **LCC result** | | | |
| **NPV** | | € 732,759 | *€ 1,395,865* | € 1,493,264 | € 1,465,273 |
| **IRR** | | 4.96 % | *6.08 %* | 6.92 % | 6.60 % |
| | | **Deviation in percentages** | | | |
| **% GWP** | | 0% | *-14 %* | 2 % | 0 % |
| **% AP** | | 0% | *-90 %* | 14 % | 10 % |
| **% EP** | | 0% | *-90 %* | 0 % | 0 % |
| **% PM** | | 0% | *-100 %* | 3 % | 168 % |
| **% NPV** | | 0% | *-90 %* | -104 % | -100 % |
| **% IRR** | | 0% | *-22 %* | -39 % | -33 % |

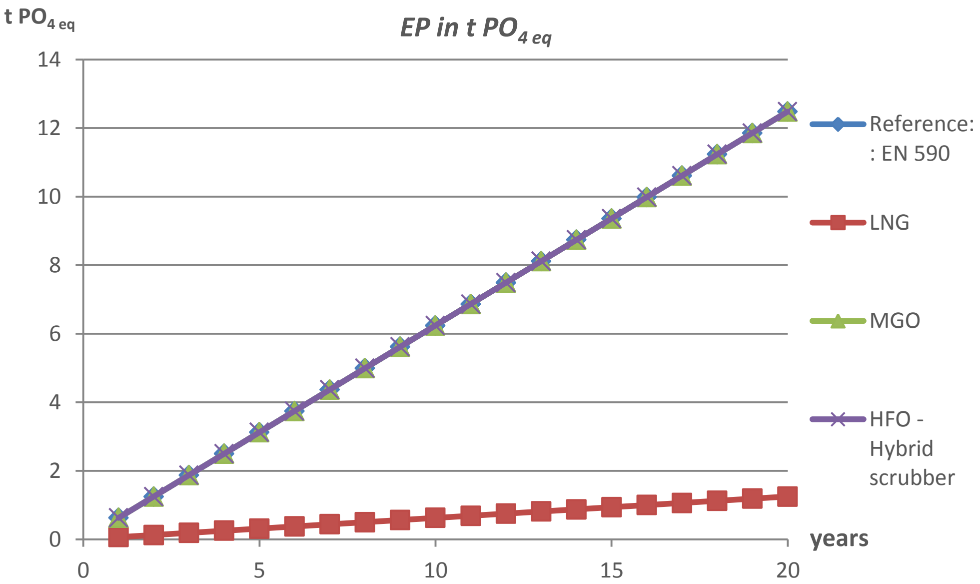


| | Reference: EN 590 | *LNG* | MGO | HFO & Hybrid scrubber |
|---|---|---|---|---|
| **Fuel costs** | € 3,544,533 | *€ 1,304,211* | € 2,606,016 | € 1,698,633 |
| **Consumables costs** | € 354,453 | *€ 65,211* | € 260,602 | € 254,795 |
| **EGTS costs** | € 0 | *€ 0* | € 0 | € 109,150 |
| **Manning** | € 4,403,801 | *€ 4,844,181* | € 4,403,801 | € 4,623,991 |
| **Maintenance** | € 550,475 | *€ 412,856* | € 550,475 | € 688,094 |
| **Insurance** | € 1,100,950 | *€ 1,321,140* | € 1,100,950 | € 1,181,320 |
| **Classification** | € 33,029 | *€ 33,029* | € 33,029 | € 33,029 |
| **Port tariffs** | € 0 | *€ 0* | € 0 | € 0 |
| **Unforeseen** | € 550,475 | *€ 550,475* | € 550,475 | € 550,475 |
| **OPEX** | € 10,537,716 | *€ 8,531,103* | € 9,505,348 | € 9,139,487 |




t SO2 eq
AP in t SO2 eq
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber


t PO4 eq
EP in t PO4 eq
14
12
10
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0
0
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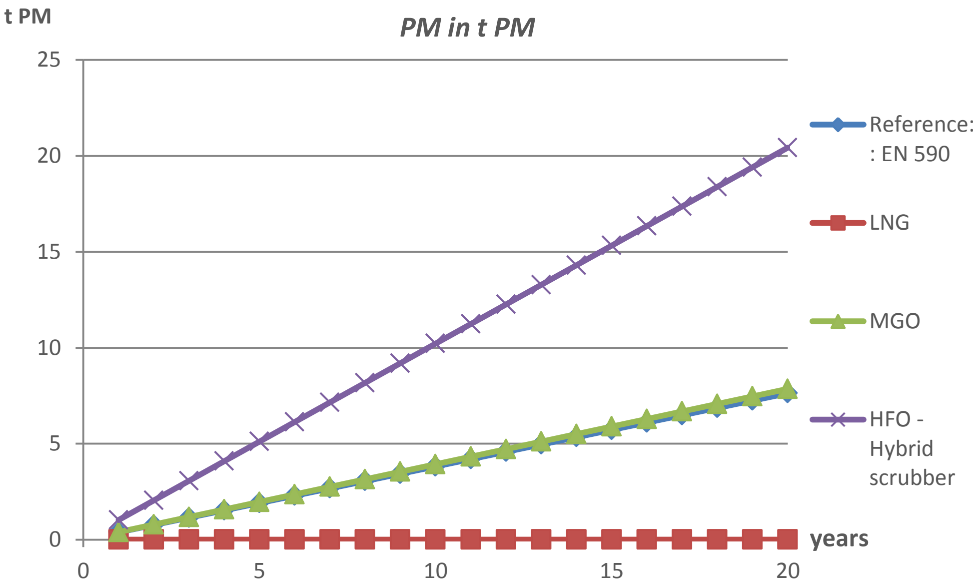
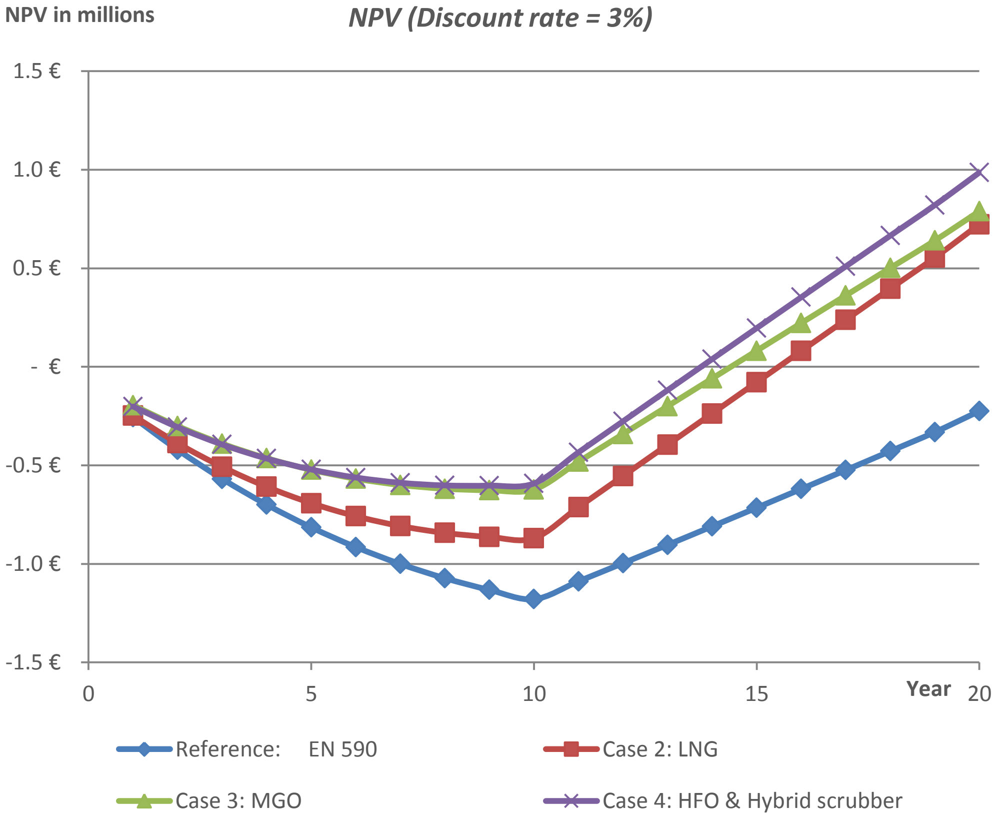
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

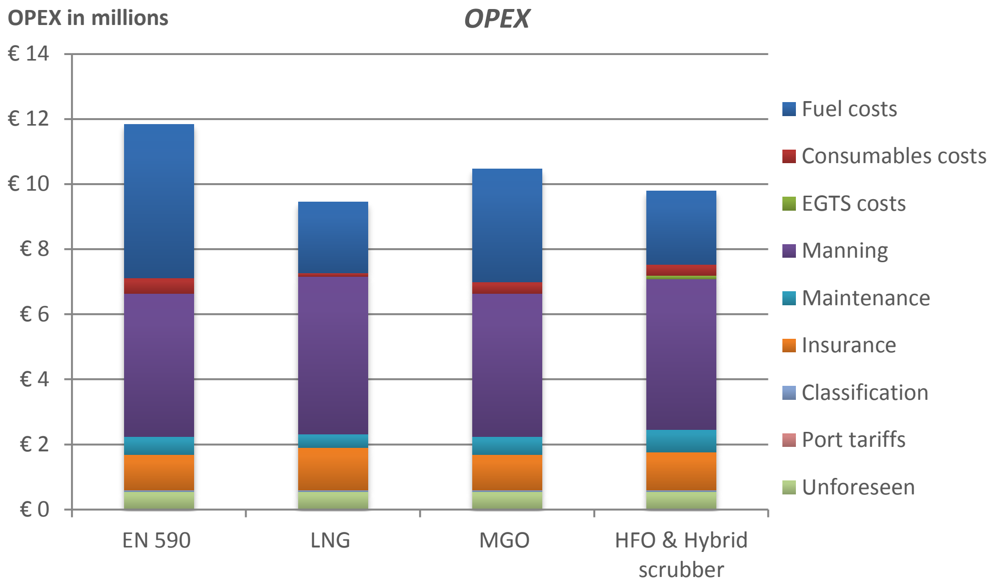

t PM
PM in t PM
25
20
15
10
5
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

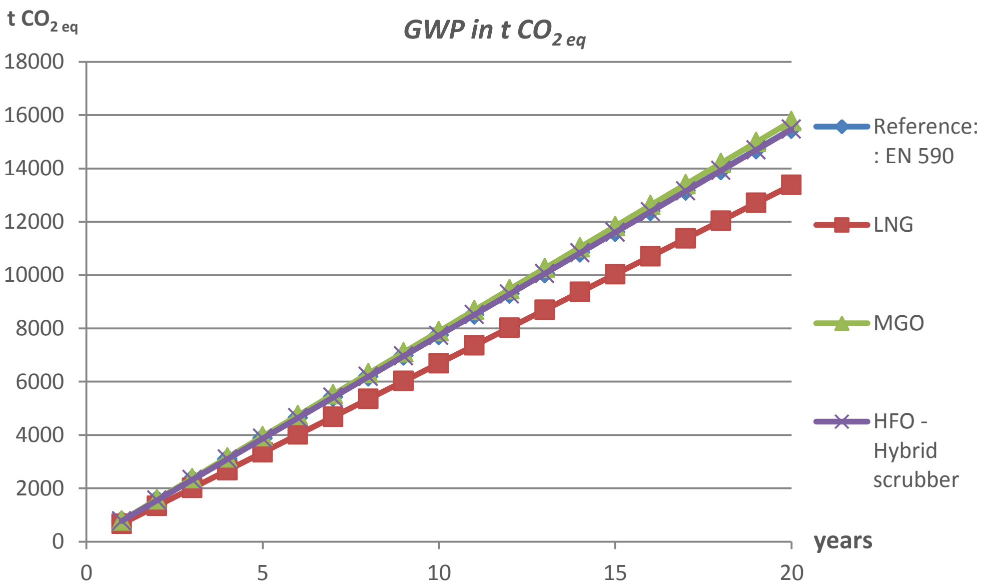
## SIXTH LCPA: HIGHER LNG PRICE

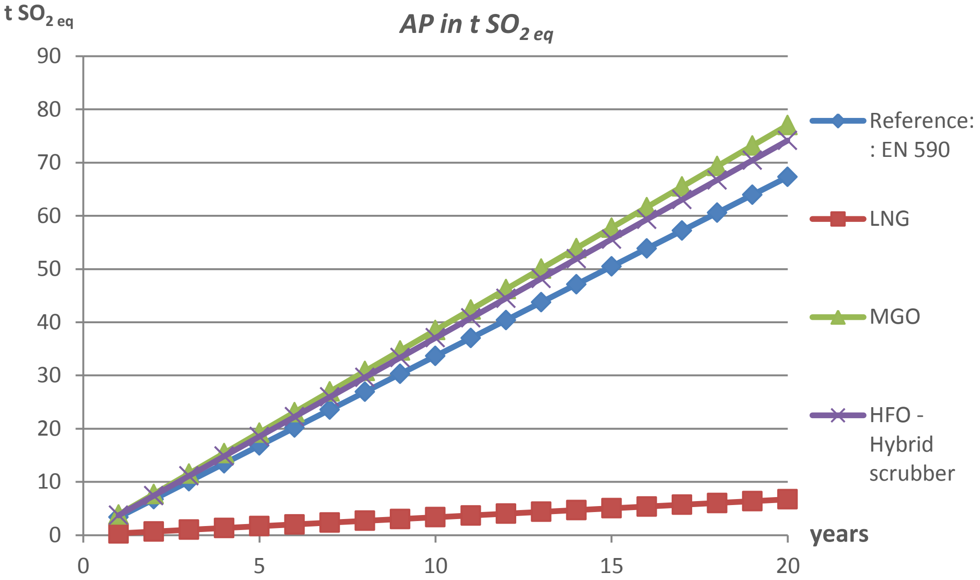
| | | Reference | *Case 2* | Case 3 | Case 4 |
|---|---|---|---|---|---|
| | | EN 590 | *LNG* | MGO | HFO & Hybrid scrubber |
| **Fuel** | - | EN 590 | *LNG* | MGO | HFO |
| **Fuel price** | $ / mt | $ 1,188.08 | *$ 653.75* | $ 873.50 | $ 564.00 |
| **EGTS** | - | None | *None* | None | Hybrid scrubber |
| | | **LCA result** | | | |
| **GWP** | t $CO_{2\,eq}$ / year | 774.238 | *668.667* | 788.659 | 773.404 |
| **AP** | t $SO_{2\,eq}$ / year | 3.366 | *0.336* | 3.852 | 3.708 |
| **EP** | t $PO_{4\,eq}$ / year | 0.624 | *0.062* | 0.624 | 0.624 |
| **PM** | t PM / year | 0.381 | *0.000* | 0.393 | 1.021 |
| | | **LCC result** | | | |
| **NPV** | | -€ 224,650 | *€ 723,333* | € 789,356 | € 985,602 |
| **IRR** | | 2.38 % | *4.62%* | 5.11 % | 5.45 % |
| | | **Deviation in percentages** | | | |
| **% GWP** | | 0% | *-14 %* | 2 % | 0 % |
| **% AP** | | 0% | *-90 %* | 14 % | 10 % |
| **% EP** | | 0% | *-90 %* | 0 % | 0 % |
| **% PM** | | 0% | *-100 %* | 3 % | 168 % |
| **% NPV** | | 0% | *-422 %* | -451 % | -539 % |
| **% IRR** | | 0% | *-94 %* | -115 % | -129 % |

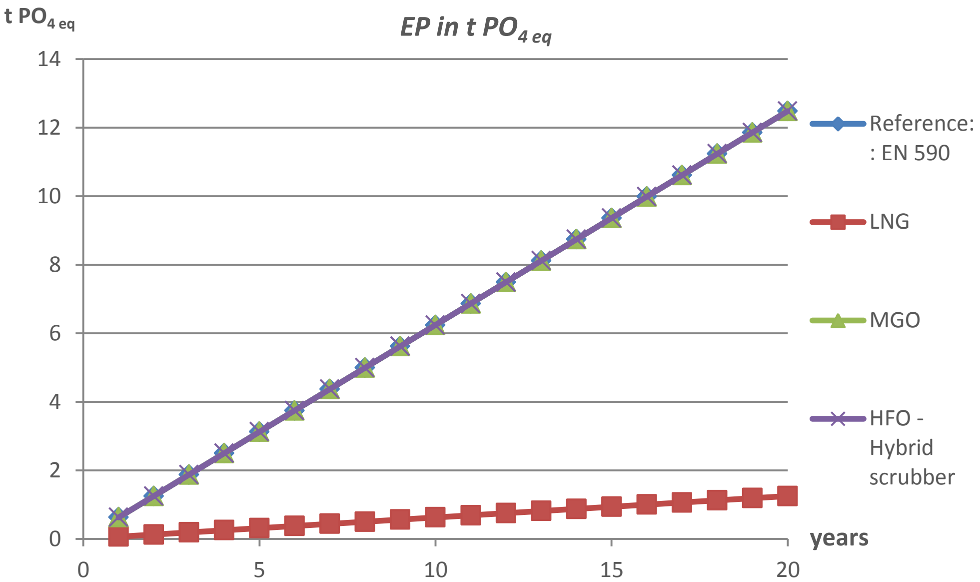


| | Reference: EN 590 | *LNG* | MGO | HFO & Hybrid scrubber |
|---|---|---|---|---|
| **Fuel costs** | € 4,726,044 | *€ 2,173,686* | € 3,474,688 | € 2,264,844 |
| **Consumables costs** | € 472,604 | *€ 108,684* | € 347,469 | € 339,727 |
| **EGTS costs** | € 0 | *€ 0* | € 0 | € 109,150 |
| **Manning** | € 4,403,801 | *€ 4,844,181* | € 4,403,801 | € 4,623,991 |
| **Maintenance** | € 550,475 | *€ 412,856* | € 550,475 | € 688,094 |
| **Insurance** | € 1,100,950 | *€ 1,321,140* | € 1,100,950 | € 1,181,320 |
| **Classification** | € 33,029 | *€ 33,029* | € 33,029 | € 33,029 |
| **Port tariffs** | € 0 | *€ 0* | € 0 | € 0 |
| **Unforeseen** | € 550,475 | *€ 550,475* | € 550,475 | € 550,475 |
| **OPEX** | € 11,837,379 | *€ 9,444,051* | € 10,460,887 | € 9,790,629 |




t SO2 eq
AP in t SO2 eq
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber


t PO4 eq
EP in t PO4 eq
14
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10
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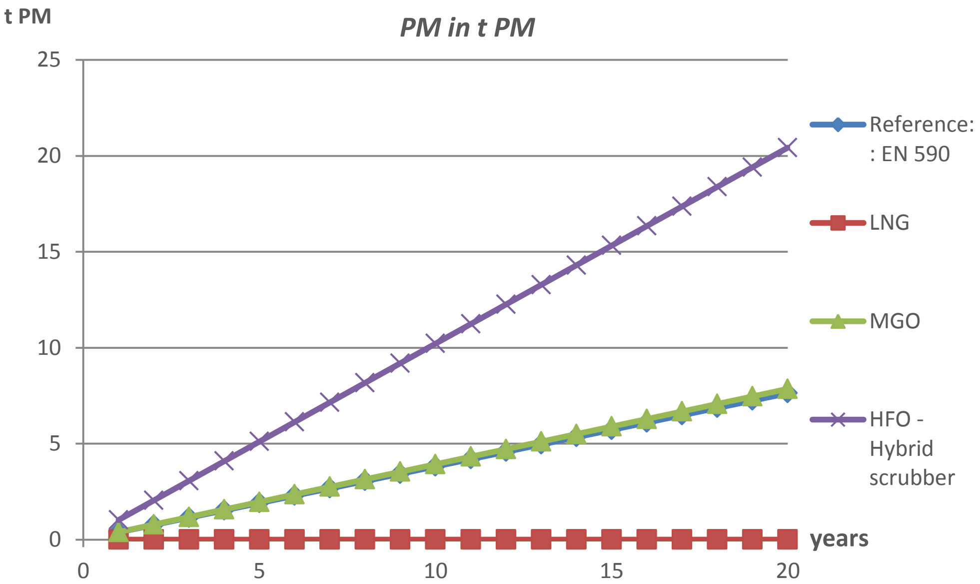
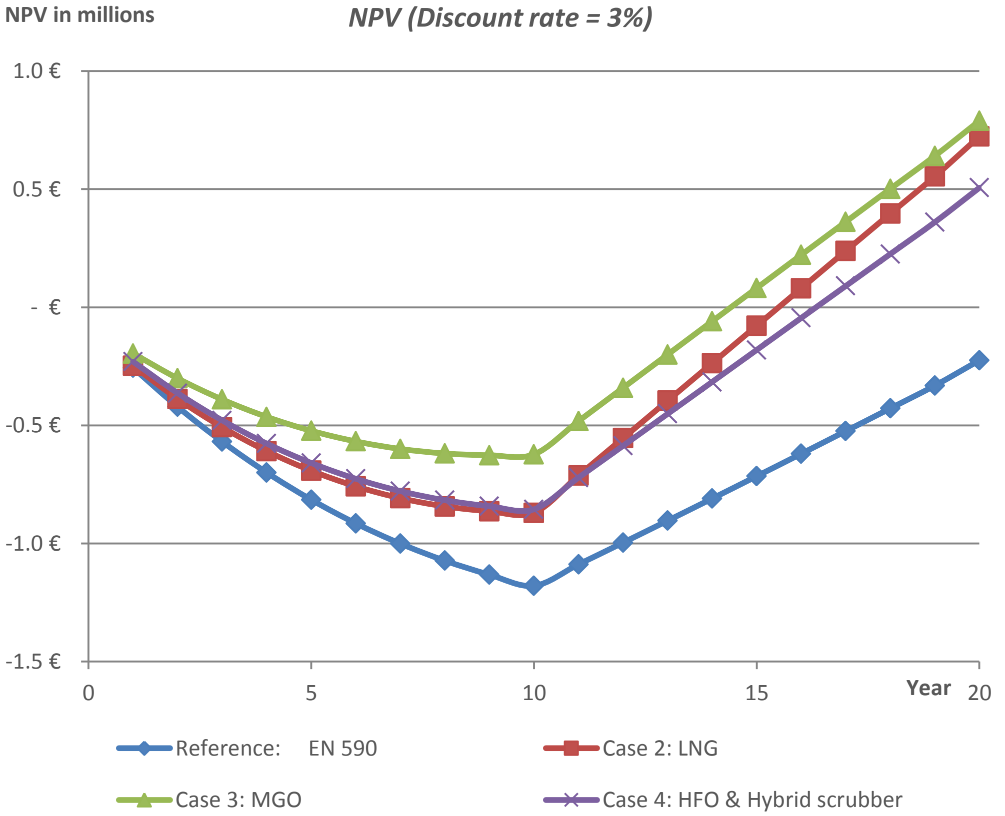
2
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

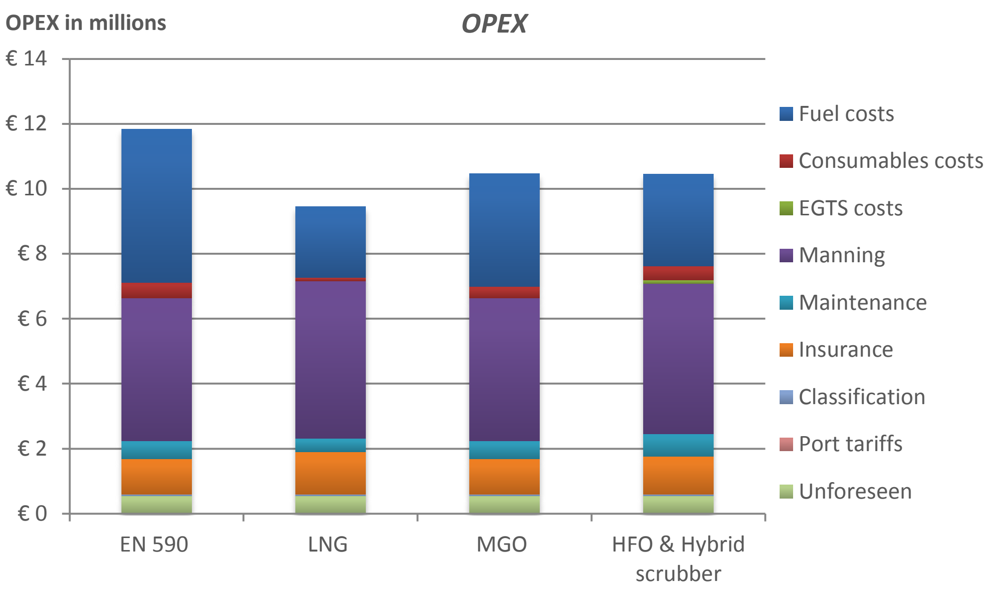

t PM
PM in t PM
25
20
15
10
5
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

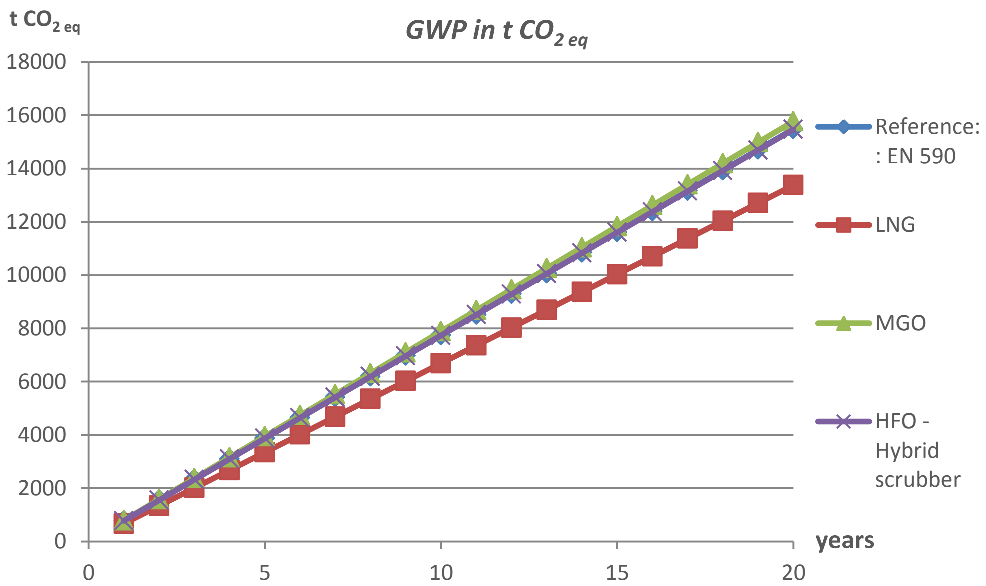
## SEVENTH LCPA: HIGHER HFO PRICE

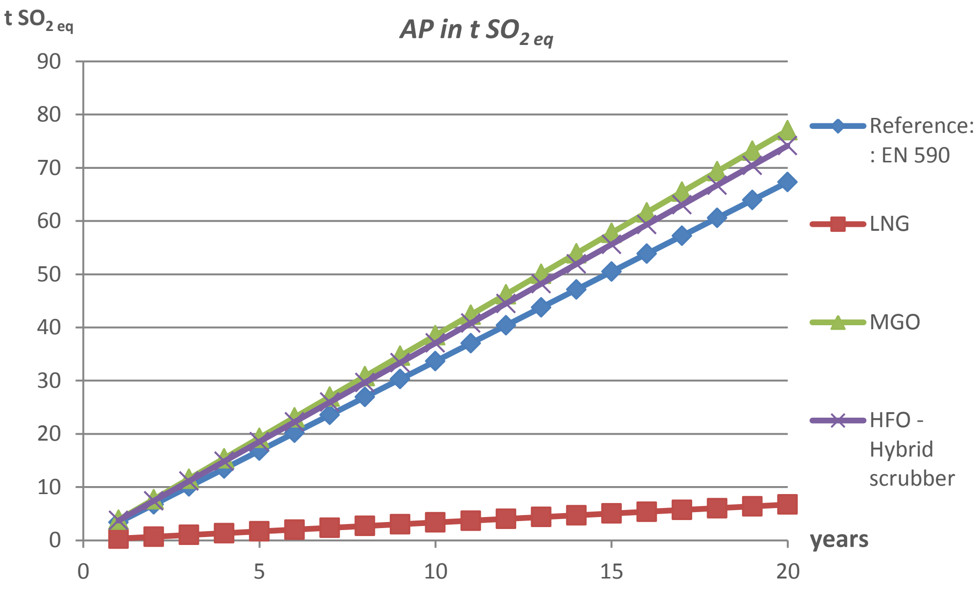
| | | Reference | Case 2 | Case 3 | *Case 4* |
|---|---|---|---|---|---|
| | | EN 590 | LNG | MGO | *HFO & Hybrid scrubber* |
| **Fuel** | - | EN 590 | LNG | MGO | *HFO* |
| **Fuel price** | $ / mt | $ 1,188.08 | $ 653.75 | $ 873.50 | *$ 705.00* |
| **EGTS** | - | None | None | None | *Hybrid scrubber* |
| | | **LCA result** | | | |
| **GWP** | t $CO_{2\ eq}$ / year | 774.238 | 668.667 | 788.659 | *773.404* |
| **AP** | t $SO_{2\ eq}$ / year | 3.366 | 0.336 | 3.852 | *3.708* |
| **EP** | t $PO_{4\ eq}$ / year | 0.624 | 0.062 | 0.624 | *0.624* |
| **PM** | t PM / year | 0.381 | 0.000 | 0.393 | *1.021* |
| | | **LCC result** | | | |
| **NPV** | | -€ 224,650 | € 723,333 | € 789,356 | *€ 505,391* |
| **IRR** | | 2.38 % | 4.62% | 5.11 % | *4.27 %* |
| | | **Deviation in percentages** | | | |
| **% GWP** | | 0% | -14 % | 2 % | *0 %* |
| **% AP** | | 0% | -90 % | 14 % | *10 %* |
| **% EP** | | 0% | -90 % | 0 % | *0 %* |
| **% PM** | | 0% | -100 % | 3 % | *168 %* |
| **% NPV** | | 0% | -422 % | -451 % | *-325 %* |
| **% IRR** | | 0% | -94 % | -115 % | *-80 %* |

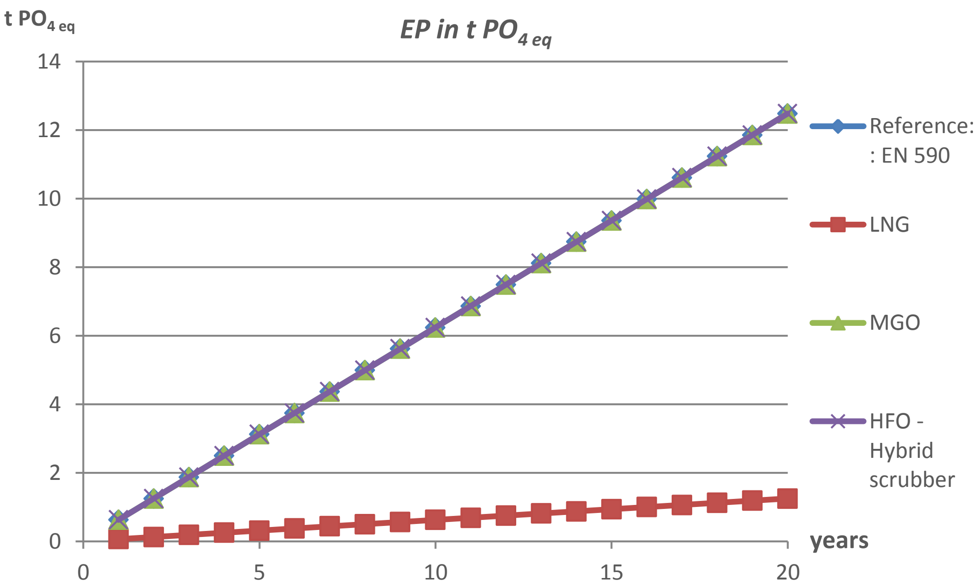


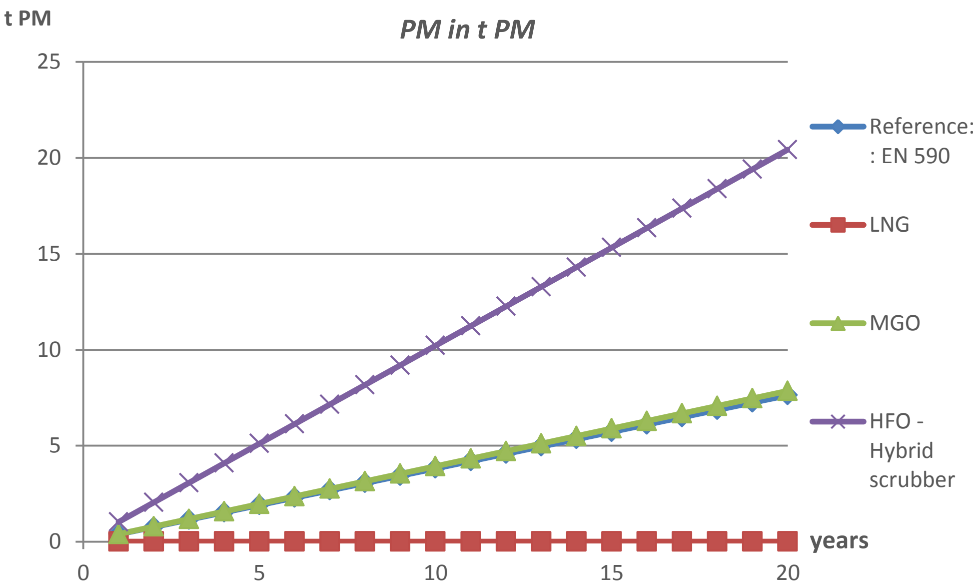
| | Reference: EN 590 | LNG | MGO | *HFO & Hybrid scrubber* |
|---|---|---|---|---|
| **Fuel costs** | € 4,726,044 | € 2,173,686 | € 3,474,688 | *€ 2,831,056* |
| **Consumables costs** | € 472,604 | € 108,684 | € 347,469 | *€ 424,658* |
| **EGTS costs** | € 0 | € 0 | € 0 | *€ 109,150* |
| **Manning** | € 4,403,801 | € 4,844,181 | € 4,403,801 | *€ 4,623,991* |
| **Maintenance** | € 550,475 | € 412,856 | € 550,475 | *€ 688,094* |
| **Insurance** | € 1,100,950 | € 1,321,140 | € 1,100,950 | *€ 1,181,320* |
| **Classification** | € 33,029 | € 33,029 | € 33,029 | *€ 33,029* |
| **Port tariffs** | € 0 | € 0 | € 0 | *€ 0* |
| **Unforeseen** | € 550,475 | € 550,475 | € 550,475 | *€ 550,475* |
| **OPEX** | € 11,837,379 | € 9,444,051 | € 10,460,887 | *€ 10,441,772* |



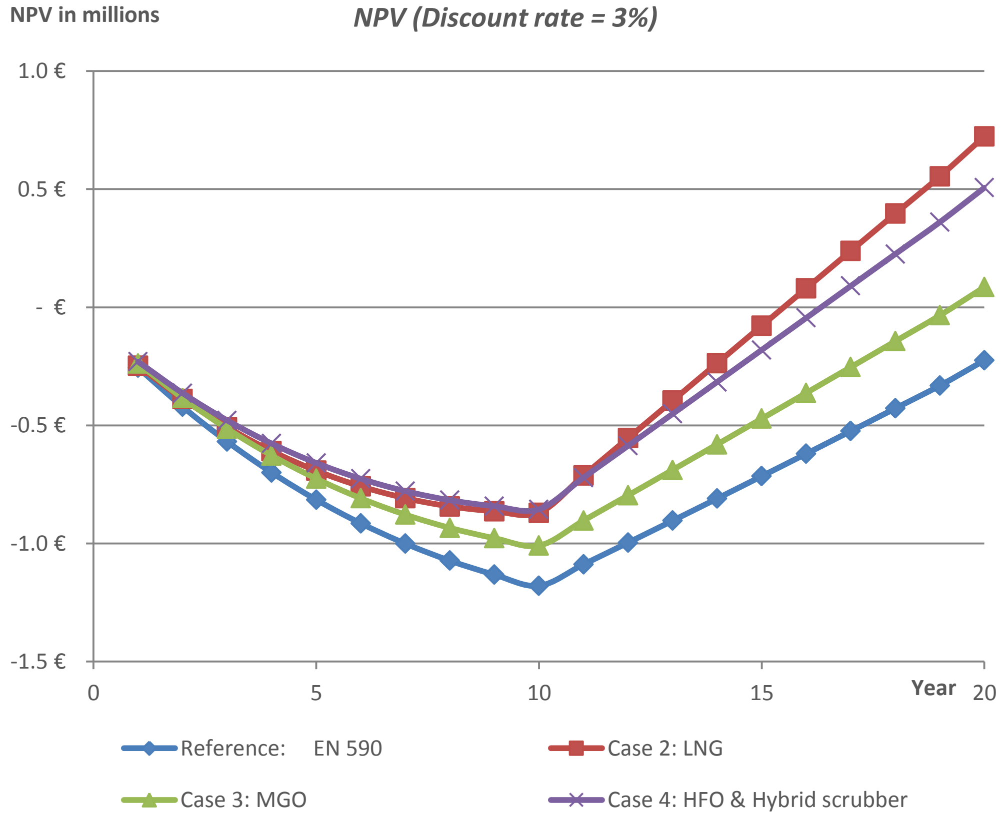

t $SO_{2\ eq}$
AP in t $SO_{2\ eq}$
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber


t $PO_{4\ eq}$
EP in t $PO_{4\ eq}$
14
12
10
8
6
4
2
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

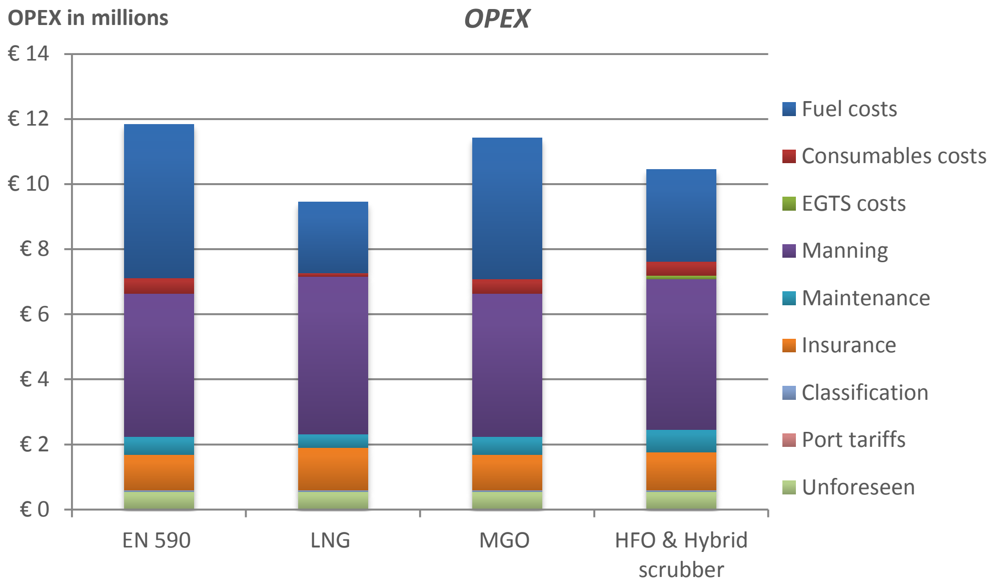

t PM
PM in t PM
25
20
15
10
5
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

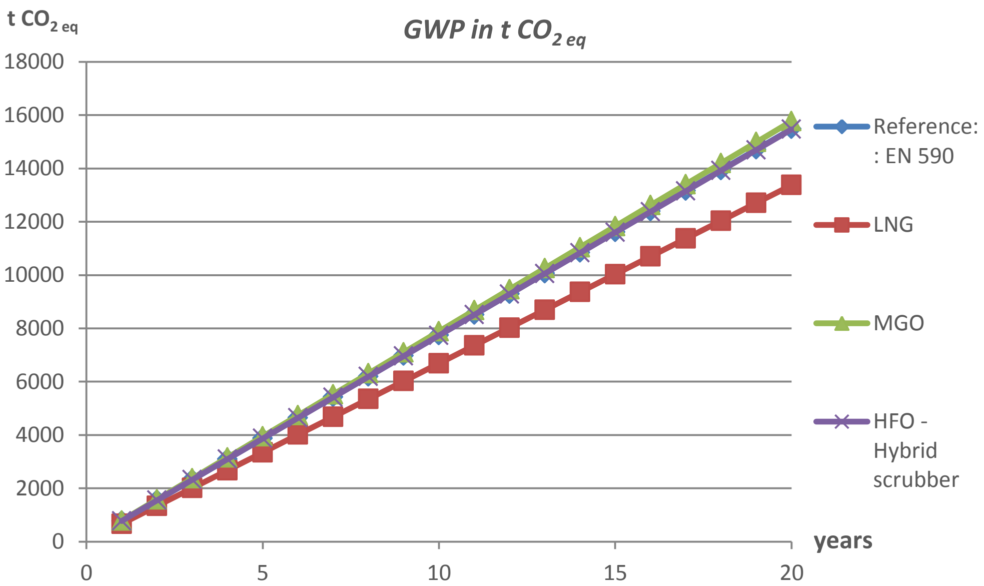
## EIGHT LCPA: HIGHER MGO PRICE

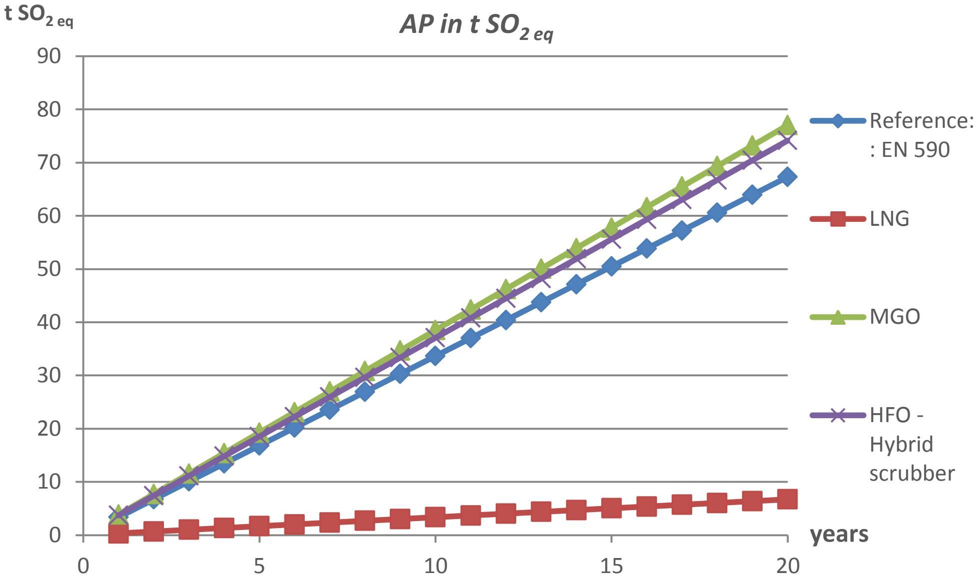
| | | Reference | Case 2 | *Case 3* | Case 4 |
|---|---|---|---|---|---|
| | | EN 590 | LNG | *MGO* | HFO & Hybrid scrubber |
| **Fuel** | - | EN 590 | LNG | *MGO* | HFO |
| **Fuel price** | $ / mt | $ 1,188.08 | $ 653.75 | *$ 1091.88* | $ 705.00 |
| **EGTS** | - | None | None | *None* | Hybrid scrubber |
| | | **LCA result** | | | |
| **GWP** | t $CO_{2\ eq}$ / year | 774.238 | 668.667 | *788.659* | 773.404 |
| **AP** | t $SO_{2\ eq}$ / year | 3.366 | 0.336 | *3.852* | 3.708 |
| **EP** | t $PO_{4\ eq}$ / year | 0.624 | 0.062 | *0.624* | 0.624 |
| **PM** | t PM / year | 0.381 | 0.000 | *0.393* | 1.021 |
| | | **LCC result** | | | |
| **NPV** | | -€ 224,650 | € 723,333 | *€ 85,449* | € 505,391 |
| **IRR** | | 2.38 % | 4.62% | *3.23 %* | 4.27 % |
| | | **Deviation in percentages** | | | |
| **% GWP** | | 0% | -14 % | *2 %* | 0 % |
| **% AP** | | 0% | -90 % | *14 %* | 10 % |
| **% EP** | | 0% | -90 % | *0 %* | 0 % |
| **% PM** | | 0% | -100 % | *3 %* | 168 % |
| **% NPV** | | 0% | -422 % | *-138 %* | -325 % |
| **% IRR** | | 0% | -94 % | *-36 %* | -80 % |

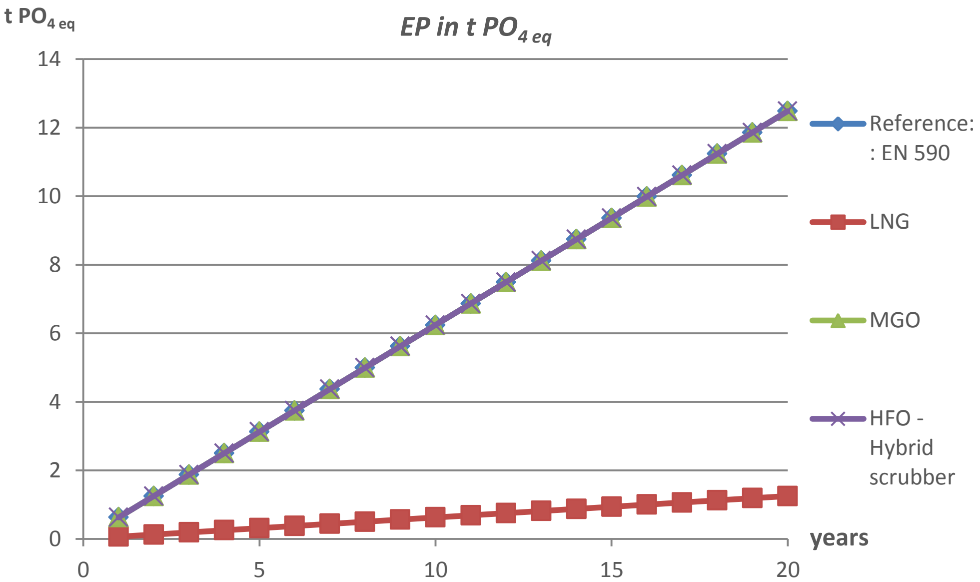


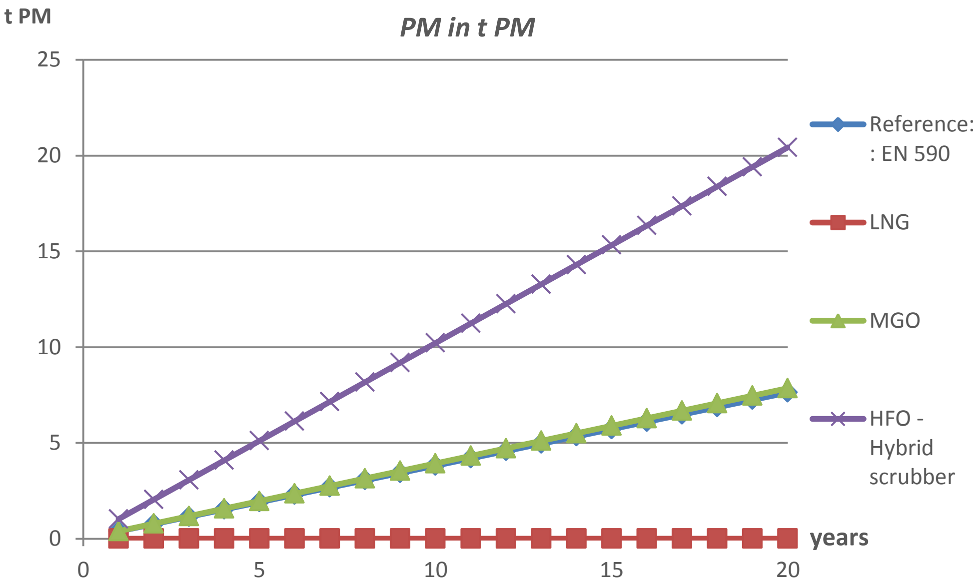
| | Reference: EN 590 | LNG | *MGO* | HFO & Hybrid scrubber |
|---|---|---|---|---|
| **Fuel costs** | € 4,726,044 | € 2,173,686 | *€ 4,343,361* | € 2,831,056 |
| **Consumables costs** | € 472,604 | € 108,684 | *€ 434,336* | € 424,658 |
| **EGTS costs** | € 0 | € 0 | *€ 0* | € 109,150 |
| **Manning** | € 4,403,801 | € 4,844,181 | *€ 4,403,801* | € 4,623,991 |
| **Maintenance** | € 550,475 | € 412,856 | *€ 550,475* | € 688,094 |
| **Insurance** | € 1,100,950 | € 1,321,140 | *€ 1,100,950* | € 1,181,320 |
| **Classification** | € 33,029 | € 33,029 | *€ 33,029* | € 33,029 |
| **Port tariffs** | € 0 | € 0 | *€ 0* | € 0 |
| **Unforeseen** | € 550,475 | € 550,475 | *€ 550,475* | € 550,475 |
| **OPEX** | € 11,837,379 | € 9,444,051 | *€ 11,416,426* | € 10,441,772 |



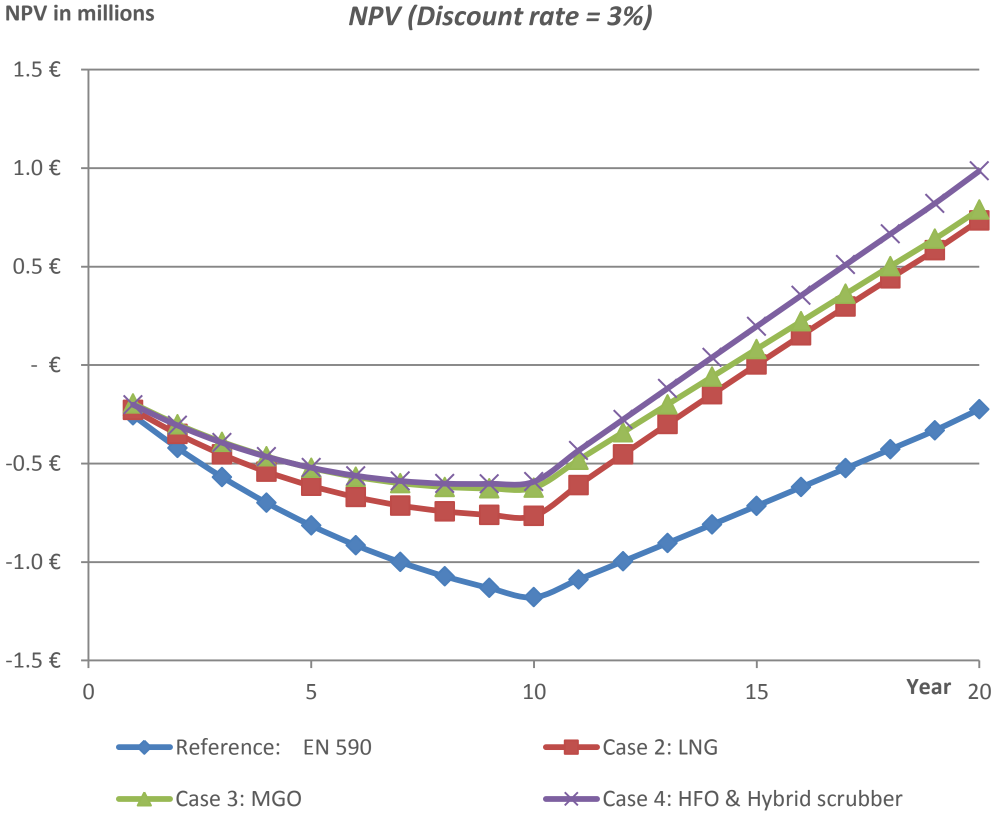

t $SO_{2\ eq}$
AP in t $SO_{2\ eq}$
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber


t $PO_{4\ eq}$
EP in t $PO_{4\ eq}$
14
12
10
8
6
4
2
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

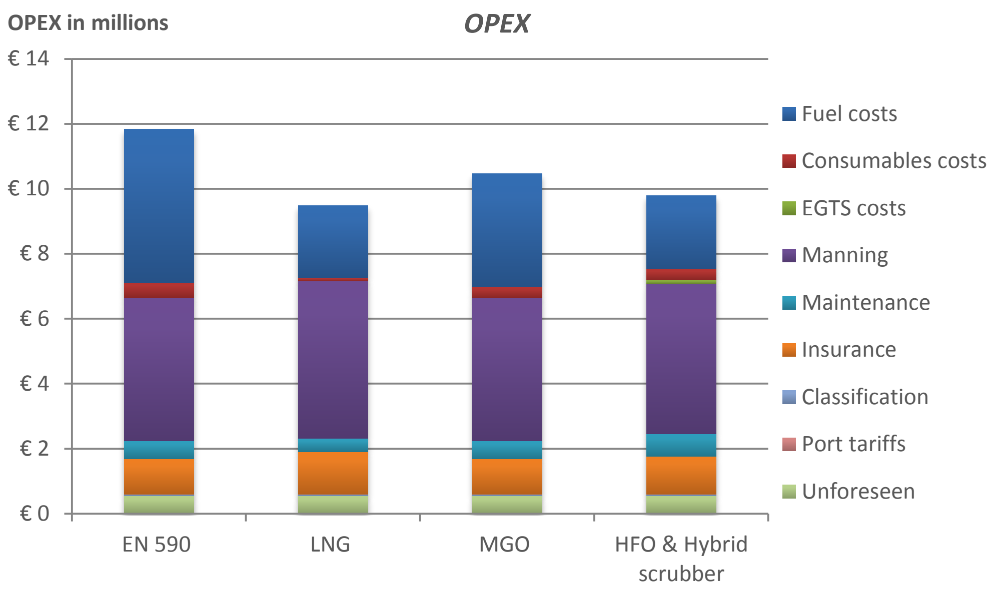

t PM
PM in t PM
25
20
15
10
5
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

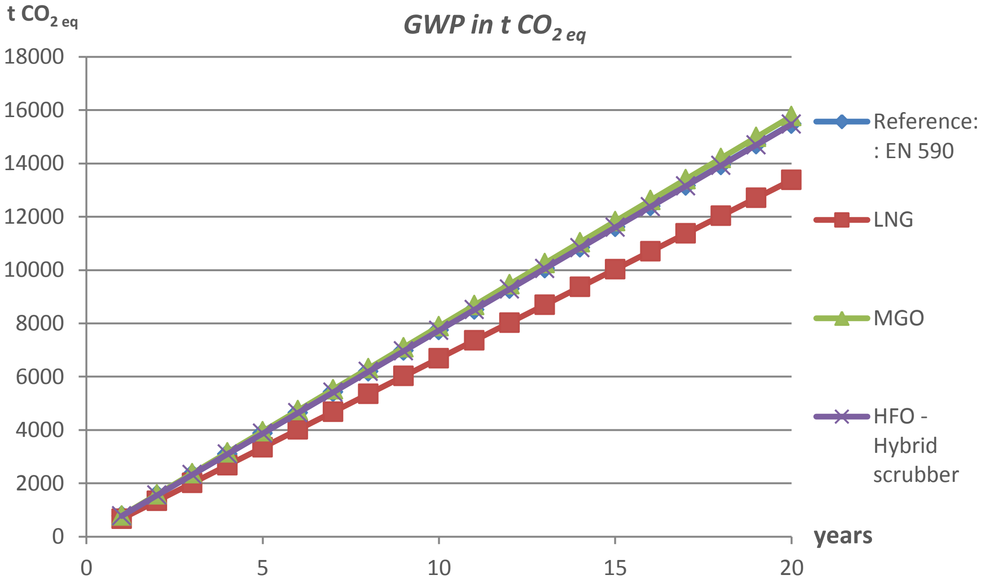
## NINTH LCPA: HIGHER PRICE INCREASE OF LNG

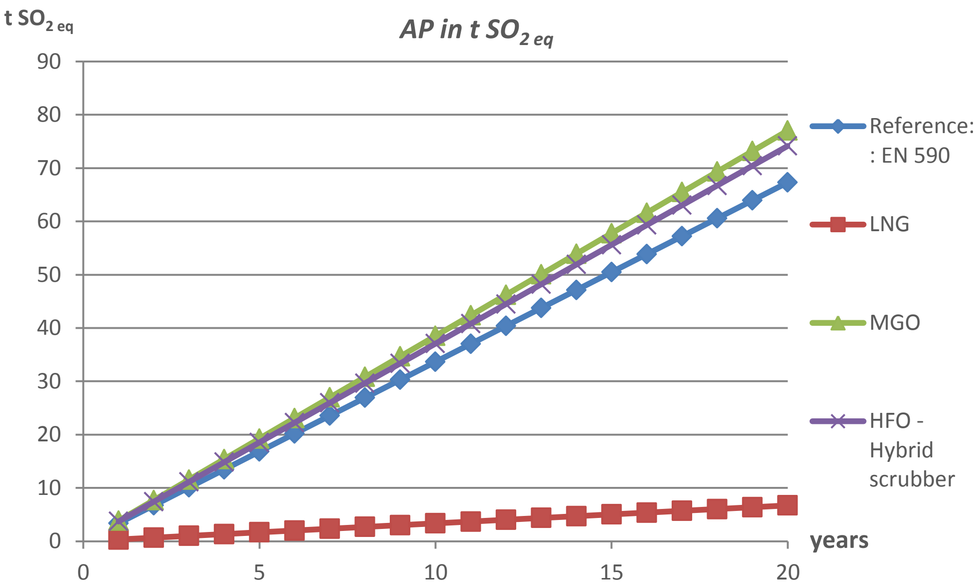
| | | Reference | *Case 2* | Case 3 | Case 4 |
|---|---|---|---|---|---|
| | | EN 590 | *LNG* | MGO | HFO & Hybrid scrubber |
| **Fuel** | - | EN 590 | *LNG* | MGO | HFO |
| **Fuel price** | $ / mt | $ 1,188.08 | *$ 523.00* | $ 873.50 | $ 564.00 |
| **EGTS** | - | None | *None* | None | Hybrid scrubber |
| | | **LCA result** | | | |
| **GWP** | t $CO_{2\ eq}$ / year | 774.238 | *668.667* | 788.659 | 773.404 |
| **AP** | t $SO_{2\ eq}$ / year | 3.366 | *0.336* | 3.852 | 3.708 |
| **EP** | t $PO_{4\ eq}$ / year | 0.624 | *0.062* | 0.624 | 0.624 |
| **PM** | t PM / year | 0.381 | *0.000* | 0.393 | 1.021 |
| | | **LCC result** | | | |
| **NPV** | | -€ 224,650 | *€ 734,297* | € 789,356 | € 985,602 |
| **IRR** | | 2.38 % | *4.69 %* | 5.11 % | 5.45 % |
| | | **Deviation in percentages** | | | |
| **% GWP** | | 0% | *-14 %* | 2 % | 0 % |
| **% AP** | | 0% | *-90 %* | 14 % | 10 % |
| **% EP** | | 0% | *-90 %* | 0 % | 0 % |
| **% PM** | | 0% | *-100 %* | 3 % | 168 % |
| **% NPV** | | 0% | *-427 %* | -451 % | -539 % |
| **% IRR** | | 0% | *-97 %* | -115 % | -129 % |

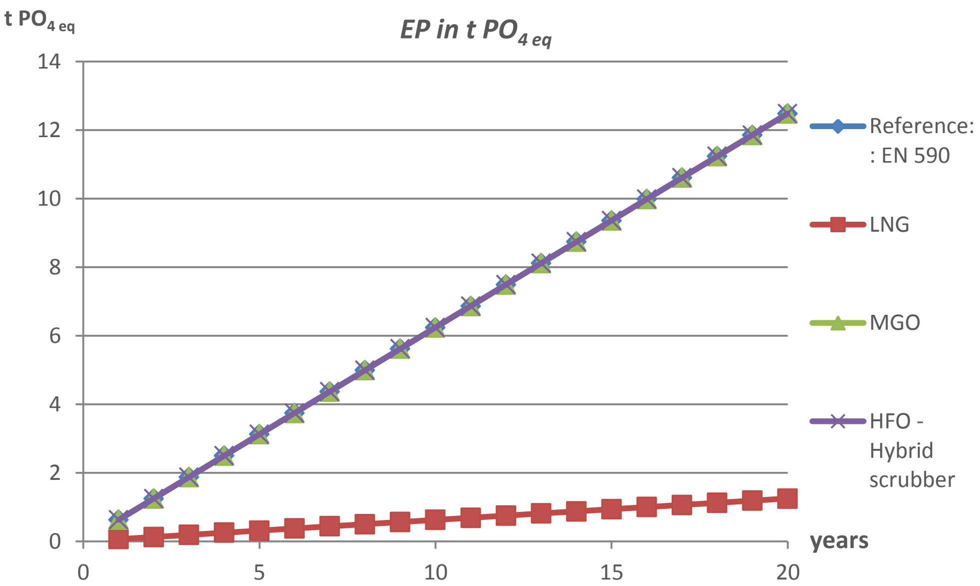


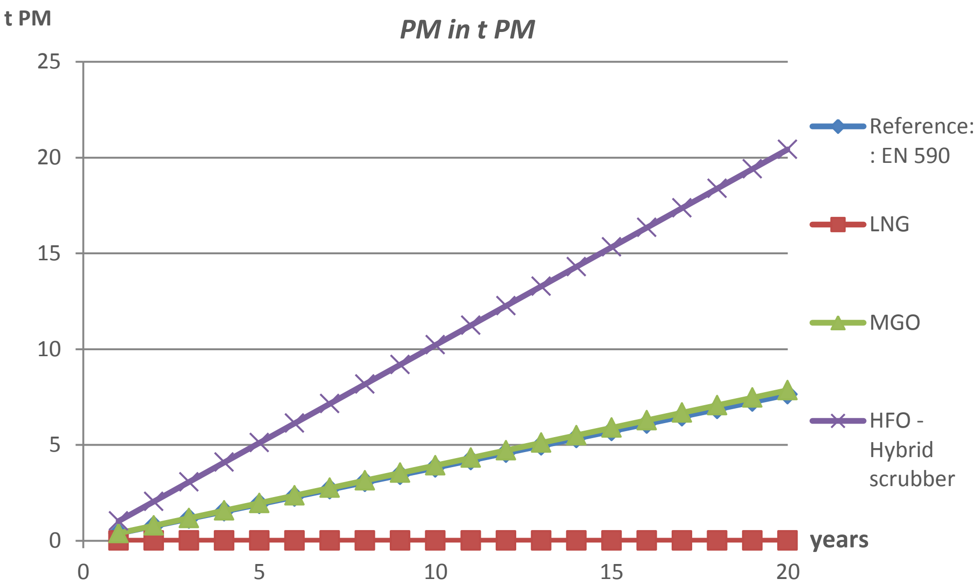
| | Reference: EN 590 | *LNG* | MGO | HFO & Hybrid scrubber |
|---|---|---|---|---|
| **Fuel costs** | € 4,726,044 | *€ 2,233,385* | € 3,474,688 | € 2,264,844 |
| **Consumables costs** | € 472,604 | *€ 86,947* | € 347,469 | € 339,727 |
| **EGTS costs** | € 0 | *€ 0* | € 0 | € 109,150 |
| **Manning** | € 4,403,801 | *€ 4,844,181* | € 4,403,801 | € 4,623,991 |
| **Maintenance** | € 550,475 | *€ 412,856* | € 550,475 | € 688,094 |
| **Insurance** | € 1,100,950 | *€ 1,321,140* | € 1,100,950 | € 1,181,320 |
| **Classification** | € 33,029 | *€ 33,029* | € 33,029 | € 33,029 |
| **Port tariffs** | € 0 | *€ 0* | € 0 | € 0 |
| **Unforeseen** | € 550,475 | *€ 550,475* | € 550,475 | € 550,475 |
| **OPEX** | € 11,837,379 | *€ 9,482,013* | € 10,460,887 | € 9,790,629 |



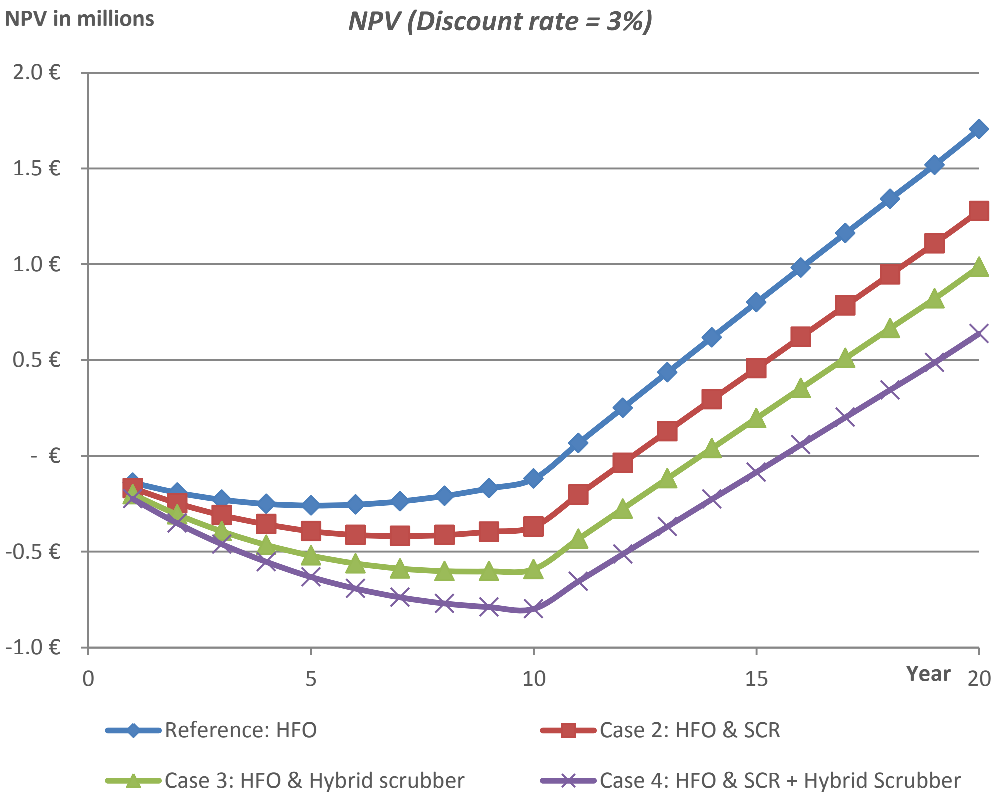

t $SO_{2\ eq}$
AP in t $SO_{2\ eq}$
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber


t $PO_{4\ eq}$
EP in t $PO_{4\ eq}$
14
12
10
8
6
4
2
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

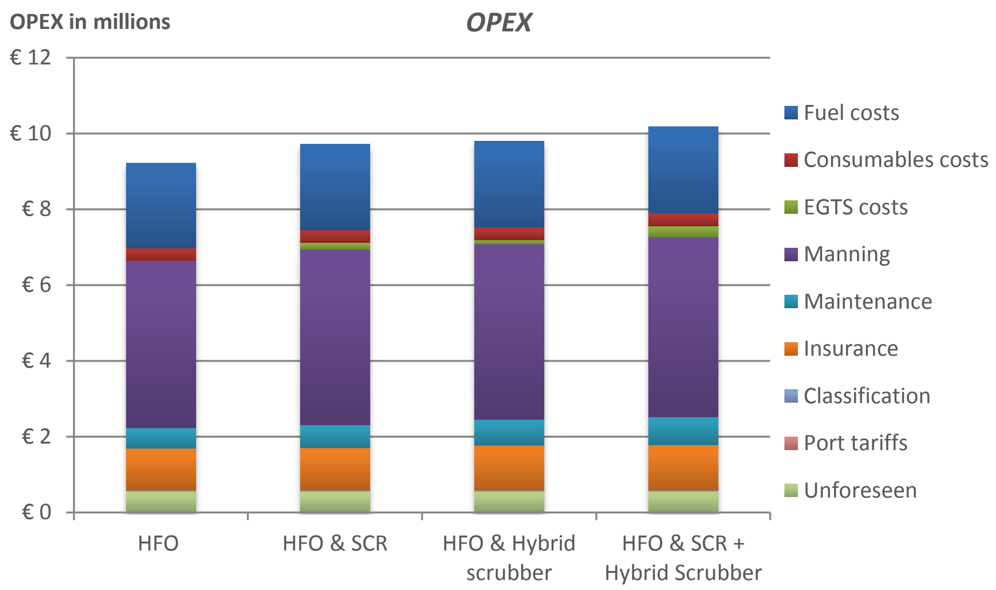

t PM
PM in t PM
25
20
15
10
5
0
0
5
10
15
20
years
Reference: : EN 590
LNG
MGO
HFO - Hybrid scrubber

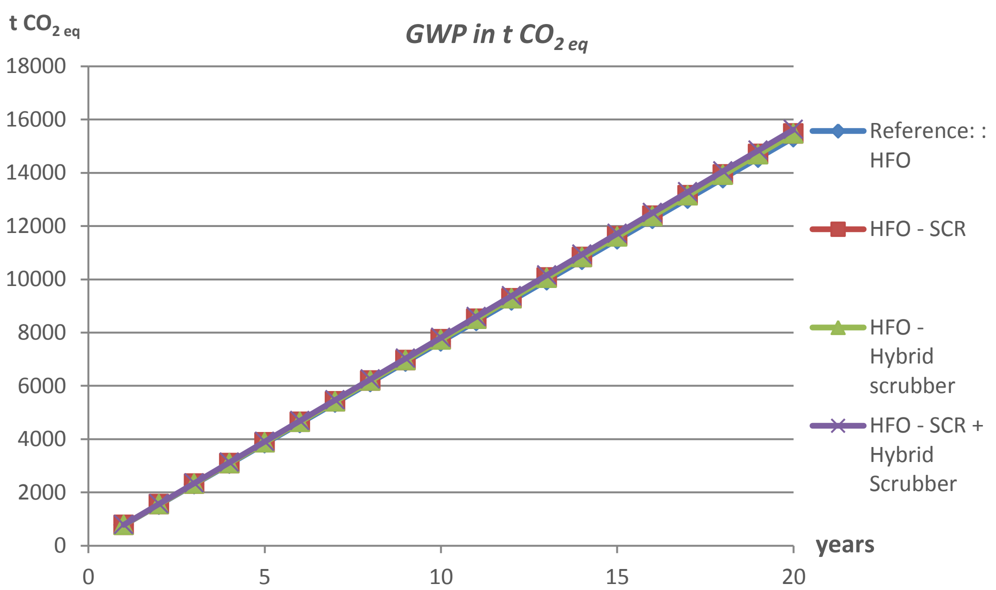
## TENTH LCPA: ALL HFO WITH FOUR DIFFERENT

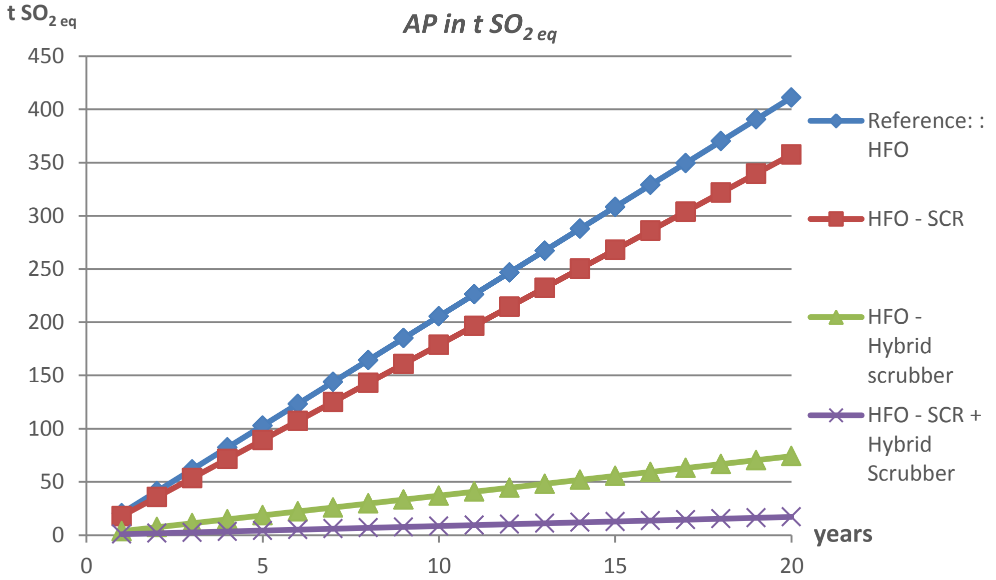
| | | Reference: | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|---|
| | | HFO | HFO & SCR | HFO & Hybrid scrubber | HFO & SCR + Hybrid Scrubber |
| **Fuel** | - | HFO | HFO | HFO | HFO |
| **Fuel price** | $ / mt | $564.00 | $564.00 | $564.00 | $564.00 |
| **EGTS** | - | None | SCR | Hybrid scrubber | SCR + Hybrid Scrubber |
| **LCA result** | | | | | |
| **GWP** | t $CO_{2\ eq}$ / year | 766.126 | 773.788 | 773.404 | 781.066 |
| **AP** | t $SO_{2\ eq}$ / year | 20.562 | 17.877 | 3.708 | 0.855 |
| **EP** | t $PO_{4\ eq}$ / year | 0.624 | 0.094 | 0.624 | 0.094 |
| **PM** | t PM / year | 5.058 | 5.109 | 1.021 | 1.031 |
| **LCC result** | | | | | |
| **NPV** | | € 1,704,359 | € 1,276,992 | € 985,602 | € 637,374 |
| **IRR** | | 7.45% | 6.33% | 5.45% | 4.58% |
| **Deviation in percentages** | | | | | |
| **% GWP** | | 0% | 1% | 1% | 2% |
| **% AP** | | 0% | -13% | -82% | -96% |
| **% EP** | | 0% | -85% | 0% | -85% |
| **% PM** | | 0% | 1% | -80% | -80% |
| **% NPV** | | 0% | 25% | 42% | 63% |
| **% IRR** | | 0% | 15% | 27% | 39% |

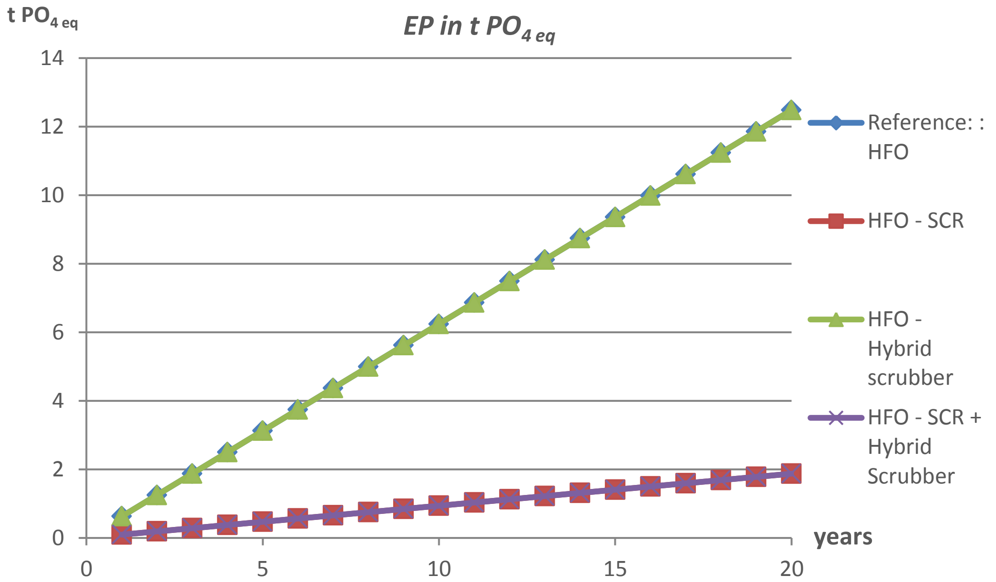


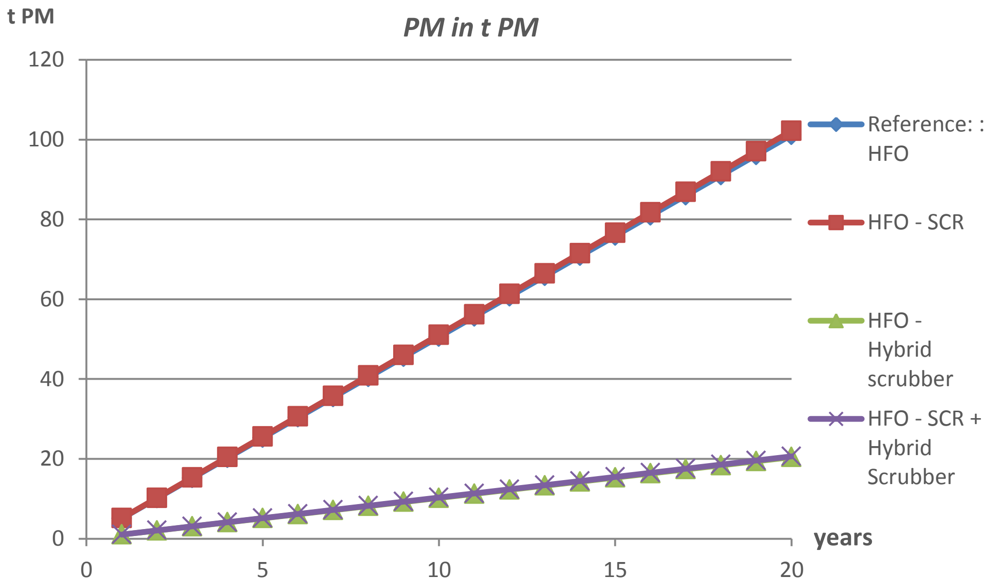
| | Reference: : HFO | HFO & SCR | HFO & Hybrid scrubber | HFO & SCR + Hybrid Scrubber |
|---|---|---|---|---|
| **Fuel costs** | € 2,243,531 | € 2,265,966 | € 2,264,844 | € 2,287,280 |
| **Consumables costs** | € 336,530 | € 339,895 | € 339,727 | € 343,092 |
| **EGTS costs** | € 0 | € 182,974 | € 109,150 | € 294,789 |
| **Manning** | € 4,403,801 | € 4,623,991 | € 4,623,991 | € 4,734,086 |
| **Maintenance** | € 550,475 | € 605,523 | € 688,094 | € 743,141 |
| **Insurance** | € 1,100,950 | € 1,117,024 | € 1,181,320 | € 1,197,393 |
| **Classification** | € 33,029 | € 33,029 | € 33,029 | € 33,029 |
| **Port tariffs** | € 0 | € 0 | € 0 | € 0 |
| **Unforeseen** | € 550,475 | € 550,475 | € 550,475 | € 550,475 |
| **OPEX** | € 9,218,790 | € 9,718,876 | € 9,790,629 | € 10,183,285 |




t SO2 eq
AP in t SO2 eq
450
400
350
300
250
200
150
100
50
0
0
5
10
15
20
years
Reference: : HFO
HFO - SCR
HFO - Hybrid scrubber
HFO - SCR + Hybrid Scrubber


t PO4 eq
EP in t PO4 eq
14
12
10
8
6
4
2
0
0
5
10
15
20
years
Reference: : HFO
HFO - SCR
HFO - Hybrid scrubber
HFO - SCR + Hybrid Scrubber


t PM
PM in t PM
120
100
80
60
40
20
0
0
5
10
15
20
years
Reference: : HFO
HFO - SCR
HFO - Hybrid scrubber
HFO - SCR + Hybrid Scrubber