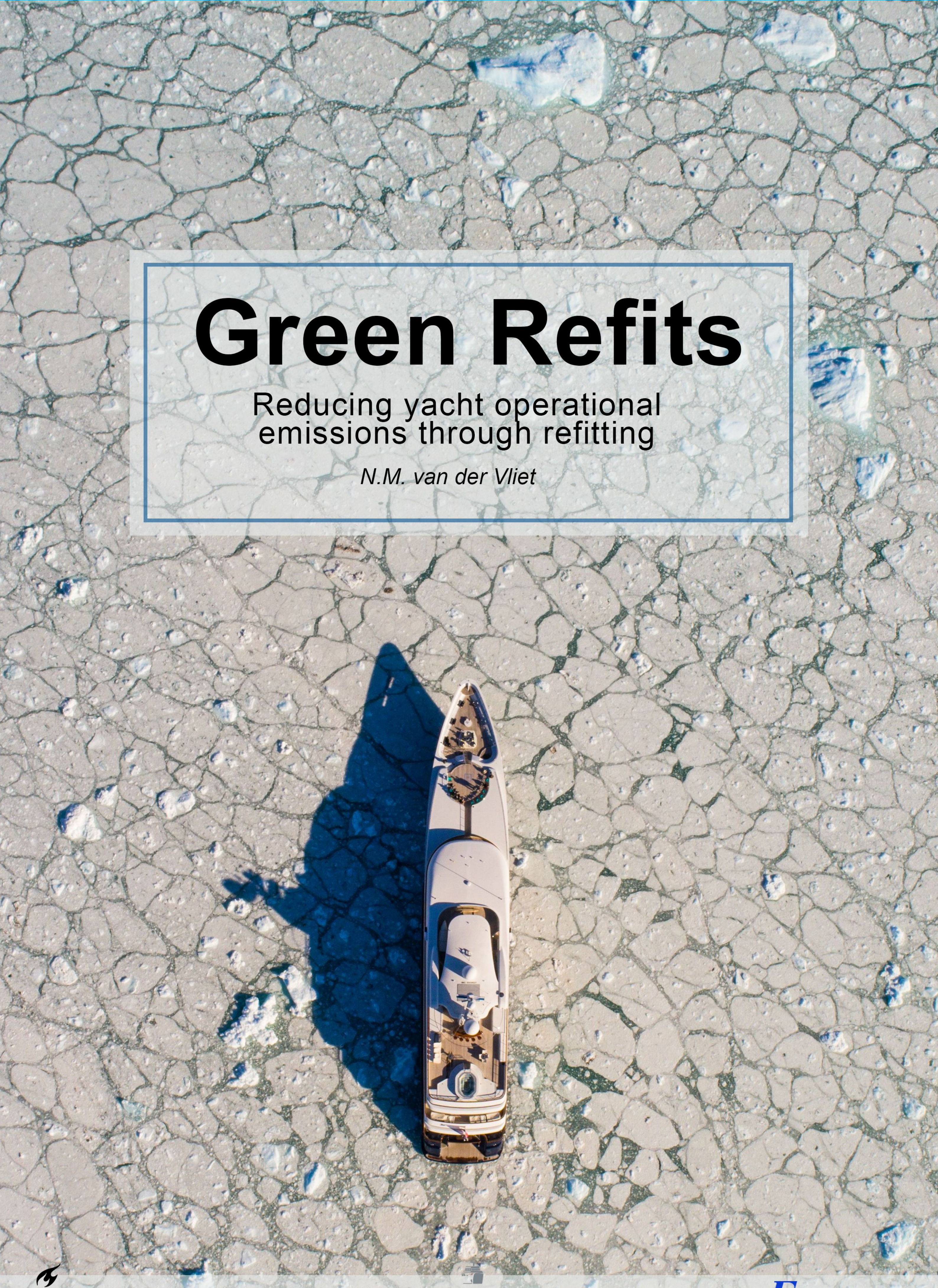

Green Refits

Reducing yacht operational emissions through refitting

N.M. van der Vliet

TU Delft DE VOOGT NAVAL ARCHITECTS FEADSHIP ROYAL DUTCH SHIPYARDS

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Reducing yacht operational emissions through refitting

by

N.M. van der Vliet

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tuesday May 27th, 2021 at 14:00 PM.

Student number:	4278216	
Project duration:	September 1st, 2020 – May 27th, 2021	
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Preface

This report is part of the MSc. thesis project to obtain the MSc. degree Marine Technology at the Delft University of Technology. This project is performed at De Voogt Naval Architects in collaboration with the Feadship Refit & Services group. This research is aimed to give insight into the impact reduction and cost-effectiveness of refit options for yachts. It aims to create a selection tool to aid in the sustainable refit decision making process, helping to make sustainable refits more widely applied in the yachting industry.

Firstly I would like to express my gratitude to both Jeroen Pruyn and Giedo Loeff for giving me the opportunity to do this project. Your contributions have guided me through the process and helped me shape this thesis. I am also grateful to De Voogt Naval Architects for facilitating this research through an inspiring work environment and access to the internal research which layed the base of this project.

Furthermore I would like to thank Mattijs Zonnevijle from the Feadship Refit & Services department for his enthusiasm and helpfulness, which have greatly aided this project. I also would like thank Arthur Remeijers from Van Lent and the rest of the Refit & Services department, who have always helped and motivated me during and after our meetings.

Furthermore, I would like to thank the other graduation interns at De Voogt for the inspiring coffees, lunches and drinks, which were always enjoyable. My thanks goes out to my family, friends and my girlfriend, who have all supported me throughout this study.

N.M. van der Vliet
The Hague, May 2021

Summary

The current yacht industry must reduce its environmental impact significantly in order to comply with increasingly stringent regulations and goals. Building only sustainable yachts is not sufficient to reduce the impacts of yachting, existing ships must be adjusted as well. With a sustainable refit, existing ships can be altered to reduce operational emissions in order to reduce their impact. Several options are available to increase the efficiency of a ship or reduce its emissions. In order to evaluate which refit options are most suitable for specific yachts an overview is needed of the impact reduction and cost effectiveness of these measures. The aim of this research is therefore to create an appraisal tool to determine the cost-effectiveness of yacht operational emissions reducing refit options. In order to gain insight into the current refit process an overview of the service area's was made and data on past refits was analysed.

In order to define the fitting decision making method, an analysis was made of abatement decision making in literature. Furthermore, the refit process was analysed and distributed into three phases: the upstream, yard processes, and downstream. Since the majority of emissions are in the operational part, the focus of this research is on this phase. The operational emissions consist of exhaust-, noise- and sewage emissions. In the selection tool the Well to Tank (WTT) and Tank to Well (TTW) emissions are taken into account. The impacts to ecosystems, human health and climate by different air emissions were evaluated, as well as methods to express them. The main environmental impacts by yacht operational emissions are eutrophication, acidification, global warming, photochemical oxidation, particulate matter and ozone layer depletion.

With the Marginal Abatement Cost Curve, an overview can be created of the impact abatement and marginal costs of refit options. In this research the curve was constructed both for both CO_2-equivalent units, to assess the difference in global warming potential, and for external cost reductions, in order to take into account the total impact, including other harmful effects of emissions, set out over the listed abatements. To provide a complete overview of the financial aspect a business case was added to supplement the curves with, among others, payback time.

The tool was then supplemented with a selection of five refit options, ranging from power generating and power consuming to emission reducing. Solar panels were implemented as power generating solution. As propulsionary power consuming refit option, anti-fouling techniques were analysed. A waste heat recovery system as well as LED light implementation were analysed as auxiliary power consumption reducing options. As an emission reducing option the implementation of a selective catalytic redactor system was analysed. These refit operations were evaluated in terms of technology, refit implementation and finally capital- and operational expenditure costs. The specific inputs needed for implementing these refit options in the model were evaluated and added to the tool.

The model was subjected to multiple case studies in order to asses the impact of length, fuel price and biofuel implementation on the cost effectiveness of refit options. The first case is done on a 54 meter ship, which is the average refit length, using the current fuel price. The implementation of these refit options could reduce its Global Warming Potential (GWP) with 23 % and its total impact with 54 % at a yearly cost increase of 79.7 k€, or 35% extra on fuel expenditures. A fuel price increase of 158 % resulted in the refit options being cost neutral. Using biofuel, Hydrotreated Vegetable Oil (HVO), the GWP is reduced by 78 % and external costs are reduced by 70 % at a yearly cost increase of 167.4 k€, or 47%. The same situations were evaluated for a 100 meter ship, in which similar relative impact reductions were found at a smaller increase of yearly costs.

The results of these studies showed that using HVO for GWP reduction and a SCR unit for reducing NO_x impact can significantly decrease the impact of a yacht. Higher fuel prices of HVO make efficiency improving refit options more cost effective, since fuel saving revenue is higher. HVO therefore provides a possibility for yachts to decrease their impact significantly without large investment at a relatively small extra operational expenditure cost. The combination of MACC's and a business case present an opportunity to present an overview of cost effectiveness of all refit options, if supplemented.

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List of Abbreviations

(F)MDAM	(Fuzzy) Multiple-Attribute Decision Making
AHP	Analytical Hierarchical Process
ANP	Analytical Network Process
CA	Classic Algorithm
CED	Cumulative Energy Demand
CO	Carbon Monoxide
CO_2	Carbon Dioxide
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
ESD	Energy Saving Device
FEMA	Energy Efficiency Operational Indicator
GloMEEP	Global Maritime Energy Efficiency Partnerships
GWP	Global Warming Potential
HC	HydroCarbon
HVAC	Heating, Ventilation & Air Conditioning
HVO	Hydrotreated Vegetable Oil
ILCD	International Reference Life Cycle Data
ILP	Integer Linear Programming
IMO	International Maritime Organisation
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LED	Light-Emitting Diode
LNG	Liquefied Natural Gas
MACC	Marginal Abatement Cost Curve
MGO	Marine Gas Oil
NB	New Build
NOX	Nitrogen Oxides
PM	Particulate Matter
PSSA	Particularly Sensitive Sea Area
PV	Photovoltaic
RF	Refit
SCR	Selective Catalytic Reductor
SDG	Sustainable Development Goals
TTW	Tank to Well

UN	United Nations
UV	Ultraviolet
WTT	Well to Tank
WTW	Well to Wake

1

Introduction

The maritime industry is known to be a large emitter of greenhouse gasses and other harmful substances, which affect ecosystems, climate and human health. The environmental impacts of maritime emissions are becoming increasingly relevant, especially in vulnerable and unique locations. Increasingly stringent regulations, such as emission control areas and particularly sensitive areas determined by the International Maritime Organisation (IMO), make it necessary for superyacht owners to reduce their emissions and increase the sustainability of their yacht. Furthermore, the IMO has set a goal to reduce maritime emissions to 50 % of the amount that it was in 2008.[55] This means that the current total amount of yacht emissions must be cut down significantly, while the global yacht fleet and its global warming potential are still increasing. Adjustments to existing ship designs to reduce global warming potential are therefore inevitable. Furthermore, the IMO is denying access to polluting ships in emission control areas. It can therefore be expected that the amount of sustainable yachts will increase in future years. Since the value of a superyacht is also determined by the ability to visit pristine and unique locations, sustainability also has a commercial motive. Not only is it of influence on the resale value of a superyacht, a charter rate, if applicable, is also dependent on the possible destinations of a superyacht. Apart from this factor, pressure from society on the yachting sector to become more sustainable is rising. Luckily the yachting sector has the possibility to be a frontrunner in sustainable maritime technology. The superyacht industry has been known to implement new techniques that are not yet applied widely within the marine industry, because of their financial resources.

In new designs innovative energy saving options are often implemented. Existing ships can be adapted and thereby improved in order to be more energy-efficient and less polluting, a so-called ”green refit”. By refitting it is possible to extend the lifetime of a superyacht significantly. A lifetime that would otherwise span 20 years. Since designs, operational profiles and owners’ wishes differ with each case, there is no single solution of refit options to reduce the environmental impact through refitting. Each case must be evaluated separately, in order to determine the suitable refit composition for the ship, the owner and the environment.

Several options are available for reducing the operational impact of a yacht. These measures can be either energy producing, efficiency increasing or emission reducing. For shipowners, a sustainable refit requires a significant investment. It is therefore of importance that the impact reduction is also cost-effective in order to make impact reducing option implementation commercially attractive and increase the incentive to implement such a solution.

This chapter will give insight into different aspects of sustainability for yachts in section 1.1. Furthermore the background on refits is elaborated on in section 1.2. The problem statement is given in section 1.3 and the research objective in section 1.4. Thereafter the research questions are given in section 1.5. An overview of the structure is given in 1.6.

1.1. Sustainability

Increasing sustainability in yachts has gained more attention in recent years, mainly due to increasingly strict environmental regulations and societal pressure. The definition of sustainability according to the Oxford

English Dictionary [87] is as follows:

> *“The property of being environmentally sustainable; the degree to which a process or enterprise is able to be maintained or continued while avoiding the long-term depletion of natural resources“*

This definition can be expressed in several ways with respect to yachts, through sustainability management tools, elaborated on later in section 2.3. In this section, the different aspects of the value of sustainability in yachting are examined. Firstly through a global perspective and subsequently through the perspective of owners and shipyards.

Global
The United Nations has set 17 sustainable development goals to transform the financial, economical and political systems that govern current society to guarantee human rights for all.[108] By also looking at the sustainable development goals (SDG), we can conclude that sustainability for yachts encompasses more than only environmental impact. Sustainable yachting contributes to the following goals, as seen in figure 1.1

As seen in the figure, sustainable yachting contributes to goals 3, 7, 9, 12, 13, 14 & 15. It contributes not only by reducing emissions, but also by being a front runner for implementing new innovative technologies in, for example, alternative fuels. The International Maritime Organisation (IMO), being part of the United Nations, state that SDG 14 is central to them, but aspects of their work can be linked to all individual goals. [53] Emission regulations such as the ones described below help achieve the goals shown in figure 1.1.

Figure 1.1: Sustainable yachting contribution to UN sustainable development goals

The maritime industry is known to be a large contributor to greenhouse gas emissions. It is estimated that the share of shipping emissions in the global anthropogenic emissions has risen to 2.89%. [56] Sustainable yachts can contribute to the reduction of harmful emissions by the maritime sector. The IMO is the agency of the United Nations that is responsible for the safety and security of shipping, as well as the prevention of pollution by ships. It provides the legislation against marine- and air pollution by marine traffic. In order to regulate pollution, the IMO has developed the International Convention for the Prevention of Pollution from Ships. This convention is divided into six annexes, each dealing with the regulations on a specific type of ship emissions. The IMO has also established several Emission Control Area’s (ECA), in different coastal areas of Europe and North-America, in which stricter limits on nitrogen oxides (NO_x) and sulfur oxides (SOx) are present.[56] Starting January 1st of 2020, the IMO has stated a global sulphur cap, lowering the amount of sulphur permitted in ship's fuel oil from 3.5% to 0.5 % [13] of which the IMO expects a 77% reduction of SO_x emissions from ships.[50] Within ECA's the sulphur limit in fuels has been 0.1 % since 2015. [13]

If yachts do not comply with these stricter regulations, they are not allowed into the ECA's. These area's are shown in figure 1.2.

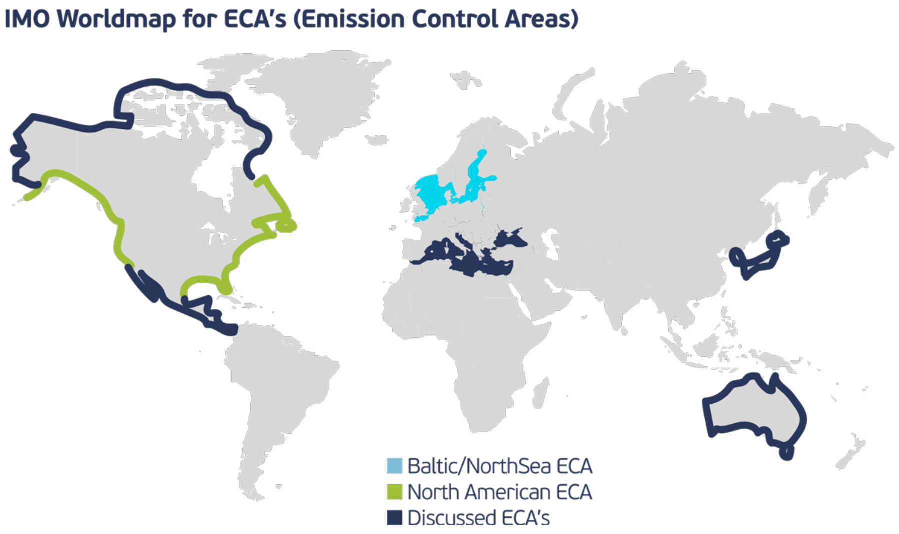

Figure 1.2: Emission Control Area's [88]

As seen in the figure, the current ECA's are in the North-American coastal area's and the Baltic and North Sea in Europe. More area's in the world are being discussed as possible future ECA, such as the Mediterranean sea. In these ECA's the IMO Tier III regulations are valid, which are stricter than the global emission requirements, Tier II. A Tier III compliant engine emits 75% less $\mathrm{NO_x}$ than a Tier II compliant engine. These ECA meaures are valid for vessels with keel-laying, or engine replacement after January 1st 2016 in the North-American ECA and the United States Caribbean Sea ECA.[49] In the Baltic or North Sea ECA this date is January 1st 2021.[49] The Norwegian Maritime Authority has declared that all ships of 1,000 gross tonnage and upwards constructed, or having had a major diesel engine conversion, on or after 1st of January 2000 visiting the Norwegian world heritage fjords from January 1st 2025 onward have to be Tier III compliant.[83] This means that without design adjustments, several superyachts will not be allowed into the Norwegian Heritage fjords.

The Mediterranean area has been visited by 46.8 % of active superyachts in the period 2015-2018. Furthermore, it has the highest average number of unique yachts of any area. It is therefore undoubtedly an important area for superyacht activity.[76] If an ECA were to be established there it would have far stretching impacts on a large number of superyachts. Adjustments to ship design would have to be made in order to maintain access to this area, therefore having a sustainable yacht increases the amount of available destinations, increasing the operational area, thereby adding value to the yacht.

Apart from ECA's, the IMO has also designated Particularly Sensitve Sea Areas (PSSA). These are area's that need special protection and are recognised for their ecological, socio-economic or scientific attributes. [51] Special measures can be introduced in these areas. For example, it can be defined as an area to be avoided in ship routing systems, or sewage discharge in the area could be prohibited. [51] Examples of PSSA's are The Great Barrier Reef, where stricter sewage rules apply [4] and the Galapagos Islands, where strict admission limitations apply for yachts. [79]

Owner

Firstly, increasingly stringent regulations could limit the reach of an owners' superyacht. If access to, for example, the Mediterranean area would be restricted to a certain yacht, it could lose value for owners, since it is one of the most prominent superyacht destinations [76], and also decrease resale value since prospective owners will take this into account. If the owner would make their yacht available for charter, the rate would also be depended on the possible destinations. For an owner having a sustainable yacht could have a positive social status effect as well. Since social pressure on yacht-owners has been increasing, sustainability has become a more frequent topic within the yacht sector. It is not uncommon for relatively new techniques, such as diesel electric propulsion, to be implemented on yachts. In this case the yachting industry is a driving factor for sustainability in the maritime industry. Sustainable yachts use less energy as well, so operational costs could be reduced for owners.

Shipyard

Sustainability also has value for shipyards, as being a frontrunner in sustainable yacht technology could benefit customers. Since more ECA's are most likely coming, yacht owners will need yards to implement design changes. Being a front runner for implementing new sustainable technologies could help in achieving a favourable market position. Since more prospective yacht owners are looking for sustainable solution, a sustainable yacht portfolio could help persuade these future owners. From a refit perspective, a yard could implement solutions in yachts in order to comply with stricter regulations present in ECA's.

1.2. Refit background

In order to determine the essence of a sustainable refit, an overview is needed on how a refit is currently defined and executed. The term refit is generally used when, apart from regular necessary maintenance, adjustments or replacements are made to the interior, exterior or ship systems. A refit is viewed in this thesis as a new life for a yacht. Normally the lifecycle of a superyacht is around 20 years, after this period all components except the hull and superstructure have reached their end of life.[18] The lifetime of the yacht can however be extended by refitting the ship.[18] So instead of a ship being built from scratch, a ship can also be refitted. In this case refitting replaces the need for a new built hull, therefore preventing the emissions and other negative environmental impacts from the production of steel and aluminium. A refit doesn't have to be solely for the purpose of extending the lifecycle of a yacht. It can also be used to implement components that reduce a ship's energy consumption, such as a waste heat recovery system, or installing solar panels. Another refit activity could be the installation of a selective catalytic reactor to reduce NO_x emissions.

The different service area's of a yacht refit are explained in section 1.2.1, subsequently the current Feadship refit market is examined using refit data in section 1.2.2.

1.2.1. Service area's

A distinction is made between the following service area's:

- Hull and superstructure extensions and remodeling
- Interior rebuild and redecoration
- Technical refits and maintenance
- System updates
- Exterior reconditioning

Hull and superstructure extensions and remodelling

As owner's wishes often change over time, extra space is sometimes needed in a yacht to introduce another guest bedroom for example. Another example could be the removal of guest cabins in order to create space for an on-board beach club. If more space is needed on board, the hull can be extended at the stern. In order to retain the flow and balance of the profile, the superstructure must then be extended as well. Older boats often have limited bridge sizes, therefore an extension of the superstructure can add significant value to the ship.

Interior rebuild and redecoration

If an interior is designed and produced 20 years ago, odds are that by now it will not be up to modern standards and will look outdated. A change in taste or family situation could also be a reason to renew a yacht interior. Even if, after 20 years, the owner is still satisfied with the current interior design, the yacht will be stripped anyway and the old design will be remade with new materials, as these materials will have reached their maximum lifetime. A frequently executed refit activity is the replacement of the interior lights to LED. This also requires the replacement of all cabling due to a change in net frequency.

Technical refits and maintenance
Technical refits and maintenance take place in the engine room and the technical spaces. Class-surveys and more long-term wear and tear require regular maintenance, repair and replacement of machinery and equipment. Usually a major engine room refit is needed every five to ten years and is often combined with other yacht work.

System updates
Electronic systems, such as navigation and communication systems, audio/video equipment, internet facilities, and other gadgets are quickly outdated and in need of replacement. After 20 years it is imaginable that a television, or any other entertainment system is no longer according to the owners wishes. Electrical cables of this age have to be replaced as soon as they are touched, as they become more brittle with age. [18] Furthermore, changing demands in ship safety and communications require up to date bridge equipment.

Exterior reconditioning
Since most yachts are almost constantly exposed to salt water, teak decks and other exterior hardware have to be maintained and replaced after a couple of years. Anti-fouling and superstructure paint must be redone every couple of years. Every 2.5 years the underwater ship has to be cleaned, repainted and protected against corrosion and every 5 years the superstructure is repainted as well. [18]

1.2.2. Refit data

In order to gain more insight into the current refit process and to determine the appropriate conditions for an average refit, past refits are analysed. Feadship refit data from the Super Yacht Group [105] of 101 refits is analysed in order to gain more insights into the distribution of ship ages at refit and refit duration. Since every yacht is unique, every refit composition is as well. There are no standard durations that apply to every ship, some trends explained below can however still be distinguished. For evaluation purposes, the ship age at the moment of refit is divided into 5 year periods and the refit lengths are divided into one month intervals. The different ship ages at refit are shown in figure 1.3.

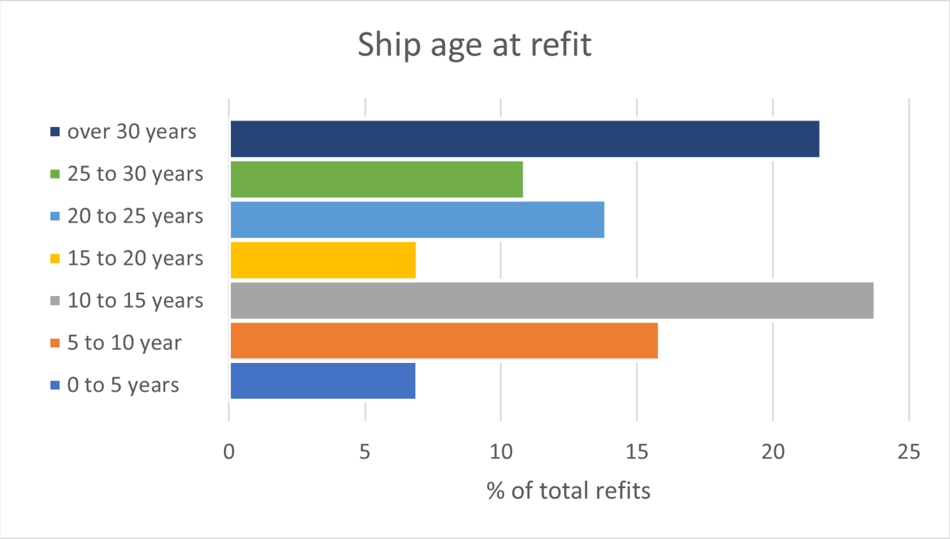

Figure 1.3: Distribution of ship ages at refit [105]

This data includes only refits, therefore, dockings followed by only underwater ship repainting without other refit activities are not included in the data-set, as well as regular maintenance. As seen in the figure, the largest groups are ships of 10 to 15 years and ships of over 30 years. Since around two thirds of the Feadship fleet is over 30 years of age [105], a lot of refits are done on this age group. Ships aging from 10 to 15 years account for 23.8 % of all Feadship refits. This is prior to the presumed end of life of a superyacht. The reason for this refit can be a resale or a change of taste or requirements of the owner. The smallest share of refits is of the age group of 0 to 5 years, which can be attributed to the fact that these yachts are still relatively new and thereby fitted with modern equipment and furniture.

In figure 1.4 the percentage of total refits in refit duration groups is shown, as well as the age distribution of the categories. As seen in the figure, 22.8 % of refits take longer than 12 months. Of these long refits, the biggest share is of ships that are over 30 years of age, followed by ships of 10 to 15 years. These refits of more than 12 months happen on relatively old ships, probably due to the time intensive interior and cabling replacement. Previous research on docking time statistics by Cozijnsen [18] showed a spike of docking time at 5 to 6 months, with a similar graph shape to figure 1.4, due to the repainting of the entire yacht. In figure 1.4, a similar peak is at 7 to 8 months. This could mean that Feadship refits take longer, or perhaps they are more often combined with other ship improvements. Also higher values in 0 to 3 months were reported in the research of Cozijnsen. The difference between the results is that the data from figure 1.3 and 1.4 is only from refits, where short maintenance dockings are not included. Examples of short maintenance dockings are warranty issues and underwatership cleaning and repainting. The research by Cozijnsen also reported a very small share of refits that lasted over 12 months, this is also due to the difference in docking and refit data. The largest share of dockings take place in the first few months of a superyacht, but not the largest share of refits.

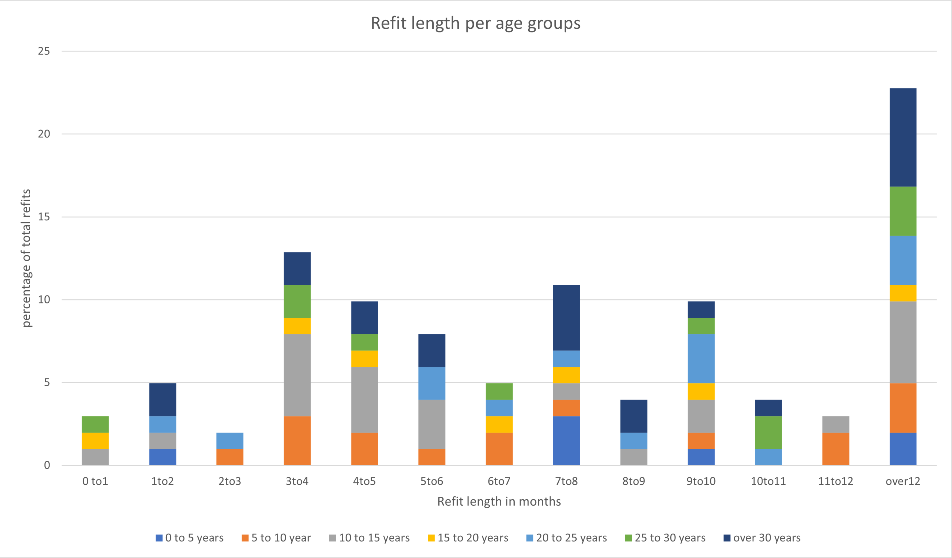

Figure 1.4: Distribution of ship ages per refit duration [105]

The distribution of ship lengths at refit is shown in figure 1.5.

As seen in the figure, the largest represented length group is 40 to 50 meters, with ships from 40 to 60 meters taking up 58 % of total refits. This can be explained by the fact the trend of building larger ships is relatively recent. Therefore, older, smaller ships require refits more often than newer, larger ships. It can therefore be expected that in the future the average ship length at refit will be higher than the 54 meter it is currently, since larger ships, over 80 meters, have been built by Feadship only since around 2010. This can also be seen when looking at the average ship length per year, as seen in figure 1.6.

As seen in the figure, at the end of the 20th century, the average ship build length at Feadship was 53 meters, and this average has been higher in the last 10 years, with a current average built length is around 77 meters, with 3 out of 4 ships being built over 70 meters. This is in line with the findings of figure 1.5 and 1.3, since a large amount of ships is over 20 years and between 40 to 60 meters.

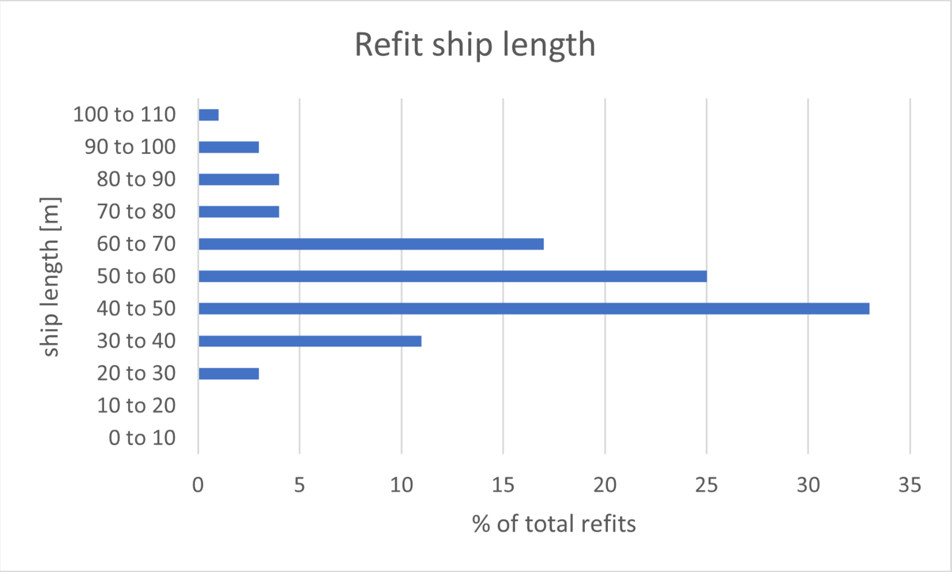

Figure 1.5: Distribution of ship ages per refit duration [105]

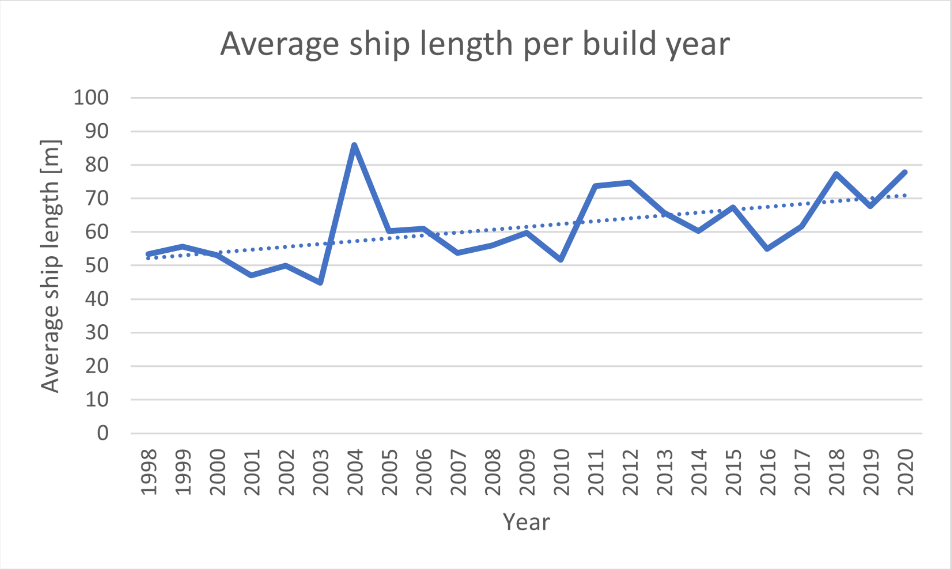

Figure 1.6: Average ship length per build year

1.3. Problem statement

Several impact reducing refit options are known in the maritime industry, yet sustainable refits are not that common. For yacht owners, yards and policy makers, who have effect on the decisions on which refit options to implement, a financial overview is often required. In order to aid in decision making and abatement selection, an overview of refit options, including costs and impact reductions, is to be made. If sustainable refits are not cost-effective, or it is not clear whether they are, the chances of it being commercially accepted are lower, as it requires a significant investment from an owner. Since environmental measures and goals are becoming increasingly stringent, the sustainable refit is inevitable. For commercial vessels the IMO has established a computer based appraisal tool [54] to evaluate the effectiveness of operational energy efficiency measures called Global Maritime Energy Efficiency Partnerships (GloMEEP). This tool is however not applicable to yachts, since yachts have a fundamentally different design and operational profile. Firstly, a yachts energy demand consists for around 50 % of auxiliary power, created by generators. For container vessels this is around 17 % [3]. The propulsionary power that is used by a yacht varies more then that of transport vessels, since it is more often used for day trips instead of ocean crossings. Furthermore, yachts design differs fundamentally from cargo ships as they have no cargo space since they are designed for pleasure instead of transport. So not only the energy demand is different, but also the operational profile. This means that an impact reducing measure that suits a shipping vessel, could not work for a yacht and therefore an assessment of impact reducing options for shipping vessels would not be accurate for a yacht. Furthermore the GloMEEP focuses only on greenhouse gas abation of refit options. No tool exists that can evaluate the cost effectiveness of yacht refit abatements, while taking into account the impact reduction.

1.4. Research objective

The objective of this research is to connect the impact reduction of sustainable refits with an overview of the economic perspective, with a focus on operational emissions reduction. To do this, firstly the value of sustainability for yachts must be determined as well as the possibilities to increase a yachts' sustainability. This can be done by creating a universal tool for which the cost effectiveness of impact reducing refit options is evaluated. This tool should take into account that each yacht is different, each owner has different preferences and uses their yacht differently. Therefore not a single optimal solution is present for each situation, but an overview of cost effectiveness and impact reduction per measure can be used to aid and possibly persuade an owner interested in a sustainable refit.

Since not all refit options can be evaluated in this research, the objective of this research is to create a tool in which other refit options can be added to. The five refit options that are selected will be evaluated in terms of investment costs and yearly costs, including installation and maintenance costs. With this the payback time of each refit option in each situation can be determined. Case studies will be done on several ship sizes to determine the scale effects of refit options. Furthermore with this tool the effects of circumstances will be evaluated. For instance the effect of fuel price on the cost effectiveness of refit options or the implementation of biofuels as main fuel.

1.5. Research question

The main research question is formulated as follows:

> *What is a cost-effective method to reduce the operational emissions of an existing yacht through "refitting"?*

1.5.1. Subquestions

The subquestions are formulated as follows:

1. How can the impact reduction of a yacht be quantified and measured?
2. What are the options for reducing emissions throughout the refit process?
3. Which refit options are feasible for reducing operational emissions?
4. How can owners wishes, operational profile and all refit phases be incorporated into a selection tool?
5. How can the cost-effectiveness of these abatements be determined?
6. To what extent is the solution sensitive to input variations?

1.6. Structure

The structure of this thesis is visualised in figure 1.7. In the introduction, chapter 1, the basics of sustainability for yachting and the refit background are treated. After this, in chapter 2, the sources, effects and distribution of the impacts of yachts are treated. In chapter 3 selection tool outline is created. After the design requirements are determined, the literature is reviewed and a selection method is chosen as well as the output determination. Once the basics of the selection tool are determined, the tool is further supplemented with 5 refit operations, selected and treated in chapter 4. Their corresponding inputs are determined and calculated in this chapter as well. Now that the refit options have been added to the tool, the case studies of the small and large yacht are treated in 5. To further elaborate on the tool, the outline is showed with the base case results in appendix A. The conclusion and recommendation for further research are given in chapter 6.

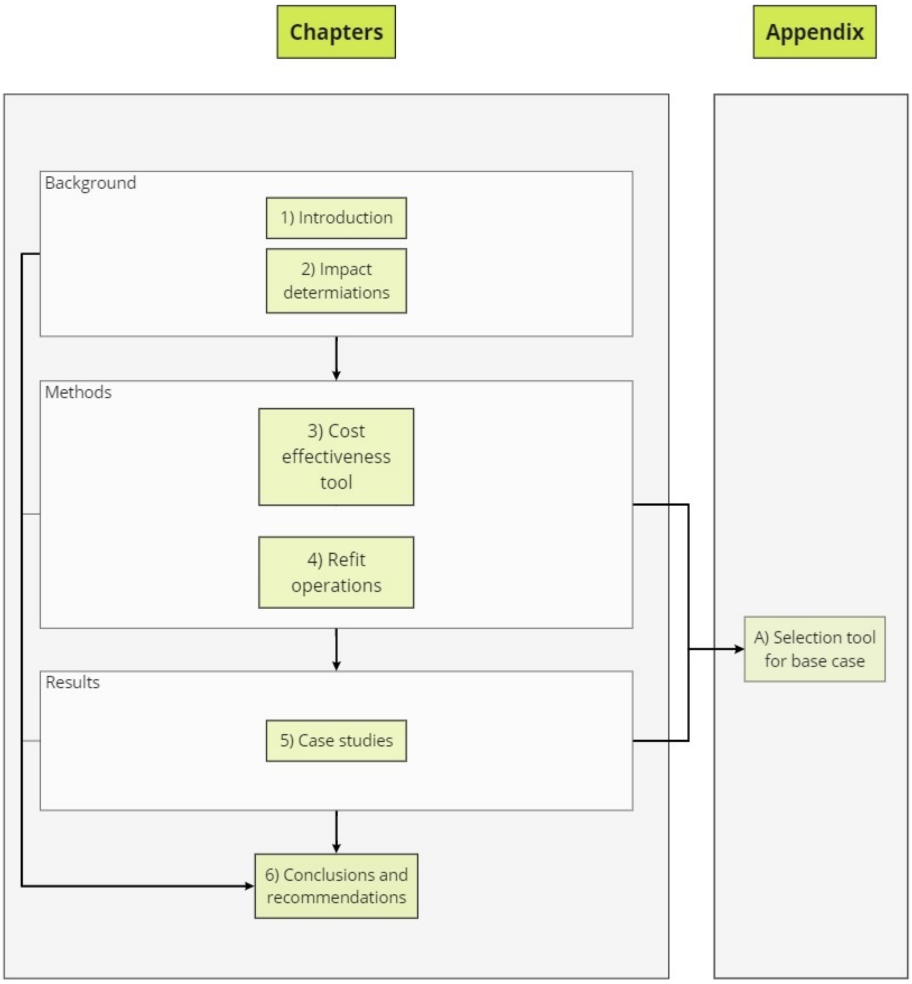

Figure 1.7: Outline of the thesis

2

Impact determination

In order to reduce a the impact of a yacht, it is essential that the sources, effects and distribution of these impacts are known. These aspects are treated separately in this chapter. First the refit is divided into three phases, which is treated in section 2.1. The operational emissions are treated in depth in section 2.2. The assessment different environmental impacts is then treated in section 2.3 and the chapter is concluded on in section 2.4.

2.1. Refit abatements

In order to asses the impact of a refit process, an overview is made of the composition of a refit in this section. The refit process is divided into three chronological parts, the upstream, execution and downstream part. This is visualised in figure 2.1.

Figure 2.1: Refit phases

2.1.1. Upstream

The upstream part encompasses everything that happens before the refit is executed. Important aspects are material origins and how components are manufactured.

Material origins

Some examples of materials incorporated in a yacht are teak, leather and heavy metals. Illegal logging can seriously threaten forest ecosystems in the tropics. As teak often depends on deforestation and degradation of natural rain forests [59], the environmental impact of the origins are significant. As leather in the interior of Feadship is of high quality, the environmental aspect of this material might be reduced if an artificial replacement were available. Furthermore, multiple heavy metals are used in a Feadship, of which around 78 kg of gold [18]. As not all of this is recycled, the environmental impact of this material in yacht building is relatively high. The extraction of gold requires a large amount of energy per gram of gold obtained, because of the scarcity of the material in the soil.

Production methods
The production of components to be refitted can also be taken into account. For example the working conditions in factories of electronics manufacturers, or the environmental impact of the production of a stabiliser.

2.1.2. Yard Processes

Yard processes encompass everything that happens during the refit. This includes for example the waste management of the refitting yard, as well as the energy supply.

Waste management
A refit is a large operation in which new components are introduced and old components discarded. The waste streams are also of influence on the environmental impact of the refit. For example, the packaging of replacement screws, seals or other components is now usually plastic, but perhaps a more sustainable solution is available. Also the stream of discarded furniture, carpets, electronics and other waste materials are of importance.

Energy management
A refit requires a lot of energy. Not only the amount of energy, but also how efficiently it is used is of importance. Firstly, it is of importance that the shipyard energy supplier is green. Furthermore, the wharf can install their own source of supply, such as solar panels and wind turbines combined with connecting to a hybrid micro grid system.[97] This way the fluctuating supply of energy can be matched with the demand of the shipyard. With solar panels the investment period of return is in some cases approximately seven years for the entire electrical energy demand of a shipyard. [41] Efficient project management can decrease the energy usage of a shipyard as well. A well structured shipyard with knowledge of internal processes contributes to this. Furthermore, efficiency of machinery can be taken into account.

2.1.3. Downstream

The downstream part of the refit encompasses what happens with the ship after the refit is completed. The focus of this part is therefore on operational emissions. These can be reduced by efficiency improving- and emission reduction options, as well as operational improvements.

A wide range of options is possible to increase the efficiency and therefore reduce the energy consumption of a yacht. A separation is made between energy producing- and energy consuming components. Within energy consuming components propulsive and auxiliary consumers. Operational improvements incorporate changes in the usage of a yacht that reduce energy consumption or emissions.

Overview
A schematic overview of the refit impact reduction opportunities is seen in figure 2.2.

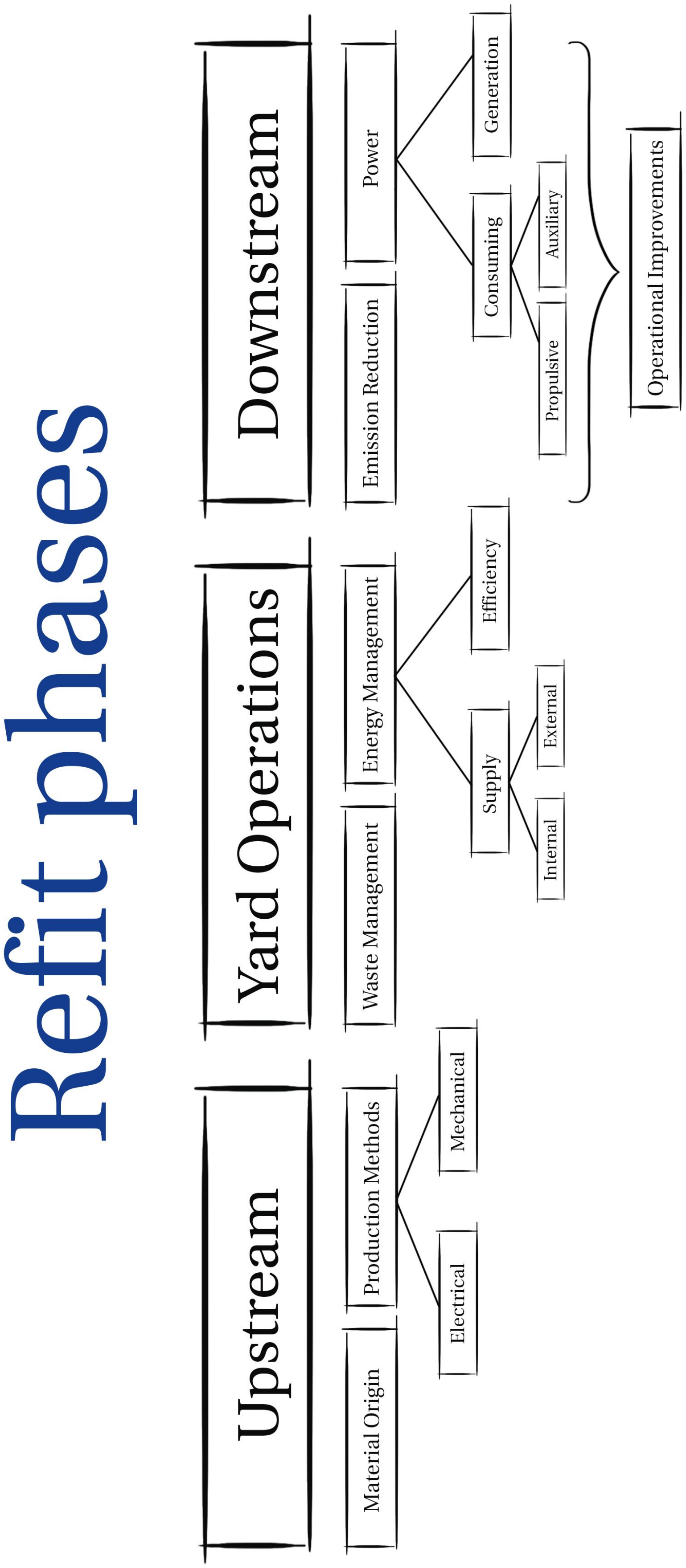

Figure 2.2: Refit phases

2.1.4. Emission distribution

In LCA of ships, a distinction is made between 4 phases: construction, operation, maintenance & dismantling.[16] The emissions in these phases are shown in figure 2.3.2 by [16]

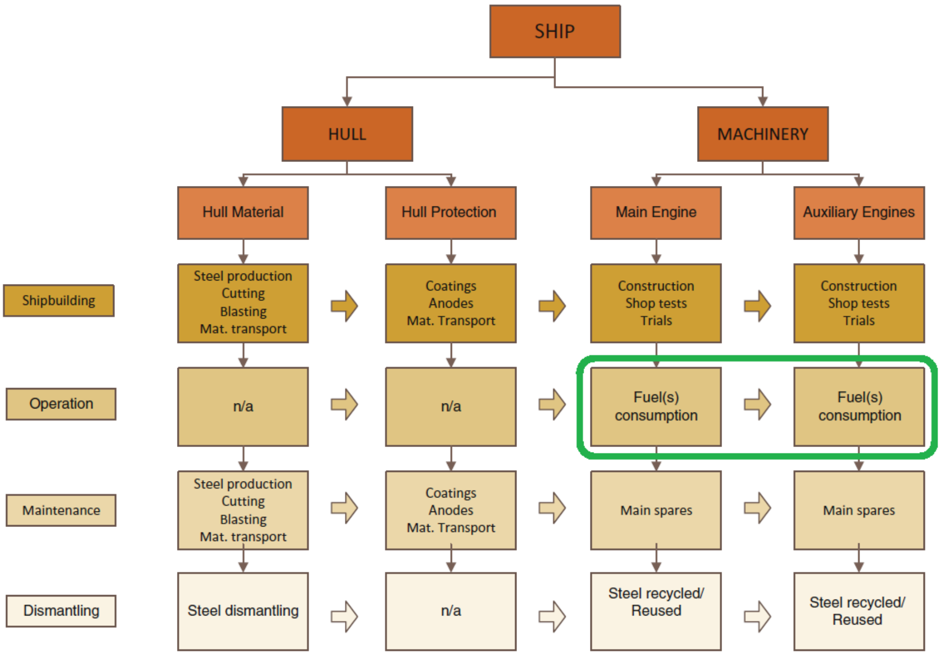

Figure 2.3: LCA framework for the assessment of air emissions in a life cycle perspective, by [16]

The operational emissions are highlighted in green, this is because within the two boxes indicated on the right side of the figure, more than 90 % of the total lifetime emissions are included.[16] This means that the remaining 10 % of emissions is provided by the other, not-indicated, boxes in the shipbuilding, maintenance and dismantling phase. The operational part of ship emissions is therefore by far the biggest influence on the lifetime emissions of a ship. [16] This is however for a new built ship. When executing a large refit, the hull material is not produced, thereby reducing the share of non operational emissions. Other emissions play parts here, such as the production or replacement of improvement components. An example is the production of batteries or solar panels. Using this knowledge, different operational reducing options will be compared, by using their respective upstream, yard and operational emissions and comparing them.

2.2. Operational emissions

Since operational emissions amount to the largest part of emissions in a ships lifecycle, as concluded in section 2.1.4, they are a large part of the impact of a ship. These emissions are evaluated in more detail in this section. Within operational emissions, a distribution is made between exhaust emissions, noise emissions and sewage emissions.

2.2.1. Exhaust emissions

The main pollutant exhaust emissions from marine diesel engines, also seen in figure 2.6, are as follows: [28]

- CO_2, Carbon dioxide
- NO_x, Nitrogen oxides
- SOx, sulphuric oxides
- HC, hydro carbons
- CO, Carbon monoxide
- PM, Particulate matter

In table 2.1, the effects of these emissions are shown, derived from the European Environment Agency report on air quality [40].

Table 2.1: Exhaust emission impacts

	Eutrofication	Acidification	Climate forcing	Ground-level ozon	Particulate matter
CO2		X	X		
NOx	X	X	X	X	X
SOx		X	X		X
HC			X	X	X
CO			X	X	
PM			X		X

Carbon dioxide

Carbon dioxide (CO_2) is the most well known exhaust gas component, mainly known for it global warming potential. Carbon dioxide is formed in all combustion processes in which a hydrocarbon is used. The amount of carbon dioxide emissions is therefore directly dependent on the amount of fuel burnt. Apart from a climate forcer, CO_2 is also a contributor to acidification.

Nitrogen oxides

Nitrogen oxides (NO_x) are released by oxidation of organic nitrogen in fuels. The amount and composition of nitrogen oxides released, depends on the local conditions in the combustion chamber of the engine. Nitrogen oxides are eutroficating, acidificating, climate forcing, ground-level ozon increasing, as well as contributing to particulate matter levels.

Sulphuric oxides

The amount of sulphuric oxides(SO_x) in exhaust emissions is derived directly from the sulphur content of the fuel used. SO_x Emissions contribute to climate forcing, acidification and particulate matter contents. [63]

Hydrocarbons

Hydrocarbons, also known as volitile organic compounds(VOC), consist of unburnt or partially burnt fuel with lubricating oils. They are therefore generally a product of incomplete combustion. They can consist of many chemical variations, therefore it is difficult to quantify these emissions. Apart from climate forcers, they are also known as ground-level ozon substances and particulate matter. [63]

Carbon monoxide

Carbon monoxide (CO) is a product of incomplete combustion. High rates of CO can therefore indicate a low combustion efficiency in an engine. CO-levels are therefore often higher in poorly maintained engines or at low power ranges. CO is mainly known for its direct health risks, however it also contributes to ground-level ozon and climate forcing. [63]

Particulate Matter

Particulate matter is already described in section 2.3.1. It is a collective term of organic and inorganic materials with a diameter no larger than 10 micrometers. Because of this small size it can be encountered in different area's than larger exhaust emissions. Apart from a direct health risk, it is also a climate forcer. [63]

Nitrogen oxides & particulate matter

Among others, Nitrogen oxides emission production depends on combustion temperature, oxygen concentration and in-cylinder composition ratio. Nitrogen oxides can be predicted if the exhaust gas recirculation rate (EGR) rates are known. [68] As seen in figure 2.4 [69], there is a trade-off between particulate emissions (soot) and Nitrogen oxides.

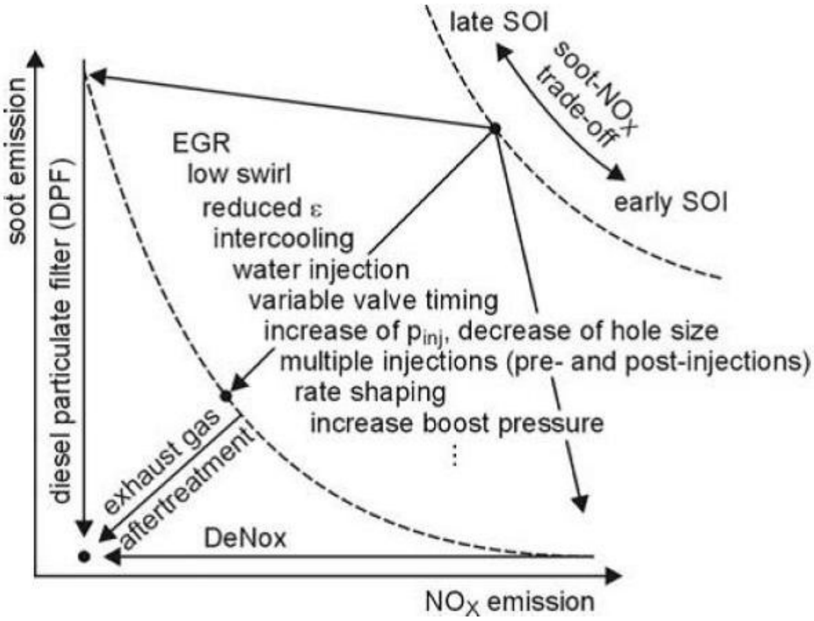

Figure 2.4: Soot(PM) and NO_x trade-off [69]

This figure also shown several measures for reducing soot or NO_x emissions. At higher temperatures more NO_x is formed, but less particulates and vice versa. A method for reducing NO_x emissions is to inject fuel late into the combustion chamber, thereby reducing chamber temperatures. Doing this also decreases fuel efficiency and increases particulate matter emissions. [81]

2.2.2. Noise emissions

Underwater noise emissions are cause by propellers, engines, generators and water flow around the hull and propeller wake. The highest levels of noise can be found behind the propeller, underneath the hull.[7] Ships are known to emit noise in frequencies in which marine mammals communicate, as seen in figure 2.5. A difference is made between mysticetes (baleen whales) and odontocetes (toothed wales).

In the graph the typical ship noise spectra are shown, the two different lines represent the level of sound from a ship at a 5 meter distance and a ship at 500 meter distance. The audiogram of odontocedes is shown with the black lines. The horizontal axis represents the sound frequency. On the bottom axis of the graph the communication range of mysticetes is shown in blue and of odontocetes is shown in red. A conclusion that can be drawn from this graph is that the higher frequencies of ship noise can correspond to the lower frequencies of ontocedete noise.[11] Noise pollution can cause behavioural change in individual animals and could also have a reductive effect on communication between members of the same species. [11]

2.2.3. Sewage emissions

Nitrogen in sewage discharges from ships can create a disbalance in aquatic ecosystems by means of eutrophication [12]. Some ports facilitate sewage disposal and often sewage treatment plants are on-board to reduce the environmental impact of sewage. Within superyachts, the capacity of on-board sewage storage can be a limiting factor.

2.3. Assessment of environmental impacts

These tools can be environmental, social or integrative. [58] Some examples are environmental and social audits, eco-efficiency analysis, life cycle assessments (LCAs), environmental and social management systems, and sustainability reports. [58] The quantification of sustainability is treated further on, in section 2.3. In order to assess the sustainability of a process or enterprise, its environmental impacts must be known. Not only air emissions are part of a sustainability impact. Several impact measurement techniques are explained in this sector.

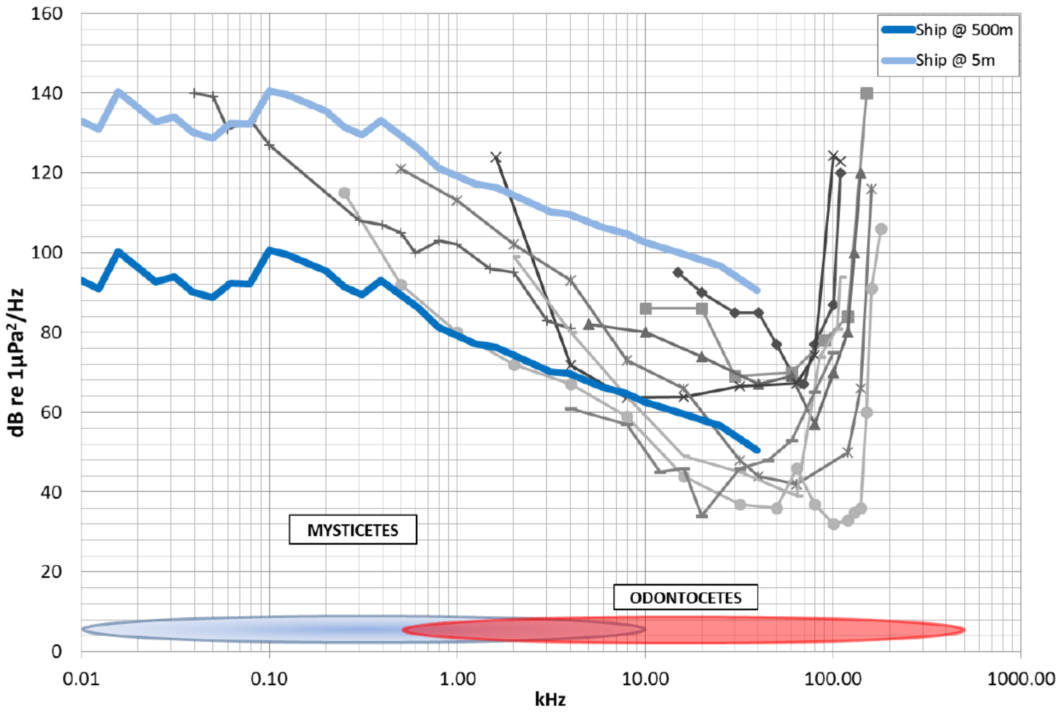

Figure 2.5: Odontocedes audiograms with ship spectra at different distances and communication ranges of both odontocetes and mysticetes [11]

2.3.1. Air Emission impacts

Air emissions have different, and sometimes even multiple, environmental impacts. Figure 2.6 of the European Environment Agency [40] is a schematic overview of this.

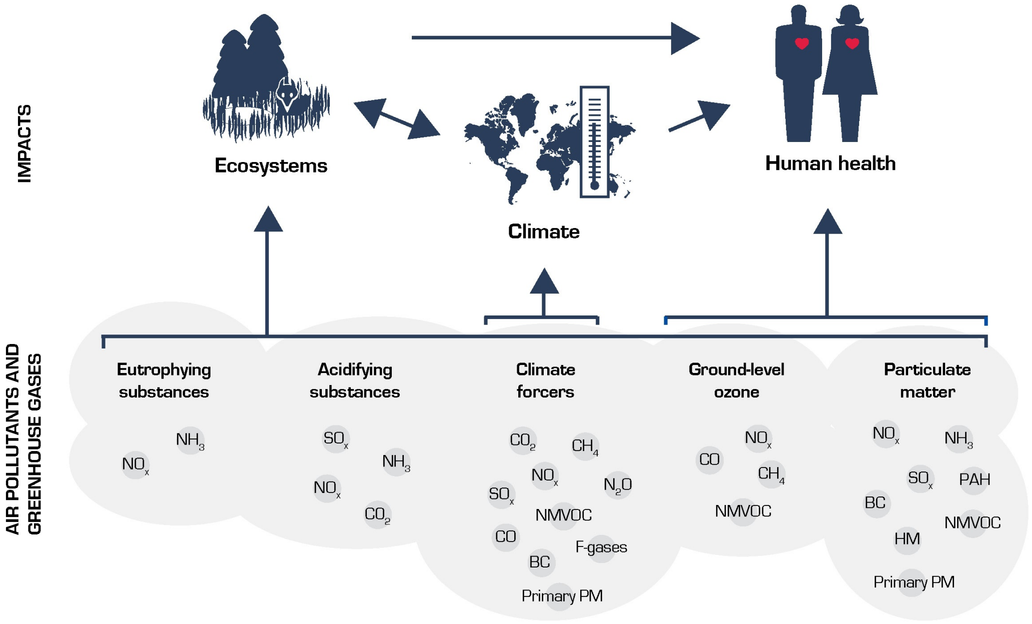

Figure 2.6: Impacts of air pollution [40]

The environmental impacts of emissions of the lifecycle of yachts can be expressed using environmental indicators used by the Water Revolution Foundation [114] shown in table 2.2. A selection of these impacts focused on air emissions are explained below.

Table 2.2: Environmental indicators

Environmental indicator	Unit
Eutrophication	[kg PO_4^{-3} eq.]
Acidification	[kg SO_2 eq.]
Global warming potential(GWP)	[kg CO_2 eq.]
Photochemical oxidation	[kg C_2H_4 eq.]
Particulate matter>10µm	[kg]
Ozone layer depletion (ODP)	[kg $CFC-11$ eq.]

Eutrophication [kg PO_4^{-3} eq.]
Eutrophication happens when a body of water or soil becomes overly enriched with nutrients, causing excessive grow of algea's. This can subsequently cause oxygen depletion in the water, decreasing its ecological quality.

Acidification [kg SO_2 eq.]
Emissions of sulphates, nitrates and phosphates can cause an increase of acidity in soil or water, creating a disbalance. Several different emissions contribute to this phenomenon, and are expressed as SO_2 equivalent units.

Global warming potential (GWP) [kg CO_2 eq.]
The global warming potential (GWP) of a greenhouse gas depends on the amount of time it stays in the atmosphere and the amount of potential it has to absorb energy. This unit is based on a 100-year time horizon.

Photochemical oxidation [kg C_2H_4 eq.]
Photochemical oxidation is also known as "summer smog" or ground-level ozon. It is the product of the reaction of nitrogen oxides and volatile organic compounds by sunlight and is harmful to human health and ecosystems.

Particulate matter>10μm [kg]
Particulate matter consists of inhalable particles from a variety of origins. These matters have an adverse effect on human health as well as the health of other species.

Ozone layer depletion (ODP) [kg CFC-11 eq.]
The ozone layer depletion potential (ODP) represents the reduction on the protective effects on the stratospheric ozone layer, based on a 100-year time horizon. This stratospheric layer reduces the amount of UV-radiation that reaches the surface of the earth. Excessive UV-radiation can cause damage to humans, animals, plants and materials.

2.3.2. Life cycle analysis methods

The field of Environmental System Analysis (ESA) addresses the interaction between human-made systems and the environment. A life cycle analysis is a method to determine the environmental impacts of a products life cycle, from material extraction, via production and use phase, to waste management. [32] It is widely applied in the industry. Since sustainability consists of multiple aspects, many measuring systems are known. Measuring in air impact category equivalent, as shown in section 2.3.1, is a well known method, often used in combination with a life cycle assessment. This method is standardised as the CML2001 method.[73][9] In the following part, more impact expression methods used in LCA's are explained.

Well to Wake

In order to paint a complete picture of the impact of marine emissions, it is not enough to measure the emissions from the exhaust. During the extraction, production of the fuel, a significant part of the emissions take place as well. This part from fuel production to the fuel tank of a ship is called well-to-tank (WTT). Once it is in the tank and consumed by the ship, they are tank-to-wake (TTW) emissions. These phases together are called well-to-wake (WTW) and this complete process is essential for a life cycle assessment. In comparing, for example, different ship fuels it is important to take into account the entire production chain. An overview of the WTW emissions of marine gas oil (MGO), liquefied natural gas (LNG) and hydrogen fueled ships is seen in figure 2.7.

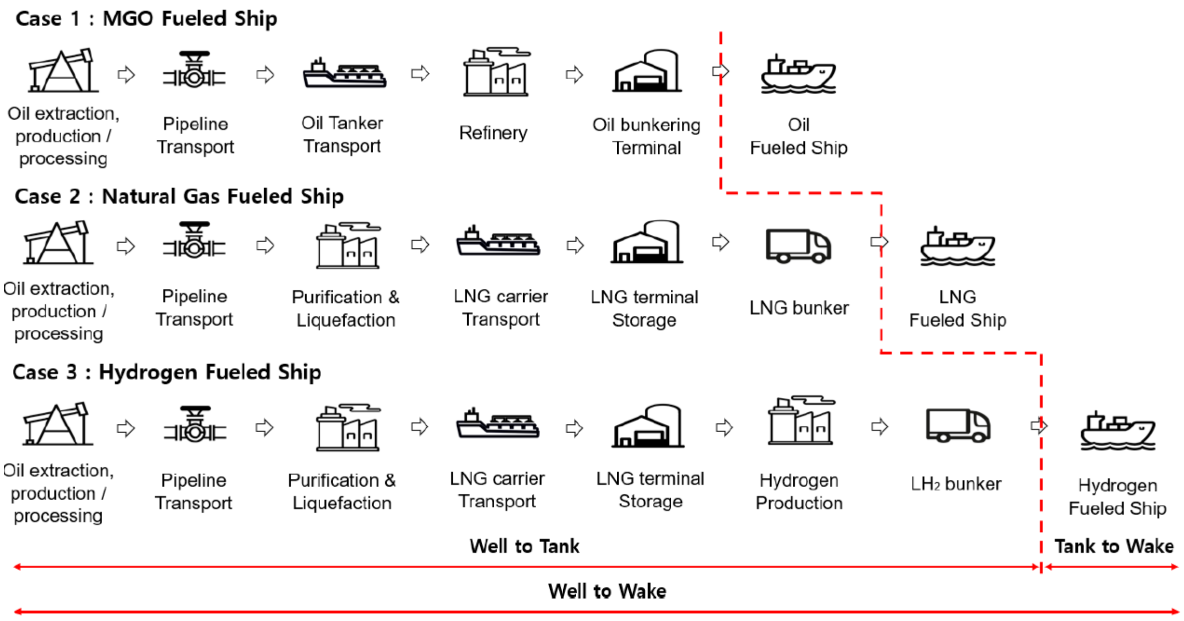

Figure 2.7: Well-to-wake emissions of marine gas oil, natural gas and hydrogen [47]

In the case of the hydrogen fuel ship, there are no operational (TTW) emissions. If the WTT part is not taken into account, it will paint an incomplete picture of the impact of hydrogen with respect to other fuels that might have more operational emissions but less WTT emissions. If the efficiency of a ship is increased, this also means that not only the operational emissions are reduced, but also all the emissions by the production of the fuel.

Taking the full lifecyle of fuels into account, also shows the benefit of biofuels, such as HVO, which is a fuel produced by hydrotreating and refining vegetable oil from oil crops.[43] The amount of operational CO_2 emissions are relativly similar for regular MGO and HVO. [23] The full life cycle emissions differ more, with MGO emissions at 87 g/MJ CO_2-equivalent and HVO at 8-25 g/MJ CO_2-equivalent, meaning that using HVO would decrease WTW emissions 71 to 91 %. HVO does cost around 50% more than diesel, making it commercially less attractive.[23]

Eco-indicator99

A different, broader method is an Eco-indicator manual, which comes down to a single indicator for weighting the three following damages:[21]

- Human health: Expressed as the number of years lost and the number of years lived disabled, both due to environmental causes.
- Ecosystem quality damage: The effect on species diversity
- Resources: The surplus energy needed in the future to extract mineral an fossil resources

These three damages can be combined into one final Eco-indicator; The Eco-indicator point (Pt), where each point corresponds to 1/1000 of the yearly environmental load caused by the average European inhabitant. [21] This can then be used to express, among others, the environmental impacts from figure 2.6 in for example a ship life cycle assessment. [16] [37] A similar method is the International Reference Life Cycle Data System, or ILCD [26], which uses more specific impact categories like acidification in mole of hydrogen ion equivalent and is developed by the European Commission.

ReCiPe

ReCiPe is a LCA method that combines both CML and Eco-indicator99.[38] In the method, first the midpoint impacts are determined, which are then expressed in the endpoint as Eco-indicator99.[38] Cozijnsen [18] has applied this method to detemine the footprint of yacht production. It is also applied to, among others, commercial buildings [20] or even dairy sheep [93].

External costs

Another method for expressing impact is cost to society, also known as external costs or environmental prices. This method is also used by van Grootheest [110] for selecting cost-effective abatement options in early stage ship design. In this case the effects are expressed using a monetary value. This value expresses the cost to society per emission, it is an indication of the loss of economic welfare when one additional kilogram of the pollutant finds it way into the environment.[15]It can also be used to calculate effects for immaterial forms of pollution by for example noise or radiation.[15] The value encompasses the costs of an activity that is not accounted, or compensated for. An example would be the health damage from NO_x by a person driving a car. These costs are not accounted to the driver. These costs are determined according to the relations shown in figure 2.8.

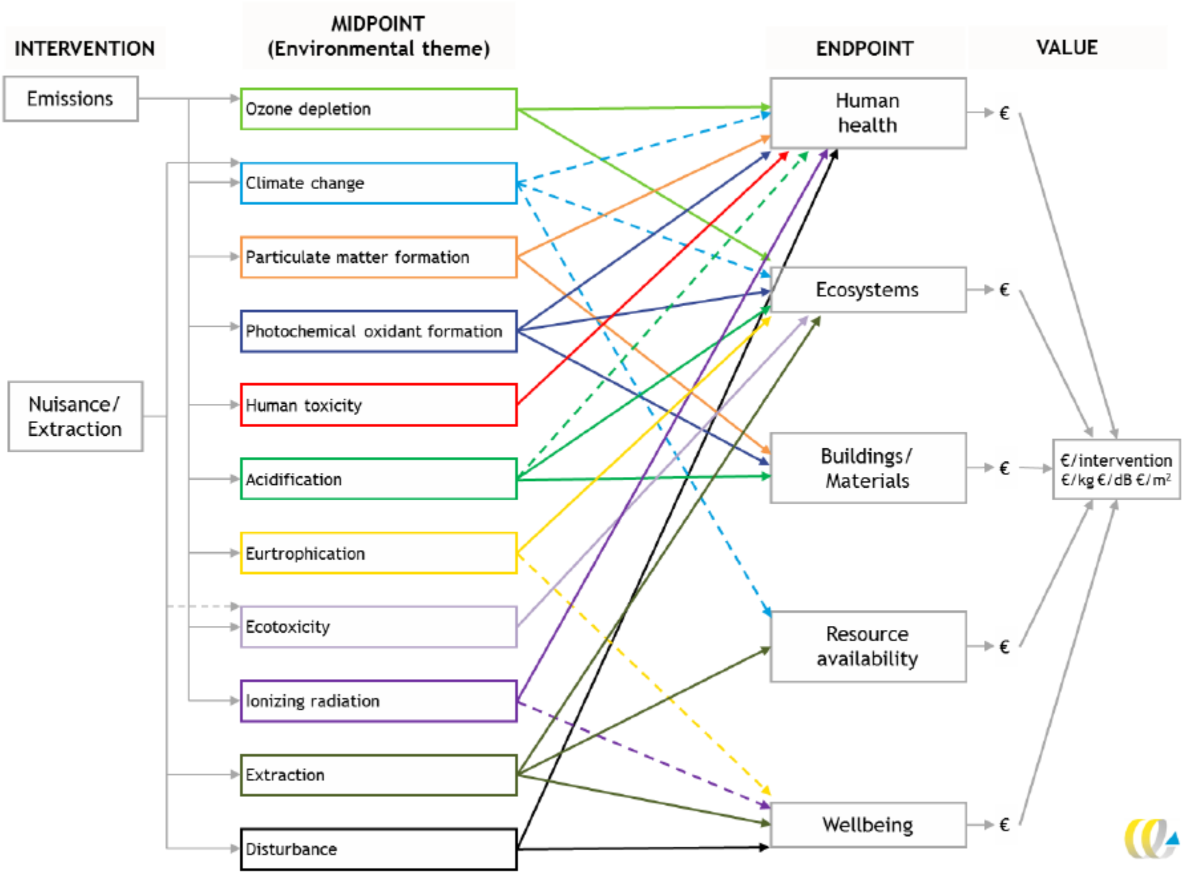

Figure 2.8: Environmental prices relations schematic [15]

On the left side of the figure the interventions are shown, this can be either an emission or a nuisance/extraction. This represents the first level, the pollutant level, in which values represent the emissions of environmentally damaging substances.[15] These can the be expressed at midpoint level, in which values represent environmental themes such as climate change or acidification, as seen in table 2.2.[15] For climate change, values are represented in a CO_2-equivalent value for example. This way different emissions can be factored in using GWP-factors. These environmental themes can then be used to calculate endpoint levels, values for the impact of environmental pollutions, such as damage to human health, ecosystems or resource availability.[15] This calculation is also dependent on location for some, such as particulate matter. When this is emitted at sea, it will have less impact on human health than when it is emitted in the middle of an urban area. The endpoints are expressed in a monetary value and can be added. Using this approach the external cost of emissions can be determined, taking into account all the environmental effects in one value.

These methods of expressing sustainability have as a disadvantage that they are abstract. A common method to make emissions quantities comprehensible is to compare them to for example a forest area intake equivalent for CO_2 or NO_x equivalent of the annually emitted amount of a truck. This avoids the complexity and abstractness of the previous methods, which in some cases could deviate the focus of a research, making it more complex than necessary.

2.4. Conclusion

In this chapter, firstly the different phases of a refit, upstream, yard processes & downstream are explained in section 2.1. The focus on the upstream phase is elaborated on in section 2.2. In section 2.3 different air emission impacts are treated and the life cycle analysis method is treated to determine the life cycle impact of a product. Different methods for expressing environmental impacts in a lifecycle analysis are evaluated. The main expressions used are in monetary terms, Eco-indicator99 equivalents, emission equivalents or a combination of the latter two. At this point the impacts of a refit has been determined, and the scope has been set on operational air emissions. In order to obtain a complete picture of the impact of a yacht, different impacts have to be taken into account. Furthermore, the impact of the production of fuels is an important factor in this as well, since a significant part of yacht impacts is in the production of fuels.

Now that the impacts have been determined, distributed and quantified, a method can be selected to determine which impact reducing options are most suitable in terms of cost effectiveness and impact reduction per yacht, owner and operational profile. This selection tool is set up in chapter 3.

3

Cost effectiveness tool

In order for impact reducing refits to become commercially attractive, it is of importance to determine the cost effectiveness of refit options. A selection tool with a focus on cost-effectiveness could therefore aid in refit abatement decision making. In this chapter the cost effectivity tool for the assessment of sustainable refit options will be created. This is done by firstly establishing the design requirements for the selection tool in section 3.1. Using these requirements the fitting abatement decision making method can be selected by evaluating the literature on this topic in section 3.2. Using the literature analysis, a decision making method is chosen in section 3.3 and the tool is further shaped in section 3.4. Hereafter the specific outputs are determined in section 3.5 and this chapter is concluded on in section 3.6.

3.1. Design requirements

Since this selection tool should aid in the decision making, it is of importance to create an overview of the impact reducing and financial aspects of impact reducing refits. In order for sustainable refits to be commercially accepted, it must be evident what the investment- and maintenance costs as well as impact abatement of refit options are. Since refit decisions are ultimately made by a yacht owner, cost-effectiveness is an important aspect of the results. The obtained decision making tool should therefore help in making a substantiated decision on whether and/or which sustainable refit is most suitable for a yacht and owner. This tool should aid in decision making early on the the refit negotiations between owners and yards to help gain insight into the sustainable options for refitting. In order to measure and compare the cost effectiveness of emission reducing refit operations, a framework is needed that compares the financial and emission aspects of the refits. Since not every refit operation is included in the scope of this research, the tool should be structured so that other refit operations can be added easily and existing components can be altered with changes in for example energy efficiency of components. Upstream emissions must also be taken into account, in order to gain more insight into the actual impact of these abatements. The result of the model should be in a format that allows owners to choose abatement options relevant to their situation and preferences.

The outcome of this model should be usable to create a clear overview of global warming potential reduction and overall impact through external cost reduction. These aspects are then coupled with an investment value, in order to marginalise the impact, so that different impact units per marginal costs can be compared when using the tool for a specific yacht. Since this tool will be a generic yacht refit tool, a large part of the inputs will be determined via trends in the Feadship yacht database. For this, several inputs are to be determined, elaborated on in section 4.8, which include auxiliary and propulsion demands, as well as specific emission compositions and several ship parameters.

3.2. Abatement decision-making in literature

In order to adequately select a method for determining the cost-effectiveness of emission reduction abatements, an overview of relevant literature is made. This corresponds with subquestion 4 and 5 from subsection 1.5.1. Several methods of abatement selections are known in the literature. A distinction is made between financial and environmental assessment tools and operations research (OR) techniques, according to the framework of I. van Grootheest, as seen in figure 4.2 [110]. This overview will be used as a framework to categorise the different decision making techniques in the literature analysed later in this chapter.

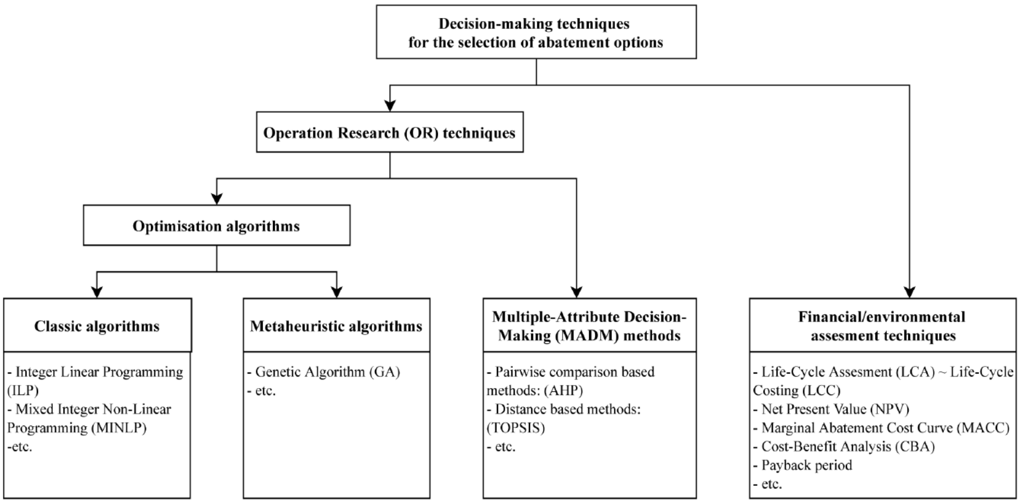

Figure 3.1: Decision-making techniques for the selection of abatement options [110]

Within OR techniques, Grootheest distinguishes between optimisation algorithms and multiple-attribute decision-making (MADM) methods. Within optimisation algorithms, a distinction is made between classic algorithms and metaheuristic algorithms. These OR techniques are suited for optimisation problems, whereas financial/environmental techniques are more suitable for comparison of options.

The focus of the literature research done is on financial assessment techniques. Because of the client oriented approach of this review, a comparison technique is better suited for creating an overview of cost-effectiveness. For yacht owners wanting to explore the options for sustainable refitting it is important that they are able to make their own decision. Results are required that can give an overview of different abatement options and allow for a decision making based on the owners preference, the available options for the ship and how suitable it is for their current operational profile. Furthermore, possible conflicts in compatibility within refit abatements have to be taken into account as well. Since the scope of this research is on currently implementable refits, ship conversion to different fuels, such as hydrogen or LNG, are not taken into account. This is not because it is not possible to refit this power system change, but because the current infrastructure is not deemed sufficient for owners to maintain the same level of comfort and reach with these alternative fuels.

An overview of relevant abatement selection literature is shown in table 3.1. Per evaluated research it is shown whether it focuses on new-build (NB) or refitting activities (RF). Furthermore, the decision-making method is shown and how the results are expressed. In the second to last column the evaluated emissions are shown and in the last column the subject of the research is shown Apart from marine power systems, research on the steel sector[71] or heating sector[70] with relevant selection decision making methods are also reviewed. Interestingly, a life cycle assessment is usually expressed using sustainability indicators[73] [72]. It is however also possible to use a life cycle assessment to make a marginal abatement cost curve. By combining these elements, it is possible to assess the environmental impact of the entire lifecycle of different options and asses the costs and emissions abatement benefits similarly. No literature has been found that combines the aspect of these two methods. By combining these methods cost-effectiveness with environmental impact can be determined. In this research it can be done by implementing corrections for upstream and yard process emissions within the curve. This removes the problem of shifting emissions upstream and not addressing them. This is especially relevant for for example batteries, that are known to have a relatively large upstream impact.

Gap analysis
As seen in the table 3.1, there has been research on marine power plant-[73] system[72] refitting, as well as

Table 3.1: Relevant Research with respective methods, expressions, emissions and targets (LCA: Life Cycle Assesment, MACC: Marginal Abatement Cost Curve, CA: Classic Algorithm, ILP:Integer Linear Programming, (F)MADM:(Fuzzy)Multiple-Attribute Decision Making, ANP: Analytical Network Process, AHP: Analytical Hierarchical Process, CED: Cumulative Energy Demand, LCC: LifeCycle Cost)

Research	**Type**		**Method**	**Expression**	**Emissions**				**Subject**
	NB	**RF**			**CO2**	**NOx**	**SOx**	**PM**	
Ling-Chin (2016) [73]	X	X	LCA	ECO-Indicator99, ILCD, CML2001	X	X	X	X	Marine power systems
Ling-Chin (2016) [72]	X	X	LCA	ECO-Indicator99, ILCD, CML2001	X	X	X	X	Marine power plants
Favi (2017) [30]	X		LCA	CO2 equivalent, CED	X	X	X	X	Complex marine vessels
Li (2014) [71]		X	MACC	Energy saving cost [$/Gj]	X				Steel sector
Levihn (2014) [70]	X		MACC	MAC, Cost effectiveness [$/tCO2]	X				City district heating system
Balland (2012) [8]		X	CA(ILP)	% Emission reduction	X	X	X		Marine air emission controls
Schinas (2014) [95]	X		MADM (ANP)	Relative score	X	X	X		Marpol compliance technology selection
Trivyza (2018) [107]	X		MA(GA)	Multi-objective optimisation [CO2,NOx,SOx,LCC]	X	X	X		Sustainable marine energy systems
Yang (2012) [118]		X	MADM (AHP)	Relative score		X	X		Marine emission reduction systems
Olcer (2015) [85]	X	X	MADM (FMADM)	Relative score	X	X	X	X	Clean maritime transport
IMO (2011) [52]	X	X	MACC	MAC, Cost effectiveness [$/tCO2]	X				CO2 emission reduction
Grootheest (2019) [110]	X		MA(GA)	Abatement option configuration	X	X	X	X	Cost effective marine emission abatements
GloMEEP (2016) [54]	X		MACC	MAC, Cost effectiveness [$/tCO2], EEDI & EEOI	X				technical and operational energy efficiency abatements

marine air emission reduction refitting [8] [118] or a combination of these [85]. No research has however been done on the cost-effectiveness of refit abataments for superyachts. Furthermore, no research has been done on creating a MACC for emission reduction abataments while taking into account downstream emissions of these components. By doing this the life cycle analysis, an environmental assessment technique, can be combined with the marginal abatement cost curve, a financial assessment technique. By combining these techniques the cost-effectiveness of sustainability in yacht refitting can be determined. Since emissions reducing options on yachts are chosen by yacht owners, the economical aspect is of utmost importance. The marginal abatement cost curve on its own does not provide a complete picture. Abatement specific value's such as payback time must be included as well to give an insight into the financial aspect of refit abatements. Since the MACC provides a picture of total reduction and marginal costs, it cannot be used on its own. These marginal costs include, but do not show the investments needed for an refit option. When supplemented with a business case, it can add great value by showing the absolute impact reduction and it cost effectiveness.

The GloMEEP [54] project creates marginal abatement cost curves for energy saving and efficiency improving options for commercial vessels, such as oil tankers, general cargo ships and cruise vessels, but not for yachts. Firstly the operational profile of yachts is highly different. In yachts, around half of the power is used by auxiliary consumers, a number that is significantly lower in the ships evaluated in GloMEEP. Furthermore, the power demand of a yacht fluctuates highly, since it is dependent on the owners being present and the ship being used in day trips, for example. For commercial vessels such as cargo ships and oil tankers, it is understandable that these have a much more constant usage profile, since they travel long distances at constant speeds. The fundamental differences make for efficiency measures for yachts to be evaluated in a different manner, taking into account the design- and operational profile differences.

Furthermore, it is focused on new-built ships and does not take refitting into account. Also, by only calculating abatements in GWP-reduction, the negative impacts of acidification and eutrification by other emissions, such as NO_x, are not taken into account. In order to evaluate a sustainable yacht refit the different effects of operational emissions must be taken into account. Lastly, the entire life cycle emissions of fuels and abatements should be taken into account in order to paint a complete picture. This is, for example, relevant for evaluating the impact reduction of bio fuels, which have significantly lower well to tank emissions then conventional fossil fuels. Furthermore, the life cycle impact of refit options were to be taken into account, it would give a more accurate overview as well. This is relevant in the case of battery-related refit options, in which the impact of production is relatively large and should be taken into account in an accurate assessment in order to provide a relevant overview.

3.3. Format

In this section, the format of the cost effectiveness tool will be treated. As stated in section 3.1, it is of importance to compare the impact reductions of refits with their cost-effectiveness. Since refit operations are selected finally by yacht owners, a reduction of emissions or impacts is not sufficient for decision making. A result is required that shows yearly costs and yearly impact/emission savings. In order to create an overview, a result format is needed that shows all emissions and how they relate to each other.

Therefore multiple financial analysis techniques were evaluated. For owners it is important to have an insight in to the financial aspect of the investment of the abatement. A method that expresses saved emissions per costs is therefore needed. Since there is no optimal combination to be calculated per situation, an overview is needed of each abatement and its respective investment value. Within abatement decision making methods, the Marginal Abatement Cost Curve (MACC) is a method that satisfies these criteria. Looking at the literature in the previous section, methods like Multi-objective optimisation or Multiple-Attribute Decision Making would be less suitable, since the aimed result of this model is to create an overview of cost-effectiveness and impact reduction, what these methods are less suitable for.

This can, however, be done in a Marginal Abatement Cost Curve, based on net present cost. This curve can ve constructed to take into account the lifecycle emissions of components and fuels. A concept example of this graph is shown in figure 3.2. In this research this graph will be constructed for both CO_2-equivalent units, to assess the difference in global warming potential, and for external cost reductions, in order to take into account other harmful effects of emissions, set out over the listed abatements. The costs are based on net present cost, thereby taking into account the present value and the revenue an investment creates over its lifetime.

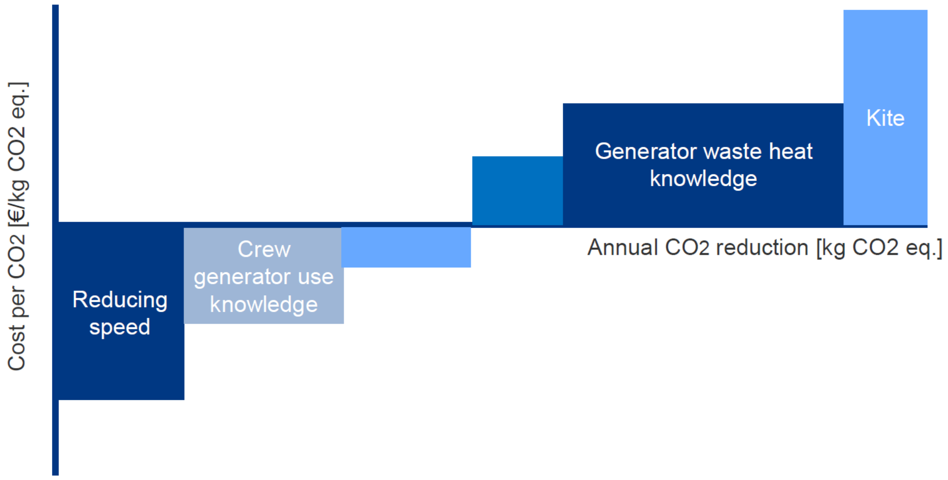

Figure 3.2: MACC concept example

Note that these values are not representative of any factual data and the figure should only be used to comprehend the concept of the marginal abatement cost curve. Looking back at the environmental impacts of yachting, increased efficiency and reduced power consumption by implementing the downstream emission reduction options cause less fuel being burnt by the generator and the engine. A reduction of the exhaust emissions from section 2.2 causes a decrease of the environmental impacts shown in table 2.1. The importance of a MACC in both global warming potential and external costs is of importance since, as shown in section 2.3.2, the external costs also take into account the effects shown in the table of 2.1, thereby creating a value representing the impact to human health, eco-toxicity, resource scarcity and carbon footprint. Since climate change is one of the largest environmental impacts of the maritime sector, the global warming potential abatements will be shown in one curve. To take into account the other effects of the emissions, such as the eutrification and acidification, the impact reduction is also expressed in external costs. This way a complete picture can be made of the impact reduction and multiple impact reductions can be taken into account at the same time.

In order to obtain this graph, each specific ship and usage must be taken into account. Since each owner has a different way of using their yacht, the operational profile is also taken into account.

3.4. Method

Firstly the tool will be suitable for several ship sizes and profiles. The aim is to create a tool on which refit option can be added through a template. The more refit options that are added, the more complete the overview is as a result. Since it is not possible to treat every refit option possible is this research, a representative selection of refit options is made later on. With this selection the relative effects of the refit options will be examined.

Per refit option, the production impact will be taken into account as well, to weigh in the impact of production on emission abatements. The impact of yard work will not be taken into account. For each abatement the savings in fuel or emission will then be expressed in a GWP-equivalents saved and a external cost that is saved. The combination of these two values can be used to examine the relative impacts of measures. For example, a measure that reduces NO_x-emissions, will reduce external costs more than it will reduce global warming potential, since the largest impact of NO_x is not it global warming potential.

3.5. Output determination

Using emission measurements from sea trails of the main pollutant emissions from marine diesel engines, the emissions in weight, global warming potential (GWP) and external costs are determined. These measurements express emissions in g/kwh and are assumed to be constant over different engine load conditions. In order to take each specific global warming potential into account, the GWP-factors of these emissions are used to express the GWP of each emission, as shown in table 3.2. Note that emissions other than CO_2 have significantly higher GWP factors, but the main part of the global warming potential is still by CO_2 emissions, because the other emissions are a lot less in weight. Adding the value of the extraction and production of diesel (WTT), the total WTW GWP_{100} is 3.39 kg CO_2 – equivalent. Since these emissions can also be expressed in external cost, a similar calculation is done to obtain the WTW- impact of the emissions of 1 kg diesel burned by a superyacht. In external costs the upstream impact amounts to half of the total WTW impact. The total WTW impact of 1 kg diesel is €1.84. These numbers now lay the base for a the calculation of impact reduction of several refit options, because they are able to help express the impact of a fuel consumption reduction.

Table 3.2: Emissions per kg diesel burned in GWP and external costs

	GWP_{100}-factor	**GWP** [kg CO_2 – eq per kg diesel]	**External costs** [€ per kg diesel]
CO_2	1	2.64	€ 0.18 [15]
CO	2.2 [66]	0.02	€ 0.00[15]
NO_x	8.5 [65]	0.15	€ 0.74[15]
HC	12 [2]	0.00	€ 0.00[15]
PM	900 [6]	0.05	€ 0.01 [15]
WTT		0.52	€ 0.92[22]
Total (WTW)		3.39	€ 1.84

3.6. Conclusion

In this chapter, the refit cost-effectiveness tool is shaped. The requirements for a yacht refit abatement selection tool are treated in section 3.1. With these requirements the literature is consulted in section 3.2, and a format for the tool is created in section 3.3. Using this the method is determined in section 3.4. To further complete the tool, the outputs are determined in section 3.5.

The selection tool will evaluate the global warming potential reduction in CO_2-equivalent units and the total impact reduction in external costs. Since the global warming potential does not take into account the effect of harmful emissions such as NO_x, it is important that the results are presented in a way in which this is evident. In order to compare these quantities they will be portrayed in separate marginal abatement cost curves, combined with a business case. Other appraisal tools such as GloMEEP[54] assess the global warming potential reduction of commercial ships, however they do not take the total impact of all ship emissions into account. Furthermore, they are not suitable for yachts, since the operational profile and design is fundamentally different. Lastly the GloMEEP project does not take different power systems into account, which is essential for assessing yacht refits.

To further supplement this model, a selection of refit operations is treated in chapter 4, together with their respective input determinations.

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4

Refit operations

In order to determine and compare cost-effectiveness of different refit operations, a selection of five operational emission reducing refit options is made. First an extensive list of refit options based on previous research and expert opinion is treated in section 4.1. A representative selection of 5 refit options in various catagories is then made in section 4.2. The first refit option, solar panels is treated in section 4.3, the second option, LED lights is treated in section 4.4. The third option, anti-fouling, is treated in section 4.5. The fourth option is the implementation of a waste heat recovery system, treated in section 4.6. The fifth and final option, the selective catalytic reduction system is treated in section 4.7. Of each of the options, the technology, implementation and calculation is treated subsequently. The required inputs to implement these options are treated in section 4.8. Section 4.9 serves as a summary to this chapter and a preparation for to the case studies in chapter 5.

4.1. Refit options

In order to make a selection of refit options to be treated within this research, the downstream emissions reducing options are stated below. The options are derived from section 2.1.3, based on the GloMEEP[54] selection, the International Council on Clean Transportation selection [48] and current existing refit options, together with other found refit opportunities. The options can be divided into the following categories, also shown in figure 2.2:

- Power generating
- Power consuming
- Emission reducing
- Operational improvements

The refit options per category are explained below.

A wide range of options is possible to increase the efficiency and therefore reduce the energy consumption of a yacht. As stated above, a separation is made between power producing and power consuming components.

Power generating

- Generator replacement: Often multiple generators are implemented in a Feadship. Depending on the current installed model, a newer, more efficient model might be available. Or depending on the energy usage data, perhaps the current generator is not suitable for its current loading.
- Engine replacement: Depending on the current installed engine, a newer, more fuel efficient version might be available. A propulsion system could also be adjusted to run on a different kind of fuel, such

as hydrogen-natural gas combustion in a spark ignited engine[94] or a solid oxide fuel cell and advanced combustion engine combined cycle [19]. Different options as nitrogen based fuels can be implemented, where fossil fuels are no longer needed in the supply chain. [39] The current available infrastructure for yachts must also be taken into account for these technologies, since the refit options must be feasible for owners as well.

- Wind assisted propulsion: Using win energy for propulsion can be promising in some cases as well. Several options are evaluated, such as rigid sails[10] or kite drives.[98]
- Solar energy: Solar panels can be used to generate electricity on board. As incorporated in the "Zero Emission Super Yacht"[77] design, the whole deck of a ship can be used for teak integrated solar panels of Solbian [100]. This way the appearance of teak can be maintained up to a certain level.

Power consuming
Power consuming refit options are divided into propulsive- and electrical consumers.

Propulsive

Several adjustments can be made to increase propulsive efficiency, as stated below.

- ESD: Several energy saving devices (ESD) are taken into account for possible applications on a Feadship. A pre swirl stator [62], such as the Wartsilla EnergoFlow could provide a significant power demand reduction, while still meeting fail safe design requirements. [111] [112] An introduction of a propeller boss cap fin could reduce hub vortex cavitation, thereby increasing fuel efficiency. [80]
- Air lubrication: Air lubrication on ships can be used in several way to reduce hull drag.[92] It does however require a flat bottom for the air cavity to be present, therefore its application on yachts is to be examined. [106]
- Anti-fouling: Since it is not uncommon for a Feadship to be sailing around 10 % of the time, a specific type of anti-fouling is needed for this. Per ship the suitable anti-fouling type would have to be determined. When using softer coatings, fouling will attach when not sailing, creating an increase in drag. In many Feadship cases, a harder coating will be more suitable, since the sailing time is relatively small.[29] Propeller fouling can lead to an efficiency loss of 11.9 to 30.3 % in some cases. Frequent propeller polishing can help reducing this effect. [86]
- Contra-rotating propeller: Contra rotating is a technique in which two propellers placed behind each other rotate in opposite direction.[54] By doing this part of the energy lost by rotational flow production can be recovered, thereby increasing propulsive efficiency. [78]
- Rudder optimisation: A twisted rudder can reduce fuel efficiency by increasing the hull efficiency, thereby reducing fuel consumption. Several different constructions for twisted rudders are available.[61]
- Propeller polishing: The surface of a propeller becomes less smooth over time due to strain, cavitation and fouling growth. Regular cleaning of the propeller has proven to reduce this effect, thereby increasing propulsive efficiency. [54]

Electrical

Using load list data the different electrical consumers can be arranged by their respective usage of power, to see where adjustments have the most effect.

- Lights: Changing lighting to LED is a refit option that is not uncommon. Since lights are a also significant power consumers and heat generators, gains in this area might also be promising.
- Batteries: Batteries can be introduced to the yacht in order to comply with fluctuating energy demand and help keeping generators at an optimal efficiency. An electrical day drive, charged by shore power, could provide emission free sailing for a short amount of time. This way visits to area's with strict emission norms could be made possible for otherwise non-complaint yachts.

- Waste heat: Waste heat of the engine and the generator can be used for heating up water for for example pools or showers. This is a refit option that has been implemented in a Feadship before. In other literature the implementation of waste heat engine[24] [74] and generator[57] usage has proven to be a promising technique.

- Frequency converters: The actual load of electrical components such as pumps and fans is often lower then their designed capacity. The generator can therefore run at a too high load. Frequency converters can regulate the frequency in order to adapt the engine load to the demand. [54]

- Exhaust gas boilers: Excess heat from exhaust gasses can be captured in exhaust gas boilers in order to generate steam and/or hot water, thereby reducing generator load. [54]

- Heating, Ventilation and Air Conditioning (HVAC): As HVAC systems play a significant role in a Feadship's energy consumption, gains in this area can be very promising. Creators of new HVAC technologies claim a reduction of energy usage by 30 - 40 %. [104] It is however questionable if these numbers are of the same magnitude when implemented in yachts.

- Pumps: If pumps have a significant contribution to the energy usage, the option of replacing old pumps by newer, more efficient models, can be evaluated.

- Stabilizers: Stabilisers are used in yachts to reduce unwanted movements due to swell, waves and wind. Currently they are often hydraulically driven. Within yachts they are a significant energy consumer and newer, more efficient technologies such as electric stabilizers could possibly be installed.

- Load banks: In older designs, load banks were in some cases implemented to account for the change in demand of electricity. Using waste electricity, heat is transferred to seawater. In these cases it could be promising to examine whether a solution is possible for this waste of energy. Perhaps it could be solved by proper generator control or a different application for the waste heat.

Emission reduction

Apart from Efficiency improving options, it is also possible to reduce emissions. This can be done for example with a selective catalytic reactor (SCR). The SCR system can be implemented in order to significantly reduce NO_x emissions. [42] SCR's have been implemented in Feadship designs. Refit possibilities might be possible.

Operational improvements

A crew can have a large influence on energy usage, direct and indirect, as explained below.

- Voyage execution: In international shipping [17] a reduction of speed of 10 % has proven reductions of 10 to 20 % of CO_2 emissions. These results are obviously not the the same for yachts, but a speed reduction could still decrease fuel consumption and therefore reduce emissions. Furthermore, autopilot use leads to decreased rudder movement, thereby reducing fuel consumption. [54]

- Route planning: Route planning software can be introduced to take into account among others: winds, currents, ice, sea state and marine traffic. [36]

- Environmental awareness: For the crew to know what the actual impact is of their actions could result in less unnecessary voyages. For example an owner could be advised to not take an unnecessary detour, because of being noted of the fuel benefits.

- Equipment usage knowledge: With the usage conclusions drawn by the load list and the operational profile, it can be determined whether the generator is used effectively. As generators have a load dependent efficiency, it is possible that a higher efficiency can be reached when operated with more specific knowledge.

An overview of the refit options treated in this section is seen in table 4.1. Since not every refit option can be added to the tool, a selection is made in the following section.

4.2. Selection

In this research a selection of refit abatements is chosen to be evaluated in the cost effectiveness tool. The cost-effectiveness tool can be used to evaluate any of the operational emission reduction measures in figure 2.2, but a selection is made to limit the scope of the research.

The measures must be:

- Feasible
- Universal
- Aesthetic
- Commercially attractive
- Impact reducing

Firstly some refit options treated in GloMEEP [54] might not work for yachts, since the hull shape and power system configuration is different. Therefore the first criteria is that the refit option should be feasible for a yacht, The refit options must also be universal, as they should be applicable to any Feadship and not just suitable for a single ship. Furthermore the aesthetics are in important factor, as they play a large role in how attractive an option is for an owner. This includes the looks of the option, as well as the on-board experience of the guest. Commercial attractiveness is also important, since it would make owners more open to implementing impact reducing measures. Lastly, impact reduction is important as well. This can also be by, for example, limiting the transport of non-indigenous invasive species on the hull. It is therefore broader than only GWP reduction. With these criteria, a diverse selection is made between the possibilities, in order for the results to be used for comparing a wider range of measures. The complete list of refit options determined in the previous section is shown in the following table 4.1.

Table 4.1: Refit option categories

Power generating	**Power consuming**		**Emission reducing**	**Operational improvements**
	Propulsionary	**Auxiliary**		
Generator replacement	ESD	Lights	SCR	Voyage execution
Main engine replacement	Air lubrication	Batteries		Route planning
Wind assisted propulsion	Anti-fouling	Waste heat recovery		Environmental awareness
Solar cells	Contra-rotating propeller	Frequency converters		Equipment usage knowledge
	Trim/draft optimisation	Exhaust gas boilers		
	Rudder optimisation	HVAC		
	Propeller polishing	Pumps		
		Stabilizers		
		Load bank		

Power generating

An engine or generator replacement is not a frequently chosen refit option, since it is very labor intensive, and the gains in efficiency have to be put into relation to the price of a new engine and its installation. Looking at the engine development of the last few years, a 20 year old diesel engine will not be significantly less efficient than a new diesel engine. [117] Wind assisted propulsion is an aesthetically compromising option, due to the large container having to be put on the front deck when installing a kite, or retractable vertical rotors being in sight. The solar panels have the potential to be a aesthetically pleasing, relatively easy to implement, power generating option.

Power consuming

The energy saving device (ESD) is a design intensive propulsion measure, but it could provide significant efficiency gains. It is however not implemented on yachts yet, and the difference in hull shape and speed might require a more engineering and other efficiency gains. Air lubrication technologies have only been applied to ships with flat bottoms, and are therefore not currently applicable on yachts. Fouling is a increasingly relevant topic, not only due to efficiency gains, but also in the spread of non-indigenous species [31], making it a versatile option. Adding the fact that currently, fouling can increase resistance for up to 40% [84], and new developments are frequent in this option, this is a very relevant topic. A contra-rotating propeller could help reducing losses in the propeller, at a relatively high capital and operational cost. Trim and draft optimisation is most effective when compensating for changes due to cargo loading, which are not present in yachts. Rudder optimisation is, like contra-rotating propellers, an option with high capitol costs and relatively small gains. Finally, propeller polishing could be implemented on a yacht, requiring a diver to clean the propeller multiple times per year.

Within auxiliary measures, consumers such as lights present an option for significant gain. Implementing batteries might help reduce peak shaving, however the relatively high impact of battery production does not outweigh the gains in efficiency.[18] Waste heat recovery is implemented more often in new built ships. Using generator waste heat to heat up for example pools or Jacuzzi's, saves energy by taking load of the generator. Frequency converters are often already implemented in yachts, as they have a relatively high auxiliary power demand and running at full auxiliary load would create a significant overcapacity. Exhaust gas boilers would be difficult to implement on a yacht, but could reduce their load significantly. It is questionable whether they would also be efficient at low auxiliary loads. Since HVAC amount to a relatively large part of a yacht's auxiliary power consumption, an efficiency increase would have a large effect. The same can be said for pumps and stabilizers. Furthermore, if present, the altercation of a power system to improve generator load control and eliminate the need for load banks could decrease energy waste.

Emission reduction
The SCR-unit does not only reduce harmful NO_x-emissions, but it also grants access to ECA's, thereby adding value to the yacht.

Operational improvements
Reducing speed could reduce fuel consumption significantly, it could however also compromise the comfort of a yacht. This could mean that the owner spends more time travelling on the ship, or the ship does not arrive when the owners wants. Furthermore, route planning could avoid area's or times when the sailing conditions are not favourable, but the same problem arises as with speed reduction, compromising the owners experience. Environmental awareness could provide certain benefits. However, reminding the owner of unnecessary environmental impact, by advising not to take a detour, compromises the owners experience as well. Equipment usage knowledge could help eliminate superfluous power losses, such as generators running at non-optimal loads.

Conclusion
Of these refit options, five will be examined that are assumed to be the most attractive for yacht owners in terms of feasibility, universality, aesthetics, commercial attractiveness and impact reducing. Since engine replacements are less likely to be cost effective and wind assisted propulsion compromises the aesthetics, solar cells are chosen as power generating option. As a propulsion option, anti-fouling is chosen as the most universal solution. Air lubrication is not likely to be implementable due to the hull shape. Also, ESD's are not known to be implemented on yacht, and the engineering to realise this is assumed to be very cost-intensive with respect to anti-fouling. Trim/draft optimisation are less effective on yachts as there is less significant trim or draft change due to loading. The twisted rudder and contra-rotating propeller are both very high investment options with relatively small efficiency gains.Propeller polishing is therefore an attractive option, but anti-fouling seems the most lucrative options, looking at the change in resistance.

Implementing batteries does not reduce a ships impact[18] and frequency converters, exhaust gas boilers and load banks are not universal options. HVAC, pumps and stabilisers are possible impact reducing options. A commonly done refit, changing to LED-lights is commercially attractive since it reduces heat load and improves efficiency of light consumers. Waste heat recovery provides heat for the pools, as well as reduces the generator load by taking load of boilers. Therefore both of these options are considered attractive refit options requiring more research in their cost-effectiveness. The SCR is a essential part of the sustainable refit, since it reduces the relatively large impact of NO_x, as seen in table 3.2. Furthermore it grants access into tier III area's thereby adding value to the yacht. The operational improvement options are assumed to be aesthetically compromising due to negatively influencing owners' experience. Furthermore they are difficult to measure because of their subjectivity, and therefore less fit for an implementation in the selection tool.

Now that the five refit options have been selected, they are treated individually in the following 5 sections.

4.3. Solar panels

As noted in section 2.1.3, solar panels have been considered as an option for reducing fuel consumption on a ship by reducing generator load. Photovoltaic cells use solar energy to produce electricity. [77] Since yachts are often in destinations with high solar irradiation factor, such as the Mediterranean sea, they have a potential to be relatively effective. Examples have been shown where panels with a masking layer replace teak decks. This option is offered by Solbian [100], a solar panel manufacturer with experience on ship applications. In 2020 a joint interdisciplinary project by TU Delft and Feadship was done on the possibilities of using solar energy on superyachts.[91]

4.3.1. Technology overview

Within photovoltaic technologies three main groups are identified, as shown in figure 4.1. These three groups are described in more detail below.

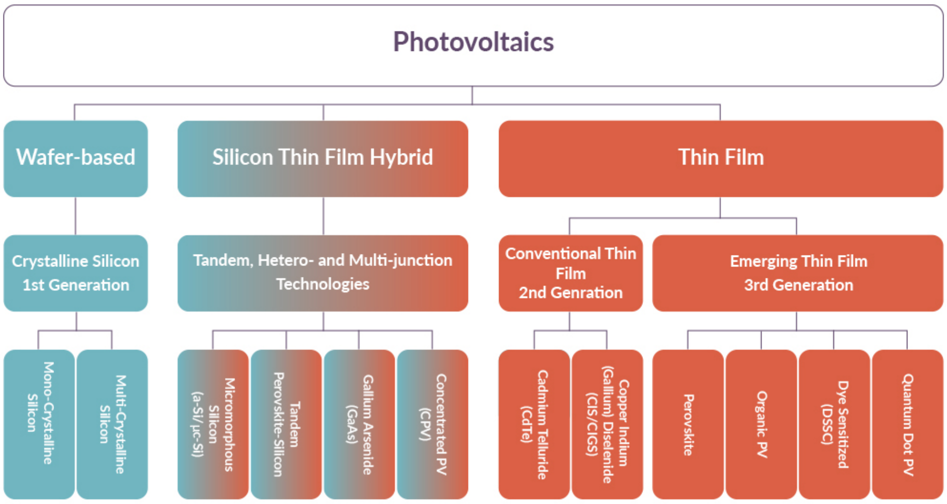


Figure 4.1: Photovoltaics technology tree [89]

Wafer-based technologies

Wafer-based crystalline silicon is most widely adopted PV technology. It is produced by smelting silica sand to produce metallurgical silicon. [27] This is then refined and cast into long ingots with either mono-or multi-crystalline microstructures. [27] Wafer-based photovoltaics amount to 95 % of total production in 2019.[34] Mono-crystalline silicon panels amount to 66 % of total solar panel production.[34]

Thin film technologies

Mono-cristalline silicon cells have a record cell lab efficiency of 26.7 % and for multi-crystalline silicon cells that is 22.3 %. [27] Thin film photovoltaics are devices with an active layer of a few microns deposited on a substrate.[27] An advantage to this technology is that it is widely applicable due to its flexible nature. As shown in figure 4.1, multiple thin film technologies are available. The highest level of lab efficiency in thin film technology is 23.4 % for CIGS, 21.0 % for CdTe and 21.6 % for Perovskite cells.[34]

Silicon thin film hybrid technologies

Hybrid panels combine both of the previous technologies by stacking thin film and wafer based silicon. Hybrid technologies are now reaching lab efficiencies of 33.3 %.[27] Application of these technologies may be restricted by high production cost and limited material availability. [27]

4.3.2. Implementation

Several application of these technologies are possible on a yacht, as shown in figure 4.2.

Figure 4.2: Available surfaces on Feadship Anna [102][91]

The horizontal surfaces of the decks and front dodgers, canopy, and the helipad can be used as surfaces for placing PV panels. The side dodgers and the hull provide feasible options as well, since these area's also collect reflection from the sun. Since the panels are going to be refitted onto a ship, it is of importance that a custom solution is possible. The dodger will be part of the solution for any ship, and the helipad and owners deck will be an optional addition. Since not every yacht has a helipad or available owners deck, it will be possible to select or deselect it in the tool. Additional, vertical, side surfaces available on the side dodgers or hull will be an option in the model as well, in order to determine a custom solution for multiple yacht designs. The Furthermore the possibility of a masking layer will present for each individual option. If solar panels were to be implemented instead of teak decking, several negative effects would play a role in this. The decks will be safe to walk on, but they wont be able to be used as a recreational space any more. An efficiency reduction of 5-20 % is present when a masking layer, such as a teak print, is used over a solar cell. [100] On the surfaces where teak is replaced by solar panels, impact reduction of reducing teak production will also be taken into account.

In order to provide a clear, easy to refit solution for any ship, the front dodger will be used as a standard surface for solar panel implementation. Because these surfaces have easy access to cabling in the roof, they provide the most favourable position for a solar panel solution on a superyacht. The roof space below the dodgers is also well isolated, thereby greatly reducing the impact of extra heat load by solar panels heating up. A possibility of a white masking layer is present, to increase the aesthetics of the panels, at a cost of an efficiency decrease, but it might help convince owners who don't want to change the looks of their yacht, while increasing its sustainability. This option is therefore available as an option in the tool. The panels implemented on the yacht will be from Wattlab, currently delivering an efficiency of 23 % on custom made solar panels, that can be made to fit a dodger, or other surfaces.

For each available surface, a custom fitted design will be made, maximising the potential of each horizontal surface. This will then be applied to the surface using a suitable marine adhesive, such as the 3M marine 3000 UV adhesive sealant. [1] This adhesive is suitable for long term marine applications, above and below the water line. Furthermore it is suited to fit a polymer solar panel to a metal dodger surface. [91] The wiring will then be done through holes in the dodger or deck, and then connected to the inverters below deck. An added advantage of the placement of solar panels on the dodger surface is that the surface does not have to be repainted like the rest of the superstructure. This removes the need for cleaning, applying epoxy, sanding, applying primer and regular paint, which is the case when a superstructure has to be repainted every 5 years. If applied to a surface to replace teak, the costs of teak replacement will be saved as well.

The solar panels have to be cleaned regularly by the crew, in order to keep the salt off and maintain optimal efficiency. Furthermore, if placed on surfaces on which they are walked on, it is of importance that no obstructing objects are placed on them, blocking the sunlight. If placed around a helicopter circle, they must not be landed on by a helicopter, risking damage to the panels. It is therefore concluded that placement on a walkable surface is possible, but more difficult to implement and more prone to damage then when placed on the dodgers. It is however still a possible refit option.

Teak

The implementation of solar panels on deck could serve as a replacement for teak wood, which is now layed on deck. Since teak wood depends mostly on deforestation and degradation of natural forests [59], it is considered an unsustainable practice. Apart from this it is also a very costly affair, since the laying of teak is also a skilled labor-intensive practice. Not laying teak could therefore save significant amounts of GWP and external costs, as well as regular costs. Since the laying of teak is an option highly depending on owners preference, being the industry standard on yachts, it is not taken into account in the general business case. It will be implemented in the tool as an option, possible enhancing the cost-effectiveness of solar panels significantly if taken into account.

4.3.3. Calculation

Firstly the dodger size must be determined, in order to calculate the amount of solar panels that can be installed. Secondly the amount of solar energy a ship can convert is dependent on its position, therefore the annual solar irradiation is determined, based on the operational profile. Using these parameters, the annual amount of energy produced can be determined and the business case can be made.

Energy production

As stated before, the energy produced by the solar panels is taking load off the generators, thereby resulting in a fuel saving. In order to determine the amount of energy produced by the solar panels per year, E_pv in [MWh], must be determined using equation 4.1.

$$P_{PV} = S_D \cdot \varepsilon_{PV} \cdot I_{s,avg} \cdot \varepsilon_{corr} \tag{4.1}$$

In this equation the dodger surface $\mathrm{S_D}$ is multiplied with the efficiency ε_{PV} and the annual horizontal solar irradiation factor $\mathrm{I_{s,avg}}$, from table 4.9 and finally a correction factor. This factor accounts for the shading of the mast due to non optimal orientation of the vessel and the electrical efficiency of the system, including cables and dust accumulation on the panels. This factor is assumed as 0.85, of which 10 % of the losses are from shading and 5 % is from dissipation in electrical components. Furthermore a correction is made of the panels heating up, because of a change of color, and the extra HVAC load this brings. With all options included, the solar panel energy supply never exceeds the ship energy demand, since it is around 2%. This means that no batteries are needed to compensate for an excess in energy supply. If this were the case the batteries could be used for a combination of surplus energy storage and peak shaving.

With the amount of energy produced, $\mathrm{E_{PV}}$, the amount of load reduced on the generator can be determined, thereby the emission reduction.

Business case

An overview of the business case for solar panels is shown in table 4.2. As seen in the table the capitol expenditures consist of 5 parts. Firstly the PV-panels itself, delivered by Wattlab. Furthermore an inverter is needed to convert the AC current into DC current. An inverter is chosen that can handle a peak wattage of 50 kWp or 25 kWp, dependent on the amount of solar panels installed.[25]. Since the solar panels create less energy at peak wattage than the auxiliary demand, the inverter is connected to the grid and not used to charge a battery system, Therefore the use of an on-grid inverter is used instead of an off grid inverter.

The amount of cabling is estimated at €200 per 9 kWp [91]. Furthermore the balance of system, including extra switching, cabling and other components, is estimated at 20 % of the costs of the inverter and cabling costs. The installation of the solar panels, including the placing of the cables, though the dodgers to the inverter and connecting the inverter to the grid is estimated at 2 hours per square meter of solar panels, at €100 per hour. Even though the Wattlab panels are fairly easy to apply, a custom solution is created for each ship, therefore hours are calculated in generously to compensate for unforeseen difficulties. Secondly, paint costs are saved. This is because in normal cases the entire superstructure is repainted every 5 years. Since repainting is at an average cost of €250 per m^2, these savings are also significant. Since teak is replaced every 12 years, generally and costing up to €1800 per m^2, it amounts to a relatively large saving when solar panels are placed instead of teak deck. As stated before, teak will not be taken into account in the general business case but will be added as an option in the model, since it could provide an distorted picture of the cost-effectiveness of solar panels.

The operational expenditures include the maintenance of the solar panels, chosen on the high end of general estimates, again because of the custom solutions fitting the dodger.[115] The revenue firstly consists of the amount of fuel not burned by the generator, which has a reduced load due to a reduction in ship auxiliary engine power demand by the solar panel electricity production. Since the costs are often generalised to a single value to create universality in the model, the effect of variations on these inputs will be determined in the case studies as well.

Table 4.2: Business case solar panels

Business case solar panels		
CAPEX		
Panel cost	€2300	per m^2
Inverter(25 or 50 kWp) [25]	€2719 or €4948	
Cables	€ 200	per 9 kWp
Balance of systems	20% of inverter + cable cost	
Installation	€100 per hour	4 hours per m^2
Paint saved	-€ 250	per m^2 per 5 years
OPEX		
Maintenance [**?**]	€ 7.5	per kWp per year
Revenue		
Fuel saved	Dependent on auxiliary fuel consumption reduction	

Impact reduction

The global warming potential reduction consists of the WTW CO_2-equivalent reduction of the diesel saved. The global warming potential of the production of the solar panels is subtracted from these savings, thereby resulting in the net GWP savings. As for external costs, this calculation is done in the same manner, except then in external costs instead of CO_2-equivalent units.

4.4. LED

Yachts have a relatively large amount of both internal and external light sources. An increase of light efficiency could reduce the energy compensation significantly. Light-emitting diode lamps have been gaining popularity as a light source, replacing low efficiency light bulbs and fluorescent lights containing harmful substances. LED-lights have a higher efficiency, long lifespan and are generally more environmentally friendly.[64]. Furthermore, they can make use of a broad range of wavelengths in lights, creating the possibility for customisation in a variety of settings of intensity and colors.[113] This last case has added value for yachts as well, since owners might want to adjust light settings to create a certain atmosphere. On top of this, halogen and incandescent lights are becoming harder to come by, therefore it is more difficult for the yacht crew to maintain a stock of back-up lights.

4.4.1. Technology overview

New built ships are almost always fitted with LED lights for interior and exterior lights. As shown in figure 1.3 a large part of ships is 10 years or older, meaning there is a significant chance that they are not fitted with LED lights, but with halogen or incandescent lights. New built ships feature LED lights with a power of 10 watt, whereas old yachts are known to have been fitted with 40 watt lights. Since a 110 meter yacht has around 4000 lights, this is a significant factor in energy usage. Since LED-lamps have a higher efficiency, they use less power to create the same amount of light, with respect to other lights sources, such as incandescent lights. This means less energy will be converted to heat, thereby reducing load on HVAC on top of consuming less energy then other light sources.

4.4.2. Implementation

Refitting a ship to LED lights requires a lot more work than changing the bulbs. LED lights require different drivers , sockets and junction boxes, thereby requiring all the cabling to be redone. A LED-refit generally involves the following activities:

- Dismantling the old lighting system
- Engineering the new lighting plan including fixtures, e-plan, cable drawings, wiring diagram, connection diagram and wiring list
- Installation of cabling, fixtures, switches and sockets

This is done by an external party, requiring yard assistance to open up ceilings and walls, also amounting to the cost of the system.

4.4.3. Calculation

For the installation of LED lights in ships ranging from 40 to 120 meters the following cost calculation is made, seen in table 4.3. These values are based on multiple brochure's. Note that these values are now scaled per lamp, this is only representative for ship lengths from 40 to 120 meters.

Firstly the main infrastructure including system design fixtures, cabling, switching, drivers and sockets is scaled to €1500 per lamp. In order to install this, yard assistance is needed to open up ceilings and walls. This is calculated at 1.5 hours per lamp and with an hourly rate estimated at €100 per hour, this amount is a general average for the entire light system. There will be area's with more or less lights per ceiling panel, requiring different amounts of hours per lights, but as an entire ship system, 1.5 hours per lamp is kept as a constant value. Furthermore both exterior and interior lights, fixtures and sockets are estimated at €220 euros per lamp. As operational expenditures, the replacement of the bulbs have been included. For this a lifespan of 50,000 hours is estimated, amount to around 9 years, if used 60 % of the time. [103]. The revenue is partly due to fuel savings for less energy needed for light production and partly due to fuel savings for less energy needed for compensation of the heat production of lesser efficient lamps. Note that this business case is only accurate if LED-lamps are not currently installed in the vessel.

Impact reduction

As for impact reduction, the amount of fuel and its WTW impact is calculated for both GWP and external costs. Then the extra LED production is subtracted from this, making the reduction smaller. Other factors, like cabling, fixtures and other components are left out of the scope, this is because they have a marginal impact on the total abatement.

4.5. Anti-fouling

The settlement and growth of vegetable and animal organism play a big role in a ships propulsive energy demand. Growth of these organism roughs up the hulls surface, reducing speed and increase resistance. [90] Furthermore the organisms attached to the hull can introduce non-indigenous invasive species into ecosystems. [31]The first form of biofouling is biofilm, a green slime formation that appears after 2-4 weeks, increasing drag for up to 20 %. On this layer, after 4-12 weeks, barnacles an other organisms begin to attach, reducing the drag to up to 40 %.[84] This process is visualised in figure 4.3. The amount growth of fouling is also affected by factors such as idle time, operational area, applied anti-fouling technique and maintenance.[109]

Table 4.3: Business case LED

Business case LED lights		
CAPEX		
Main infrastructure	€1500	per lamp
Yard assistance	€100 per hour	1.5 hours per lamp
Interior fixtures, switches & sockets	€ 220	per lamp
Exterior fixtures, switches & sockets	€ 220	per lamp
OPEX		
Interior LED replacement [103]	€ 80	per lamp per 9 years[103]
Exterior LED replacement	€ 120	per lamp per 9 years[103]
Revenue		
Fuel saved (HVAC)	Dependent on auxiliary fuel consumption reduction	
Fuel saved (light)	Dependent on auxiliary fuel consumption reduction	

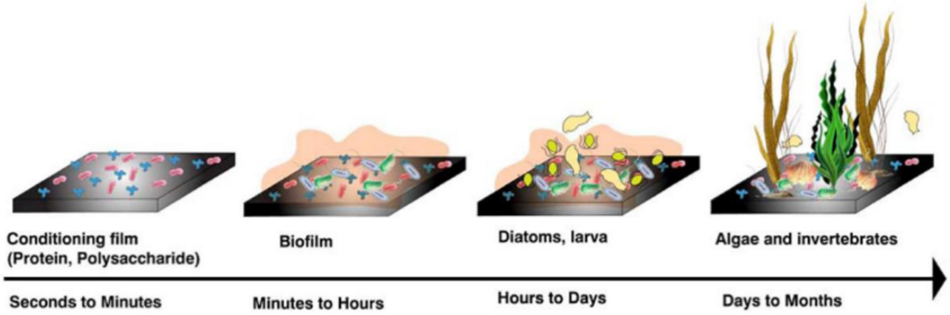


Figure 4.3: The typical growing process of marine bio-fouling [119]

After algea and invertebrates have been nested, the cleaning off the hull becomes difficult and with a high risk of releasing toxins of the paint into the water, when a biocidal paint is used. Furthermore the cleaning reduces the thickness and thus effectiveness of the anti-fouling layer with around 30 %. This means that after 3 to 5 years a full re-coating is required. In practice a superyacht is generally repainted every time it is dry docked, bringing the average to around 2.5 years.

4.5.1. Technology overview

Several technologies solutions are known to prevent the negative effects of fouling composition on ship hulls, which are categorised below:[109]

- Coatings
- Films/foils
- Vibrations
- Lighting
- Hull isolation
- Cleaning

Below is a short summary of the anti-fouling systems mentioned above. Coatings are are divided into two categories, biocidal and non-toxic coatings [29]. Where biocidal paint is based on an active toxic substance that prohibits the settlement of organisms on the hull, non-toxic coatings make use of the creation of unstable surfaces that prevent early growth of organisms and facilitate easy removal. [29] This is also the currently used system.

An example of films is the technology of Finsulate, a physical fouling-resistant wrap supplies as pressure sensitive adhesive tape. [33] This technology uses a flocked surface on the foil to prevent larger organisms to attach to the hull. Development into sharkskin-like coatings is being done, however none were found that are not still at an experimental stage. Vibrations using ultra- or infrasound and UV-lights are also methods to reduce fouling inhabitation, however also still at an experimental stage. Hull isolation can be done by either lifting the ship out of the water, or creating a barrier between the hull and the surrounding waters. Cleaning of the hull can be done by either divers or cleaning robots.

4.5.2. Implementation

In the current situation a biocidal paint, micron 99, is applied to the ships hull and then repainted every 2.5 years. Because of this the use of a hard coating, which has can have a lifespan of up to 15 years, can be a viable alternative. In Feadship internal research, shown in figure 4.4, the current case, micron 99 biocide paint, is compared with Finsulate and ecospeed coatings in different cleaning scenario's.

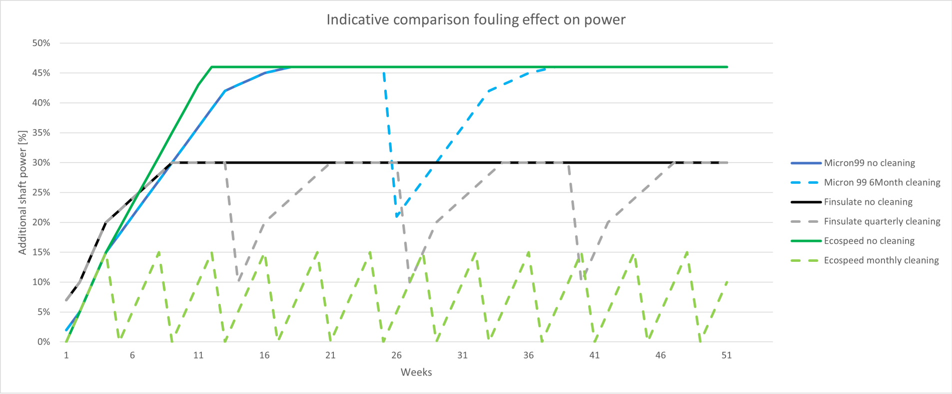


Figure 4.4: Effects of fouling on resistance [source:Feadship internal research]

The hard coating combined with robotic cleaning turned out to be the most fitting solution for yachts in terms of least additional required power to due to fouling, by limiting the amount of additional required shaft power to 15 % max, compared to 30 % with Finsulate and 46% with standard biocide paint. Due to these number in addition to a Feadship internal business case, the standard anti-fouling case will be compared to the Eco-speed case.

4.5.3. Calculation

For the calculation of the the 2 business cases of eco-speed and regular micron 99 anti-fouling will be compared. This is shown in table

Table 4.4: Business case for both Anti-fouling scenario's

Business case Anti-fouling				
	Micron 99		Eco-speed	
		CAPEX		
Surface preparation	€ 13	per m^2	€ 13	per m^2
Material	€ 42	per m^2	€ 70	per m^2
Application	€ 10	per m^2	€ 10	per m^2
Cleaning equipment	€ -		€ 40,000	
		OPEX		
Cleaning fees	€ -		€ 25000+25 per m^2	
Fouling replacement	€ 65	per m^2 each 2.5 years	€ 105	per m^2 each 10 years
Extra fuel costs	Dependend on propulsion fuel demand		€ -	

The main difference between the two cases is the higher material price for Eco-speed and the purchase of cleaning equipment and fees. Looking at figure 4.4, the expectation is that the extra fuel costs will be relatively high, since there is a significant difference in resistance between the two cases.

As for GWP reductions, they will be mainly in the difference of burnt fuel between the cases, as well as the paint production not taking place. An external costs reduction will be calculated similarly. The effect of the biocide release and production of cleaning equipment will not be taken into account.

4.6. Waste heat recovery

Yacht generators are generally cooled by a sea water loop. This means that the heat from cooling water from the engine is transferred to seawater, without being in contact with it. This last past is essential, since salt water would cause corrosion within the generator. This heat is then, in essence, used to warm up seawater. Before losing at the heat to sea, it is possible to use some of the heat that would otherwise go to waste by putting a heat exchanger in the loop before the engine cooling fluid is cooled down by the seawater.

4.6.1. Technology overview

This extra cooling loop is illustrated by the simplified schematics in figure 4.5.

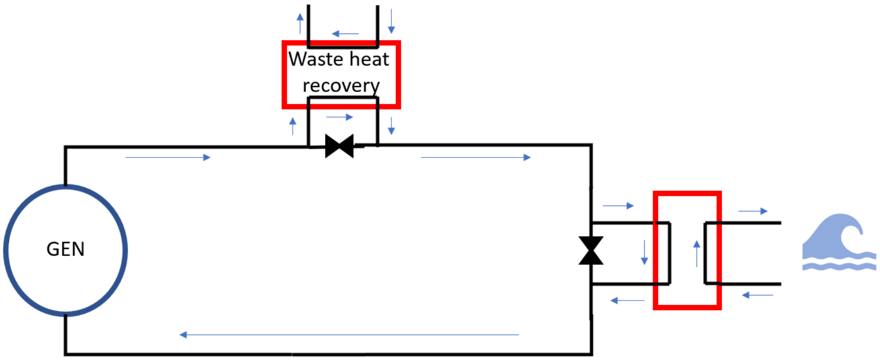


Figure 4.5: Waste heat recovery schematics

As seen in the figure, the warm cooling fluid of the generator is first fed through a waste heat recovery heat exchanger, before it reaches the sea water loop to obtain the temperature needed to cool the generator again. Both heat exchangers have bypass valves, since the temperature of the cooling fluid cannot become too low.

4.6.2. Implementation

For the implementation a standard marine plate heat exchanger can be used such as in figure 4.6

Furthermore the system consists of a heat recovery circulation pump, temperature sensors, valves, expansion vessels and a renewed switchboard. Other than that all the piping, cabling, installation and calibration must be done.

4.6.3. Calculation

Around 3 % of the total amount of installed generator power is recoverable in heat. This is based on a previously installed waste heat recovery system. It is assumed that this level of output is constant and can be used in full to heat up water boilers and cabin heaters. Furthermore the output is dependent on the amount of generators in the ship, since one heat exchanger per generator, except emergency generators, can be installed. Virtually no maintenance is needed, and is therefore assumed to be incorporated in the general generator maintence at no extra cost. The overview of the business case is shown in table 4.5

4.7. Selective catalytic reduction

As shown in table 3.2, NO_x emissions from yachts play an important role in the impact of yacht operational emissions. As seen in figure 2.6 , NO_x emissions contribute to eutrification, acidification, climate forcing,

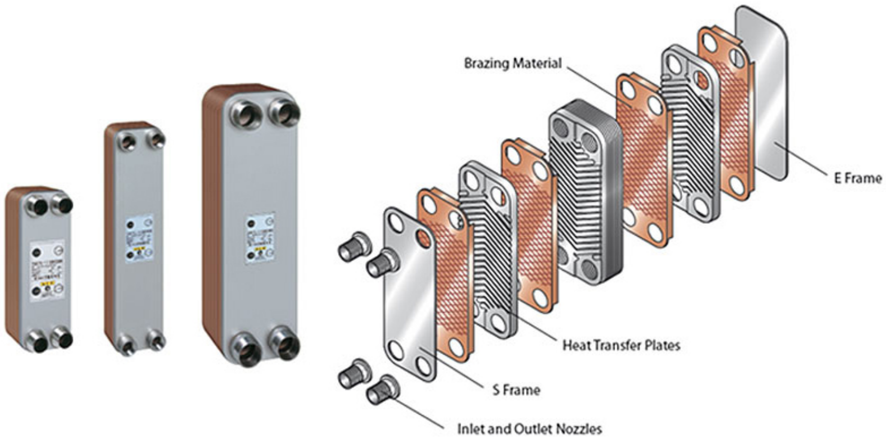


Figure 4.6: Marine plat heat exchanger [44]

Table 4.5: Business case waste heat recovery

Business case Waste heat recovery	
CAPEX	
System components	Minimum 12k€ and scaling around 1k€ per 10 kW waste heat recoverable
Piping	Minimum of 10k€ and adding 4k€ per generator
Cabling	10 hours per generator
Installation/calibration	20 hours per generator

ground level ozone and particulate matter. Within external costs, it amounts to around 40 % of the external costs per kg of burned diesel. A selective catalytic reactor is capable of reducing NO_x emissions for more than 80 %, also granting access to IMO tier III regulated access. [14] By achieving this, SCR is also the only technology currently available that permits technologies to reduce NO_x to a tier III level. [5]

4.7.1. Technology overview

The SCR unit uses ammonia(NH_4)-injection to convert NOx into N_2 and water. This reaction is shown in figure 4.7.

4.7.2. Implementation

In an SCR sytem the exhaust gas, including NO_x, is passed through the catalyst, where a urea-solution is added that is the source of the ammonia. The urea solution is stored in a special tank, either freestanding or implemented in the double bottom. An overview of a system like this is shown in figure 4.8.

As seen in the figure, the exhaust gasses enter the SCR-unit, where urea is added. The mixture then passes through the catalysts before it exits the unit. This system can be implemented on both generators and main engines.

The implementation of an SCR-system requires the following components:

- SCR-unit
- Urea mixer
- Doser valves
- Pump system

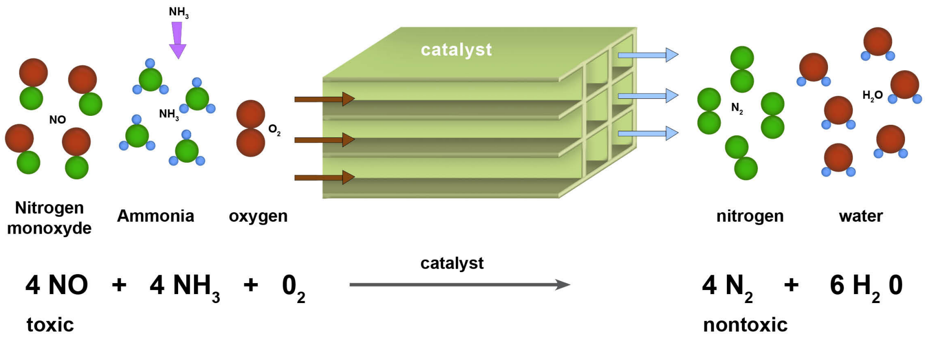


Figure 4.7: Chemical reaction SCR unit [46]

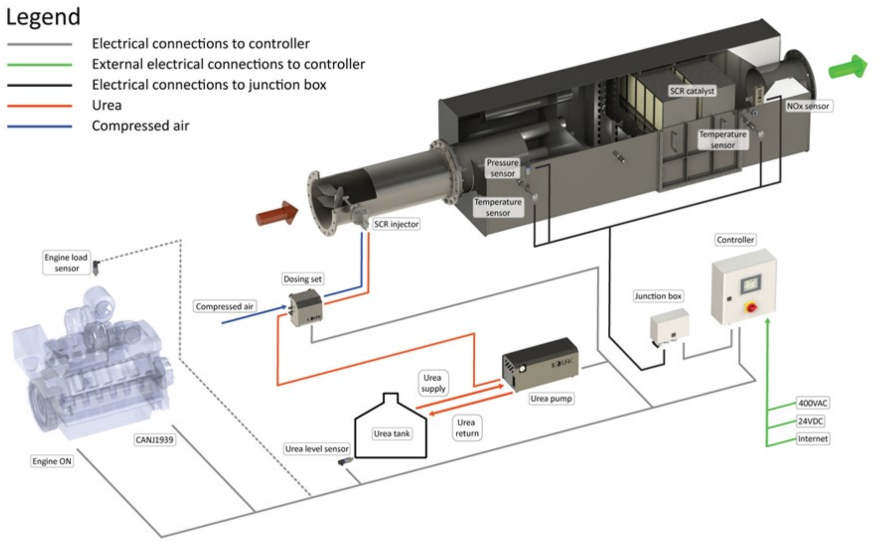


Figure 4.8: SCR system overview

- Dosing control unit
- Monitoring system
- Urea tank

The catalyst itself generally consists of vanadium pentoxide (V_2O_5), supported on titanium dioxide (TiO_2) [75], in a so called "honeycomb" structure, where the exhaust gas passes through. These catalyst have a limited lifespan and have to be replaced after several years, dependent on the amount of active SCR-hours. In order to refit an SCR-system, there must be space available in the engine room. Compact models are on the market that take in less space, so that implementation in small engine rooms is also possible. In order to put the unit in place, a hole in the hull must be made. Furthermore the creation of the urea tank is a costly and time consuming job.

4.7.3. Calculation

In this section, the costs of the business case and impact reduction of the SCR-unit will be treated. Firstly the business case is made based on the installation cost and SCR-unit cost calculation below. The SCR-unit price composition is shown in table 4.6 below. As seen in the table, SCR-units for generators are notably cheaper than for main engines. furthermore extra costs apply for the displays, switches and calibration, but the main part of the costs is in the SCR-units itself.

Table 4.6: SCR cost composition

SCR cost composition		
SCR-unit (main engine)	€ 120,000	per engine
SCR-unit (Generator)	€ 65,000	per engine
Display	€ 2,500	per SCR-unit
Switches	€ 350	per SCR-unit
Calibration	€ 3,000	per SCR-unit

The installation of the SCR-units encompass the following aspects:

- Transport (through hole in hull)
- Welding
- Painting
- Electra
- Piping
- Fitting
- Steelworks

These activities are priced at €125k for a single SCR-unit, adding €25k per additional unit. Having analysed the SCR unit and installation cost, the generalised business case can be developed.

The business case on SCR-units is as follows:

Table 4.7: Business case on SCR-units

Business case		
	CAPEX	
SCR (ME)	€ 125,000	per engine
SCR(GEN)	€ 70,000	per generator
Installation	€ 100,000 + 25,000 per SCR	
Urea tank	€ 50,000	
	OPEX	
Urea consumption	7 % ureum to fuel	
Extra diesel	1 % extra	
Catalyser replacement	Based on fuel consumption	
Maintenance	10 hours/system/year	

Emission reduction

The NO_x reduction rate is at least 81 % in all engine load conditions, with a reduction of up to 90%. [60]. On top of that, a hydrocarbon reduction of 20 % and a particulate matter reduction of 10 % is claimed. [116] As in this case the SCR-unit is refitted onto an existing engine, the fuel consumption increases due to the pressure drop with around 0.5 % [67]
Now that the amount of emissions reduced is determined, first the GWP of these emissions can be calculated with the GWP-factors. The GWP of extra fuel burned will be added, thereby creating a GWP increasing number, which is in contrast to the other measures. The GWP reduction of emissions will probably not outweigh the increase in GWP by extra fuel burned, thereby creating an addition in GWP. The increase of GWP by the production of the SCR and ureum will also be taken into account. The reduction in NO_x will decrease other negative effects of this emission significantly, such as eutrificiation, acidification, ozone forming and particulate matter.

The main impact will show in the reduction of external costs by reducing harmful emissions. This external cost reduction will be for the main part of the reduction of exhaust emissions. The reduction will be limited by the production of ureum, extra fuel and the SCR unit itself.

4.8. Input determination

In order to provide a solid base for a variety of refit options, several inputs have to be determined. Firstly the basic dimensional derivations are treated in section 4.8.1, secondly the different operational profiles are taken into account in section 4.8.2.

Apart from length, the power plant configuration is taken into account as well. The tool works for regular configurations with main engines for propulsionary demand and generators for auxiliary demand, as well as for diesel electric configurations. A custom amount of main engines and generators can be given, which can alter the effects of several refit options, such as waste heat recovery.

4.8.1. Dimensional derivations

The following dimensions, seen in table 4.8 are derived from the length of the ship using trends in the Feadship database. Firstly the breadth, the gross tonnage, wet surface and power demands are directly derived from the database. The last 7 derivations of table 4.8 are explained below.

Table 4.8: Derived dimensions from the database

Dimensional derivations	
B	[m]
GT	[t]
Wet surface	[m^2]
Auxiliary power demand	[MW/year]
Propulsion power demand	[MW/year]
Dodger area	[m^2]
Owners deck area	[m^2]
Heli deck area	[m^2]
Lights, interior & exterior	[-]

Wet surface

In order to determine the effect and cost of anti-fouling the wet surface, or underwater surface, is essential. An increased wet surface means more growth, more added resistance and extra cost for application and maintenance. To determine this a relation was found between ship length and wet surface, as seen in figure 4.9

As seen in the figure, the wet surface rises from around 400 m^2 on a 42 meter ship to over 2000 m^2 on a 110+ meter yacht.

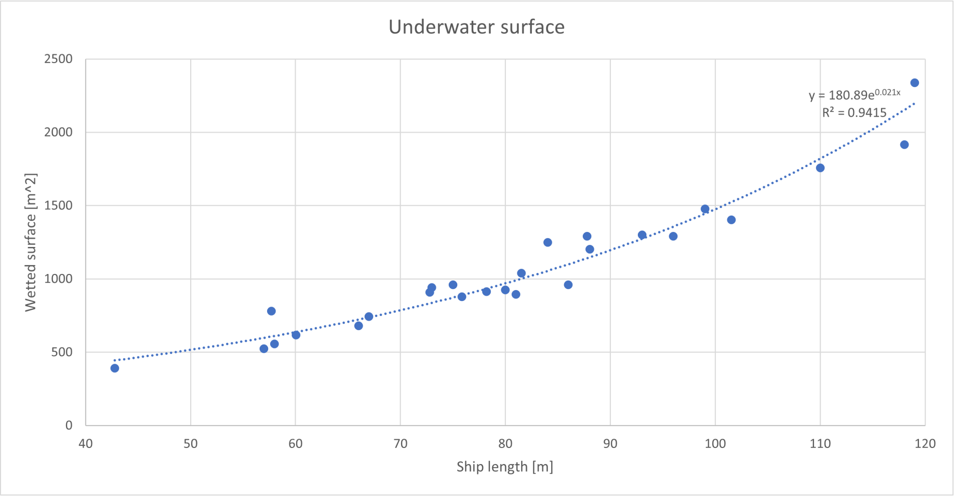


Figure 4.9: Underwater surface per length

Power demands

The auxiliary- and propulsionary power demands are dependent on ship length as seen in figure 4.10. On the left vertical axis the annual energy demand is shown and on the right side its corresponding global warming potential. Furthermore the ratio of propulsionary to sailing power demand per length can be derived from the figure.

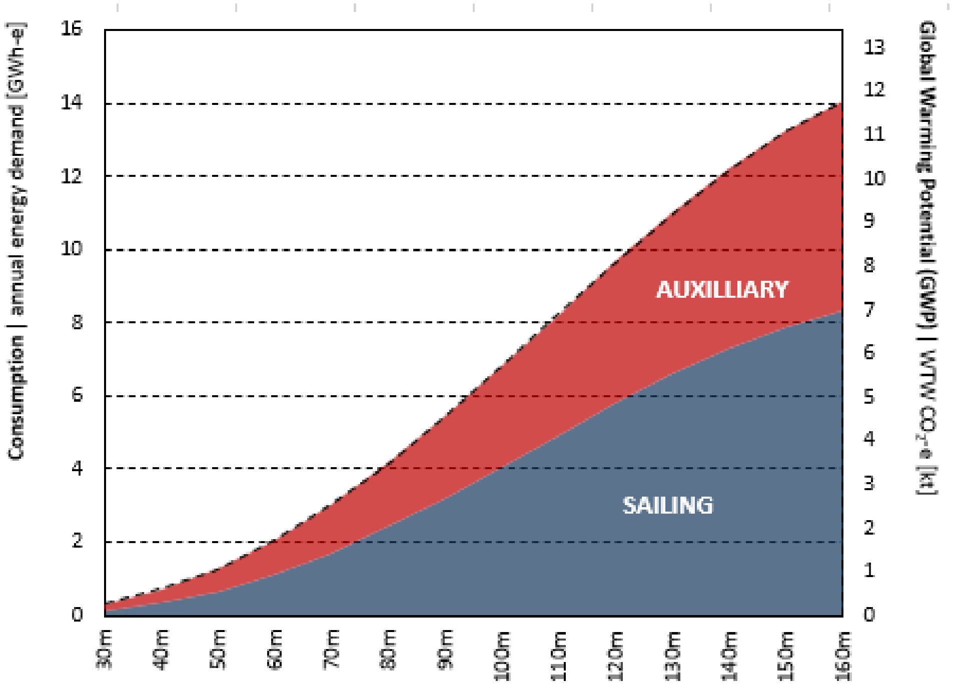


Figure 4.10: Power demands per ship length [35]

Dodger area

Since the dodgers are used as a surface for solar panels placement, the surface of this area is needed. Since the model is based on the length of the ship, the breadth is determined out of a trend using every Feadship. 15 Dodger surfaces were measured from construction drawings in order to determine the relation between ship size and dodger size. This relation is shown in figure 4.11.

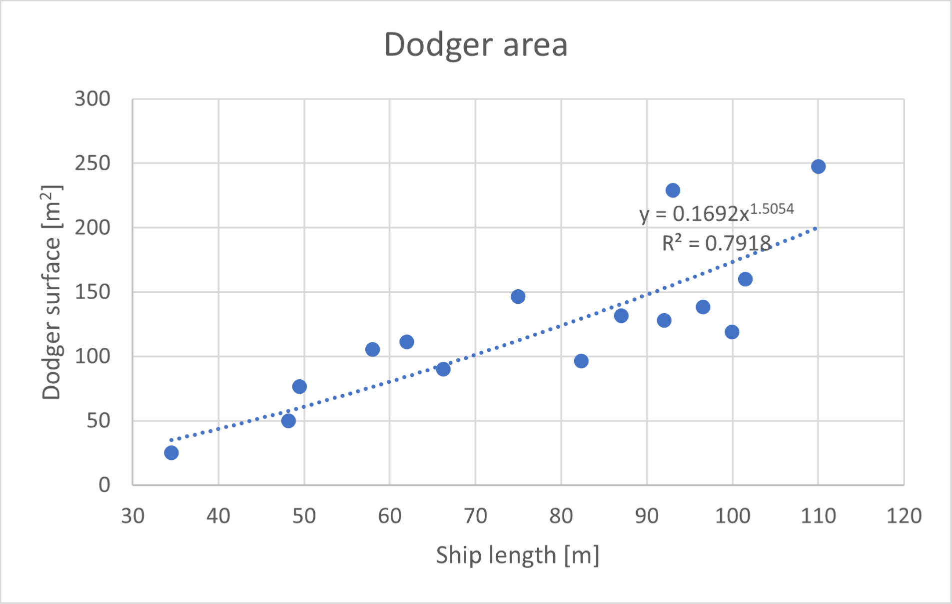


Figure 4.11: Dodger area per ship length

As seen in the figure, at larger lengths the dodger size begin to vary more, this is because at with larger designs there is more freedom to differ in dimensions. The upper dodger is usually used for the bridge, and the lower dodger covers the owners lounge. Since these spaces don't have to grow in size proportionally in length, it leaves more freedom in the design.

Owners deck area

In several ships the owners deck, at the front of the ship as seen in figure 4.2, can be used for solar panels as well. In many other cases, the owners deck is either used for tender storage or other activities prohibiting the placement of solar panels. If not, however, it is a suitable area for the placement of solar panels. The analysis of 15 owners deck area's showed no significant relation to length. For the ship of around 90 meters, the surface available varied from 78 to almost 300 m^2. This is shown in figure 4.12.

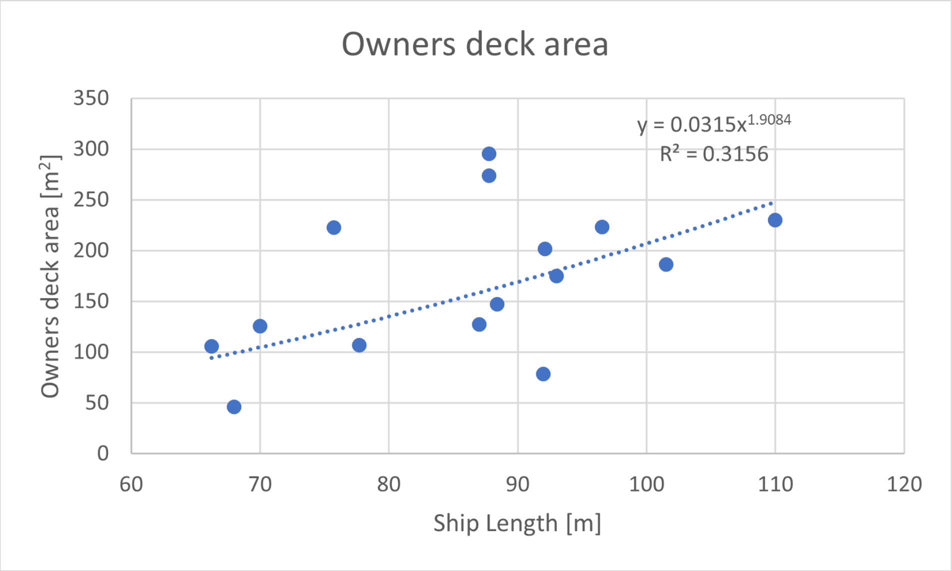


Figure 4.12: Owners deck area per ship length

Because no adequate relation between deck size and ship size was found, the option of owners deck installed solar panels will be implemented in the system as a manual input.

Heli deck area

Solar panels cannot be installed on the "H" circle on which the helicopter lands, due to regulations and the limited strength of the solar panels. A heli deck must however have significant clearance outside this circle, due to the span of the rotors. This area is a good surface for solar panels, since it is not regularly used.

Examining heli deck sizes in the Feadship database, no significant relation was found between heli deck size and ship length. Heli deck sizes range from 3.5 to over 7 meters in diameter. Since the size of this deck is based on the owners preference, there is no mathematical relation between heli deck size and ship length. In the four researched helipads the average ratio of available surrounding space to heli circle was 66.6 % . By using this ratio, the heli deck size can be used as input, since it is not possible to determine this number based on ship size. It will then be implemented as an option in the model.

Amount of lights

In order to determine the amount of lights to be replaced, an analysis is made of the Feadship database. Using the amount of lights per meter of ship length the following relation has been determined, as shown in figure 4.13.

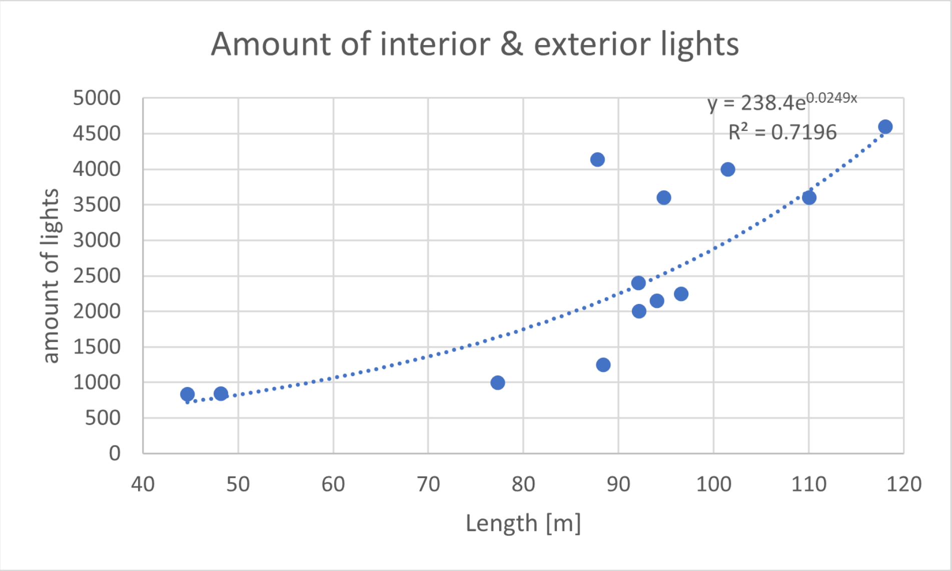


Figure 4.13: Total amount of lights per ship length

The researched ships have between 833 and 4600 lights. Furthermore, the data showed that the average amount of external lights is 21% of the total lights.

4.8.2. Operational profile

The energy production of a solar panel is dependent on the amount of solar irradiation it receives. The average yearly available sun energy differs around the globe. Based on the operational profiles and annual horizontal irradiation factors by [99], the average amount of solar irradiation received per operational profile is determined. Current operational profiles can be divided into three main categories, named A, B C. These profiles will be examined below.

- The first operational profile, **A**, is that of ship owner who's ship resides only in Europe. 10% if the time is spent in norther Europe, in parts like the Norwegian fjords, or in the south of England. The other 90 % is spent in the north side of the Mediterranean.
- The second operational profile, **B**, has a broader sailing area. This vessel is in the Mediterranean area for around 35 % of the time, and the other 65 % of the time it is in north and middle America, crossing the Atlantic twice a year.
- The third and last profile, **C**, has the widest sailing area. Like profile B it spends 35 % in the Mediterranean. 30 % is spent in north and middle America and the last 35 % is spent all over the world, in area's like the Galapagos island, Hawaii or Indonesia.

The annual horizontal solar irradiation coefficient per operational profile is shown in table 4.9

As seen in the table, the annual solar irradiation coefficients differ no more than 3.5 % per operational profile. Surprisingly, the lowest annual solar irradiation is obtained by operational profile A, which is in the Mediterranean for 90 % of the time. For vertical surfaces, it is assumed that they receive 40 % less solar irradiation than horizontal surfaces. Less direct sunlight is received by this panel, however the irradiation of the water plays a role as well.

Table 4.9: Annual horizontal solar irradiation coefficient per operational profile

Area	**Annual solar irradiation coefficient** [Wh/m^2]	**A**	**B**	**C**
Mediterranian	1600	90%	35%	35%
Northern europe	1000	10%	10%	5%
North U.S	1450		10%	10%
South U.S.	1550		25%	5%
Carribean	2000		20%	10%
Global	1520			35%
Annual horizontal irradiation per profile [kWh/m^2]		1.540	1.593	1.565

4.8.3. Fuels

Superyacht main engines and generators are designed to run on marine gas oil (MGO). This is a low sulphur mix of fossil oil distillate, with relatively high well to wake emissions. Switching to a non-fossil fuel, or biofuel, could lower a ships global warming potential, without requiring an intensive refit. As stated in section 2.3.2, the WTW emissions would decrease 71 to to 91 % using hydrotreated vegetable oil (HVO).[23] Since HVO is a second generation biofuel, it consists of refined used oils or animal fats, therefore there are no land-use issues and they do not compete with food production or aid deforestation.[23] HVO is produced by hydrotreating of vegetable oils and vegetable oil-heavy vacuum oil mixtures with a catalyst[45]. With little capitol investments it is possible to use petroleum refineries and their existing infrastructure to produce HVO[45]. An example of this process by Nextchem [82] is seen in figure 4.14.

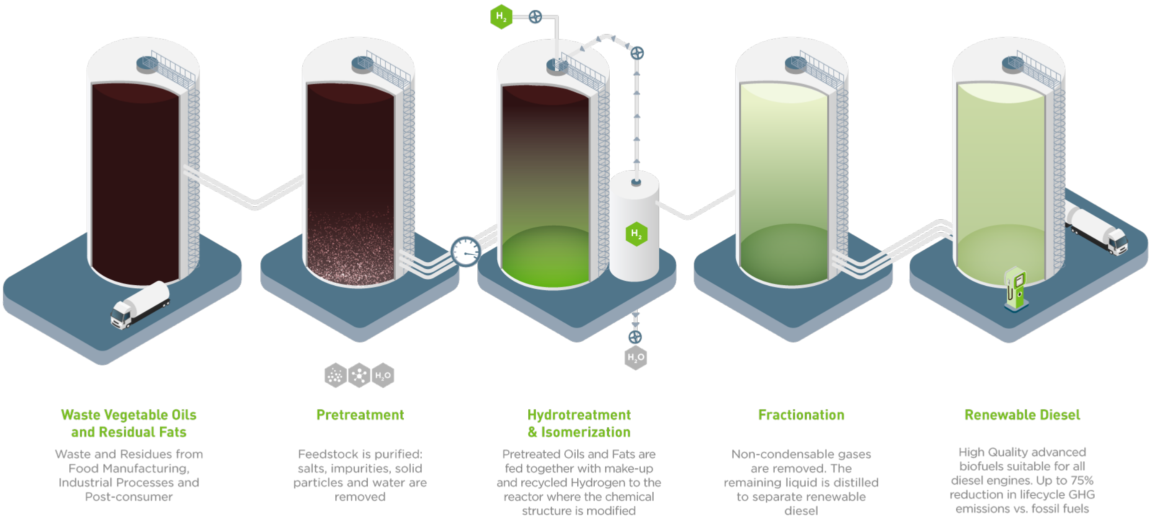


Figure 4.14: Hydrotreated vegetable oil production process [82]

As seen in the figure, the waste oils and fats undergo a refinement process in which they are treated in multiple steps in order to produce diesel suitable for regular diesel engines. Currently HVO is priced higher then MGO, and is therefore commercially less attractive.[23] Looking at GWP reduction does however have the potential to be an interesting alternative to conventional fossil fuels for combustion engines, reducing the CO_2-equivalent emissions drastically without requiring an (capital) intensive refit.

To implement this into the selection tool, the same conditions will apply as in the MGO scenario, only the fuel will be HVO, priced higher than regular fuel and with 80 % WTW CO_2-equivalent reduction. In terms of external costs, the WTT hydrocarbon emissions have been reduced by 22 % and the CO emissions have been reduced by 17 %. [101] No significant changers to other emissions have been noted. [101] Furthermore, the external costs of the production per kg of fuel (WTT) have been reduced by 22 %. [22]

4.9. Conclusion

In this chapter the selection of the five refit options to be treated in this research is made. First an extensive list of refit options is made in section 4.1. To create a diverse selection with different categories of refit options to implement in the selection tool, a power generating option is treated, a propulsive and and two auxiliary power consuming options together with an emission reduction option are chosen in section 4.2. Of each of these options, the technology, implementation and calculation are treated in section 4.3 to 4.7, forming parts in the selection tool as treated in section 3.4. In order to finalise the implementation of these refit options in the selection tool, the specific inputs are determined in section 4.8, including dimensional derivations, operational profile and choice of fuel.

Now that the tool is complete for the selected refit options, the impact of input variations can be determined using the case studies in chapter 5.

5

Case studies

In order to determine the effect of ship length on the cost effectiveness of refit options, the case studies will be done on multiple lengths. The first case is the base case, for which the length will be set as the current average ship length at refit, in order to create an accurate depiction of the possibilities of a current refit. This base case length is set at 54 meters, as is the average ship length of refits to date, as analysed in section 1.2.2. The second case will be of a ship in a higher length category, of 100 meters, to determine the scale effects of length on the model, in section 5.2. In the recent years more ships of 100 meter+ have been built, and could therefore be a potential refit opportunity in the future.

Within each case, three main scenario's will be treated. First a regular scenario is treated in which the fuel price is set as the current fuel price of €0.45 per liter of marine gas oil (MGO) [96]. In the second scenario the fuel price is fluctuated to find the point on which the implementation of all 5 options is cost neutral. The value of this resulting fuel price can give an indication on whether fuel price fluctuations, such as increased taxation, will effect the attractiveness of sustainable refit options. In the third scenario HVO is used as a fuel instead of MGO, to asses the effects of the emission reduction treated in section 4.8.3. In the long ship case, a fourth scenario is added in which the effect of teak prevention due to solar panel decking is taken into account.

As results the marginal abatement cost curves will be constructed for global warming potential and external cost reduction. In order to evaluate the individual payback times and the total abated external costs and global warming potential, as business case is executed as well.

To check the input sensitivity of the model an analysis on several input changes is done subsequently in section 5.3. Firstly the effects of local emission factors are examined, followed by input variations in different refit options. Lastly the effects of not laying teak is examined.

Assumptions
For both the docking costs are not taken into account, since it is assumed that every 2.5 years the ship has to dock for renewed paint, therefore docking costs are not an extra cost of each refit option. Extra docking times due to extensive refit work is also not taken into account. The scenario is that of a large refit in which extra, sustainable, options are evaluated. Labor costs are included in the scope, as they can amount to a significant amount of the costs of a refit.

5.1. Base case

As stated above, the base case will be of a ship of 54 meters in length, since this is the current average ship length at refit. An exemplary ship of a current average refit could be the Gitana, built in 1998 and shown in figure 5.1.

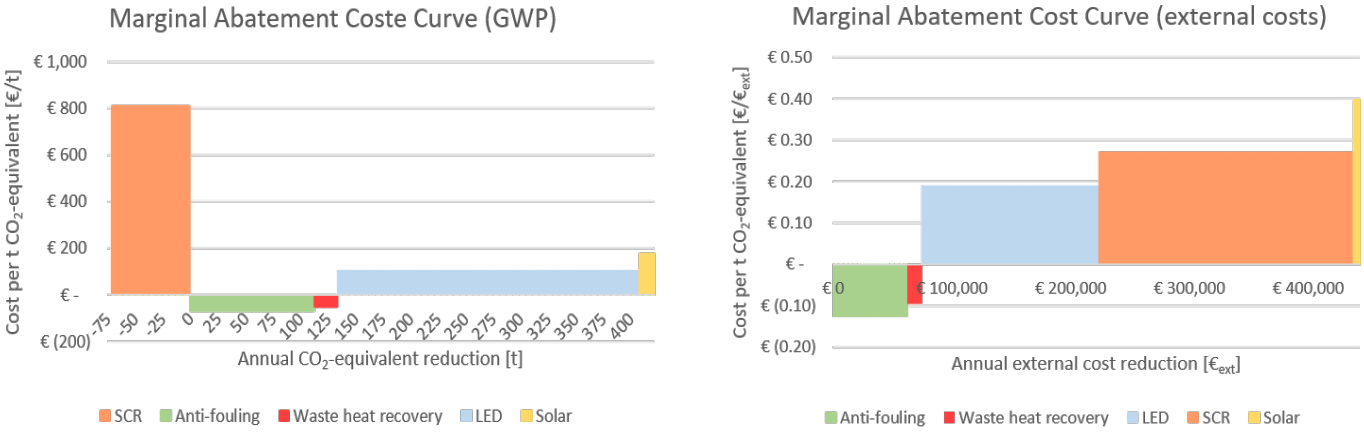
Figure 5.1: MACC (GWP) with SCR

5.1.1. Assumptions

This ship has no helipad and 2 main diesel engines, and 2 main generators, as is the case for 82 % of this age group of 1998 to 2003. This ship is also currently not fitted with LED-lights and it is assumed it sails with operational profile B. This profile means that the ship has a broad sailing area in both America and the Mediterranean, which effects the energy production of the solar panels slightly. Its front deck is unavailable for solar panel placement, but the dodgers are.

5.1.2. Regular scenario

For a ship of 54 meters the abatements on a global warming potential level and an external costs level are shown below.



(a) Marginal abatement cost curve of global warming potential

(b) Marginal abatement cost curve of external costs

Figure 5.2: Marginal abatement cost curves in the base case: regular scenario

As seen in the figure, the SCR unit is a relatively large factor. This can be related to the fact that it causes a 1 % increase in fuel consumption. Furthermore it is, unlike the other abatements, not a profitable measure, as it does not reduce fuel consumption. It therefore has a negative abatement at a positive price, thereby costing money and adding CO_2-equivalent emissions. After the SCR unit, the anti-fouling system follows. This measure has the highest number of CO_2-equivalent abated per euro. Together with the waste heat recovery system they are the options that are profitable, having a negative cost per year while abating global warming potential. LED is an option that abates a relatively large amount of global warming potential. The least cost-effective method for global warming potential is the solar option, which also has the lowest impact reduction.

In figure 5.2b, the external costs MACC is shown. As seen in the figure, the anti-fouling abatement saves the most external costs per amount of euro earned. And the SCR-unit, while costing around €0.29 per external euro abated, has the potential to reduce the highest amount of external costs, around €213.8k. Thereby having the potential of the highest impact reduction.

Business case

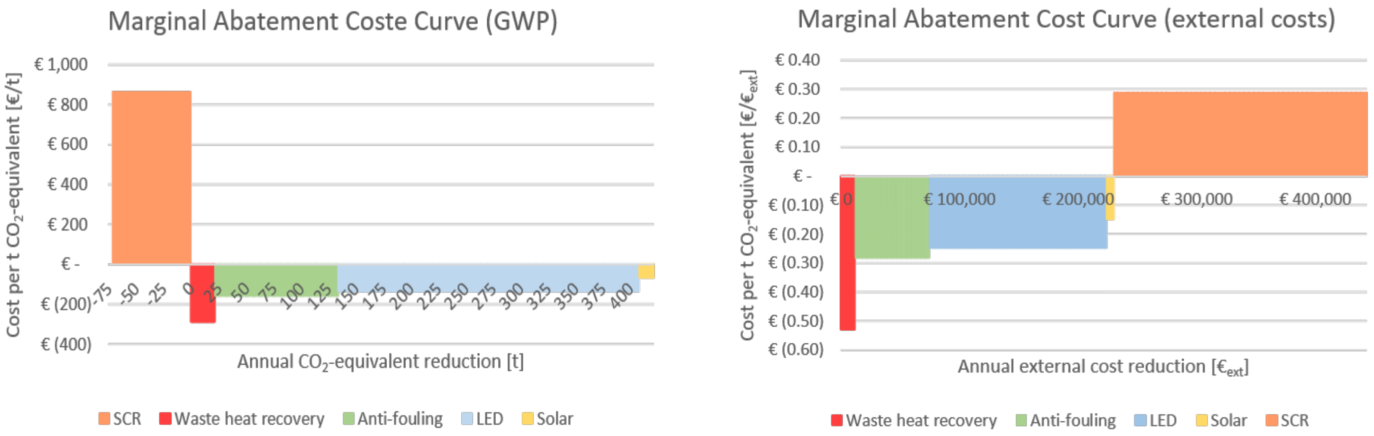
An overview of the business case of the green refit of the 54 meter yacht can be seen in table 5.1. If all refit options are executed, the total yearly costs of fuel and refit options increase by 379.7 k€ or an increase of 35 %. This also reduces 351 tonnes of CO_2-equivalent emissions, meaning a total reduction of 23 %. The total impact, measured in external costs is reduced by 443.7 k€, or 54 %. This number is higher than the relative CO_2 abatement, this can be accounted to the NO_x reduction of the SCR-unit. In the last columns the payback times of the individual refit options are shown. The anti-fouling system has the shortest payback period, of 4 years, and the solar panels have a period of 44 years, making them not profitable.

Table 5.1: Business case 54 meters: base case

	Yearly cost	**Total WTW CO2 abated**	**Total external cost abated**	**Payback period**
	[€]	[$tCO_2 - eq/year$]	[$€_{ext}$]	[years]
Anti-fouling	-7.8 k€	112	62.4 k€	5
Waste heat recovery	-1.1 k€	21	11.7 k€	13
LED	28.1 k€	274	149.0 k€	36
Solar	2.6 k€	14	6.4 k€	44
SCR	57.9 k€	-71	214.3 k€	-
Total	79.7 k€	351	443.7 k€	-
Difference with pre-refit	35%	23%	54%	-

5.1.3. Cost-neutral scenario

In this variation on the base case, the effect of variation on the fuel price is evaluated. The exact same situation as in the base case is assumed, only the fuel price is fluctuated until these refit abatements are cost neutral. In this case the fuel price is determined with a goal seek function. The resulting fuel price is €1.16, which is a 158 % increase of the actual fuel price. The resulting marginal abatement cost curves are shown in figure 5.3b and 5.3a.



(a) Marginal abatement cost curve of global warming potential

(b) Marginal abatement cost curve of external costs

Figure 5.3: Marginal abatement cost curves in the base case: cost neutral scenario

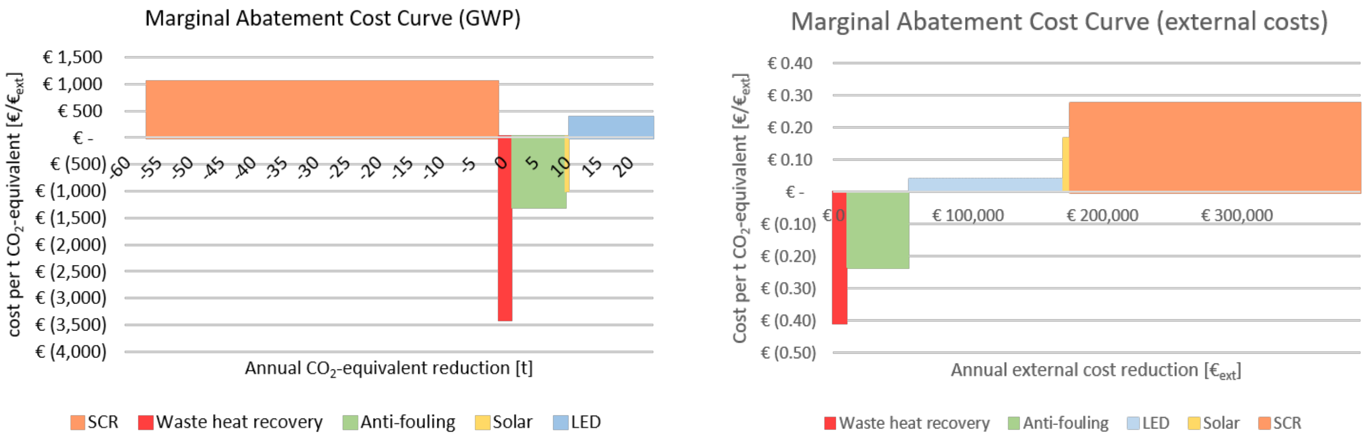
In both figures the total abatement amount is the same as in the base case, as the fuel price does not impact the GWP or external cost abation amount. With respect to the base case, the waste heat recovery system has gained cost-efficiency, now being the most profitable measure. Furthermore, every non-SCR measure is now profitable, as was not the case in the previous scenario with a lower fuel price. The business case is seen in table 5.2. As stated before, the total abatements of GWP and external costs are the same. The differences between this scenario and the base case are seen in the yearly costs and payback times. When comparing these to the base case we see lower payback periods, all under 20 years. This means that every efficiency improving option is now profitable. The LED-option now creates the highest profit, of 36.9 k€.

Table 5.2: Business case 54 meter: cost neutral scenario

	Yearly cost	**Total WTW CO2 abated**	**Total external cost abated**	**Payback period**
	[€]	[$tCO_2 - eq/year$]	[$€_{ext}$]	[years]
Anti-fouling	-17.7 k€	112	62.4 k€	0
Waste heat recovery	-6.2 k€	21	11.7 k€	5
LED	-36.9 k€	274	149.0 k€	12
Solar	-1.0 k€	14	6.4 k€	17
SCR	61.7 k€	-71	214.3 k€	-
Total	0 k€	351	443.7 k€	-
Difference with pre-refit	0%	23%	54%	-

5.1.4. Biofuel scenario

In this section the case study on Hydrotreated Vegetable Oil (HVO), as an alternative to conventional fuel, is treated. the impacts on GWP and external costs are treated in section 4.8.3. It is assumed that HVO is a drop-in fuel, and therefore no adjustments to the system have to be made to run on HVO. The resulting marginal abatement cost curves are shown in figure 5.4a and 5.4b.



(a) Marginal abatement cost curve of global warming potential

(b) Marginal abatement cost curve of external costs

Figure 5.4: Marginal abatement cost curves in the base case: HVO scenario

A significant reduction in total annual reduction by the refit options can be seen, this can be written of to the fact that the 80 % WTW GWP reduction is not included in the graph. Since there is now 20 % of the original amount of CO_2-equivalent to be abated, the total amount to be reduced by refit options is significantly lower. The marginal abatement costs are significantly lower for waste heat recovery, solar, LED and anti-fouling. This is because the amount of fuel saved is worth more is the fuel price is higher. In this curve, again higher values for marginal abatement costs can be seen due to the increase in fuel price. The total amount of external cost reduced is less than when regular fuel is used, however this graph does not paint a complete picture. In the business case in table 5.3 an overview is seen of the complete abatement of HVO and refit options.

Including the extra fuel costs affiliated with HVO, the total increase in yearly fuel costs, including sustainable refit options, is 47 %, or 167.4 k€. With this a reduction in GWP of 78 % and an external cost reduction of 70 % is achieved. Both of these are significantly higher rates then when regular MGO is used.

Table 5.3: Business case 54 meters: cost neutral scenario

	Yearly cost [€]	**Total WTW CO2 abated** [$tCO_2 - eq/year$]	**Total external cost abated** [$€_{ext}$]	**Payback period** [years]
Anti-fouling	-10.9 k€	8	46.5 k€	4
Waste heat recovery	-3.7 k€	1	9.0 k€	5
LED	4.7 k€	13	115.2 k€	21
Solar	-0.8 k€	1	4.6 k€	25
SCR	59.1 k€	-57	215.9 k€	-
Extra fuel	119 k€	1218	187.3 k€	-
Total	167.4 k€	1185	578.6 k€	-
Difference with pre-refit	47%	78%	70%	-

5.2. Long ship case

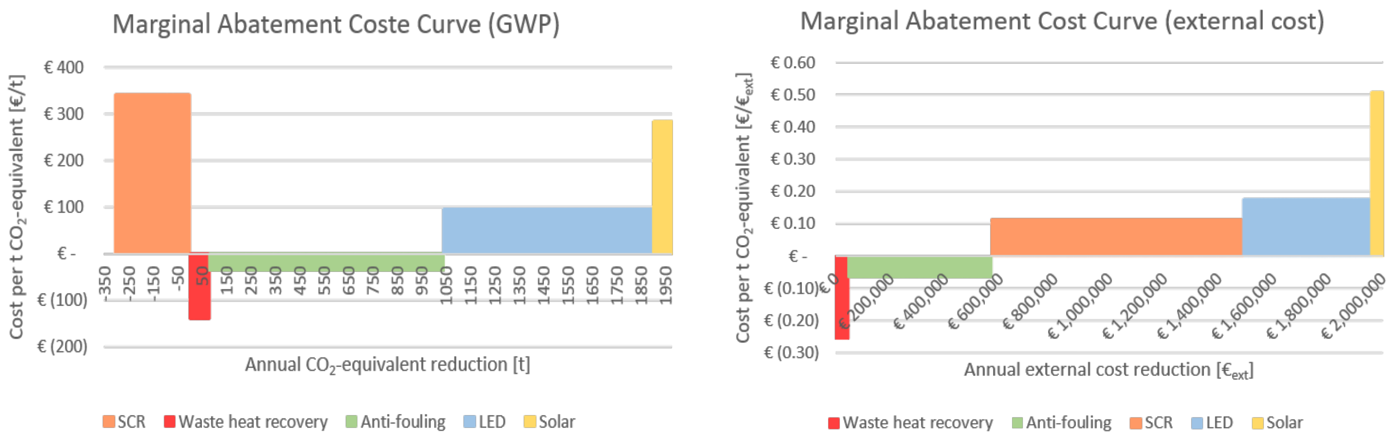
For the case based on a long ship, a length of 100 meters will be taken. The ship will be of similar exterior to Feadship Anna, as shown in figure 4.2, with a helipad and a useable front deck for PV-cells. A larger ship has a large power consumption, meaning that several abatements could have a larger influence. For example the SCR-unit could have a lower value of cost per abated CO_2-equivalent units. Furthermore a large ship has a much larger surface for solar panels and, if placed on decks while replacing teak, the savings could also rise.

5.2.1. Assumptions

The assumptions of this case will be as follows: The ships power is generated by 2 main diesel engines and 2 main generators. Furthermore this ship will have a heli-circle of 7.05 meter diameter, meaning that 26 m^2 around the circle will be available for solar panel placement. Furthermore a owners deck of 200 m^2 will be made available for solar panel placement, all without masking layer. The ship has the same operational profile as the 54 meter ship. In the first three cases the replacement of teak will not be taken into account. In the final scenario the effects of teak production and costs are taken into account.

5.2.2. Regular scenario

As in the base case, the regular scenario will be treated firstly, which will then serve as a reference for the cost-neutral and HVO scenario. For this case the fuel price is again set as the current actual fuel price of 0.45 euro per liter. The results of this scenario are shown in figure 5.5a and 5.5b.



(a) Marginal abatement cost curve of global warming potential

(b) Marginal abatement cost curve of external costs

Figure 5.5: Marginal abatement cost curves in the long ship: regular scenario

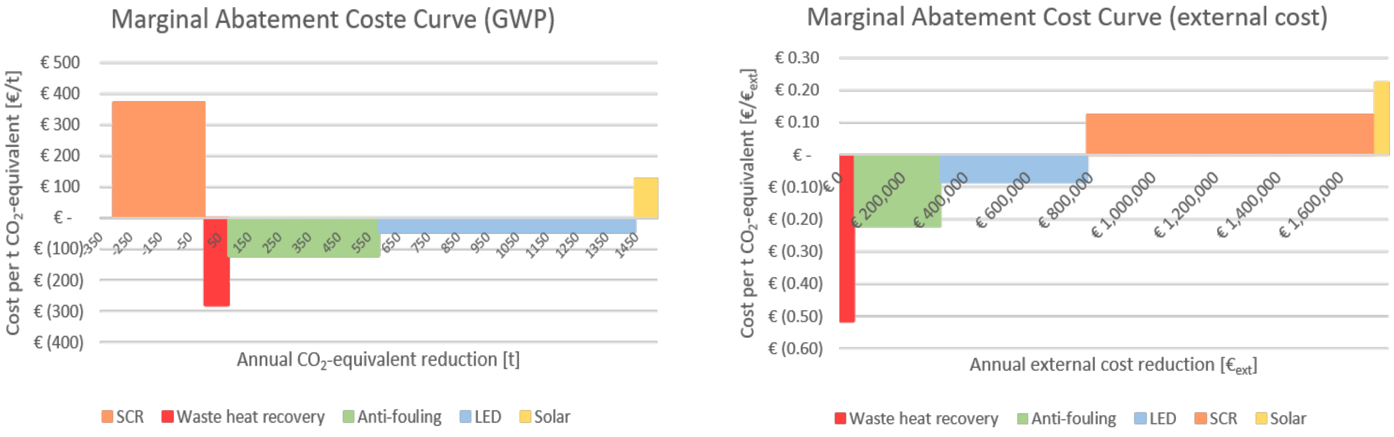
In this case the absolute abataments are significantly larger then in the 54 meter case. Furthermore the waste heat and anti-fouling are the only two profit creating options. In terms of external costs, the SCR unit abates the largest share. An overview of the results is seen in table 5.4. An increase in fuel costs of 15.9 % abates 25 % of the GWP and 56 % of the total impact.

Table 5.4: Business case 100 meters: base case

	Yearly cost	**Total WTW CO2 abated**	**Total external cost abated**	**Payback period**
	[€]	[tCO$_2$ – eq/year]	[€$_{ext}$]	[years]
Anti-fouling	-34.6 k€	960	525.5 k€	2
Waste heat recovery	-11.1 k€	80	43.5 k€	2
LED	82.2 k€	860	468.4 k€	34
Solar	21.9 k€	77	43.2 k€	54
SCR	104.7 k€	-307	920.5 k€	-
Total	163.1 k€	1671	2001.0 k€	-
Difference with pre-refit	15.9%	25%	56%	-

5.2.3. Cost-neutral scenario

In this scenario, the fuel price is again fluctuated to the point to where the combination of refit options is cost neutral. For the long ship, this is a fuel price of €0.86 per liter, a 95% increase of the current fuel price. The resulting curves are shown in figure 5.6a and 5.6b.



(a) Marginal abatement cost curve of global warming potential

(b) Marginal abatement cost curve of external costs

Figure 5.6: Marginal abatement cost curves in the long ship case: cost neutral scenario

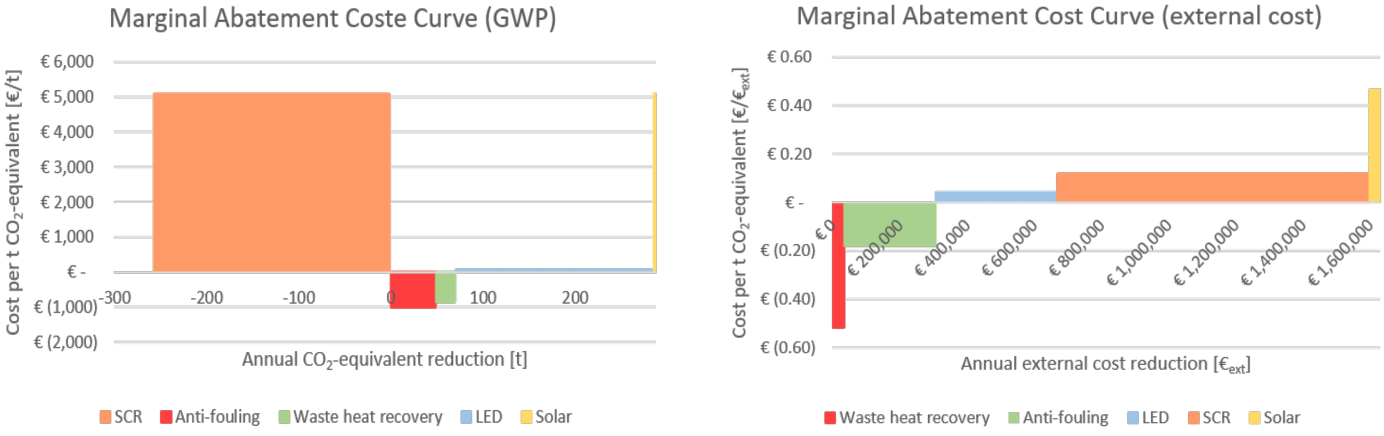
Since the only difference from the base case is the fuel price, the actual abated amounts are the same. The cost effectiveness of the efficiency improving and power generating options is higher. An overview of the results is seen in table 5.5. Since the cost-effectivity has risen, the payback times have declined. Now only the solar panels are a non-profitable option. With this fuel price and all refit options, 25 % of the GWP and 56 % of the total impact could be reduced at no increase of annual costs.

Table 5.5: Business case 100 meters: cost neutral scenario

	Yearly cost	**Total WTW CO2 abated**	**Total external cost abated**	**Payback period**
	[€]	[$tCO_2 - eq/year$]	[€$_{ext}$]	[years]
Anti-fouling	-61.7 k€	505	277.9 k€	1
Waste heat recovery	-22.4 k€	80	43.5 k€	2
LED	-39.5 k€	860	468.4 k€	16
Solar	9.7 k€	77	43.2 k€	28
SCR	114.0 k€	-307	920.5 k€	-
Total	0 k€	1671	2001.0 k€	-
Difference with pre-refit	0%	25%	56%	-

5.2.4. Biofuel scenario

In this section the influence of the implementation of HVO on the cost-effectiveness of refit options on a 100 meter yacht is evaluated. The marginal abatament cost curves are seen in figure 5.7a and 5.7b



(a) Marginal abatement cost curve of global warming potential

(b) Marginal abatement cost curve of external costs

Figure 5.7: Marginal abatement cost curves in the long ship case: HVO scenario

The largest amount of GWP reduction is by the LED option, and the SCR option increases the GWP 258 tonnes of CO_2-equivalent. In this scenario the curves do not paint a complete picture, as the influence of switching to HVO as fuel is not seen. In the overview of the business case in table 5.6, the effect is seen. The GWP potential of switching to HVO is large, relatively. Because of this, the GWP of the other refit options is smaller. Higher fuel prices create lower payback times, as is seen in earlier cases as well. At a yearly cost increase of 584.5 k€, or 38% with respect to original fuel expenses, the total WTW GWP is reduced by 80 % and the total impact is reduced by 68 %.

Table 5.6: Business case 100 meters: HVO scenario

	Yearly cost	**Total WTW CO2 abated**	**Total external cost abated**	**Payback period**
	[€]	[$tCO_2 - eq/year$]	[$€_{ext}$]	[years]
Anti-fouling	-49.6 k€	49	273.0 k€	2
Waste heat recovery	-17.4 k€	20	33.7 k€	1
LED	14.9 k€	216	362.2 k€	21
Solar	15.1 k€	-3	32.5 k€	35
SCR	109.8 k€	-258	929.3 k€	-
Extra fuel	512 k€	5242	799.1 k€	-
Total	584.5 k€	5272	2429.9 k€	-
Difference with pre-refit	38.1%	80%	68%	-

5.3. Sensitivity analysis

Since the case studies depend on several variables, it is of importance that the effect of variation on these inputs is evaluated. Firstly the effect of local emission impact reduction is analysed in subsection 5.3.1. Following this the impact of changes in LED capitol expenditure costs is evaluated in subsection 5.3.2, waste heat recovery system piping costs in subsection 5.3.3, anti-fouling lifetime in subsection 5.3.4 and solar panel input variation in subsection 5.3.5. Lastly the effect of teak laying is evaluated in section 5.3.6.

5.3.1. Local emission impact

From the case studies it can be concluded that a large part of the impact reduction of the SCR-system is due to its NO_x reduction. As stated in section 3.5, the factor for external costs of NO_x emissions is based on the methodology of the environmental prices handbook by CE Delft[15]. For the calculations, the midpoint value was taken of €34.7 per kg, which represent the external costs of NO_x emissions in a European country. Since yachts are not always in port in a European city, but also in less dense populated area's or even at sea while sailing, it can be argued that a lower value for this can be taken as well. This is especially true for ships that spend less time in port and more time sailing. For this, the lower bound value of the NO_x emission impact is taken, which is €24.1 per kg. This leads to an external costs decrease of €0.22 per kg diesel. The lower bound value of particulate matter is taken as well, since this is also an emission with local impacts. The effect of this variation is less than €0.01.

Implementing this change into the base case with the regular fuel price the marginal abatement cost curve for external cost reduction is as follows in figure 5.8

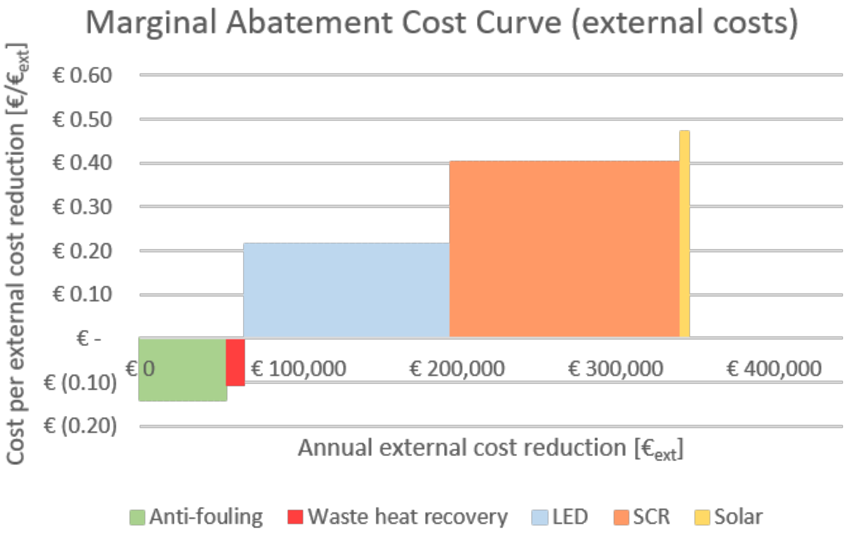


Figure 5.8: Marginal abatement cost curve of impact reduction with lower bound local emission impact

To visualise the effect of the decrease in impact reduction the horizontal axis of the graph is as in the base case in figure 5.2b. The total impact reduction is now 345.7 k€, or 22 % less then when the central bound value was taken. The cost effectiveness in terms of external cost reduction has also been reduced, seen in the values on the vertical axis. The costs for per external euro abated have also risen with 22 % since the costs have remained constant, but the impact has been reduced. Especially the SCR-system has a smaller impact reduction due to its external cost abatement being a result of mostly NO_x abatement.

5.3.2. LED

As seen in table 4.3, the LED placement capital expenditure costs are estimated at €1500 euro per lamp for the main infrastructure. This amounts to 61% of yearly costs. Furthermore 1.5 hours of yard assistance per lamp is estimated, which amounts to 12 % of yearly costs, creating a payback time of 36 years in the situation of a 54 meter yacht. In a more optimistic scenario, extra scale effects of large groups of fixtures could be taken into account further, thereby limiting the yard assistance to 1 hour per lamp. Furthermore the main infrastructure costs could 33% due to scale effects, for example. These changes would decrease yearly costs with 25%, decreasing the payback time to 26 years, meaning the cost-effectivity has risen. Since the impact reduction is still constant the marginal abatement costs have decreased. As the payback time is still longer then the expected lifetime of the LED-system, which is 20 years, the measure is still not profitable for a 54-meter yacht.

5.3.3. Waste heat recovery

Since the piping system of a waste heat exchange system can be a complicated process the effect of extra piping work due to detours or system altercations is evaluated. This scenario is expected to increase piping costs with 50 %, or 9k€. For a 54 meter yacht, this means an increase of 9k€ in investment, which raises the payback time from 13 to 16 years. This means that even with heavily increased piping costs, the waste heat recovery system is still a profitable refit option.

5.3.4. Anti-fouling lifespan

The cost-effectiveness of eco-speed anti-fouling is dependent on its lifetime. The main difference in yearly costs is due to the difference in lifespan. As regular anti-fouling is repainted every 2.5 years, eco-speed claims to last 10 years. In this situation the effect of a reduction of this lifetime to 7.5 years is evaluated. In the original situation the break-even point with biocidal paint was around 5 years. With this decreased lifetime the break even point has risen to 7 years. Since the investment of cleaning equipment of 40k€ has to be earned back by reduced repainting costs, the margin becomes increasingly smaller when the lifetime of the eco-speed coating is decreased. This has little impact on the impact reduction as the impacts of extra paint production due to the reduced lifecycle are negligible.

5.3.5. Solar panel input variations

Since solar panel prices have been decreasing for years [27], the cost-effectiveness of solar panels in the future will be higher. The capitol expenditure costs for solar panels are expected to be 20 % lower by 2050.[27] If applied to the solar panel price, it would decrease to 1840 € per m^2. For a 54 meter yacht, this would reduce the capital expenditure by 25 k€, or 27%. The payback time would lower from 44 to 33 years. This increase would still mean that solar panels are not profitable on a yacht, due to its revenue being 2.2 k€ per year. This can be attributed to the low cost of energy generation by the on board generators.

Using the regular solar panel prices, the effect of extra installation costs is evaluated as well. Currently the installation is estimated at 4 hours per m^2, however extra challenges due to design complications could arise. Since the cabling of the panels has to be connected to the switchboard in the engine room, this large amount of cabling could be vulnerable to problems requiring extra installation hours. If the amount of hours per m^2 is doubled from 4 to 8, the installation costs also rise from 21 k€ to 42 k€, meaning an increase in payback time from 44 to 54 years. The installation costs now amount to 25 % of the total investment.

5.3.6. Teak alternative

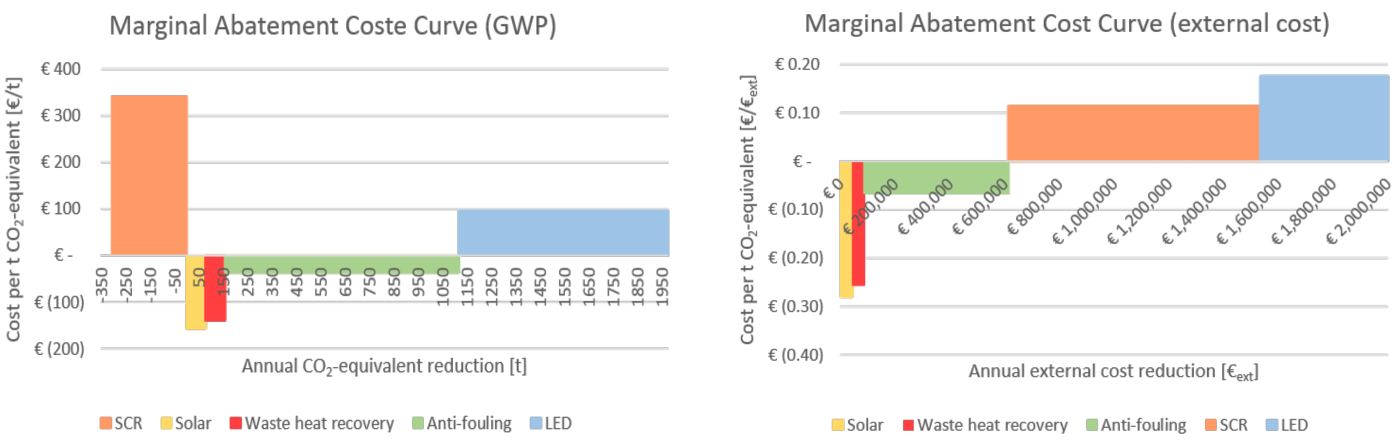
The laying of teak is an expensive and impacting procedure. If solar panels are placed on large deck area's, it could be assumed that the absence of teak can also be taken into account in the impact reduction of the action. Since in this case the owners deck and heli circle are teak, and teak is generally replaced every 12 years, the impact could be significant. Since these surfaces are only available for the long ship, the variation will be done on the long ship case.

In this variation on the regular scenario, the effects of teak are taken into account. The curves are shown in figure 5.9a and 5.9b.

As seen in the curves, the solar panel option is the most profitable option. On a yearly basis, not laying teak on these surfaces, totaling 226 m^2, amounts to 34 k€ and saved 1.1 tonnes CO_2-equivalent units and 1.4 k€ in external costs. The numbers on external costs and GWP of teak are however estimates, since much is unknown about the actual origin and impact of teak.[59]

5.4. Conclusion

An overview of the results of the 7 scenarios over the 2 case studies can be seen in table 5.7. In the base case of a ship with the current average refit length, it is possible to decrease its operational global warming potential with 23 % and its total operational impact with 54 %, at an increase of yearly costs of 79.7 k€, or 35%. In a larger ship, as in the second case, it is seen that the impact reduction is more cost effective, with yearly



(a) Marginal abatement cost curve of global warming potential

(b) Marginal abatement cost curve of external costs

Figure 5.9: Marginal abatement cost curves in the long ship case: teak scenario

costs increasing less and impact reducing more, both relatively. The impact reduction increase can be partly attributed to the fact that they are dependent on auxiliary and propulsionary power demand, which grow almost exponentially with size.

The cost neutral case required a fuel price of €1.16 for the 54 meter ship and €0.86 for the 100 meter ship in order to have exactly 0 yearly costs. These are both significantly more expensive than the current price, but it can be concluded that refit options are more cost effective if the fuel price is higher. This could be achieved by taxation for example. This way policies could impact the willingness of yacht owners to implement sustainable refit options.

The HVO scenario provides the possibility for the highest impact reduction, at a yearly fuel and refit cost increase of 47% for the 54 meter yacht and 38.1 % for the 100 meter yacht. A global warming potential reduction of 77 % and 80 %, respectively, is the result of running on HVO with all refit abatements. This is lower than the 80 % WTW reduction of when only HVO is used without refit options, but an external cost abatement of 70 % and 68 % paints a complete picture of the situation. Interestingly, the switch to HVO makes for the non-SCR refit options to have a marginal GWP reduction. Instead they are more attractive in a cost reducing manner. The SCR-unit is still a significant impact reducer due to its NO_x-reducing potential, in both MGO and HVO scenario's. It can be concluded that the most sustainable refit is that of all refit options combined while running on HVO, this way the GWP reduction of HVO is combined with the impact reduction of the SCR.

The effect of the operational profile, as assessed in table 4.9, is expected to be of minor significance, since it is only taken into account in the energy production of solar cells. As the operational profile is kept as a constant throughout the different cases and scenario's it is not clear what the exact impact is, but since the solar irradiation coefficient differs for no more then 5 % the results are not expected to fluctuate heavily due to a change in operational profile, as the annual energy demand is kept as a constant. It is possible to implement energy demand in a more detailed level in the future, in order to further increase the accuracy of the results.

In section 5.3 the effect input variations is examined. The more rural a local impacting emission is made, the lower its impact is. Ships in urban area's therefore have an increased impact. The lower bound local emission values resulted in a 22 % reduction of total impact, stressing the importance of emission factors. Furthermore, the decrease in LED capital expenditures increased its cost-effectiveness. An increase of piping costs due to difficulties in implementation increased the payback time from 12 to 16 years. The shortened lifespan of the eco-speed coating raised the break even point with 2 years and solar panels price reductions lower the payback time. Extra installation hours had quite a large influence, which is realistic, stressing the design challenges of solar panel refits once again. Lastly the effect of not laying teak is predominantly large in the cost-effectiveness of the solar panels. Implementing this in the standard tool would therefore create a distorted view of the cost-effectiveness of solar panels.

It can be concluded that the input variations and changes in cost-effectiveness are proportional and the selection tool functioned as required. Since many of the calculations are based on assumptions of lifetime and installation hours, these factors are a big influence in the results and should be determined with care to create a relevant result.

Table 5.7: Overview of case results

	Fuel type **& price** [€/liter]	**Yearly cost** [€]	**Total WTW CO_2-eq abated** [$tCO_2 - eq/year$]	**Total external cost abated** [$€_{ext}$]
		54 meters		
Base case	MGO €0.45	79.7 k€ 35%	351 23%	443.7 k€ 54%
Cost neutral	MGO €1.16	0 k€ 0%	351 23%	443.7 k€ 54%
Biofuel	HVO €0.68	167.4 k€ 47%	1185 78%	578.6 k€ 70%
		100 meters		
Base case	MGO €0.45	163.1 k€ 15.9%	1671 25%	2001.0 k€ 56%
Cost neutral	MGO €0.86	0 k€ 0%	1671 25%	2001.0 k€ 56%
Biofuel	HVO €0.68	584.5 k€ 38.1%	5266 80%	2429.9 k€ 68%

6

Conclusion and recommendations

In this chapter the conclusions are given in section 6.1 and the recommendations are given in section 6.2.

6.1. Conclusion

The main objective of this thesis is to determine a cost effective method to reduce operational emissions of existing yachts, through "refitting". The tool in this thesis is created to determine the cost-effectiveness of impact reducing refit options. This tool is designed so that it can be used universally, in the sense that other technologies than the ones treated in this research can be added to it using the attached template. The calculations are done using Excell spreadsheets and the results are in the form of marginal abatement cost curves and a business case. In this section first the conclusions on the sub questions will be treated in subsection 6.1.1 and subsequently the main research question will be answered in subsection 6.1.2

6.1.1. Sub research questions

The first sub question is on **"How can the impact reduction of a yacht be quantified and measured?"**. This can be answered by first determining the value of sustainability, or impact reduction, for the planet, the owner and the yard. For the planet, yacht emissions contribute damage to human health, damage to ecosystems and climate change. These are the results of environmental changes due to harmful ship emissions, such as ozone depletion, acidification and global warming. The International Maritime organisation aims to reduce annual greenhouse gas emissions to 50 % by 2050 and has instated emission control area's in which sulfur and NO_x emissions are regulated by denying access to polluting ships, hereby reducing the negative local effects of these pollutants, such as acidication and eutrification. The value of sustainability for the planet is thereby present in limiting the damage to health, ecosystems and climate. For a shipowner, a sustainable yacht can provide reputational value, as owning a large yacht can induce pressure from society. Furthermore sustainable option, such as a selective catalytic reduction can, for some ships, grant access to otherwise prohibited emission control area's, such as the Norwegian fjords. This would mean the vessels resale value as well as possible charter income could increase.

Since societal pressure is rising on the yachting sector, excelling in the implementation of sustainable technology could create business opportunities for a refitting shipyard, as for shipowners, it is important that the ship suffers no installation related downtime or malfunction. By establishing a reputation as a reliable sustainable refit yard, a unique market position could be obtained. Since environmental measures are expected to only get more stringent in the future, the demand for sustainable refits could rise significantly. The impact of a yacht is not only in the operational phase, but material production and building contribute as well. Sustainability for a yacht is therefore in reducing the negative impacts of the materials, production and operation of a yacht. In order to measure the impact of a yacht, it is important to take into account multiple results, by for example using external costs as a unit. By doing this all of the impacts can be taken into account into a single value. This value should be used relatively as it can compare impact reductions of different scenario's, but as a stand alone value, less relevant conclusions can be made.

In order to gain insight into the refit process the second question is as follows: **"What are the options for reducing emissions throughout the refit process?** The process can be divided into three phases, first the upstream part, second the yard operations part and third, the downstream part an overview of this is shown in figure 2.2. In the upstream part, the material origin of for example teak or leather can be analysed. Furthermore the production methods of the components used to install on a ship can be taken into account as well. The second phase, all the yard operation are included. This includes energy production and efficiency of processes. A sustainable yard could use solar panels or wind energy for example to provide energy for its operations. Furthermore the waste management is an aspect of yard operations, in a refit, large amounts of waste are produced and recycling or sorting of this waste can reduce the impact of this phase. The downstream part is the largest part of refits in terms of impact. Several measures are possible for reducing operational emissions, which are treated in the answer to refit question three: **"which refit options are feasible for reducing operational emissions?"** The following categories are determined:

- Emission reducing
- Power consuming
- Power generating
    - Propulsive
    - Auxiliary
- Crew training

Of these categories several examples are made in section 2.1.3, of which a selection is made of the 5 most feasible options, while taking at least 1 of the first four categories to compare different types of measures. In the scope of this research are the following refit options:

- Selective Catalytic Reduction system
- Conversion to LED lights
- Waste heat recovery
- Anti-fouling techniques
- Solar panels

Firsly, the selective catalytic reduction system is chosen since it is the most suitable technique for reducing NO_x-emissions, which not only have a significant impact of around 40 % of WTW operational external costs, it is also a measure that grants access to IMO tier III area's thereby adding value to the yacht. A conversion to LED lights not only increases light efficiency, but also reduces HVAC load, since non-LED lights produce more heat. Waste heat recovery systems are used to gain energy from cooling water of the generators, this can be used to heat up pools, jacuzzi's or cabins for example. Furthermore durable anti-fouling techniques can reduce propulsionary resistance and reduce repainting frequency. Lastly large deck area's can be used for implementing solar panels to generate energy and thereby reduce generator fuel consumption.

In order to analyse these measures and their impacts **a selection tool is needed that can incorporate the owners wishes, operational profile and all refit phases**. This coincides with the fourth research question. For this tool, multiple refit options and their impact reducing results should be compared with cost-effectiveness to give a complete picture of the costs and benefits of sustainable refits. Since the production emissions of refit components, as well as the well-to-wake emissions are taken into account, just as the upstream part of operational emissions. The yard operations part is left out of the scope. To create a tool that can be used for multiple ships, owners and usage profiles, several aspects have to be taken into consideration. The Feadship database is used to determine the first basic parameters of the ship, based on its length. With this the auxiliary and propulsionary energy demand is determined, as well as the current emissions and their impact. The operational profile is incorporated to the extent of taking into account the conditions of the ships destinations, in order to determine the effect of different solar irradiation coefficients on the energy production of solar panels.

In order to create a complete picture of the effects of emission reduction, both the global warming potential reduction and external cost reduction are compared in marginal abatement cost curves, which is part of the answer of question five: **"How can the cost-effectiveness of these abatements be determined?"** By using these curves, the impact reduction of several measures can be compared by looking at the total abatement per option, combined with the marginal abatement cost. This way the cost effectiveness of impact reduction can be evaluated. Since global warming is one of the largest environmental impacts of the marine sector, the cost effectiveness of the reduction of global warming potential will be shown in one curve. To provide a complete picture of the total impact the emission reduction, it is important to take other effects of ship emissions also into account. External cost abatements is chosen as the method to compare total emission impact reduction of refit operations. Since marginal abatement cost curves are not enough to provide an overview of the cost effectiveness a business case will be created as well, giving an overview of yearly cost/profit, GWP and external cost reduction as well as payback time of refit options.

The sixth and final sub question is: **"To what extent is the solution sensitive to input variations?"** To answer this question 2 case studies with multiple scenario's have been developed. The first case is based on the average ship length at refit, which is 54 meters. Firstly, the scenario using the current fuel price of €0.45 is evaluated. In the second scenario, the effect of fuel price fluctuations is investigated by finding the cost neutral point. In the third scenario the implementation of HVO is evaluated, to determine the effects of the biofuels on the impact of a yacht. These scenario's are then applied to the case of a 100 meter ship as well. The results show that increasing the length of the ship increases the cost-effectivess, while the share of total GWP and external costs reduction is slightly smaller. For these refit options to be cost-neutral for a ship with a length of 54 meters, a fuel price of €1.16 per liter is required, which is significantly higher than the current price. This means that higher fuel prices make sustainable refits more cost-effective. Using HVO as a fuel, combined with the 5 refit options, the total GWP can be reduced with 78% and the total impact in external costs be reduced by 70 %. To achieve this, the yearly combined fuel and refit costs are increased with 47 %, mainly due to higher fuel costs. For a 100 meter ship the impact reduction was relatively similar in each scenario, but the cost increase was significantly lower. This can attributed to the scale advantages of a larger ship. In the large ship a final scenario was evaluated in which the replacement of teak was also taken into account. This had a large effect on the cost-effectiveness of solar panels, but since the total abatement of solar panels is relatively small, the impact of this on the total yearly cost increase is around 3% less costs.

Further more the fuel price is a big factor in the cost-effectiveness of these options.. Since a large part of options can be traced back to fuel not being burned by the generator, the price of fuel is determining how much this abatement is worth.

Lastly, the input sensitivity analysis showed the importance of the assumptions in lifespan and installation costs. In the future, these costs could be determined with more certainty using refit experience. Also the impact of local emissions is dependent on how rural the location of the yacht is. For yachts sailing in a more remote location for larger parts of the year, this emission factor could be adjusted to compensate for the reduced impact.

6.1.2. Main research question

The main question to be answered in this research is: **What is a cost-effective method to reduce the operational emissions of an existing yacht through refitting?** The answer to this is in combining several results to paint a complete picture. The marginal abatement cost curves can be used to compare different refit options and see their impact reduction in global warming potential and also in total external costs impact reduction. To investigate the cost-effectiveness the support of a business case is needed in order to gain insight into the financial aspect of these abatements. It is not possible to validate the results in this tool, until these refits have been done on an actual ship. It does however create insights into how these different options relate in terms of cost-effectiveness and impact reduction and can therefore also be used to compare newer or other refit options to the 5 options treated in this research. The downside to this marginal abatement cost curve is that a single curve does not show interaction between the refit options. In this case the 5 options did not interfere with each other, but if that were the case, a new curve would have to be made for each situation. This stresses the importance of specific scenario creations in green refitting. Since the usage of other fuels or interfering refit options is probable, a the result of a refit scenario is also dependent on refit options affecting each other. This is especially evident in the final case study of HVO as a fuel, in which the cost effectiveness of the refit options had risen because of the higher fuel price, but the total abatement of individual refit option was lower. Within individual MACC distributions it is seen that the SCR plays a vital role in the reduction of total impact, mainly by reducing NO_x-emissions. The largest GWP reduction can be achieved by implementing HVO as a fuel. The implementation of HVO currently makes efficiency improving options commercially more attractive, since the fuel price is relatively high.

Since the IMO goals of 50 % reduction by 2050 cannot be reached by only building sustainable ships, the current fleet has to be refitted as well. A 22 % GWP reduction, as reached with all the 5 refit options combined on every yacht in the global fleet is still not enough to reach this goal. Biofuels provide a pathway to a large GWP reduction without requiring a large investment in a yacht at an increased fuel price. Because of this increased fuel price, the efficiency improving and energy producing refit options become more attractive commercially, since the fuel savings are worth more. Stimulation into biofuel production capacity and its required infrastructure could help implement this fuel and become more attractive commercially.

The combination of both a marginal abatement cost curve for GWP and external costs with a separate business case creates an overview in which not only the impact reduction is shown, but also portrays it commercial attractiveness. Combining these elements is an important part in making sustainable solutions more attractive commercially. Since in yachting, the implementation of sustainable refits is for a large part dependent on the willingness of owners, this must be taken into account when assessing the cost effectiveness of sustainable refits. This means that the value of a sustainable refit options is therefore evident when combining efficiency gains in MACC's with a supplementing business case.

For shipyards this tool could help give yacht owners insight into the costs and benefits affiliated with a sustainable refit. Since these results give an indication of the cost effectiveness and impact abatements of refit options, it could aid in the decision making process, thereby create more incentive for owners to choose a sustainable refit. Increasingly strict environmental regulations and fuel- or emission taxes aid in this, to make a sustainable choice more attractive. As the yachting industry is widely aware that the current trend of rising yacht emissions cannot continue indefinitely, these insight into sustainable refits could aid in the industry becoming more sustainable. Since the financial resources are often present for yacht owners, shipyard have the knowledge to help persuade yacht owners that a sustainable refit can be an impact reducing and cost effective option. Since this the sustainable refit is inevitable, expertise in this area is likely to gain more importance.

Implementation
This tool is designed to be used early on in the negotiations between refit yards and yacht owners. Since a refit is currently done not primarily to reduce a ships impact, the choice of going green can be presented in the process of determining the work list for the yacht. As refits most often require a docking, it provides an opportunity to use this docked time to also implement sustainable solutions. Since docking is an cost intensive process, sustainable refits would be commercially less attractive if the yacht had to be docked solely for the purpose of a green refit. Before entering into the negotiations with yacht owners, the yard can use this model by first filling in the ship length and operational profile. It can then create scenario's, as in the case studies, to present to the owner what the impact reduction and financial aspects of a sustainable refit are. Possible preferences could be discussed during the meeting as well, as these can be easily adjusted within the model, tending to the owners wishes. If the owner expresses his interest in one or more impact reducing refit options, the costs can then be estimated in more detail to create a more accurate cost overview based on more in-depth engineering, taking into account the challenges of implementing solutions within a specific yacht design.

6.2. Recommendations

- The annual energy demand has been based on an average value of propulsionary and auxiliary energy demand per length, based on Feadship data. Since this is also highly dependent on the owner how frequently and intensely he/she used the ship, this could be implemented in the tool to create a clearer image of the energy demand. Furthermore the fluctuating energy demands have an influence on the generator load. The generator load has an influence on the emission composition, thereby having different emissions at different loads. If this were to be implemented, the specific usage of a ship could have a bigger influence on the results and the results would increase in accuracy.

- Since the costs of abatements are often estimated by supplier cost estimates and expert opinion, more scale effects could be taken into account as well. Since information is often classified or experience-based, extensive research into this could result in more accurate cost estimates.

- Since only 5 refit options are included in the scope of this research, more could be added to give more insight into how different options relate. Furthermore, the options of implementing other power systems, such as rebuilding ships to sail diesel electric, or with fuel cells could be implemented to asses the effects of switching. To do this requires intensive design and implementation research into these refits. Apart from the design of these system in existing ships, the actual implementation with new fuel tanks and placement of components through holes in the hull or deck requires extensive research.

- Since the effects of for example NO_x differ per location, and the effect is less if emitted at sea than in a port city, the location of the ship could be taken into account as well to determine the effect of these emissions on a more detailed level. Currently the effect is taken as a general average of the operational profile, but in the future this factor could be made dependent on the remoteness of the location of the yacht over the year.

- The environmental impact of production of the refit options could be taken into account on a more detailed level, for example the environmental effects of biocide release in toxic anti-fouling paint could be taken into account as well.

Bibliography

[1] 3M. Marine Adhesives and Sealants, 2017. URL `https://multimedia.3m.com/mws/media/8118310/3mtm-adhesive-sealant-brochure.pdf`.

[2] Borgar Aamaas, Terje K. Berntsen, Jan S. Fuglestvedt, Keith P. Shine, and Nicolas Bellouin. Regional emission metrics for short-lived climate forcers from multiple models. *Atmospheric Chemistry and Physics*, 16(11):7451–7468, 6 2016. ISSN 16807324. doi: 10.5194/acp-16-7451-2016.

[3] Abdallah Aijjou, Lhoussain Bahatti, and Abdelhadi Raihani. Study on container ship energy consumption. *WIT Transactions on Ecology and the Environment*, 237:25–36, 2019. ISSN 17433541. doi: 10.2495/ESUS190031.

[4] Australian Government Great Barrier Reef Marine Park Authority. Vessel sewage regulations.

[5] Alyson Azzara, Dan Rutherford, and Haifeng Wang. Feasibility of IMO Annex VI Tier III implementation using Selective Catalytic Reduction. Technical report, 2014.

[6] john Bachmann. Black carbon: A Science/Policy Primer. Technical report, Pew Center on Global Climate Change, Arlington, 12 2009.

[7] Aglaia Badino, Davide Borelli, Tomaso Gaggero, Enrico Rizzuto, and Corrado Schenone. Noise Emitted from Ships: Impact Inside and Outside the Vessels. *Procedia - Social and Behavioral Sciences*, 48:868–879, 2012. ISSN 18770428. doi: 10.1016/j.sbspro.2012.06.1064.

[8] Océane Balland, Stein Ove Erikstad, and Kjetil Fagerholt. Optimized selection of air emission controls for vessels. *Maritime Policy and Management*, 39(4):387–400, 7 2012. ISSN 03088839. doi: 10.1080/03088839.2012.689877.

[9] Selma Bengtsson, Karin Andersson, and Erik Fridell. Life cycle assessment of marine fuels A comparative study of four fossil fuels for marine propulsion. 2008. ISSN 1652-9189.

[10] G. Bordogna, J. A. Keuning, R. H.M. Huijsmans, and M. Belloli. Wind-tunnel experiments on the aerodynamic interaction between two rigid sails used for wind-assisted propulsion. *International Shipbuilding Progress*, 65(1):93–125, 2018. ISSN 15662829. doi: 10.3233/ISP-180143.

[11] Davide Borelli, Tomaso Gaggero, Enrico Rizzuto, and Corrado Schenone. Holistic control of ship noise emissions. *Noise Mapping*, 3(1):107–119, 1 2016. ISSN 2084879X. doi: 10.1515/noise-2016-0008.

[12] Yuhang Cai, Teng Ben, Asad A. Zaidi, Yue Shi, and Kun Zhang. Nitrogen removal augmentation of ship sewage by an innovative aerobic-anaerobic micro-sludge MBR technology. *Process Biochemistry*, 82: 123–134, 7 2019. ISSN 13595113. doi: 10.1016/j.procbio.2019.04.020.

[13] Leo Čampara, Nermin Hasanspahić, and Srđan Vujičić. Overview of MARPOL ANNEX VI regulations for prevention of air pollution from marine diesel engines. *SHS Web of Conferences*, 58:01004, 2018. doi: 10.1051/shsconf/20185801004.

[14] Federico Cattaneo. Selective Catalytic Reduction System for Marine Applications Dynamic Modelling and System Integration. Technical report, 2018. URL `http://repository.tudelft.nl/`.

[15] CE Delft. Environmental Prices Handbook: Methods and numbers for valuation of environmental impacts. Technical report, 2017.

[16] S.D. Chatzinikolaou, N.P. Ventikos, and Frederick S Hillier. Critical Analysis of Air Emissions from Ships: Lifecycle Thinking and Results. In *International Series in Operations Research & Management Science*, volume 226, pages 387–412. 2016. doi: https://doi.org/10.1007/978-3-319-17175-3{_}11. URL `http://www.springer.com/series/6161`.

[17] James J. Corbett, Haifeng Wang, and James J. Winebrake. The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment*, 14(8):593–598, 2009. ISSN 13619209. doi: 10.1016/j.trd.2009.08.005.

[18] E J Cozijnsen. *The footprint of yacht production: Defining a framework for the Yacht Environmental Transparency Index.* PhD thesis, TU Delft, Delft, 2019.

[19] Flavio D.F. Chuahy and Sage L. Kokjohn. Solid oxide fuel cell and advanced combustion engine combined cycle: A pathway to 70% electrical efficiency. *Applied Energy*, 235:391–408, 2 2019. ISSN 03062619. doi: 10.1016/j.apenergy.2018.10.132.

[20] Ya Hong Dong and S. Thomas Ng. Comparing the midpoint and endpoint approaches based on ReCiPe - A study of commercial buildings in Hong Kong. *International Journal of Life Cycle Assessment*, 19(7): 1409–1423, 2014. ISSN 16147502. doi: 10.1007/s11367-014-0743-0.

[21] Eco-Indicator99. Manual for designers. Technical report, 2000. URL `https://pre-sustainability.com/files/2013/10/EI99_Manual.pdf`.

[22] Ecoinvent. ECOINVENT eco-cost database, 2021. URL `https://www.ecocostsvalue.com/EVR/model/theory/5-data.html`.

[23] M A Elsayed, R Matthews, and N D Mortimer. CARBON AND ENERGY BALANCES FOR A RANGE OF BIOFUELS OPTIONS. Technical report, 2003.

[24] Sciubba Enrico, Lorenzo Tocci, Claudia Toro, Asfaw Beyene, and Enrico Sciubba. Modelling and simulation of waste heat recovery systems for marine applications. Technical report. URL `https://www.researchgate.net/publication/282283607`.

[25] Europe-Solar Store. SMA Sunny Tripower CORE1. URL `https://www.europe-solarstore.com/sma-sunny-tripower-core1.html`.

[26] European Commission. Joint Research Centre. Institute for Environment and Sustainability. *International Reference Life Cycle Data System (ILCD) Handbook general guide for life cycle assessment : detailed guidance.* Publications Office, 2010. ISBN 9789279190926.

[27] European Commission on Low Carbon Energy Observatory. Photovoltaics Technology Development Report. 2018. ISBN 978-92-76-12540-2. doi: 10.2760/373667. URL `https://ec.europa.eu/jrc`.

[28] V. Eyring, H. W. Köhler, J. Van Aardenne, and A. Lauer. Emissions from international shipping: 1. The last 50 years, 9 2005. ISSN 01480227.

[29] Fawzy Fathalla Fawzy Dekinesh. The challenges and opportunities of anti-fouling systems: The challenges and opportunities of anti-fouling systems: investigating of future demand and identifying the potential of investigating of future demand and identifying the potential of energy saved energy saved Fawzy Fathalla Fawzy Dekinesh. Technical report. URL `https://commons.wmu.se/all_dissertations`.

[30] Claudio Favi, Federico Campi, Michele Germani, and Steve Manieri. Using design information to create a data framework and tool for life cycle analysis of complex maritime vessels. *Journal of Cleaner Production*, 192:887–905, 8 2018. ISSN 09596526. doi: 10.1016/j.jclepro.2018.04.263.

[31] Jasmine Ferrario, Sarah Caronni, Anna Occhipinti-Ambrogi, and Agnese Marchini. Role of commercial harbours and recreational marinas in the spread of non-indigenous fouling species. *Biofouling*, 33(8): 651–660, 9 2017. ISSN 10292454. doi: 10.1080/08927014.2017.1351958.

[32] Göran Finnveden, Michael Z. Hauschild, Tomas Ekvall, Jeroen Guinée, Reinout Heijungs, Stefanie Hellweg, Annette Koehler, David Pennington, and Sangwon Suh. Recent developments in Life Cycle Assessment, 10 2009. ISSN 03014797.

[33] Finsulate. Product datasheet Finsulate Seagrade. Technical report. URL `www.finsulate.com`.

[34] Fraunhover Institute for Solar Energy Systems. Photovoltaics Report. Technical report, 2020. URL `www.ise.fraunhofer.de`.

[35] G. Loeff (De Voogt Naval Architects). yacht power demands figure.

[36] Peter Gibbons-Neff and Paul Miller. Route Planning for a Micro-transat Voyage. *Robotic Sailing*, pages 183–194, 2011. doi: 10.1007/978-3-642-22836-0{_}13.

[37] Paul Gilbert, Conor Walsh, Michael Traut, Uchenna Kesieme, Kayvan Pazouki, and Alan Murphy. Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production*, 172:855–866, 1 2018. ISSN 09596526. doi: 10.1016/j.jclepro.2017.10.165.

[38] Mark Goedkoop, Reinout Heijungs, An De Schryver, Jaap Struijs, and Rosalie Van Zelm. ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level First edition (version 1.08) Report I: Characterisation Mark Huijbregts 3). Technical report, 2013.

[39] Alon Grinberg Dana, Oren Elishav, André Bardow, Gennady E. Shter, and Gideon S. Grader. Nitriogen-Based Fuels: A Power-to-Fuel-to-Power Analysis. *Angewandte Chemie*, 128(31):8942–8949, 7 2016. ISSN 0044-8249. doi: 10.1002/ange.201510618.

[40] Cristina. Guerreiro, Frank de. Leeuw, Valentin. Foltescu, Jan. Horalek, and European Environment Agency. Air quality in Europe : 2014 report. Technical report, 2014.

[41] Neven Hadžić, Hrvoje Kozmar, and Marko Tomić. Feasibility of investment in renewable energy systems for shipyards. *Brodogradnja*, 69(2):1–16, 6 2018. ISSN 0007215X. doi: 10.21278/brod69201.

[42] Koichi Hirata. Development of Marine SCR System and Field Test on Ship 2 . Development of SCR System for Field Test. *Marine Engineering*, (November), 2009.

[43] Chia-Wen Carmen Hsieh and Claus Felby. Biofuels for the marine shipping sector An overview and analysis of sector infrastructure, fuel technologies and regulations. Technical report, 2017.

[44] https://www.marineheatexchanger.org/. Marine plate heat exchanger. URL `https://www.marineheatexchanger.org/marine_plate_frame.html`.

[45] George W. Huber, Paul O'Connor, and Avelino Corma. Processing biomass in conventional oil refineries: Production of high quality diesel by hydrotreating vegetable oils in heavy vacuum oil mixtures. *Applied Catalysis A: General*, 329:120–129, 2007. ISSN 0926860X. doi: 10.1016/j.apcata.2007.07.002.

[46] HUG-Engineering. SCR catalyst reaction . URL `https://hug-engineering.com/en/technologies/scr-reduction`.

[47] Sang Soo Hwang, Sung Jin Gil, Gang Nam Lee, Ji Won Lee, Hyun Park, Kwang Hyo Jung, and Sung Bu Suh. Life cycle assessment of alternative ship fuels for coastal ferry operating in republic of Korea. *Journal of Marine Science and Engineering*, 8(9), 9 2020. ISSN 20771312. doi: 10.3390/JMSE8090660.

[48] International Councel on Clean Transportation. Reducing Greenhouse Gas Emissions from Ships. Technical report, 2011. URL `www.theicct.org`.

[49] International Maritime Organisation. Nitrogen Oxides (NOx) Regulation 13, . URL `https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx`.

[50] International Maritime Organisation. Sulphur 2020 - Cutting Sulphur Oxide Emissions, . URL `https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx`.

[51] International Maritime Organisation. A24-Res.982. Technical report, 2006.

[52] International Maritime Organisation. Reduction of GHG Emissions from ships: Marginal Abatement Coststs and Cost effectiveness of Energy efficiency Measures. 2011.

[53] International Maritime Organisation. IMO and Sustainable Development. Technical report, 2015.

[54] International Maritime Organisation. EE appraisal tool for IMO Project Report-GloMEEP. 2016. ISSN 2015-0823. URL `https://glomeep.imo.org/resources/appraisal-tool/`.

[55] International Maritime Organisation. INITIAL IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS. Technical report, 2018. URL `http://www.imo.org`.

[56] International Maritme Organisation. MEPC 75-7-15 - Fourth IMO GHG Study 2020 - Final report (Secretariat). 2020.

[57] Dongxu Ji, King Jet Tseng, Zhongbao Wei, Yun Zheng, and Alessandro Romagnoli. A Simulation Study on a Thermoelectric Generator for Waste Heat Recovery from a Marine Engine. *Journal of Electronic Materials*, 46(5):2908–2914, 5 2017. ISSN 03615235. doi: 10.1007/s11664-016-5038-8.

[58] Matthew P. Johnson and Stefan Schaltegger. Two Decades of Sustainability Management Tools for SMEs: How Far Have We Come? *Journal of Small Business Management*, 54(2):481–505, 4 2016. ISSN 1540627X. doi: 10.1111/jsbm.12154.

[59] Raymond M Keogh, Mr Walter Kollert, and Mr Jim Carle. The Future of Teak and the High-Grade Tropical Hardwood Sector: Solving the Tropical Hardwood Crisis with Emphasis on TEAK. Technical report, 2009. URL `http://www.fao.org/forestry/site/10368/en/`.

[60] Dongkyu Kim and Changhee Lee. SCR performance evaluations in relation to experimental parameters in a marine generator engine. *Journal of Marine Science and Engineering*, 7(3), 2019. ISSN 20771312. doi: 10.3390/jmse7030067.

[61] Jung Hun Kim, Jung Eun Choi, Bong Jun Choi, and Seok Ho Chung. Twisted rudder for reducing fuel-oil consumption. *International Journal of Naval Architecture and Ocean Engineering*, 6(3):715–722, 9 2014. ISSN 20926790. doi: 10.2478/IJNAOE-2013-0207.

[62] Vladimir Krasilnikov, Kourosh Koushan, Marco Nataletti, Lucia Sileo, and Silas Spence. Design and Numerical and Experimental Investigation of Pre-Swirl Stators PSS. Technical report.

[63] Hans Otto Kristenen, Hok Marineconsult, Aps Hans, and Otto Kristensen. Energy demand and exhaust gas emissions of marine engines. Technical report.

[64] Sook Youn Kwon, Kyoung Mi Im, and Jae Hyun Lim. LED context lighting system in residential areas. *Scientific World Journal*, 2014, 2014. ISSN 1537744X. doi: 10.1155/2014/851930.

[65] Gerhard Lammel and Hartmut Grassl. Greenhouse Effect of NO x Review Articles. Technical report, World Meteorological Organisation, Geneve, 1995.

[66] Daniel A Lashof and Dilip R Ahujah. Relative contributions of greenhouse gas emissions to global warming. Technical report.

[67] Changhee Lee. Performance evaluation of a urea-selective catalytic reduction system in a marine diesel engine. *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment*, 231(3):801–808, 8 2017. ISSN 20413084. doi: 10.1177/1475090216667238.

[68] Sangyul Lee, Yongjoo Lee, Youngbok Lee, Minjae Kim, Seunghyup Shin, Jihwan Park, and Kyoungdoug Min. EGR PREDICTION OF DIESEL ENGINES IN STEADY-STATE CONDITIONS USING DEEP LEARNING METHOD. *International Journal of Automotive Technology*, 21(3):571–578, 2020. doi: 10.1007/s12239ïĂŋ020ïĂŋ0054ïĂŋ3.

[69] Seunghyun Lee, Jeongwoo Lee, Seungha Lee, Dongsu Kim, Yoonwoo Lee, Seongeun Yu, and Hoimyung Choi. Study on Reduction of Diesel Engine Out Emission through Closed Loop Control based on the In-Cylinder Pressure with EGR Model. 4 2013. doi: 10.4271/2013-01-0322. URL `https://www.sae.org/content/2013-01-0322/`.

[70] F. Levihn, C. Nuur, and S. Laestadius. Marginal abatement cost curves and abatement strategies: Taking option interdependency and investments unrelated to climate change into account. *Energy*, 76:336–344, 11 2014. ISSN 03605442. doi: 10.1016/j.energy.2014.08.025.

[71] Yuan Li and Lei Zhu. Cost of energy saving and CO2 emissions reduction in China's iron and steel sector. *Applied Energy*, 130:603–616, 10 2014. ISSN 03062619. doi: 10.1016/j.apenergy.2014.04.014.

[72] J. Ling-Chin and A. P. Roskilly. Investigating a conventional and retrofit power plant on-board a Roll-on/Roll-off cargo ship from a sustainability perspective - A life cycle assessment case study. *Energy Conversion and Management*, 117:305–318, 6 2016. ISSN 01968904. doi: 10.1016/j.enconman.2016.03.032.

[73] Janie Ling-Chin and Anthony P. Roskilly. A comparative life cycle assessment of marine power systems. *Energy Conversion and Management*, 127:477–493, 11 2016. ISSN 01968904. doi: 10.1016/j.enconman.2016.09.012.

[74] Simone Lion, Ioannis Vlaskos, and Rodolfo Taccani. A review of emissions reduction technologies for low and medium speed marine Diesel engines and their potential for waste heat recovery, 3 2020. ISSN 01968904.

[75] Mathias Magnusson, Erik Fridell, and Hanna H. Ingelsten. The influence of sulfur dioxide and water on the performance of a marine SCR catalyst. *Applied Catalysis B: Environmental*, 111-112:20–26, 1 2012. ISSN 09263373. doi: 10.1016/j.apcatb.2011.09.010.

[76] William Mathieson. The Superyacht Migration Report. Technical report, 2019.

[77] MC2D (Organization), IEEE Industry Applications Society, IEEE Power Electronics Society, and Institute of Electrical and Electronics Engineers. *Zero Emission Super-Yacht.* ISBN 9781728137032.

[78] Keh-Sik Min, Bong-Jun Chang, and Heung-Won Seo. Study on the Contra-Rotating Propeller system design and full-scale performance prediction method. *International Journal of Naval Architecture and Ocean Engineering*, 1(1):29–38, 9 2009. ISSN 20926782. doi: 10.2478/ijnaoe-2013-0004.

[79] Ministerio del ambiente y agua Ecuador. Guidelines for Yachters. Technical report. URL `http://www.galapagos.gob.ec/tributo-de-ingreso/`.

[80] Kurt Mizzi, Yigit Kemal Demirel, Charlotte Banks, Osman Turan, Panagiotis Kaklis, and Mehmet Atlar. Design optimisation of Propeller Boss Cap Fins for enhanced propeller performance. *Applied Ocean Research*, 62:210–222, 1 2017. ISSN 01411187. doi: 10.1016/j.apor.2016.12.006.

[81] S. Narayan, Sasa Milojevic, and Vipul Gupta. Combustion monitoring in engines using accelerometer signals. *Journal of Vibroengineering*, 21(6):1552–1563, 9 2019. ISSN 13928716. doi: 10.21595/jve.2019.20516.

[82] Nextchem. HVO production figure, 2021. URL `https://nextchem.it/nl/node/74`.

[83] Norwegian Maritime Authority. Circular - Series V: Guidance on documentation that the NOx requirements in the Norwegian Heritage fjords are met. Technical report, 2019.

[84] Office of Naval Research. New hull Coatings Cut Fuel Use, Protect Environment. pages 36–38, 2009.

[85] A. Ölçer and F. Ballini. The development of a decision making framework for evaluating the trade-offsolutions of cleaner seaborne transportation. *Transportation Research Part D: Transport and Environment*, 37:150–170, 2015. ISSN 13619209. doi: 10.1016/j.trd.2015.04.023.

[86] David Owen, Yigit Kemal Demirel, Elif Oguz, Tahsin Tezdogan, and Atilla Incecik. Investigating the effect of biofouling on propeller characteristics using CFD. *Ocean Engineering*, 159:505–516, 7 2018. ISSN 00298018. doi: 10.1016/j.oceaneng.2018.01.087.

[87] Oxford University Press. Oxford English Dictionary. URL `www.oed.com`.

[88] Probunkers. IMO worldmap for ECA's. URL `https://probunkers.com/regulatory-requirements/`.

[89] PV Thin. http://pvthin.org/what-is-thin-film-pv/.

[90] Vicente J D Rascio. Antifouling coatings: Where do we go from here. Technical Report 3, 2000.

[91] Alex Robinson, Emma Kooi, Sai Amith Chillamcherla, and Arihant Anchalia. Joint Interdisciplinary Project: Harnessing solar energy on superyachts. Technical report, 2020.

[92] G Rotte, O Zverkhovskyi, M Kerkvliet, and T Van Terwisga. On the physical mechanisms for the numerical modelling of flows around air lubricated ships. Delft University of Technology, APA, 2016.

[93] Emilio Sabia, Matthias Gauly, Fabio Napolitano, Francesco Serrapica, Giulia Francesca Cifuni, and Salvatore Claps. Dairy sheep carbon footprint and ReCiPe end-point study. *Small Ruminant Research*, 185, 4 2020. ISSN 09214488. doi: 10.1016/j.smallrumres.2020.106085.

[94] Harsh Sapra, Milinko Godjevac, Peter De Vos, Wim Van Sluijs, Youri Linden, and Klaas Visser. Hydrogen-natural gas combustion in a marine lean-burn SI engine: A comparitive analysis of Seiliger and double Wiebe function-based zero–dimensional modelling. *Energy Conversion and Management*, 207, 3 2020. ISSN 01968904. doi: 10.1016/j.enconman.2020.112494.

[95] O. Schinas and Ch N. Stefanakos. Selecting technologies towards compliance with MARPOL Annex VI: The perspective of operators. *Transportation Research Part D: Transport and Environment*, 28:28–40, 2014. ISSN 13619209. doi: 10.1016/j.trd.2013.12.006.

[96] Ship & Bunker. Average bunker prices, 2021. URL `https://shipandbunker.com/prices/av`.

[97] Morné Irshkin Sinden. Development of a holistic framework for shipyard energy Development of a holistic framework for shipyard energy management : a case study on production facilities and management : a case study on production facilities and technology technology. Technical report, 2019. URL `https://commons.wmu.se/all_dissertations`.

[98] SkySails. Kite Drive For Yachts. Technical report.

[99] Solargis and The World Bank Group. Global Solar Atlas 2.0: Technical Report. Technical report.

[100] Solbian. Solbianflex SX series. Technical report. URL `www.solbian.eu`.

[101] Kouseki Sugiyama, Isamu Goto, Koji Kitano, Kazuhisa Mogi, and Markku Honkanen. Effects of Hydrotreated Vegetable Oil (HVO) as Renewable Diesel Fuel on Combustion and Exhaust Emissions in Diesel Engine. Technical report, 2011.

[102] Super yacht times. Feadship Anna. URL `https://www.superyachttimes.com/yachts/anna-110m/photos`.

[103] Leena Tähkämö. Life cycle assessment of light sources – Case studies and review of the analyses. Technical report, 2013.

[104] Termodinamica. Marine Inverter Air Conditioning. 2019. URL `https://www.termodinamicamarine.com/en/products/`.

[105] The Super Yacht Group. Refit data. Technical report, 2020.

[106] Cornel Thill, Serge Toxopeus, and Frans Van Walree. Project Energy-saving air-Lubricated Ships (PELS). Technical report, 2005.

[107] Nikoletta L. Trivyza, Athanasios Rentizelas, and Gerasimos Theotokatos. A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability. *Energy Conversion and Management*, 168:128–149, 7 2018. ISSN 01968904. doi: 10.1016/j.enconman.2018.04.020.

[108] United Nations. The Sustainable Development Goals Report. Technical report, 2020.

[109] Merlijn Van, Adrichem Satvik Bhatia, Benno Rooijakkers, and Yuchen Yin. Joint Interdisciplinary Project: SQUEAKY CLEAN: A Solution Space for Alternative Antifouling Techniques Team Feadship. Technical report, TU Delft, 2019.

[110] I V Van Grootheest. *Selection of cost-effective emission abatement options for early-stage ship design: A selection tool implemented for a road ferry and a workboat.* PhD thesis, 2019. URL `http://repository.tudelft.nl/`.

[111] Anton Voermans. Development of the Wärtsilä EnergoFlow: An innovative energy saving device. Technical report, 2017.

[112] Anton Voermans. Experimental determination of hydrodynamic loads on the Wärtsilä pre-swirl stator EnergoFlow and validation of a prediction methodology for design loads. Technical report, 2019.

[113] Fu Cheng Wang, Chun Wen Tang, and Bin Juine Huang. Multivariable robust control for a red-green-blue LED lighting system. *IEEE Transactions on Power Electronics*, 25(2):417–428, 2010. ISSN 08858993. doi: 10.1109/TPEL.2009.2026476.

[114] Water Revolution Foundation. Yacht Assesment Tool. URL `https://waterrevolutionfoundation.org/our-plans/yacht-assessment-tool/`.

[115] John Weaver. How solar power operations and maintenance costs fell 50%, 2019. URL `https://pv-magazine-usa.com/2019/09/13/how-solar-power-operations-and-maintenance-costs-fell-50-percent/`.

[116] XEOMOS. SCR-S system. URL `https://www.xeamos.com/nl/emissiereductie/systemen/scr-s`.

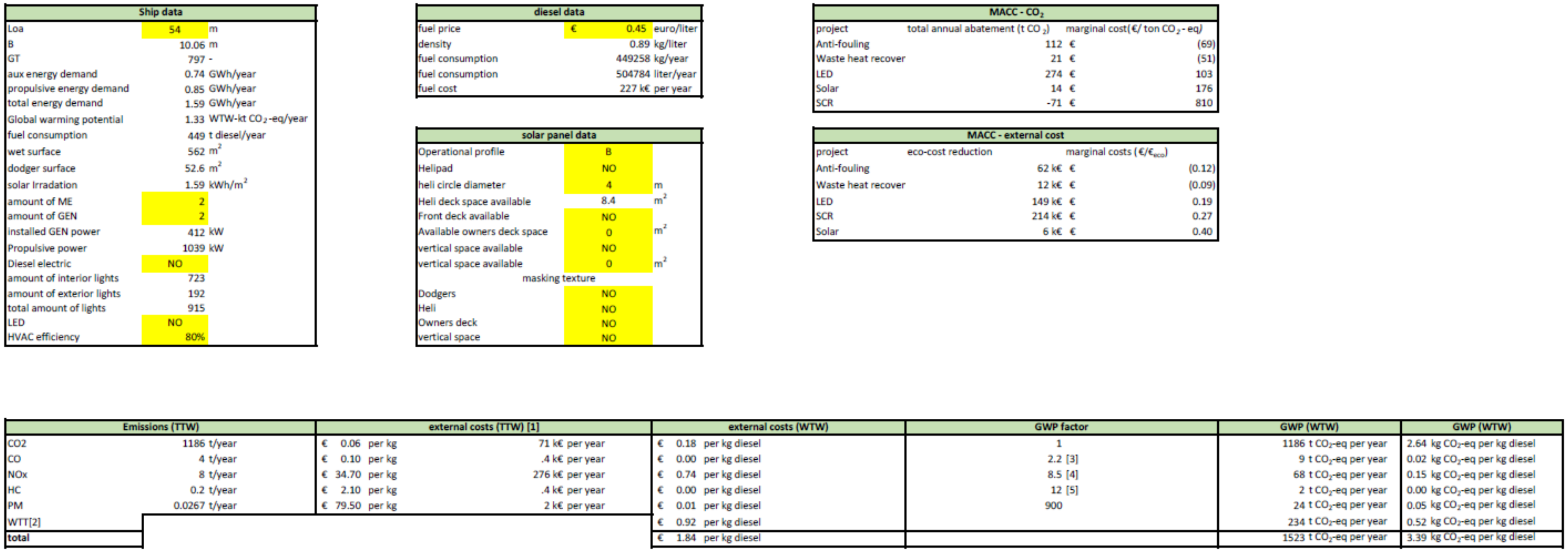
[117] Q. Xin and C.F. Pinzon. Improving the environmental performance of heavy-duty vehicles and engines: key issues and system design approaches. *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance,*, 2014.

[118] Z. L. Yang, D. Zhang, O. Caglayan, I. D. Jenkinson, S. Bonsall, J. Wang, M. Huang, and X. P. Yan. Selection of techniques for reducing shipping NOx and SOx emissions. *Transportation Research Part D: Transport and Environment*, 17(6):478–486, 2012. ISSN 13619209. doi: 10.1016/j.trd.2012.05.010.

[119] Diego Meseguer Yebra, Søren Kiil, and Kim Dam-Johansen. Antifouling technology - Past, present and future steps towards efficient and environmentally friendly antifouling coatings, 7 2004. ISSN 03009440.

A

Selection tool overview for base case



Ship data		
Loa	54	m
B	10.06	m
GT	797	-
aux energy demand	0.74	GWh/year
propulsive energy demand	0.85	GWh/year
total energy demand	1.59	GWh/year
Global warming potential	1.33	WTW-kt CO_2-eq/year
fuel consumption	449	t diesel/year
wet surface	562	m^2
dodger surface	52.6	m^2
solar Irradation	1.59	kWh/m^2
amount of ME	2	
amount of GEN	2	
installed GEN power	412	kW
Propulsive power	1039	kW
Diesel electric	NO	
amount of interior lights	723	
amount of exterior lights	192	
total amount of lights	915	
LED	NO	
HVAC efficiency	80%	

diesel data			
fuel price	€	0.45	euro/liter
density		0.89	kg/liter
fuel consumption		449258	kg/year
fuel consumption		504784	liter/year
fuel cost		227 k€	per year

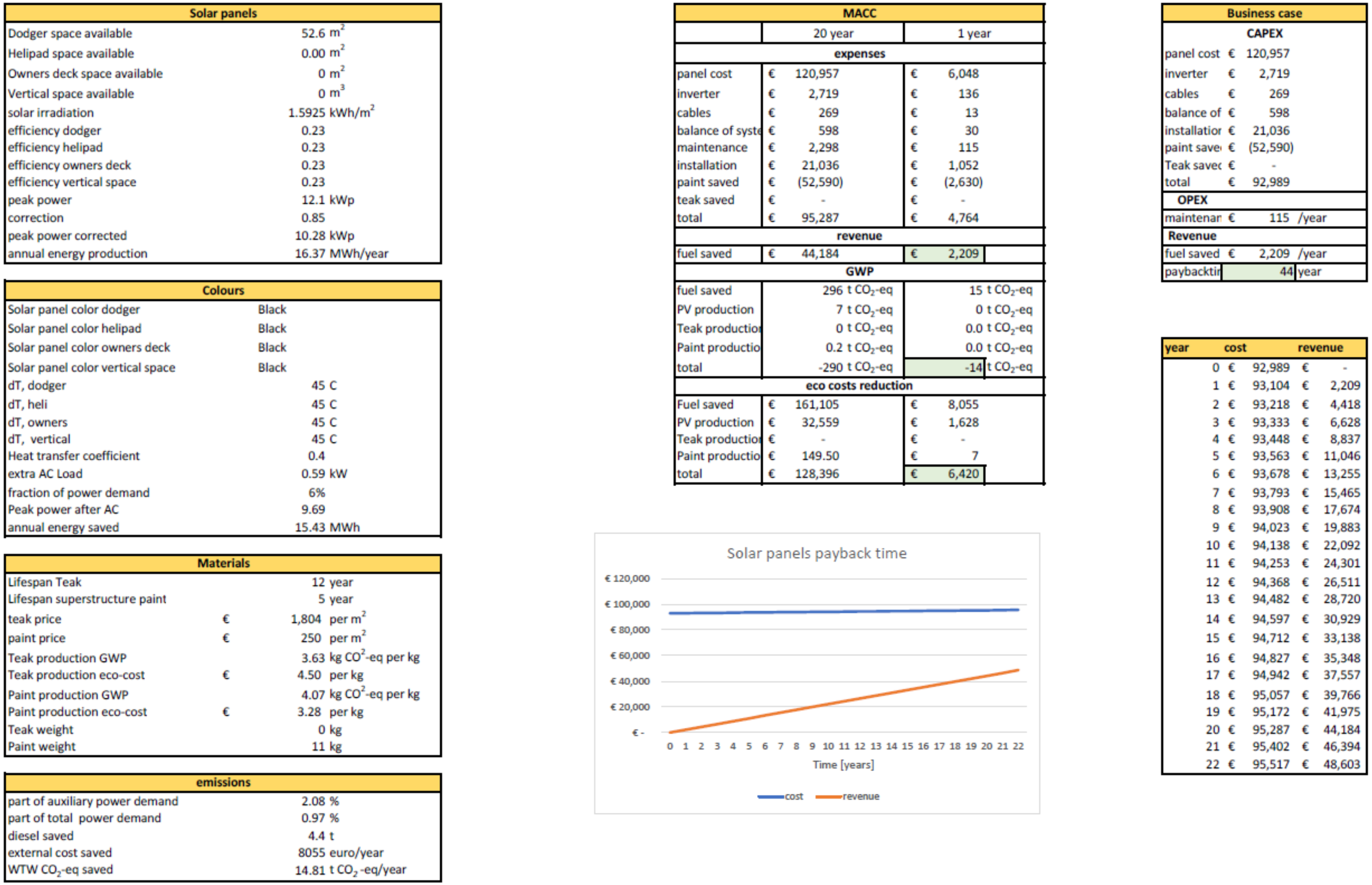
solar panel data		
Operational profile	B	
Helipad	NO	
heli circle diameter	4	m
Heli deck space available	8.4	m^2
Front deck available	NO	
Available owners deck space	0	m^2
vertical space available	NO	
vertical space available	0	m^2
masking texture		
Dodgers	NO	
Heli	NO	
Owners deck	NO	
vertical space	NO	

MACC - CO_2			
project	total annual abatement (t CO_2)	marginal cost(€/ ton CO_2 - eq)	
Anti-fouling	112	€	(69)
Waste heat recover	21	€	(51)
LED	274	€	103
Solar	14	€	176
SCR	-71	€	810

MACC - external cost			
project	eco-cost reduction	marginal costs (€/$€_{eco}$)	
Anti-fouling	62 k€	€	(0.12)
Waste heat recover	12 k€	€	(0.09)
LED	149 k€	€	0.19
SCR	214 k€	€	0.27
Solar	6 k€	€	0.40

Emissions (TTW)		external costs (TTW) [1]		external costs (WTW)	GWP factor	GWP (WTW)	GWP (WTW)
CO2	1186 t/year	€ 0.06 per kg	71 k€ per year	€ 0.18 per kg diesel	1	1186 t CO_2-eq per year	2.64 kg CO_2-eq per kg diesel
CO	4 t/year	€ 0.10 per kg	.4 k€ per year	€ 0.00 per kg diesel	2.2 [3]	9 t CO_2-eq per year	0.02 kg CO_2-eq per kg diesel
NOx	8 t/year	€ 34.70 per kg	276 k€ per year	€ 0.74 per kg diesel	8.5 [4]	68 t CO_2-eq per year	0.15 kg CO_2-eq per kg diesel
HC	0.2 t/year	€ 2.10 per kg	.4 k€ per year	€ 0.00 per kg diesel	12 [5]	2 t CO_2-eq per year	0.00 kg CO_2-eq per kg diesel
PM	0.0267 t/year	€ 79.50 per kg	2 k€ per year	€ 0.01 per kg diesel	900	24 t CO_2-eq per year	0.05 kg CO_2-eq per kg diesel
WTT[2]				€ 0.92 per kg diesel		234 t CO_2-eq per year	0.52 kg CO_2-eq per kg diesel
total				€ 1.84 per kg diesel		1523 t CO_2-eq per year	3.39 kg CO_2-eq per kg diesel

Figure A.1: selection tool page 1: Input data



Solar panels	
Dodger space available	52.6 m^2
Helipad space available	0.00 m^2
Owners deck space available	0 m^2
Vertical space available	0 m^3
solar irradiation	1.5925 kWh/m^2
efficiency dodger	0.23
efficiency helipad	0.23
efficiency owners deck	0.23
efficiency vertical space	0.23
peak power	12.1 kWp
correction	0.85
peak power corrected	10.28 kWp
annual energy production	16.37 MWh/year

Colours		
Solar panel color dodger	Black	
Solar panel color helipad	Black	
Solar panel color owners deck	Black	
Solar panel color vertical space	Black	
dT, dodger		45 C
dT, heli		45 C
dT, owners		45 C
dT, vertical		45 C
Heat transfer coefficient		0.4
extra AC Load		0.59 kW
fraction of power demand		6%
Peak power after AC		9.69
annual energy saved		15.43 MWh

Materials		
Lifespan Teak		12 year
Lifespan superstructure paint		5 year
teak price	€	1,804 per m^2
paint price	€	250 per m^2
Teak production GWP		3.63 kg CO^2-eq per kg
Teak production eco-cost	€	4.50 per kg
Paint production GWP		4.07 kg CO^2-eq per kg
Paint production eco-cost	€	3.28 per kg
Teak weight		0 kg
Paint weight		11 kg

emissions	
part of auxiliary power demand	2.08 %
part of total power demand	0.97 %
diesel saved	4.4 t
external cost saved	8055 euro/year
WTW CO$_2$-eq saved	14.81 t CO$_2$-eq/year

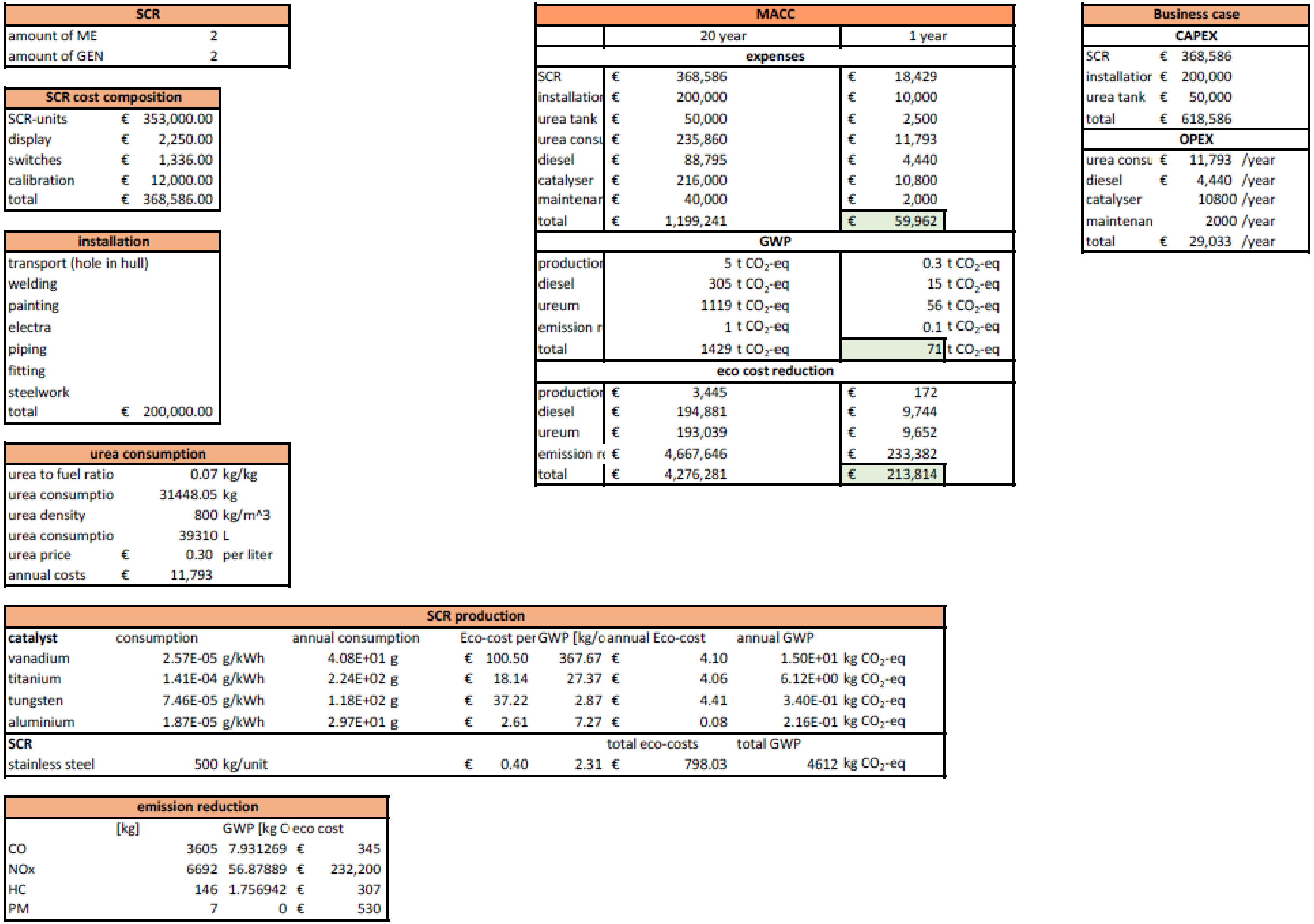
MACC				
		20 year		1 year
expenses				
panel cost	€	120,957	€	6,048
inverter	€	2,719	€	136
cables	€	269	€	13
balance of syst	€	598	€	30
maintenance	€	2,298	€	115
installation	€	21,036	€	1,052
paint saved	€	(52,590)	€	(2,630)
teak saved	€	-	€	-
total	€	95,287	€	4,764
revenue				
fuel saved	€	44,184	€	2,209
GWP				
fuel saved		296 t CO$_2$-eq		15 t CO$_2$-eq
PV production		7 t CO$_2$-eq		0 t CO$_2$-eq
Teak productio		0 t CO$_2$-eq		0.0 t CO$_2$-eq
Paint productio		0.2 t CO$_2$-eq		0.0 t CO$_2$-eq
total		-290 t CO$_2$-eq		-14 t CO$_2$-eq
eco costs reduction				
Fuel saved	€	161,105	€	8,055
PV production	€	32,559	€	1,628
Teak productio	€	-	€	-
Paint productio	€	149.50	€	7
total	€	128,396	€	6,420

Solar panels payback time

Business case		
CAPEX		
panel cost	€	120,957
inverter	€	2,719
cables	€	269
balance of	€	598
installatior	€	21,036
paint save	€	(52,590)
Teak savec	€	-
total	€	92,989
OPEX		
maintenar	€	115 /year
Revenue		
fuel saved	€	2,209 /year
paybacktir		44 year

year		cost		revenue
0	€	92,989	€	-
1	€	93,104	€	2,209
2	€	93,218	€	4,418
3	€	93,333	€	6,628
4	€	93,448	€	8,837
5	€	93,563	€	11,046
6	€	93,678	€	13,255
7	€	93,793	€	15,465
8	€	93,908	€	17,674
9	€	94,023	€	19,883
10	€	94,138	€	22,092
11	€	94,253	€	24,301
12	€	94,368	€	26,511
13	€	94,482	€	28,720
14	€	94,597	€	30,929
15	€	94,712	€	33,138
16	€	94,827	€	35,348
17	€	94,942	€	37,557
18	€	95,057	€	39,766
19	€	95,172	€	41,975
20	€	95,287	€	44,184
21	€	95,402	€	46,394
22	€	95,517	€	48,603

Figure A.2: selection tool page 2: Solar PV



SCR	
amount of ME	2
amount of GEN	2

SCR cost composition		
SCR-units	€	353,000.00
display	€	2,250.00
switches	€	1,336.00
calibration	€	12,000.00
total	€	368,586.00

installation		
transport (hole in hull)		
welding		
painting		
electra		
piping		
fitting		
steelwork		
total	€	200,000.00

urea consumption			
urea to fuel ratio		0.07	kg/kg
urea consumptio		31448.05	kg
urea density		800	kg/m^3
urea consumptio		39310	L
urea price	€	0.30	per liter
annual costs	€	11,793	

MACC					
	20 year		1 year		
expenses					
SCR	€	368,586	€	18,429	
installatior	€	200,000	€	10,000	
urea tank	€	50,000	€	2,500	
urea consu	€	235,860	€	11,793	
diesel	€	88,795	€	4,440	
catalyser	€	216,000	€	10,800	
maintenar	€	40,000	€	2,000	
total	€	1,199,241	€	59,962	
GWP					
productior		5		0.3	t CO_2-eq
diesel		305		15	t CO_2-eq
ureum		1119		56	t CO_2-eq
emission r		1		0.1	t CO_2-eq
total		1429		71	t CO_2-eq
eco cost reduction					
productior	€	3,445	€	172	
diesel	€	194,881	€	9,744	
ureum	€	193,039	€	9,652	
emission re	€	4,667,646	€	233,382	
total	€	4,276,281	€	213,814	

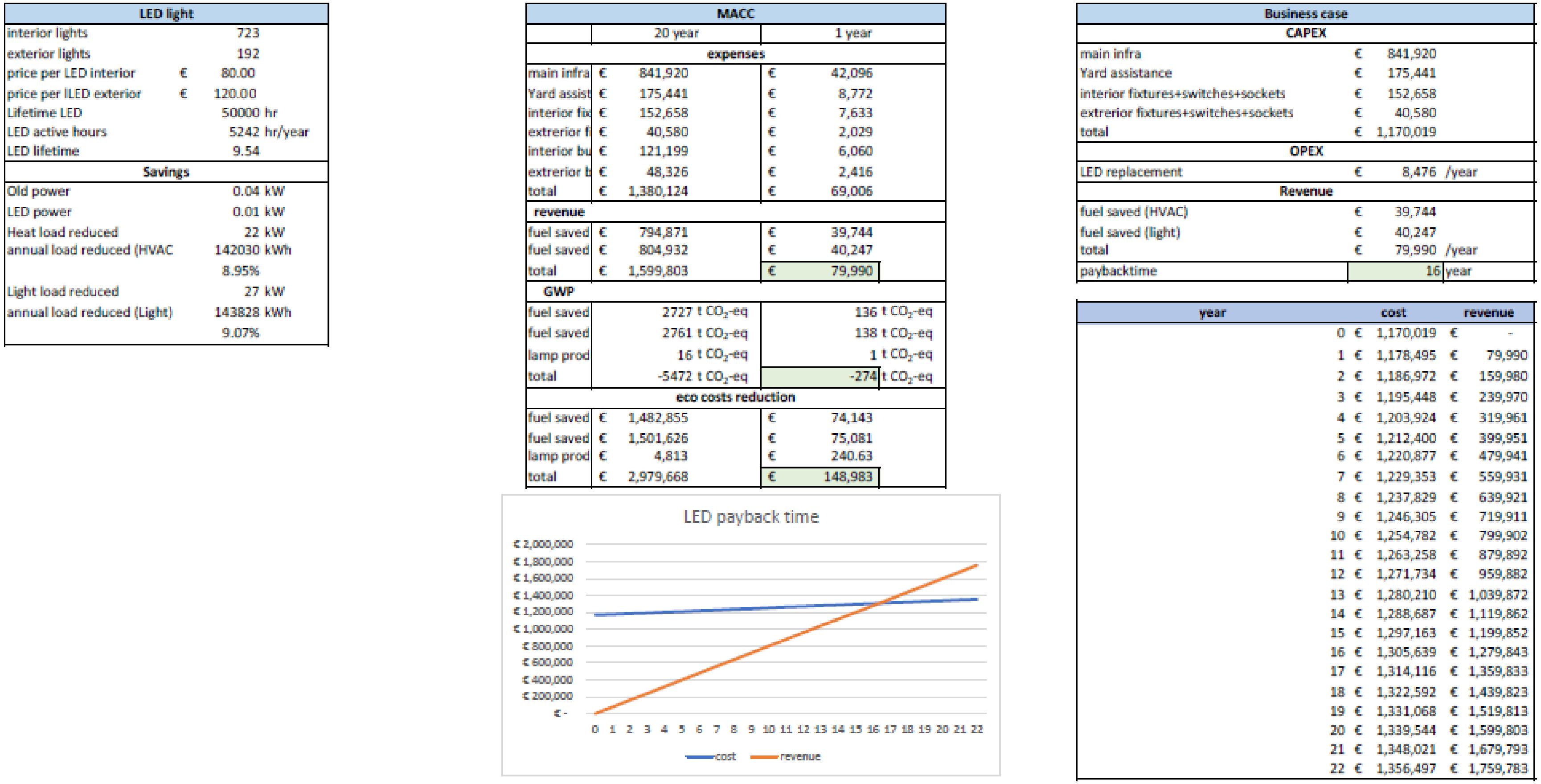
(GWP 20 year values are printed with unit: 5 t CO_2-eq, 305 t CO_2-eq, 1119 t CO_2-eq, 1 t CO_2-eq, 1429 t CO_2-eq.)

Business case			
CAPEX			
SCR	€	368,586	
installatior	€	200,000	
urea tank	€	50,000	
total	€	618,586	
OPEX			
urea consu	€	11,793	/year
diesel	€	4,440	/year
catalyser		10800	/year
maintenan		2000	/year
total	€	29,033	/year

SCR production												
catalyst	consumption		annual consumption		Eco-cost per		GWP [kg/c	annual Eco-cost		annual GWP	
vanadium	2.57E-05	g/kWh	4.08E+01	g	€	100.50	367.67	€	4.10	1.50E+01	kg CO_2-eq
titanium	1.41E-04	g/kWh	2.24E+02	g	€	18.14	27.37	€	4.06	6.12E+00	kg CO_2-eq
tungsten	7.46E-05	g/kWh	1.18E+02	g	€	37.22	2.87	€	4.41	3.40E-01	kg CO_2-eq
aluminium	1.87E-05	g/kWh	2.97E+01	g	€	2.61	7.27	€	0.08	2.16E-01	kg CO_2-eq
SCR								total eco-costs		total GWP	
stainless steel	500	kg/unit			€	0.40	2.31	€	798.03	4612	kg CO_2-eq

emission reduction				
	[kg]	GWP [kg C	eco cost	
CO	3605	7.931269	€	345
NOx	6692	56.87889	€	232,200
HC	146	1.756942	€	307
PM	7	0	€	530

Figure A.3: selection tool page 3: SCR-unit



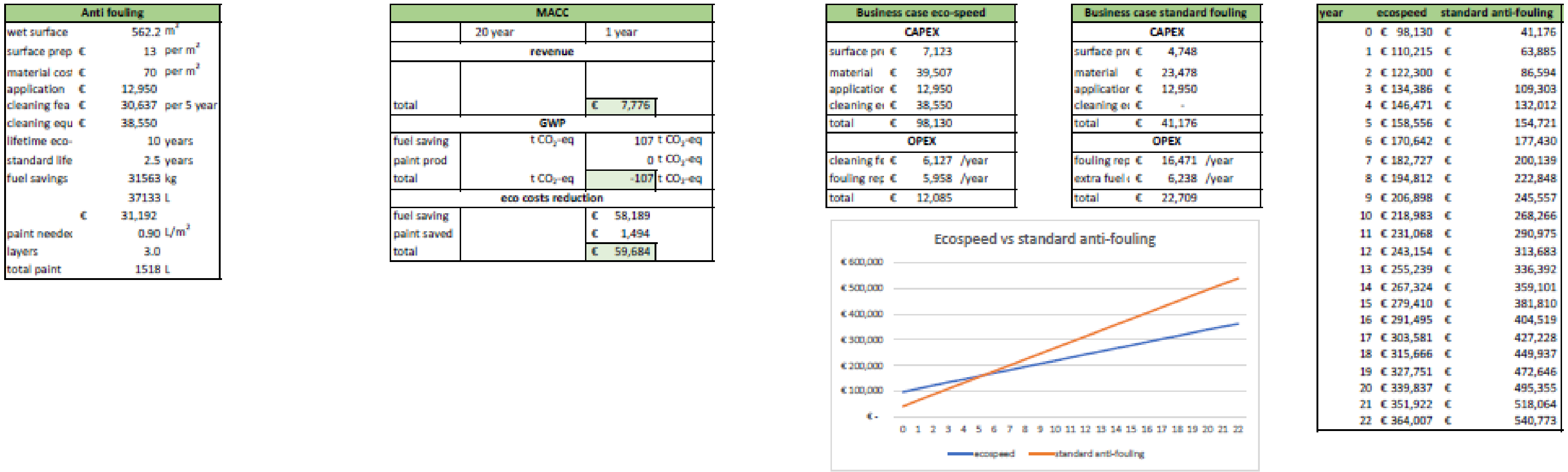
LED light			
interior lights		723	
exterior lights		192	
price per LED interior	€	80.00	
price per ILED exterior	€	120.00	
Lifetime LED		50000	hr
LED active hours		5242	hr/year
LED lifetime		9.54	
Savings			
Old power		0.04	kW
LED power		0.01	kW
Heat load reduced		22	kW
annual load reduced (HVAC		142030	kWh
		8.95%	
Light load reduced		27	kW
annual load reduced (Light)		143828	kWh
		9.07%	

MACC					
	20 year		1 year		
expenses					
main infra	€	841,920	€	42,096	
Yard assist	€	175,441	€	8,772	
interior fix	€	152,658	€	7,633	
extrerior f	€	40,580	€	2,029	
interior bu	€	121,199	€	6,060	
extrerior b	€	48,326	€	2,416	
total	€	1,380,124	€	69,006	
revenue					
fuel saved	€	794,871	€	39,744	
fuel saved	€	804,932	€	40,247	
total	€	1,599,803	€	79,990	
GWP					
fuel saved		2727 t CO_2-eq		136	t CO_2-eq
fuel saved		2761 t CO_2-eq		138	t CO_2-eq
lamp prod		16 t CO_2-eq		1	t CO_2-eq
total		-5472 t CO_2-eq		-274	t CO_2-eq
eco costs reduction					
fuel saved	€	1,482,855	€	74,143	
fuel saved	€	1,501,626	€	75,081	
lamp prod	€	4,813	€	240.63	
total	€	2,979,668	€	148,983	

Business case			
CAPEX			
main infra	€	841,920	
Yard assistance	€	175,441	
interior fixtures+switches+sockets	€	152,658	
extrerior fixtures+switches+sockets	€	40,580	
total	€	1,170,019	
OPEX			
LED replacement	€	8,476	/year
Revenue			
fuel saved (HVAC)	€	39,744	
fuel saved (light)	€	40,247	
total	€	79,990	/year
paybacktime		16	year

year		cost		revenue
0	€	1,170,019	€	-
1	€	1,178,495	€	79,990
2	€	1,186,972	€	159,980
3	€	1,195,448	€	239,970
4	€	1,203,924	€	319,961
5	€	1,212,400	€	399,951
6	€	1,220,877	€	479,941
7	€	1,229,353	€	559,931
8	€	1,237,829	€	639,921
9	€	1,246,305	€	719,911
10	€	1,254,782	€	799,902
11	€	1,263,258	€	879,892
12	€	1,271,734	€	959,882
13	€	1,280,210	€	1,039,872
14	€	1,288,687	€	1,119,862
15	€	1,297,163	€	1,199,852
16	€	1,305,639	€	1,279,843
17	€	1,314,116	€	1,359,833
18	€	1,322,592	€	1,439,823
19	€	1,331,068	€	1,519,813
20	€	1,339,544	€	1,599,803
21	€	1,348,021	€	1,679,793
22	€	1,356,497	€	1,759,783

Figure A.4: selection tool page 4: LED



Anti fouling			
wet surface		562.2	m^2
surface prep	€	13	per m^2
material cos	€	70	per m^2
application	€	12,950	
cleaning fea	€	30,637	per 5 year
cleaning equ	€	38,550	
lifetime eco-		10	years
standard life		2.5	years
fuel savings		31563	kg
		37133	L
	€	31,192	
paint needec		0.90	L/m^2
layers		3.0	
total paint		1518	L

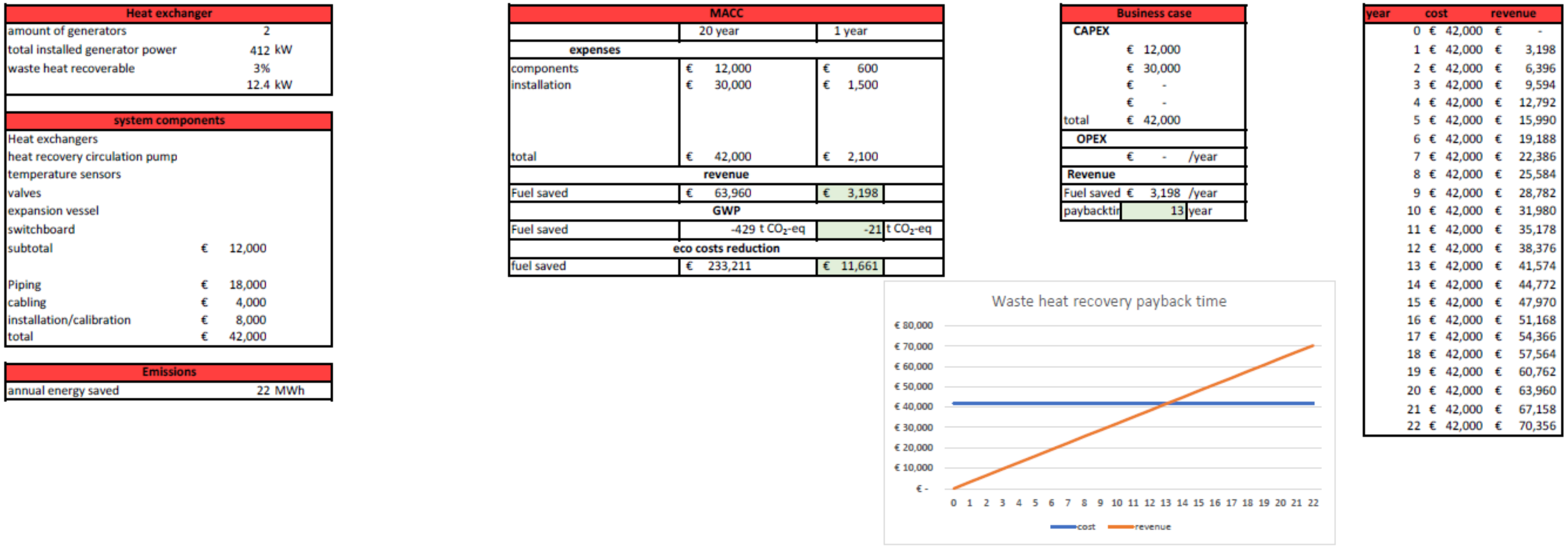
MACC		
	20 year	1 year
revenue		
total		€ 7,776
GWP		
fuel saving	t CO_2-eq	107 t CO_2-eq
paint prod		0 t CO_2-eq
total	t CO_2-eq	-107 t CO_2-eq
eco costs reduction		
fuel saving		€ 58,189
paint saved		€ 1,494
total		€ 59,684

Business case eco-speed			
CAPEX			
surface pre	€	7,123	
material	€	39,507	
applicatior	€	12,950	
cleaning e	€	38,550	
total	€	98,130	
OPEX			
cleaning fe	€	6,127	/year
fouling re	€	5,958	/year
total	€	12,085	

Business case standard fouling			
CAPEX			
surface pre	€	4,748	
material	€	23,478	
applicatior	€	12,950	
cleaning e	€	-	
total	€	41,176	
OPEX			
fouling rep	€	16,471	/year
extra fuel	€	6,238	/year
total	€	22,709	

year	ecospeed	standard anti-fouling
0	€ 98,130	€ 41,176
1	€ 110,215	€ 63,885
2	€ 122,300	€ 86,594
3	€ 134,386	€ 109,303
4	€ 146,471	€ 132,012
5	€ 158,556	€ 154,721
6	€ 170,642	€ 177,430
7	€ 182,727	€ 200,139
8	€ 194,812	€ 222,848
9	€ 206,898	€ 245,557
10	€ 218,983	€ 268,266
11	€ 231,068	€ 290,975
12	€ 243,154	€ 313,683
13	€ 255,239	€ 336,392
14	€ 267,324	€ 359,101
15	€ 279,410	€ 381,810
16	€ 291,495	€ 404,519
17	€ 303,581	€ 427,228
18	€ 315,666	€ 449,937
19	€ 327,751	€ 472,646
20	€ 339,837	€ 495,355
21	€ 351,922	€ 518,064
22	€ 364,007	€ 540,773

Figure A.5: selection tool page 5: Anti Fouling



Heat exchanger		
amount of generators	2	
total installed generator power	412	kW
waste heat recoverable	3%	
	12.4	kW

system components		
Heat exchangers		
heat recovery circulation pump		
temperature sensors		
valves		
expansion vessel		
switchboard		
subtotal	€	12,000
Piping	€	18,000
cabling	€	4,000
installation/calibration	€	8,000
total	€	42,000

Emissions		
annual energy saved	22	MWh

MACC			
	20 year	1 year	
expenses			
components	€ 12,000	€ 600	
installation	€ 30,000	€ 1,500	
total	€ 42,000	€ 2,100	
revenue			
Fuel saved	€ 63,960	€ 3,198	
GWP			
Fuel saved	-429 t CO$_2$-eq	-21	t CO$_2$-eq
eco costs reduction			
fuel saved	€ 233,211	€ 11,661	

Business case		
CAPEX		
	€ 12,000	
	€ 30,000	
	€ -	
	€ -	
total	€ 42,000	
OPEX		
	€ -	/year
Revenue		
Fuel saved	€ 3,198	/year
paybacktir	13	year

year	cost	revenue
0	€ 42,000	€ -
1	€ 42,000	€ 3,198
2	€ 42,000	€ 6,396
3	€ 42,000	€ 9,594
4	€ 42,000	€ 12,792
5	€ 42,000	€ 15,990
6	€ 42,000	€ 19,188
7	€ 42,000	€ 22,386
8	€ 42,000	€ 25,584
9	€ 42,000	€ 28,782
10	€ 42,000	€ 31,980
11	€ 42,000	€ 35,178
12	€ 42,000	€ 38,376
13	€ 42,000	€ 41,574
14	€ 42,000	€ 44,772
15	€ 42,000	€ 47,970
16	€ 42,000	€ 51,168
17	€ 42,000	€ 54,366
18	€ 42,000	€ 57,564
19	€ 42,000	€ 60,762
20	€ 42,000	€ 63,960
21	€ 42,000	€ 67,158
22	€ 42,000	€ 70,356

Figure A.6: selection tool page 6: Waste heat recovery