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Retrofit Solutions for Energy Efficiency in Shipping

A Study of Effects, Cost-Efficiencies, Implementation Rates and Barriers

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Abstract

This thesis has a purpose which is twofold. Firstly, several retrofit fuel reduction measures used in the shipping industry are examined. The goal is to compare the actual effects of the measures with the estimated effects presented in the literature. It is found that most actual effects are lower than what the literature expects. The second goal of the study is to analyze the measures in an economical way, seeking to find which, if any, of the measures are cost-efficient. This is done through calculations of marginal abatement costs and creating marginal abatement cost curves for sixteen different combinations of factors including vessel type, fuel cost and the different effects found in the previous part. Weather routing, trim and draft optimizations and propeller polishing are the measures found to be cost-efficient in all scenarios. Waste heat recovery, air lubrication, wind propulsion and biofuels are found to be cost-ineffective in all scenarios.

The results from the marginal abatement cost curves are used to design “No regret”- and “Zero-cost”-scenarios. A possible global reduction potential of between 77.5m-132m tonnes of CO_2 per year is calculated in the “No regret”-scenario, while the interval for the “Zero cost”-scenario is 127m-181.5m tonnes of CO_2 per year.

Finally, some barriers for implementation of the measures are presented and discussed. The principal-agent problem, where the shipowner not necessarily reaps the benefit for his/hers investment is one of the main barriers. The volatile fuel cost causing uncertainties in investment calculations is also identified as important. Options for shipowners, regulators and governments in order to reduce these barriers include market-based measures as fuel tax and CO_2-trading schemes, speed reduction measures as virtual arrival and speed limits as well as energy-rating systems and government incentive schemes.

The thesis is built upon a literature review, a group of interviews and a survey, and does contain some uncertainties. Firstly, the small sample size may lead to the data being less generalizable and that single responses may be given too much weight. Secondly, the fact that a large part of the respondents are headquartered in Norway may lead to biases, if the answers and effects are varying geographically. Caution must also be taken when analyzing the marginal abatement cost curves, as the influence of additive effects has not been considered.

Contents

1. Introduction

For centuries shipping has been one of the key parts in creating and developing the highly globalized world we live in. As new discoveries in navigational knowledge, hull construction, materials and propulsion made the use of ships to discoveries, trade and transport faster, safer and more reliable, it contributed to the integration of the world we see today. During the last fifty years the use of shipping as a mean of transporting goods has had a great increase. Eskeland and Lindstad (2016) showed that the increase in shipping demand from 1970-2012 was around 250%, compared to an increase in global energy usage of about 170% and only a 90% increase in global population.

Transport by ship is widely considered to be one of the most energy efficient modes of transport (World Shipping Council, 2020). With a single cargo it is estimated that a short sea vessel may replace as much as 200-400 trucks (Norwegian Shipowners´ Association, 2019). This ratio increases with vessel size and the miles transported. Eskeland and Lindstad (2016) showed that the grams of CO_2 emitted per tonne-kilometre is 120 for a Boeing 747 Freighter, 85 for road transport and around 50 for rail transport. The smaller container vessels are as effective as rail transport, while the largest capesize dry bulk vessels emit around 3-4 grams CO_2 per tonne-kilometre.

According to the International Marine Organization (Smith, et al., 2014), the global fleet emitted 938Mt of CO_2 in 2012. This constituted a total of 2.6% of the worldwide emissions. Compared to the numbers from 2007 we see a decrease both in absolute numbers from 1100Mt CO2, and in percent of global emissions of 3.5%. During the period from 1970 until 2012 the global freight increased by 268% (Lindstad, et al., 2015). As the world continues to globalize, the trade between countries and regions is expected to further increase. Projections are showing that the increase will be largest in the transport of unitized cargo, while bulk trading is more saturated. According to Smith et al. (2014) we may see an increase in shipping emission of 50-250% if operating in a business as usual way, where most of this is related to the increase in trade volumes.

Over the last decades the CO_2-emissions from ships has got more and more attention from policy makers and the industry itself. In September 1997, an International Conference of Parties to the MARPOL Convention adopted a resolution on CO_2-emissions from ships (International Maritime Organization, 2020). This led to the Marine Environment Protection Committee starting to work on identifying CO_2-reduction solutions. In 2011, the European Commission launched a paper where it was suggested that emissions from the maritime industry in 2050 should be reduced by at least 40%, but hopefully 50% of 2005-levels (European Maritime Safety Agency, n.d.). Lindstad et al. (2011) claim that the emissions per nautical mile must be reduced from 25 grams to 4 grams of CO_2 in 2050 in order to reach these goals.

There are several studies identifying, examining, and discussing different CO_2-reduction solutions for the shipping industry (Buhaug, et al., 2009; Harrould-Kolieb & Savitz, 2010; Gilbert et al., 2014; Lindstad, et al., 2015). Several of the studies have estimations on the perceived reduction potential of both fuel consumption and CO_2-emissions of different solutions. As the studies are carried out in different years, and as the technology is rapidly evolving, the estimates related to a single measure may vary a lot from study to study. This makes it hard for shipowners and policy markers to compare different measures, and decide which measure to install or to support and promote. Adding to this complexity is the fact that many of the studies use few test cases or even just mathematical calculations in order to provide estimations. In order to further the research into fuel reduction and CO_2-abatement solutions, it seems important to clarify what actual effects shipowners see from the measures they have implemented. By comparing this to the theoretical effects given in a range of studies, it may narrow down the potential CO_2-saving interval, and simplify decision making regarding such investments. As this is a master’s thesis, the scope is limited to solutions which can be retrofitted, or in other words solutions that may be installed or performed after the ships were originally built. This leads to the first of the research questions sought to be answered in this thesis:

What are the actual fuel consumption and CO_2-emission reduction effects of different, retrofit solutions in shipping, and how do these effects compare to the theoretically estimated effects?

While conducting the research seeking to answer the research question above, an added bonus effect will be the ability to identify to which degree different measures are implemented throughout the business.

To install or to implement retrofits solutions leading to reductions in both fuel consumption and CO_2-emissions, usually either an investment cost, an operational cost or both is needed to be paid by the shipowner. However, by reducing fuel consumption the fuel cost of running the vessel also reduces. Several studies have examined the relationship between costs and savings related to fuel- and CO_2-reduction measures (Faber et al., 2011; Eide et al., 2011; Wang & Lutsey, 2013; Lindstad, et al., 2015). Many of the studies have estimated marginal CO_2-abatement costs, and showed that for certain measures it is possible to reduce CO_2-emissions while also saving money. The majority of these studies examining the cost-effectiveness of different measures use their own estimates on the abatement effects of the measure. As discussed previously, these theoretical effects vary a lot from study to study.

When conducting the research connected with the first research question, the plan is to collect both the actual effect of different measures, but also examine the range of the effects presented in theoretical works. The results may then be used to examine the relationship between costs and gains of the different measures, with both their actual effect and a range of theoretical effects. From this, the cost-effectiveness may be discovered for a more correct set of data. The second research question sought to be answered in this master’s thesis is:

What is the cost-effectiveness of different retrofit measures, and what is the CO_2-abatement potential for a combination of such measures, considering both theoretical and actual data?

The contribution of this research is threefold. Firstly, a comparison between actual and theoretical effects may find discrepancies that may be of importance when considering which measures should be installed or further researched. If no such discrepancies exist, meaning that actual and theoretical effects are similar, this is also of interest due to the same reasons. Secondly, the development of marginal abatement cost curves is using present data on effects and fuel prices. Even though such curves have been created before, the updated data will be giving the curves developed increased relevance compared to previous ones. Finally, a discussion of implementation barriers and the possible solutions to remove them, may inspire the actors of the business to increase the efforts to reduce barriers and facilitate the implementation of fuel reduction measures in shipping.

The remainder of this thesis is organized as follows: Chapter 2 present the literature review, Chapter 3 presents the methodology, Chapter 4 contains the presentation and analyzation of the data collected, while Chapter 5 includes concluding remarks and some suggestions for future research.

2. Literature review

In order to examine the research questions stated earlier, a thorough literature review must be completed. Saunders et al. (2016) claim that critically reviewing relevant literature is important to provide foundation for the rest of the research. In a thesis such as this, where one of the main goals is to compare the theoretically estimated effects of different CO_2-abatement retrofit solutions with the actual effect of the same solutions, the need to review large parts of available research on each measure is of critical importance. A summary of the discovered effects is found in Table 1. If the reader wishes to know more details about the theoretical effects, associated costs or the technologies behind the measures, detailed explanations may be found in Appendix 1.

2.1 Definitions

Before the measure-related literature review, it may also be useful to identify and explain some key terms used throughout this thesis.

Retrofit solution

According to Cambridge Dictionary (2020), to retrofit is to provide a machine with a part, or a place with equipment, that it did not originally have when it was built. In this thesis, a retrofit solution is defined as a technical or operational solution which may be installed, attached, combined or performed on a vessel which is not done during the original building stage. The term is used widely to also include measures such as hull cleaning and propeller polishing, which would not usually fall under the term. For this research they have been included, as they are solutions possible to perform on the vessel after the initial building period and while the vessel is in operation.

Marginal CO_2-abatement cost

Marginal abatement cost is defined as the cost, in this thesis either in $ or in €, related to reduce the emission of the next tonne of CO_2 (Lindstad, et al., 2015). The marginal abatement cost is usually used to plot marginal abatement cost curves. Such curves have the marginal abatement cost on the y-axis, and the potential emissions reductions on the x-axis. A negative marginal abatement cost means that the abatement measure is cost-effective, and that CO_2-emission reduction may happen while saving money.

2.2 Individual retrofit solutions

A total of 15 different measures are being examined in this thesis. The measures are categorized into five sub-categories, namely hull shape, power and propulsion systems, alternative fuel and energy sources, operational measures and cleaning and polishing.

Hull shape

The first four measures to be examined relate to the shape of the hull or modifications done on the hull. These measures are hull retrofitting, hull coatings, air lubrication and propeller retrofitting. If the speed-draught profile the vessel is designed for changes, it may be beneficial to redesign parts of the hull to increase the efficiency of the vessel. Hull retrofitting involves installing either a bulbous bow, thrusters or performing bilge keel optimizations (Glomeep, 2020). Hull coatings, as the name implies, relates to the adding of different kind of coatings to the hull to reduce growth and decrease friction (Harrould-Kolieb & Savitz, 2010). The coating is usually categorized as either self-polishing or silicone-based, where the latter is both more expensive and believed to have greater effect. Air lubrication introduces a thin layer of bubbles released at the front of the hull which decreases the density of the water, and therefore also the friction between ship and water (American Bureau of Shipping, 2019). Another positive effect by air lubrication is that the bubbles reduce noise pollution and vibrations from the engine (Wärtsilä, 2020). If the operational condition of a vessel changes throughout its lifetime, a new propeller better optimized to the current operational condition may be retrofitted (Gougoulidis & Vasileiadis, 2015). The main area of focus in design of modern propellers is to restrict vortices.

Power and propulsion systems

Three measures considered belong to the category power and propulsion systems, namely waste heat recovery, shaft generator and propulsion improving devices. Waste heat recovery involves using the heat energy from the fuel combustion process to produce electrical energy which may be reused in main or auxillary engines (Virtasalo & Vänskä, 2011). The residual heat from this conversion process may also be used for hot water, heating etc. A shaft generator uses the rotational motion of the propeller to generate electricity, which may be used for auxillary engines or other electrical machinery (Farnsworth, 2019) While older models produced electrical energy at varying frequences due to speed and wave changes, newer models can produce at a constant frequecy, which is advantagous for the vessel’s electrical supply. Nozzles, bulbs, ducts and pre- and post-swirl devices are some example of propulsion improving devices, used in a variety of ways to increase propulsion efficiency (Hai-long et al., 2016). While the goal of a pre-swirl device is to manipulate the inflow of water to the propeller to reduce drag, a post-swirl device seeks to recover some of the rotational energy from the propeller slip stream and use this to increase propulsion.

Alternative fuel and energy sources

When looking at alternative fuel and energy sources, hybridization, wind propulsion and biofuel will be examined. Hybridization entails installing batteries which can help the engine to operate at optimal level even with fluctuating power needs. This is done by charging the batteries when the power need of the vessel is low and discharge when extra power is needed (Lindstad et al., 2017). By doing so, the engine may work at its optimal level, and the efficiency of the vessel increases. Kites, sails and Flettner rotors are examples of technologies enabling the use of wind for vessel propulsion (Glomeep, 2020). While kites and sails is are familiar technologies to many, Flettner rotors is an upright-mounted cylindar rotated by a motor. By using pressure differences caused by the wind and the rotational energy, the so called Magnus effect, the vessel is pushed forward (Tillig et al., 2015). By replacing or mixing fossil fuel with biofuels generated from biological materials, CO_2-emissions may be reduced (Bengtsson, 2011). First generation biofuel are usually produced by food, like grains and oil seeds processed into methanol. Second generation biofuel are created from forest and plant residues transformed into biodiesel, while third generation biofuel uses microalgae (Gilbert et al., 2014). This third generation of biofuel is currently in early stages of development.

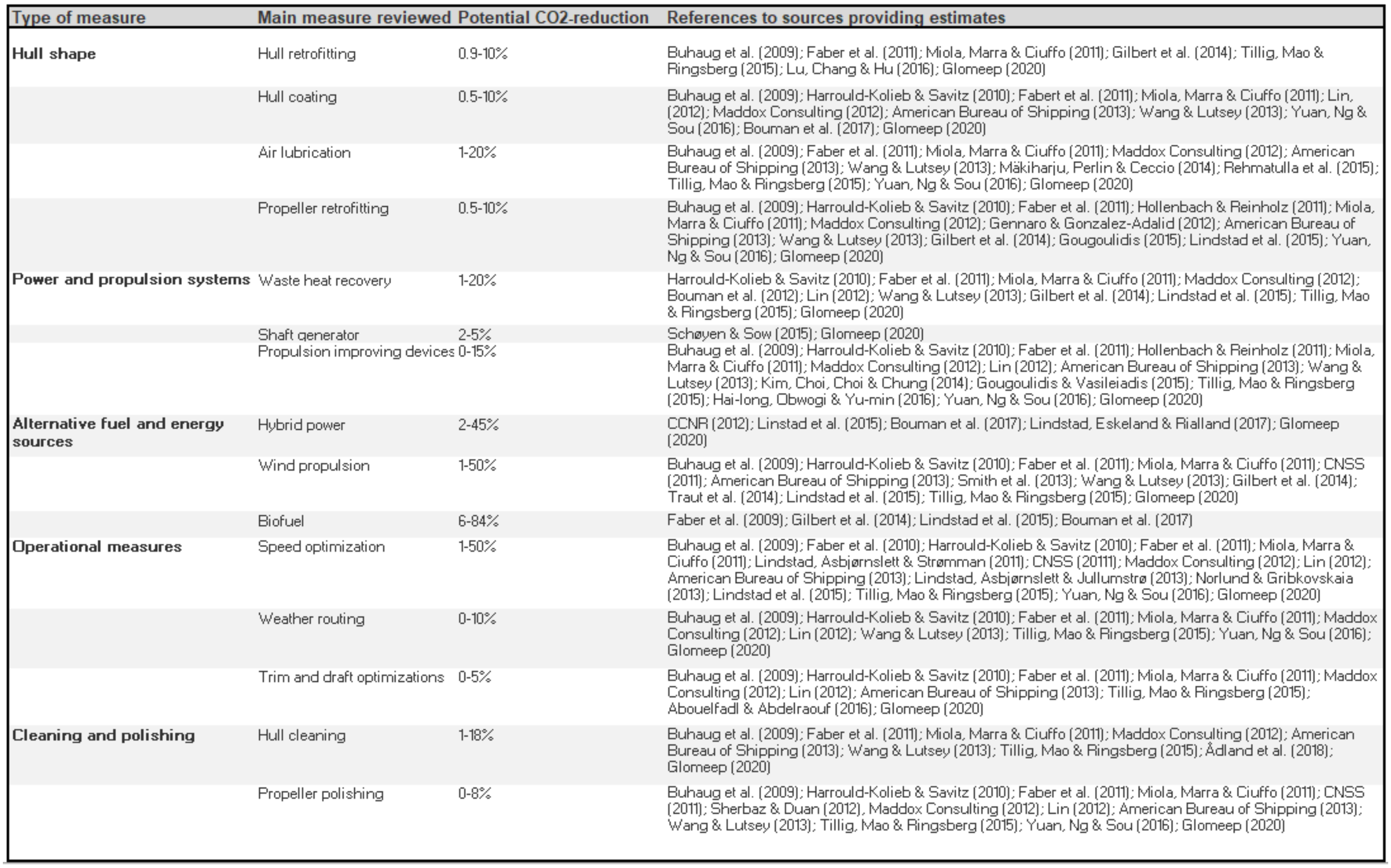
Operational measures

In this thesis, three operational measures are considered, namely speed optimization, weather routing and trim and draft optimizations. There is a cubic relationship between speed and fuel consumption, meaning that a 10% decrease of speed will lead to a 27% reduction in fuel consumption (Sherbaz & Duan, 2012). Considering that a vessel travelling at reduced speed will use longer time on a specific voyage, the net reduction from a 10% decrease of speed is a reduction of 19% in fuel consumption and CO_2-emissions (Harrould-Kolieb & Savitz, 2010). A vessel using weather routing optimizes its route by considering real-time weather and wave data to sail safer and faster routes (Maddox Consulting, 2012). The reduced time at sea, or the gain from avoiding to operate in rough weather and high waves leads to a reduction in fuel consumption. By optimizing the draft of the vessel, either by cargo planning at port or ballast water adjustments at sea, resistance may be reduced (Abouelfadl & Abdelraouf, 2016). Advanced softwares that may take wind, weather and sea state into account are available to further optimize the draft.

Cleaning and polishing

The last category to be examined is cleaning and polishing, consisting of hull cleaning and propeller polishing. The process in which biological organisms are removed from the hull of the vessels to reduce friction is called hull cleaning (Maddox Consulting, 2012). The cleaning may be done either manually by divers, or by using automated cleaners and may be done at anchor, at some ports and also in drydock. Propellers with significant growth may experience a loss in both frictional and rotational power (Sherbaz & Duan, 2012). As with the hull, propellers must therefore be polished regularly. The growth on both hull and propeller is usually greater when operating in warmer waters, when idle in port or in lay-up.

Table 1 on the next page is containing the measures examined in this review, along with their CO_2-reduction potential. An overview of examined studies connected to each measures is also found in the table. For more details regarding each measure, the reader is directed to Appendix 1.



Type of measure	Main measure reviewed	Potential CO2-reduction	References to sources providing estimates
Hull shape	Hull retrofitting	0.9-10%	Buhaug et al. (2009); Faber et al. (2011); Miola, Marra & Ciuffo (2011); Gilbert et al. (2014); Tillig, Mao & Ringsberg (2015); Lu, Chang & Hu (2016); Glomeep (2020)
	Hull coating	0.5-10%	Buhaug et al. (2009); Harrould-Kolieb & Savitz (2010); Fabert et al. (2011); Miola, Marra & Ciuffo (2011); Lin, (2012); Maddox Consulting (2012); American Bureau of Shipping (2013); Wang & Lutsey (2013); Yuan, Ng & Sou (2016); Bouman et al. (2017); Glomeep (2020)
	Air lubrication	1-20%	Buhaug et al. (2009); Faber et al. (2011); Miola, Marra & Ciuffo (2011); Maddox Consulting (2012); American Bureau of Shipping (2013); Wang & Lutsey (2013); Mäkiharju, Perlin & Ceccio (2014); Rehmatulla et al. (2015); Tillig, Mao & Ringsberg (2015); Yuan, Ng & Sou (2016); Glomeep (2020)
	Propeller retrofitting	0.5-10%	Buhaug et al. (2009); Harrould-Kolieb & Savitz (2010); Faber et al. (2011); Hollenbach & Reinholz (2011); Miola, Marra & Ciuffo (2011); Maddox Consulting (2012); Gennaro & Gonzalez-Adalid (2012); American Bureau of Shipping (2013); Wang & Lutsey (2013); Gilbert et al. (2014); Gougoulidis (2015); Lindstad et al. (2015); Yuan, Ng & Sou (2016); Glomeep (2020)
Power and propulsion systems	Waste heat recovery	1-20%	Harrould-Kolieb & Savitz (2010); Faber et al. (2011); Miola, Marra & Ciuffo (2011); Maddox Consulting (2012); Bouman et al. (2012); Lin (2012); Wang & Lutsey (2013); Gilbert et al. (2014); Lindstad et al. (2015); Tillig, Mao & Ringsberg (2015); Glomeep (2020)
	Shaft generator	2-5%	Schøyen & Sow (2015); Glomeep (2020)
	Propulsion improving devices	0-15%	Buhaug et al. (2009); Harrould-Kolieb & Savitz (2010); Faber et al. (2011); Hollenbach & Reinholz (2011); Miola, Marra & Ciuffo (2011); Maddox Consulting (2012); Lin (2012); American Bureau of Shipping (2013); Wang & Lutsey (2013); Kim, Choi, Choi & Chung (2014); Gougoulidis & Vasileiadis (2015); Tillig, Mao & Ringsberg (2015); Hai-long, Obwogi & Yu-min (2016); Yuan, Ng & Sou (2016); Glomeep (2020)
Alternative fuel and energy sources	Hybrid power	2-45%	CCNR (2012); Linstad et al. (2015); Bouman et al. (2017); Lindstad, Eskeland & Rialland (2017); Glomeep (2020)
	Wind propulsion	1-50%	Buhaug et al. (2009); Harrould-Kolieb & Savitz (2010); Faber et al. (2011); Miola, Marra & Ciuffo (2011); CNSS (2011); American Bureau of Shipping (2013); Smith et al. (2013); Wang & Lutsey (2013); Gilbert et al. (2014); Traut et al. (2014); Lindstad et al. (2015); Tillig, Mao & Ringsberg (2015); Glomeep (2020)
	Biofuel	6-84%	Faber et al. (2009); Gilbert et al. (2014); Lindstad et al. (2015); Bouman et al. (2017)
Operational measures	Speed optimization	1-50%	Buhaug et al. (2009); Faber et al. (2010); Harrould-Kolieb & Savitz (2010); Faber et al. (2011); Miola, Marra & Ciuffo (2011); Lindstad, Asbjørnslett & Strømman (2011); CNSS (20111); Maddox Consulting (2012); Lin (2012); American Bureau of Shipping (2013); Lindstad, Asbjørnslett & Jullumstrø (2013); Norlund & Gribkovskaia (2013); Lindstad et al. (2015); Tillig, Mao & Ringsberg (2015); Yuan, Ng & Sou (2016); Glomeep (2020)
	Weather routing	0-10%	Buhaug et al. (2009); Harrould-Kolieb & Savitz (2010); Faber et al. (2011); Miola, Marra & Ciuffo (2011); Maddox Consulting (2012); Lin (2012); Wang & Lutsey (2013); Tillig, Mao & Ringsberg (2015); Yuan, Ng & Sou (2016); Glomeep (2020)
	Trim and draft optimizations	0-5%	Buhaug et al. (2009); Harrould-Kolieb & Savitz (2010); Faber et al. (2011); Miola, Marra & Ciuffo (2011); Maddox Consulting (2012); Lin (2012); American Bureau of Shipping (2013); Tillig, Mao & Ringsberg (2015); Abouelfadl & Abdelraouf (2016); Glomeep (2020)
Cleaning and polishing	Hull cleaning	1-18%	Buhaug et al. (2009); Faber et al. (2011); Miola, Marra & Ciuffo (2011); Maddox Consulting (2012); American Bureau of Shipping (2013); Wang & Lutsey (2013); Tillig, Mao & Ringsberg (2015); Ådland et al. (2018); Glomeep (2020)
	Propeller polishing	0-8%	Buhaug et al. (2009); Harrould-Kolieb & Savitz (2010); Faber et al. (2011); Miola, Marra & Ciuffo (2011); CNSS (2011); Sherbaz & Duan (2012), Maddox Consulting (2012); Lin (2012); American Bureau of Shipping (2013); Wang & Lutsey (2013); Tillig, Mao & Ringsberg (2015); Yuan, Ng & Sou (2016); Glomeep (2020)

Table 1 - Summary of theoretical effects

3. Methodology

3.1 Interviews

In the preliminary research to this paper, I conducted several interviews with local shipowners. The reason for conducting these interviews was to explore the relevance of the measures included in the survey. It also provided the possibility of discovering new measures which were used in the business, but which I had not yet considered to include in my research. In total, seven interviews were conducted, where the fleet of the companies interviewed were dispersed both in size and in specialisation, allowing for some generalisation of the answers. The respondents were able to chose whether they wanted to be interviewed by telephone or face to face. Two interviews were performed face to face, while the other five were performed by telephone. Some of the shipping companies were located in a geographical distance which made face to face interviews problematic. During the interview phase, the start of the Corona pandemic broke out, which may have given several companies a preference for phone interviews instead of interviews face to face.

The interviews were conducted as semi-structured interviews. When conducting a semi-structured interview, the interviewer has a list of themes and some key questions to be covered (Saunders et al., 2016). The way the interviewer cover these topics and key questions may vary from interview to interview. According to Fylan (2005), semi-strucured interviews are great to ask the question *why*. During the interviews, one main aspect was to cover why the companies had chosen certain retrofit solutions, while disregarding others. An approach suitable for asking *why* was therefore of great help. Another important aspect of the interview process was to allow the respondents to elaborate on topics and measures that they found important for the study. A semi-structured technique is also well suited in order to accomplish this (Longhurst, 2010; Saunders et al., 2016).

All respondents were positive explaining their rationale behind the implementation or the lack to implement different retrofit measures. This insight confirmed the importance of the measures I had already identified, but the respondents also made me aware of other solutions thereby broadening my list of retrofit measures. The willingness to share actual effects of the different measures varied a lot. In one end of the scale, one company shared their opinion, calculation and measured effect on all measures that had been considered. Other companies were reluctant to share even an estimation of the effect they experienced.

3.2 Survey

In order to being able to explore the scope of this study, namely the implementation rate and the effects of different retrofit measures, I decided to create a survey. According to Saunders, et al. (2016), a survey is a good way to collect standardized data from a large population. The shipping business is a very international business, and the large geographical distance between the researcher and the respondents, as well as between the respondents themselves, led to the decision to utilize a questionnaire to complete the survey.

The questionnaire itself was divided into four parts. The first page of the questionnaire had questions relating to the shipowner's company, how many vessels they have, the vessel types and sizes and their trading pattern. These were closed-ended questions, meaning that they limited the respondents to a set of alternatives being offered (Reja et al., 2003). The respondents were then asked a number of category questions, where the shipowners were asked to indicate whether they have retrofitted, are planning to retrofit or has chosen not to retrofit the measures examined. Category questions are designed such that the respondent's answer may only fit into one of the categories (Saunders et al., 2016). Based on the answers in this part, the next bulk of questions was presented for the respondents. If they had implemented or were planning to implement a certain measure, they would be asked to indicate which effect this had on main engine fuel consumption. The alternatives were presented as closed-ended percentage intervals. These intervals were based on information gathered from the literature review and the interviews, and standardized to give data which could be easily compared between the measures. For the measures where the shipowner had indicated that they had not implemented, the reason for this decision was examined. This was done through partially closed-ended questions. Such questions are in essence closed-ended where the respondents are given alternatives, but which also gives the respondent the opportunity to enter his/her own answer under an "Other, please specify"-option. This gives the respondent the possibility to include answers that they consider important, or which may have been forgotten by the researcher (Taylor-Powell, 1998). The extensive use of close-ended questions makes the data easier to aggregate, and is well suited for comparisons (Saunders et al., 2016).

The survey was distributed in two different ways. Firstly, it was shared on an internationally renowned professor’s private LinkedIn profile. By doing this, it was possible to utilize his vast network, and therefore being able to diversify the responses that were collected. In addition to this, the survey was distributed by email to members of the Norwegian Shipowners’ Association. The organization had 133 members per April 2020 (Norwegian Shipowners' Association, 2020), and all members related to shipping were contacted. This led to about 30 responses, or a reply rate of around 22%. According to Saunders et al. (2016), a likely response rate when doing web and mobile questionnaires is around 10%, so a rate of 22% is considered acceptable. In total, 41 responses were fully recorded. As this is a cross-sectional study, it will only provide a snapshot of the outcome and the associated characteristics at a specific point in time (Levin, 2006).

4. Analysis

The analysis part of this thesis will be split into two different main parts. In the first part, the data gathered in the survey about the different retrofit measures will be compared to the theoretical data of the same measures presented in the literature review. The most important question to be answered is, to what extent the actual effects of the measures are similar to the theoretical effects. If there are significant differences in these effects, they might help to explain the number of users of the measures. This relates to the other important question which is sought to be answered in the first part of the analysis, namely to which extent the different measures are being used in practice.

In the second part of the analysis the data recorded from both literature and the survey and interviews will be analysed in a more economical term. Through net present value estimations, using investment costs, operational costs and the saved fuel costs of the different measures, the marginal CO_2-abatement costs for every measure have been estimated. By making sixteen such estimations, I have been able to compare the abatement costs both between theoretical and practical effects, but also at different price levels and for different vessel types. From the marginal abatement costs, I have further estimated the global CO_2-savings in both percentages and absolute terms in several “no regret”- and “zero cost”-scenarios.

In addition to this, different implementation barriers will be presented and discussed. This may help explain why measures are not implemented, even though they may be both economically viable as well as reducing CO_2-emissions. The actors in the industry have different ways to try to reduce these barriers, and some of these possibilities are also presented and discussed.

Before starting the discussion of the different measures it may also be interesting to examine some characteristics of the companies responding to the survey. By examining these in connection to their responses regarding implementation of measures, it is possible to gain an even deeper understanding of the questions sought to be answered in this thesis.

4.1 Categorical data

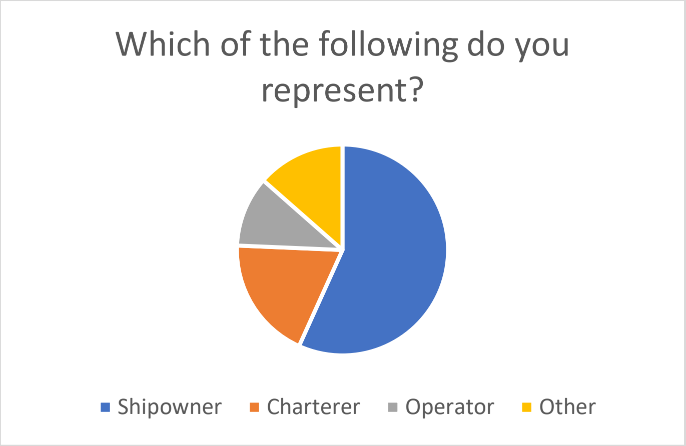


Figure 1 - Role of respondents

As seen from Figure 1, more than 50% of the respondents to the survey were shipowners. This is beneficial for the rest of the analysis, as shipowners often are the ones responsible for making investment decisions, and in many cases also are the one running the ship. Around 20% of the respondents are charterers, and it is also interesting to see whether their responses differ in comparison to that of the shipowner. As will be discussed in section 4.5.5, the interaction between shipowners and charterers are of particular interest when it comes to investment decisions.

The majority of the companies responding to the survey are headquartered in Norway. This comes as no surprise, as the survey was distributed to every member of the Norwegian Shipowners' Association. In addition to the Norwegian companies, around 25% of the respondents are located in Northern-Europe and a little more than 10% in Asia. Responses were also registered from companies originating in Southern Europe, North America and the Caribbean. Even if the respondents' headquarters are mainly located in Norway and Northern Europe, the fleet operates a lot more internationally. As seen from Figure 2, almost 60% of the respondents indicate that their fleet operate worldwide. This is an advantage for the further analysis, as regional weather effects like currents, winds and waves are less likely to influence the measured effects of the different CO_2-abatement measures.

Figure 2 - Areas of fleet operation

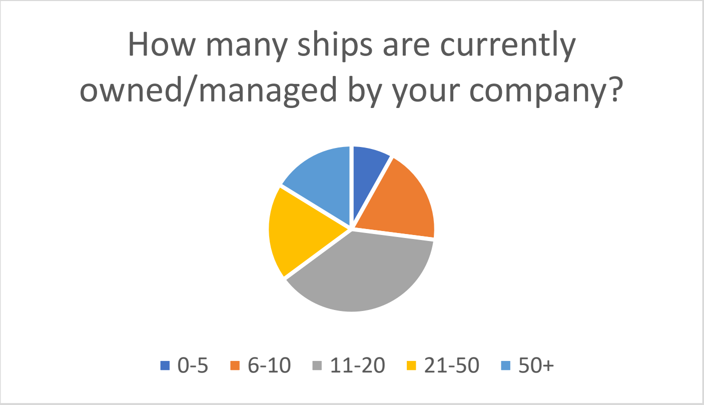


Figure 3 - Number of vessels owned/operated

The distribution in number of vessels administrered by each company and their respective sizes are also of interest. As seen from Figure 3, the size of the companies are fairly dispersed, but with most companies having between 10-20 vessels. This is important in several ways, as potential differences in implementation rate may be connected to company size. It may be that small companies are more agile, and therefore quicker to response if exiting solutions appear. On the other hand, it may be that larger companies have more capital and dedicated personnel to work with fuel reduction solutions. If so, the implementation rate will be higher for larger companies. Indeed, this seems to be the case. Of the companies that have implemented four or more measures, more than 60% own more than 10 vessels, and more than 90% own more than five. This effect becomes even clearer when considering companies with five or more implemented measures. Of these companies, over 70% own more than 20 vessels. Regarding vessel size, around 50% of the fleet of the respondents consist of vessels in the range of 30,000-120,000 dwt. Only about 10% of the vessels are larger than 120,000 dwt, while as much as 20% of the vessels are smaller than 10,000 dwt. The distribution of vessels sizes seem to align quite well compared to the numbers of the actual world fleet (Smith, et al., 2014).

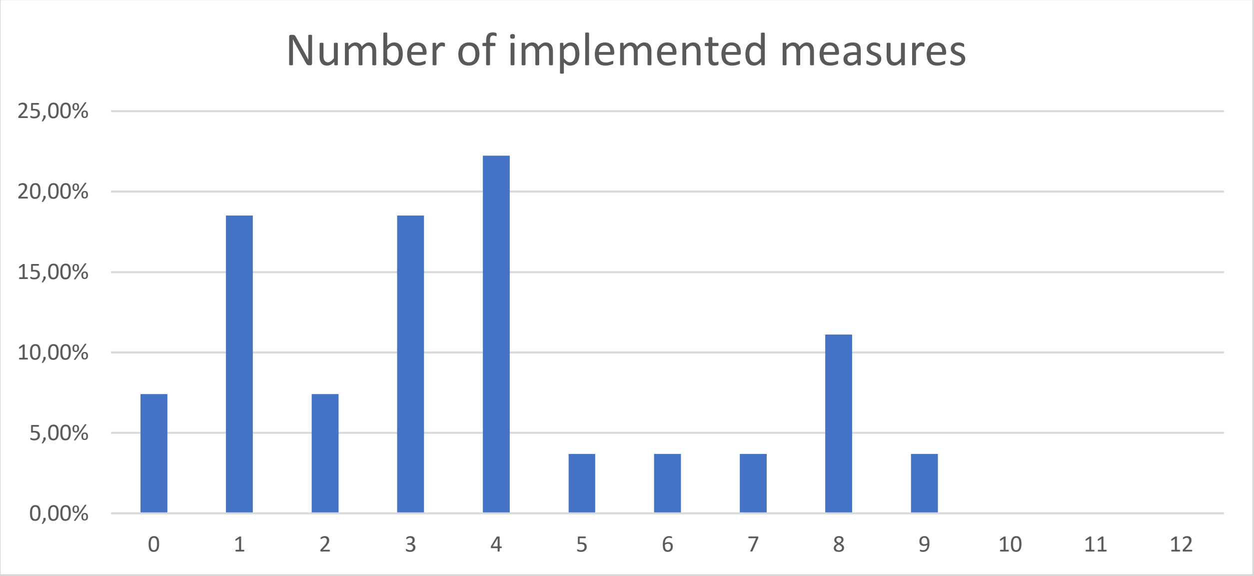


Figure 4 - Number of implemented measures

Figure 4 shows the number of different measures implemented by the companies responding to the survey. As seen, more than 90% of the companies have implemented one or more CO_2-abating solutions. 75% have more than one measure implemented, and the most common numbers of measures are 3 and 4. This may be the cause of some uncertainty in the analysis, as additive effects are ignored. Additive effects relates to the estimation of combined effect of two or more solutions. As an example, it is not given that adding two measures reducing fuel consumption by 2% when viewed isolated, automatically will lead to a 4% reduction when combined. Additive effect and the uncertainty it creates will be further discussed in section 4.7.3. As some of the measures are less likely to be combined, as wind power and biofuel, it is not surprising that no company have more than nine solutions implemented.

4.2 Individual measures – effects and prevalence

As part of the survey, the respondents were asked to indicate whether they have retrofitted, are planning to retrofit or has chosen not to retrofit the different measures. Those who had, or were planning to implement a certain measure were asked about the effect they had seen, or were expecting to see. If a shipowner indicated that they had chosen not to retrofit a measure, they would also be asked to indicate why they had made that decision.

In Figure 5 the responses for the question “Have you retrofitted these measures to one or more of your vessels?” are being presented. As witnessed from the chart, only three measures have more than around 50% implementation rate. These measures are hull coatings, trim and draft optimization and weather routing. A common denominator of these measures is that they are relatively cheap, making them more applicable for smaller vessels as well as the larger ones. Of the measures with the lowest implementation rate, we find air lubrication, propeller retrofitting and wind propulsion. While large investment cost are related to both air lubrication and wind propulsion, this is not necessarily the case for propeller retroftting.

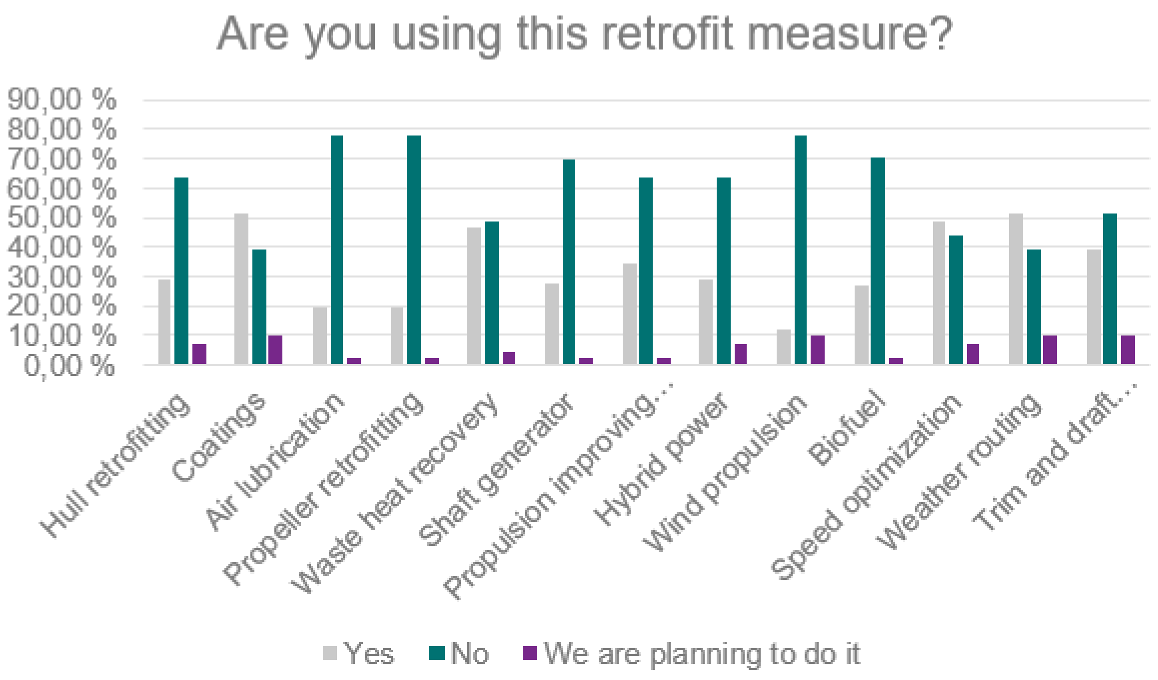
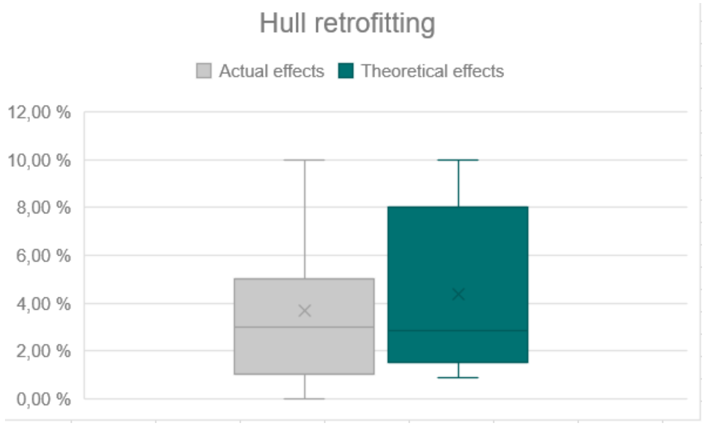


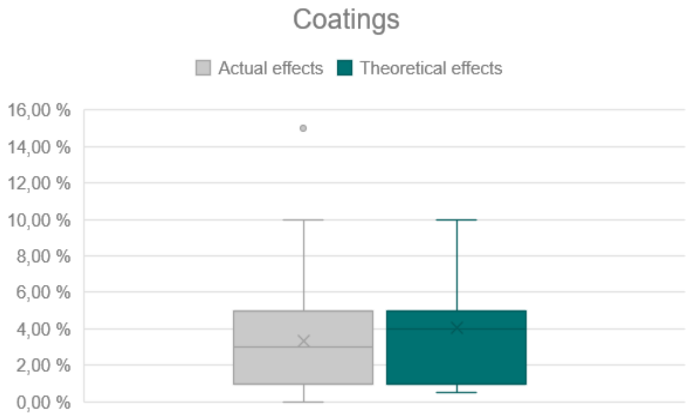
Figure 5 - Use of retrofit solutions

For the next part of the analysis the individual measures will be discussed. The differences in effects will be illustrated in box plots. The solid grey boxes indicate the interval where most observations are recorded and include the median of the data. For some boxes, whiskers are included to show observations exceeding the main interval. In a few of the charts singular points will be found outside the boxes and whiskers. These observations lie more than 150% above or below the median value. They are not values which may be ignored, but should be treated with caution.

Hull retrofitting



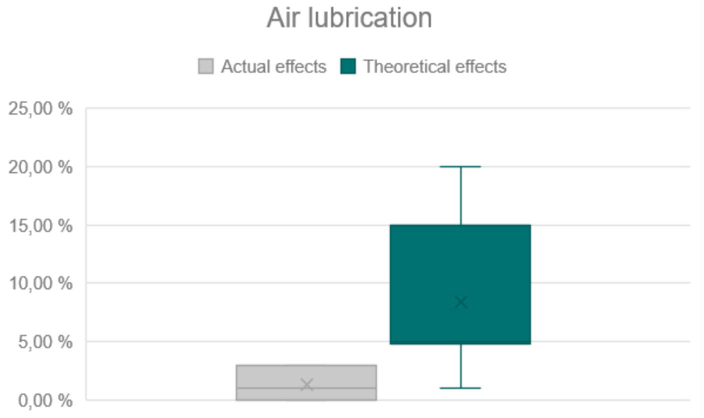
Of the hull retrofitting measures, installing a bulbous bow is performed 50% of the time. This is the effect with the largest abatement potential, but also the most expensive of the measures. Thrusters are used by 30%, while bilge keel optimizing is done by around 20%. The actual effects are in the lower intervals of the theoretical one, but with a median abatement potential of about 3%. Most of the owners which have not done any retrofitting to the hull say that it is due to the age profile of their vessels. This may be viewed in two ways. Firstly, it may be that the vessels are so old that great investments in a bulbous bow would be uneconomical. This does not explain the lack of investment in the cheaper options like thrusters and bilge keel optimizations. A different way of looking at the "age profile"-responses is also indicated by one respondee. If the vessel is fairly new, the hull is most likely still optimized to the current operational situation, and retrofitting measures are therefore not necessary.



Hull coatings

As hull coating is one of the most popular abatement measures, it is not surprising that the actual effect is somewhat similar to the theoretical. An interesting observation is that the range of effect is quite large for both intervals. Even if the main part of the obervations lay in the region of 2-4%, there are several observations from 0-10%. Responses as high as 15% were reported. A possible reason for the large interval may be that different types and price ranges of coatings give different effects. One of the interviewees explained that they had gained considerably greater effect by changing a cheaper coating for a more expensive one. It was claimed that you get what you pay for. There is not a unified feeling about this issue, and several respondents of the survey said that they experienced no effect, and even when trying many different types of coatings struggled to measure any differences. Another shipowner claimed in the interview that the effect of hull coating is very connected to the size of the vessel. In order to make the hull coatings even more effective, one company said that they sand blasted the hull before applying the coating. This had led to very good fuel reduction results.

Air lubrication

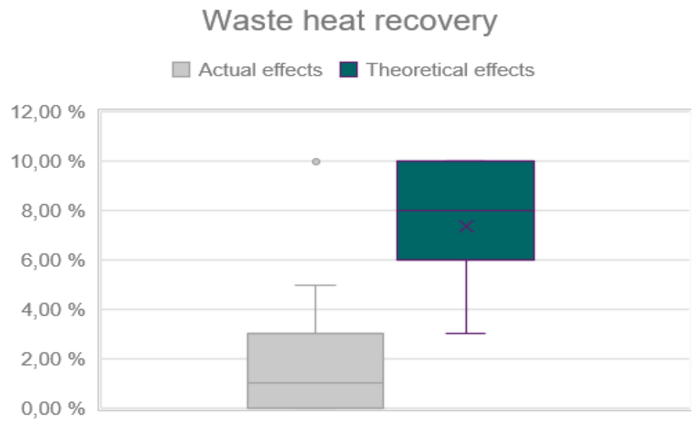


When watching the figure on the right one may understand why air lubrication is one of the least favoured abatement measures considered in this study. Compared with the theoretical estimate of 5-15%, air lubrication provides a relatively low actual effect of 0-4%. When considering the high investment and operational cost of running such systems, pointed out by several in the survey, the difference in effect becomes concerning. Another reason for the low installation rate may also be that the technology is fairly new, and also difficult to understand. As much as 25% of "No"-respondents explain that they are not familiar with the technology itself. The combination of expensive and unfamiliar may scare smaller companies away even with a high theoretical effect. The distribution of vessel types in the response group may also influence the responses, and as one respondent pointed out; air lubrication works better on wider vessels with less draft.

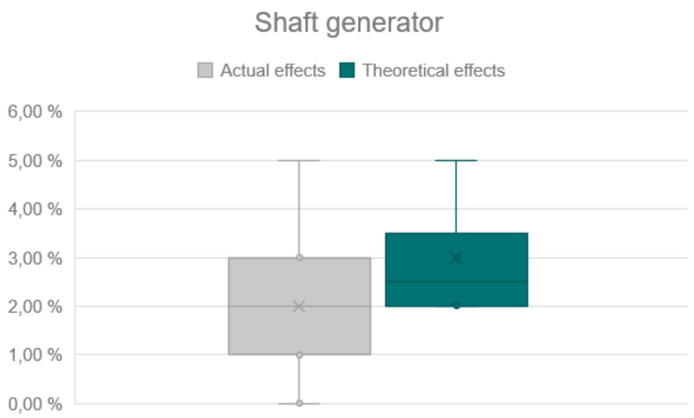
Propeller retrofitting

While the interval of theoretical effects are quite wide, this is not the case for the actual effects. An abatement potential of 1.75-4.25% is mostly within what the literature predicts. Even so, propeller retrofitting is not a very popular measure, and only around 20% of the respondents said they have considered or are considering to perform it. The reasons for not performing propeller retrofitting vary, but high cost, low effect and age profile of vessels are the most common answers. The fact that both literature and actual data shows significant effects quite far from zero, may lead to this being a more interesting prospect in the future. Regarding age profile this may be seen in two ways, as discussed previously in regards to hull retrofitting.

Waste heat recovery



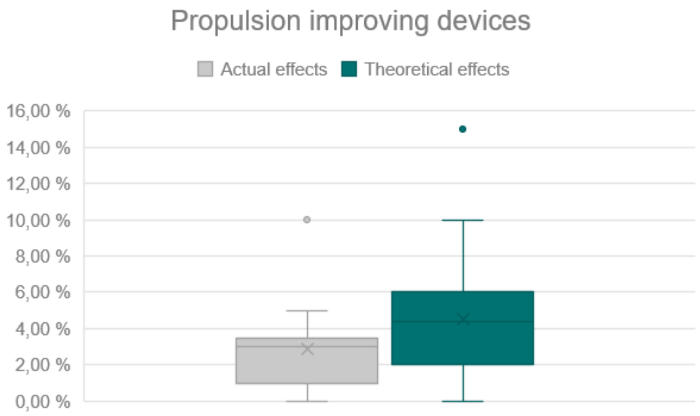
As seen by the figure on the right, there is a significant discrepancy in the reported effect of waste heat recovery compared to theoretical effects. As much as 40% of the respondents with waste heat recovery installed claimed that they had experienced no effect in fuel consumption. Despite this, waste heat recovery appears to be one of the most popular measures in terms of implementation rate. This may seem counter-intuitive as waste heat recovery also is one of the most expensive abatement measures. The most common response from shipowners that have chosen not to install waste heat recovery systems is that it does not suit the age profile of their vessels, while costs and effects are less common. From these answers one may wonder if shipowners without the technology believe that the the cost related to the believed effect is acceptable, and that only short life time of vessels prohibits the investment. Future research could investigate whether these assumptions are considering the theoretical or the actual effect of the implementation. Responds may be very different if expected values are between 0-3%, and not 6-10%.



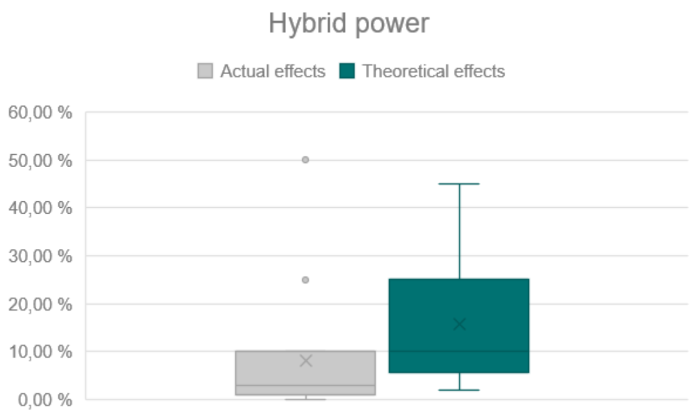
Shaft generator

According to Table 1 in the literature review, and the boxplot to the left, the theoretical effect of installing and using a shaft generator should be between 2-5%, with a most likely estimation between 2-3.5%. From the data recorded, the difference between actual and theoretical data is not very large. However, even with both a practical and theoretical positive effect, only around 30% of respondents had chosen to use shaft generators. The main reasons given for not installing a shaft generator were that it was too expensive and that the investment was not suitable for the age profile of the vessels. This do not concur with the repayment schedule of Schøyen and Sow (2015) of 3.5 years. A possibility is that the respondents that answered this on average have smaller vessels, and that the repayment in their cases therefore becomes longer. Around 15% of the respondents that answered "No", commented that the shaft generator was already implemented when they bought new vessels. This may indicate that the measure is considered as a good one, but that investment cost may elimate older, smaller vessels from choosing to retrofit it.

Propulsion improving devices



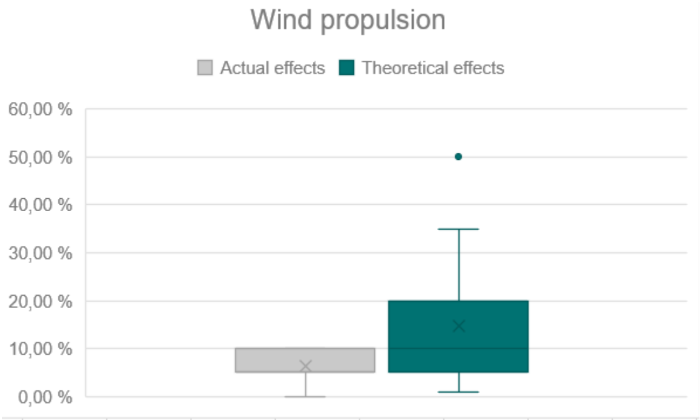
When it comes to the different propulsion improving devices examined, fins (pre-swirl/post-swirl/boss caps) are the most popular, and almost 60% of installed devices are in this sub-category.The actual effect is, also for this measure, in and slightly below the interval for the theoretical effect. As seen by the plot, outliers exist in both estimates, creating some uncertainty of the actual abatement potential. The reasons for not installing the devices vary a lot, and both age profile, too expensive and technical limitations are often answered. During the interview it was also mentioned by several respondents that increased vibrations were a negative consequence of installing ducts.



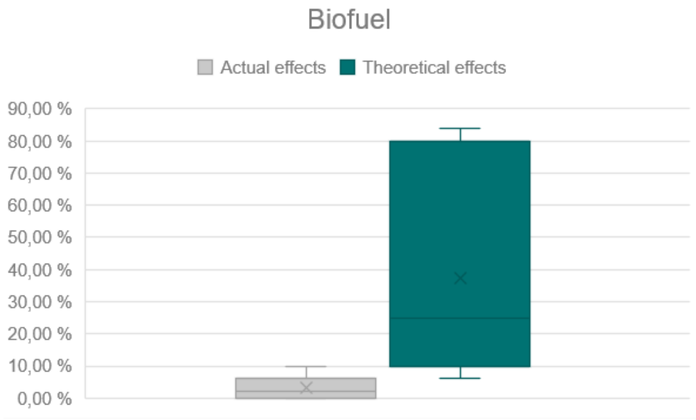
Hybrid power

The difference in effect between actual and theoretical data for hybrid power is one of the biggest in absolute terms. The median effect in the literature review is more than three times greater than the median in the actual data. The difference may be due to which extent the hybridization is implemented, in correlation to which extent the literature expects. If the main literature estimation is based on replacing main engines with electricity, and this is compared to companies reporting effect on replacing minor auxillaries this will obviously impact the results. Further studies may seek to examine this. One of the companies being interviewed informed that they had experienced a 30% reduction in CO2-emissions by replacing some of their diesel-engines running on low effects with batteries. Even if the return on investment was only around five years, the investment itself was huge, and may stop smaller companies with less liqudity from doing the same.

Wind propulsion



Of the companies responding to the survey using wind power propulsion, 50% use Flettner rotors while 50% use kites. The effects reported are between 0-10%, but the average is as high as 6.43%. Still, it is in the lower region of the theoretical interval. Even with a fairly high abatement potential, wind propulsion is the measure with the lowest implementation rate of just below 20%. A reason for this may be its high investment cost, and with Flettner rotors quite a substantial structural change of the vessel. Indeed, both the technical difficulties and the cost is the two most common reasons for not installing systems for wind propulsion. In the interviews, several respondents thought that wind propulsion was an exiting option for the coming years, and some had even decided to install such systems in the near future. The companies that did not consider this, gave vessel type as the reason for not doing so. A company running time charters on their vessels, claimed that time for installation and testing was too long for them, but that they were actively observing other companies in similar business which had the solution installed. Wind propulsion in commercial shipping seems to be an immature technology with an exiting potential in the coming years.

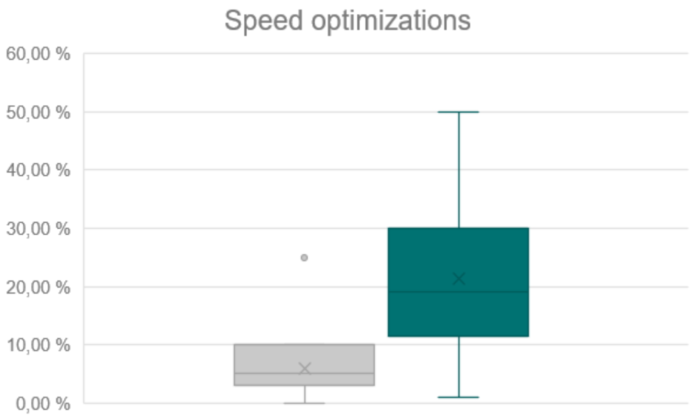


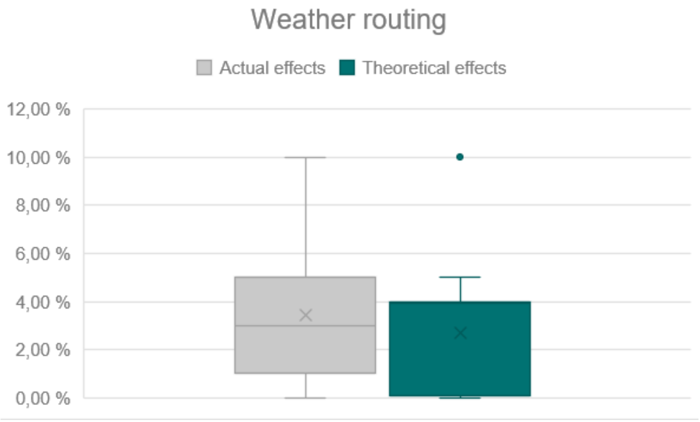
Biofuels

The largest difference in actual and theoretical CO_2-abatement potential is found when looking at biofuel. The average actual value is only 3.17%, compared to 37.14% for the theoretical average. As with hybridization, it may be that there is a difference in the way biofuel is used in real life compared to in the literature. If the literature has estimated CO_2-abatement potential from running on only biofuel, while respondents are running on a mix of biofuel and fossil diesel this may explain the big gap in effect. Another possibility may be that the respondent fails to consider the net CO_2-reduction, and answers in relation to a form of gross reduction of fuel consumption. Still, almost 25% of the respondents said that they had the option of running on biofuel. Of them, 85% said that their biofuel of choice was biodiesel, while the remaining 15% use ammonium. Of the respondents that do not have a biofuel option, many said that they did not think it would reduce consumption. Even more respondents pointed out the fact that the main obstacle from changing to biofuel, was the lack of worldwide availability and enough supply of fuel. This was also mentioned by several respondents in the interview process. Some also mentioned potential problems with increased bacteria growth if changing to biofuels.

Speed optimization

The actual effect of speed optimizations and speed reductions are quite a lot lower than the theoretical effects. As mentioned previously, there is a fairy large portion of owners of smaller vessels responding to the survey. According to a respondent in the interviews, it was said that the effect of speed reductions are greater in larger vessels. This fact is also discussed by Wang and Lutsey (2013). Even so, the average reduction in fuel consumption is 5.97%, which is a substantial amount without any investment costs occured. Some companies informed that they had invested in speed optimizing systems, which could advice on optimal speed. If the system estimated the vessel would not reach a certain point of the journey at optimal tide, it would slow down, save fuel and arrive at the optimal time instead of waiting upon arrival. Of the companies running at full speed, the most common reason was that they did not think it would reduce fuel consumption. This is most likely linked to the size of the vessel and voyage specific reasons, rather than a general disbelief in the connection between speed and fuel consumption.

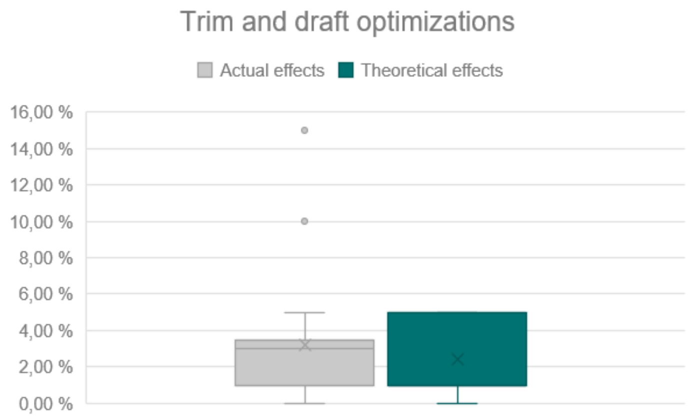




Weather routing

Weather routing is one of two measures considered in this thesis, where the actual effect seems to be higher than the theoretical effect. The average reduction in CO_2-emission with weather routing is 3.42%, compared to the theoretical average of 2.71%. As seen from the plot, effects as high as 10% has been reported. Odfjell (2020) reports savings of $18,000,000 while reducing CO_2-emissions of 48,605 tonnes by using weather routing over the last decade. This might help to explain that weather routing is the most used measure in this survey. The respondents in the survey and in the interviews that do not run weather routing programs, say that fixed routes and/or short voyages make changes due to weather less useful. There is a difference in how implemented and complicated weather routing systems are from shipowner to shipowner. Some are running full simulations, optimizations and rely heavily on the feedback from the systems. Others let the captain decide the route based on his/hers experience, and only use the input from the weather routing systems as recommendations.

Trim and draft optimizations



From the box plot it may seem like the actual effect of trim and draft optimizations are lower than the theoretical effects. However, when looking at the numbers, the average effect is actually higher in the actual data than in the theoretical, with 3.22% versus 2.45% respectively. When you look closer at the box plot it becomes clear that the outliers of 10-15% are pulling the average up. Trim and draft optimizations are fairly popular, and around 40% of the respondents indicated that they use it. From some of the interviews, trim and draft optimization were presented as one of the most important tools for fuel reduction. For some vessel types, trim and draft optimizations may be impossible to perform due to stowage prioritations. This is the most common answer by those without such systems. In addition to this, almost 30% believe trim and draft optimizations do not have any fuel reduction effects.

Cleaning and polishing

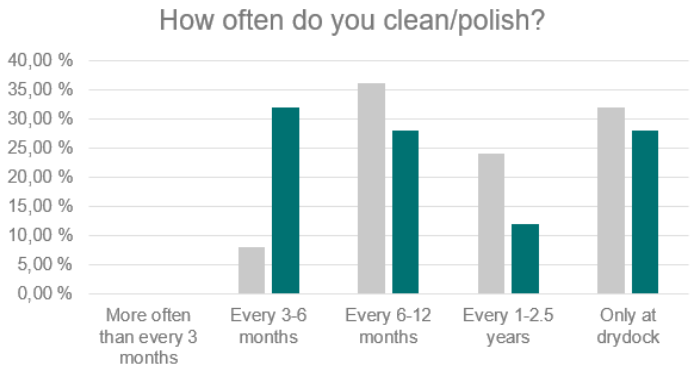
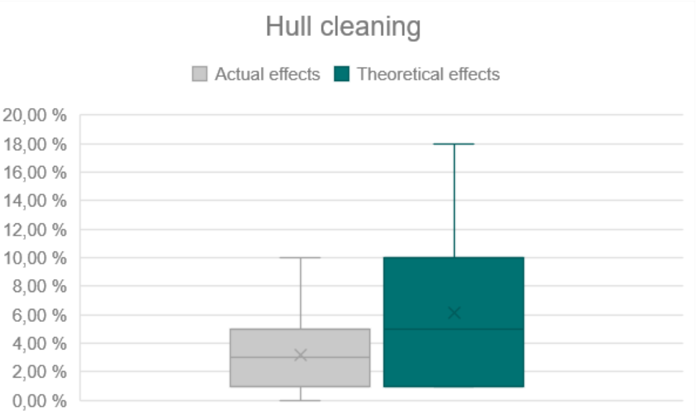


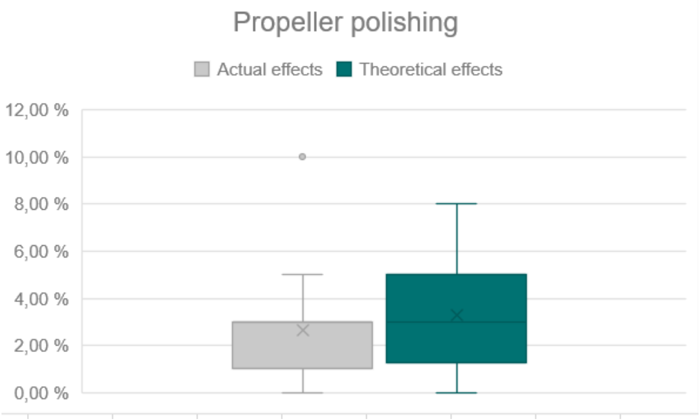
Figure 6 - Intervals of cleaning and polishing

The respondents were asked questions regarding hull cleaning and propeller polishing. These measures are, unlike most of the others, done on a fairly regular basis, and do not have initial investment costs related. Figure 6 displays the distribution of answers regarding at which intervals hull cleaning and propeller polishing are performed. As seen in the plot, no companies wash more often than every third month. While propeller polishing may happen on a quarterly basis, most hull cleaning is not done more often than semi-annually.

Hull cleaning



As with many of the other measures, hull cleaning has an actual effect in the lower part of the theoretical interval. The average effect seen in the actual data is 3.16%, compared to 6.16% for the theoretical. The lower effect may be due to that a majority of the companies responding to the survey run in colder waters with lower growth. As much as one third of the respondents gives this as a reason for not cleaning the hull more often. Another aspect worth considering was brought up in several interviews, whereby spending a lot of money on expensive hull coatings while doing frequent hull cleanings may be counter productive. By cleaning often, coating and other hull protecting substances may be removed more rapidly, leading to higher fuel consumption overall. Other arguments for not cleaning more often included too frequent interruption of trade, cleaning not available at all visited ports and that the cost of more frequent cleanings would outweigh the gain from reduced fuel consumption.



Propeller polishing

Even if propeller cleaning is less effective than hull cleaning, with an actual and theoretical effect of 2.63% and 3.28% respectively, it is still used more often than hull cleaning. In some of the interviews this was explained by pointing out that propeller cleaning was easier and quicker to perform than hull cleaning. If this was considered, propeller polishing could be even better than hull cleaning. By far, the most common reason not to polish more often, was that the increased cost exceeded the gains. Interestingly, the top reason for hull cleaning, namely running in low-growth waters, was the least common for propeller polishing. According to one of the interviewees, imperfections caused by cavitation when the propeller rotates, is a bigger factor than growth when it comes to when to polish.

4.3 Marginal abatement cost curve (MACC)

The marginal abatement cost curve shows the cost of reducing a tonne of CO_2 with the related abatement measure. Marginal abatement cost curves have been developed for sixteen different combinations of factors. These factors are related to vessel type, and bulk vessels, oil tankers, chemical tankers and container vessels were examined. There are curves where the abatement effect of the measures relies on data from the survey, and other curves where the effect is from the literature review. Finally, factors related to the fuel price is also included, and there are curves estimated at both the current fuel price of around $250/tonne , and also at a level of $500/tonne.

4.3.1 Assumptions and simplifications for MAC-curve

In order to create the abatement cost curves some assumptions and simplifications have been made:

- Data related to number of vessels in the different categories, their average fuel consumption and average CO_2-emission were found in the Third IMO Greenhouse Gas study (Smith, et al., 2014).
- In order to get a vessel specific estimate of fuel consumption, a weighted average of the data from the Third IMO GHG study was used. The study has originally split the main vessel types (bulkers, oil tankers etc) in smaller groups based on vessel size. For simplicity, in order to gain average fuel consumption information for a bulk vessel, a weighted average was taken between the subgroups in the IMO-study. As an

example, for the bulk vessel category the curves are based on the fuel consumption, CO_2-emission, investment cost and operational costs of an average sized bulk vessel. The range in vessel sizes in the subgroups means that the curves presented here may not relate fully to neither a very small vessel or as a very large vessel, even though they are the same vessel type. The curves must be seen as a simplified estimation. Further discussions around the uncertainties created by this simplification, may be found in section 4.7.4.

- To find the reduction in fuel consumption, an average of the data recorded is used. For the data collected from the survey, an average is taken from the answers related to the effect of the measure, while for the theoretical effect an average is taken from the claimed effects found from the sources covered in the literature review.
- Additive effects from combining several measures have been ignored. See section 4.7.3 for more information on the uncertainty this creates.
- A one tonne reduction in fuel leads to a 3.2 tonne reduction in CO_2-emissions (Statistics Norway, n.d.).
- The interest rate used for the NPV-calculation is 3%.
- According to Tillig et al. (2015), a shipowner prefer a payback time of investments of about 5-10 years. For the analysis, a lifetime of seven years has been used for most measures. For hull coatings which is often performed at drydock, a discount period of five years is used. Hull cleaning measures are estimated to have a lifetime of one year. When calculating for propeller polishing, the cost relates to both the cleaning itself, but also for a monitoring system enabling cleaning just when needed. Due to this additional investment, the propeller polishing NPV-calculation uses a life time of five years.
- In accordance with the estimation of Taljegard et al. (2014), the price of biofuel is around 25% higher than the price of ordinary bunker. For the analysis a bunker price of $625/tonne is used for biofuel. For the calculation a 10% net decrease in fuel consumption has also been used for biofuel.
- Wind propulsion is not included for container vessels, as they are not suitable for vessels travelling at more than 15 knots. For chemical tankers the wind propulsion estimates are only related to kites, while for oil tankers and bulkers both kites, wings and Flettner-rotors are considered.

- Speed reduction is not considered in the MAC-curves in this thesis. The reason for this is split in two. Firstly, it is difficult to calculate a marginal abatement cost on a vessel to vessel basis, as there is no single investment or operational cost directly linked to the reduction of speed. Secondly, a reduction of speed would highly influence the effect of all the other measures. This is not an argument not to consider speed reduction as a possible CO_2-reducing measure, but it is disregarded in this analysis.

4.3.2 Calculating the marginal abatement cost – example

In order to understand the calculations needed to provide a marginal abatement cost, the formulas used will be presented first. In addition, a numerical example using the data from propeller retrofitting as well as the other estimations will be provided to ensure understanding of the methods used.

The first part of the calculation is to establish the average yearly cost saving of each vessel by implementing the measure. In order to do so, either the actual or theoretical effect is multiplied with the average yearly fuel consumption of the vessel type and the considered fuel cost level. As mentioned in the assumptions, the average yearly consumption is a weighted average of consumption data from the Third IMO Greenhouse Gas Study (Smith, et al., 2014).

$$Yearly\ cost\ saving\ = Estimated\ effect\ of\ measure\ x\ Avg.fuel\ consumption\ x\ Fuel\ cost$$

After finding the yearly cost savings, and through collecting information regarding the cost of implementing each measure, it is possible to calculate the net present value of the investment. The net present value is the future cashflows of the investment discounted with an appropriate interest rate, giving a net value of both benefits and costs at present money valuation. In the calculation used in this thesis, a positive NPV-value indicates costs greater than savings, while a negative NPV-value signifies a cost-efficient measure. The interest rate used in the calculations is set to 3%. The number of years used for discounting depends on the particular measure and is discussed in section 4.3.1.

$$NPV = Investment\ cost - \sum_{n=1}^{Lifetime} \frac{Yearly\ cost\ saving - Operational\ cost}{(1 + interest\ rate)^n}$$

The last step of the calculation process is to divide the net present value of the investment with the average CO_2-emission of the vessel. This average is found by multiplying the average yearly fuel consumption with a CO_2-coefficient. This coefficient states that one tonne of reduced fuel, leads to a 3.2 tonne reduction in CO_2-emission, in accordance with the information from Statistics Norway (n.d.).

$$Marginal\ abatement\ cost = \frac{NPV}{Avg\ fuel\ consumption\ x\ CO2\ coeffisient}$$

For propeller retrofitting on an oil tanker, using the average actual effect of 3% and fuel cost of $500/tonne, the calculation will be:

$$Yearly\ cost\ saving = 3\%\ x\ 3{,}547\ tonne\ x \frac{\$500}{tonne} = \$53{,}205$$

$$NPV = \$450{,}000 - \sum_{n=1}^{7} \frac{\$53{,}205 - 0}{(1 + 3\%)^n} = \$118{,}537.35$$

$$Marginal\ abatement\ cost = \frac{\$118{,}537.35}{3{,}547\ tonne\ x\ 3{,}2} = \$10{,}44\ per\ tonne\ CO2$$

4.3.3 Explaining the MAC-curve

The below marginal abatement curves (Figure 7 and Figure 8 on page 37) show the measures for a bulk vessel with a fuel cost of $500/tonne. The different measures are presented in order below the graph. The measures are read line by line, meaning the second best measure in the below curve is trim and draft optimizations, while hull cleaning is the fifth best. The value on the y-axis shows the marginal abatement cost for the different retrofit measures. For the measures which have a negative value, CO_2-reduction may be achieved while also saving money. For the actual data below, this is the case for weather routing, trim and draft optimizations, propeller polishing, hull coatings and hull cleaning. The width of bar represents the individual effect of each measure, so the broad bar of hybrid power means that this measure has a larger percentage CO_2-abatement potential than air lubrication which is much narrower. By reading the graph from left to right you may see the effects accumulating, meaning that the combined effect of implementing both weather routing, trim and draft optimizations and propeller polishing will give an effect of 9% as can also be read of the graph. This estimation disregards the uncertainties of additive effects (see Section 4.7.3 for more info). The graph also shows that the most cost-effective measure is furthest to the left, and as one moves to the right the measures becomes more expensive and/or less effective.

Four marginal abatement cost curves will be presented and discussed in this thesis. A collection of all sixteen curves, may be found in Appendix 2.

4.3.4 Comparison between actual and theoretical effects

Figure 7 and 8 show the marginal abatement cost curves for a bulk vessel with a fuel cost of $500/tonne, estimated with actual and theoretical effects respectively. As fuel price and vessel type in this comparison is fixed, the only reason the two diagrams differ is due to the different fuel saving effects between the survey/interviews and the literature review. The first obvious observation is that the reduction potential is much larger if theoretical data is used. From the data, there is a clear trend where the theoretical data estimates a higher average fuel reduction potential than the actual data. This becomes even more clear when viewing the biofuel bar in the theoretical chart. Biofuel has a theoretical average effect of 37.14%, compared to an actual average of only 3.17%. As dicussed in the previous part of the analysis, this may be related to different ways of measuring the biofuel effect. Another difference worth pointing out is the accumulated effect of cost effective measures. For the actual data, about a 12% reduction in CO_2 may be gained without using any measures with negative abatement cost. For the theoretical value this increases to 39%. A final thing worth noticing is that the combined potential effect in the theoretical curve exceeds 100%. This is obviously not practically possible. A likely reason for this is that the effects found in the literature review often is considered isolated, and simply adding the individual effects probably constitutes an oversimplification. This will be further discussed in section 4.7.3.

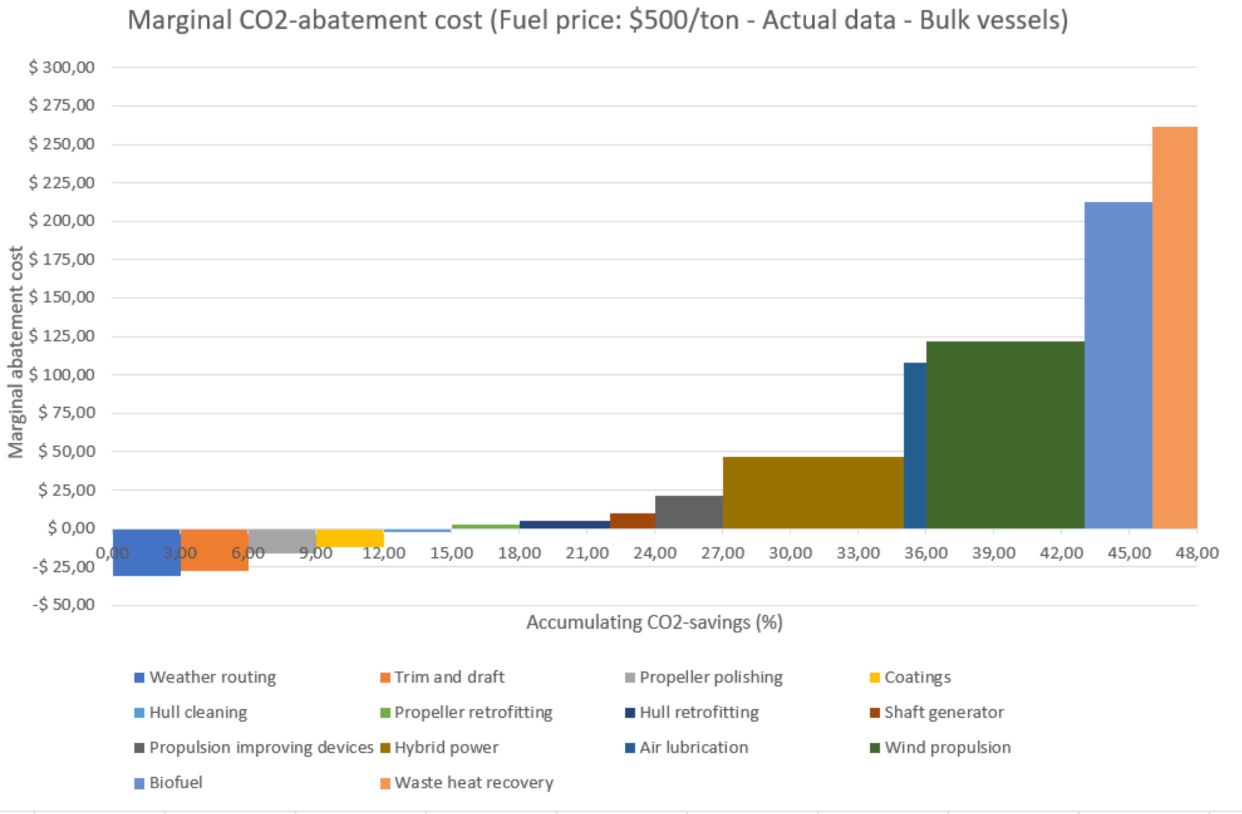


Figure 7 - Marginal abatement cost curve - Fuel price $500/tonne - Actual data - Bulk vessels

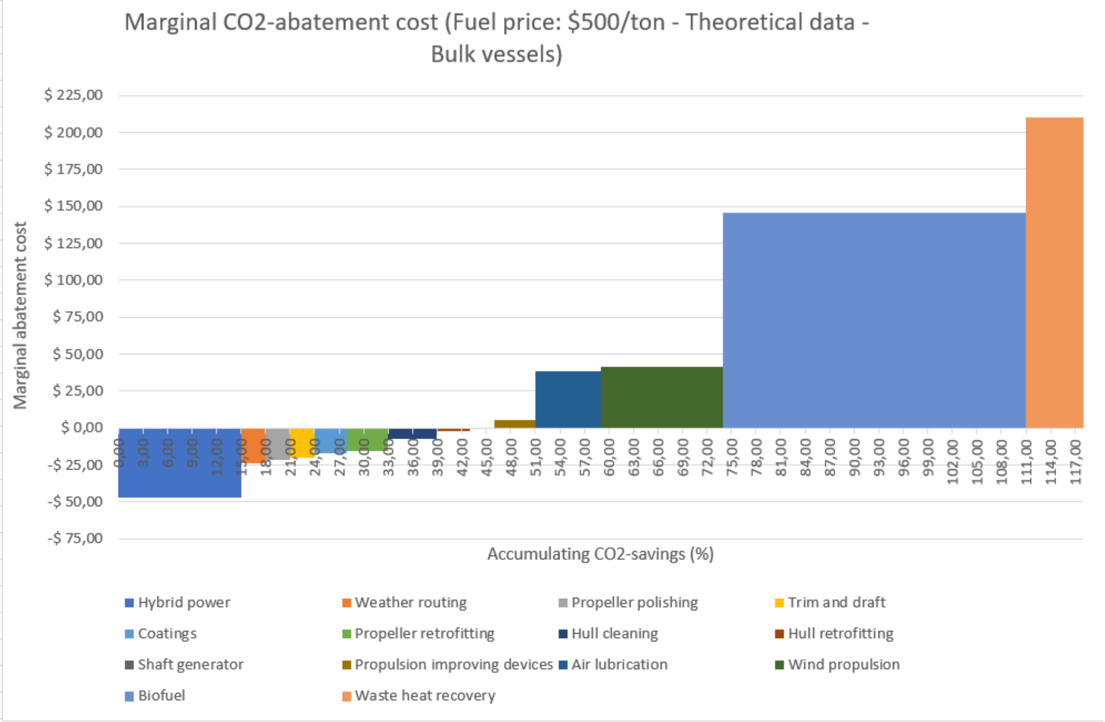


Figure 8 - Marginal abatement cost curve - Fuel price $500/tonne - Theoretical data - Bulk vessels

4.3.5 Comparison between different fuel prices

Figure 9 and Figure 10 show the marginal abatement cost curve for a bulk vessel with actual data, and with fuel prices of $250/tonne and 500/tonne respectively. The differences seen here are fairly self explanatory. As the price of fuel increases, the amount saved will also increase as long as the abatement potential is constant. The increased monetary savings from fuel cuts, leads to lower marginal CO_2-abatement costs and more measures become economically viable. The wider the bar, the larger the decrease in marginal cost when prices increase.

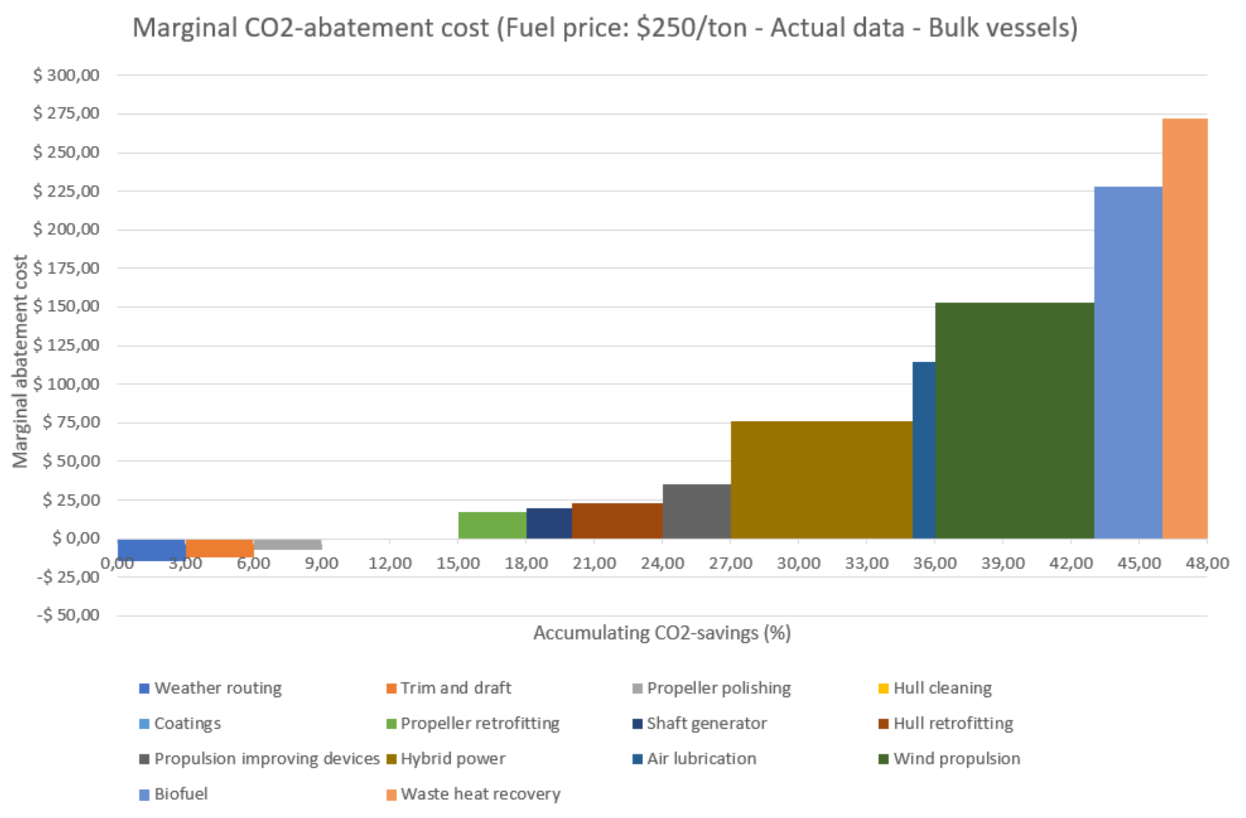


Figure 9 - Marginal abatement cost curve - Fuel price $250/tonne - Actual data - Bulk vessels

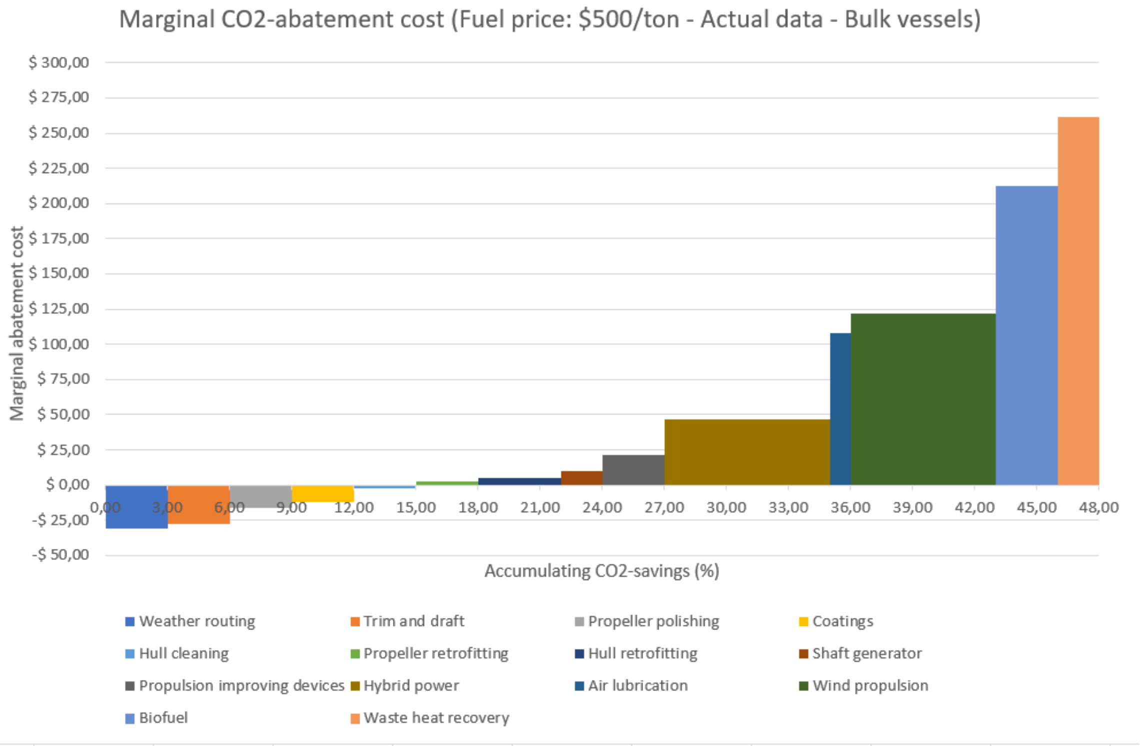


Figure 10 - Marginal abatement cost curve - Fuel price $500/tonne - Actual data - Bulk vessels

4.3.6 General observations from the MAC-curves

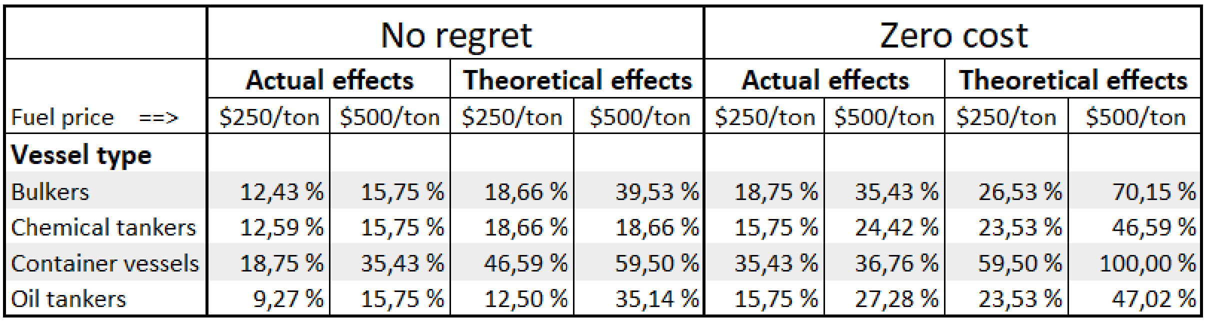
In addition to the differences seen in the MAC-curves by varying data source and fuel price, it is also possible to learn a lot by looking at the similarities between the curves.

By observing the measures with negative marginal abatement cost, one may notice that many of the measures are negative in several curves. In fact, weather routing, trim and draft optimizations and propeller polishing have negative marginal abatement cost in all sixteen scenarios. This means that these three measures could be implemented in all vessel types, and with all fuel prices above $250/tonne, and the shipowner would save money by doing so. On the other end of the curve we may in the same way observe that there are four measures that will not be economically viable for neither vessel types when looked at isolated, and with a fuel price of $500/tonne or below. These measures are waste heat recovery, air lubrication, biofuel and wind propulsion. All these measures have a high theoretical reduction potential, but the investment and/or operational cost of them are very much higher than the other measures. However, this does not mean that no shipowner should ever use them. As will be seen in the “Zero cost”-scenarios, when combining some of these measures with more cost effective ones, it is possible to implement them without increased costs for the owner.

4.4 Scenario analysis

In order to further evaluate the marginal abatement cost curves in a more comprehensive setting, the sixteen different curves will be used to create “No regret” and “Zero cost”-scenarios. In a “No regret”-scenario all of the implemented measures must be cost-effective on their own (Lindstad, et al., 2015). This means that the annual fuel saving, must be greater than the investment cost and any operational costs. In relation with the MAC-curves above, in a “No regret”-scenario only the measures on the left with negative abatement cost will be implemented. When constructing a “Zero cost”-scenario, in addition to the cost-effective measures from the “No regret”-scenario, measures that are not cost-effective are also added until the marginal abatement cost equals zero. Obviously it is not possible to partly retrofit an abatement solution, so when designing the scenarios, measures have been included until the point where the next measure will push the abatement cost above zero. Therefore, the "Zero cost"-scenarios presented will in practice actually have a more or less negative abatement cost.

Table 2 shows the different scenarios for both actual and theoretical data, fuel price of \$250/tonne and \$500/tonne, and for the four vessel types investigated.



	No regret				Zero cost			
	Actual effects		Theoretical effects		Actual effects		Theoretical effects	
Fuel price ==>	\$250/ton	\$500/ton	\$250/ton	\$500/ton	\$250/ton	\$500/ton	\$250/ton	\$500/ton
Vessel type								
Bulkers	12,43 %	15,75 %	18,66 %	39,53 %	18,75 %	35,43 %	26,53 %	70,15 %
Chemical tankers	12,59 %	15,75 %	18,66 %	18,66 %	15,75 %	24,42 %	23,53 %	46,59 %
Container vessels	18,75 %	35,43 %	46,59 %	59,50 %	35,43 %	36,76 %	59,50 %	100,00 %
Oil tankers	9,27 %	15,75 %	12,50 %	35,14 %	15,75 %	27,28 %	23,53 %	47,02 %

Table 2 - No regret and Zero cost-scenarios

As seen from the table, even at the low fuel cost of \$250/tonne, it is possible to reduce a large percentage of CO_2-emissions by using only cost-effective measures. If the cost-effective measures were installed on all vessels in the four vessel categories, and assuming that the effect gained is equal to the average effect reported in the survey, it would be possible to save 77,569,563 tonnes of CO_2 each year. By also allowing for certain uneconomical solutions, as is the case in the "Zero cost"-scenario, the amount increases to 132,088,776 tonnes of CO_2-reduced, without losing any money. This constitutes to a reduction of 2.95% of all CO_2-emissions from the European Union in 2017 (Eurostat, 2019).

The effect becomes even greater when looking at the situation at a fuel price of \$500/tonne. When still considering actual effects, the accumulated reduction in CO_2-emissions across the four vessel groups are 127,099,656 tonnes in the "No regret"-scenario, and 181,583,225 tonnes in the "Zero cost"-scenario. Compared to the EU-emissions the "Zero cost"-scenario gives a reduction equal to 4.05%.

As expected, the combined CO_2-reduction potential for the theoretical data becomes higher, as the theoretical average effects used are mostly higher than the actual average effects. It may be interesting to point out the effect for the container vessels, as this is considerably higher than the others vessel types. The main reason for this, is that the "Zero-cost"-scenario for container vessels is the only scenario to include biofuel as a measure. As discussed previously, the theoretical average of biofuels is 37.03% which is a major effect when included. Because of this, the estimated CO_2-reduction for a “Zero cost”, theoretical value, \$500/tonne fuel price, container vessel is above 100%. This is obviously not practically possible.

4.5 Barriers for implementation

Throughout this study the different effects of CO_2-abatement measures have been discussed, and it may seem that the decision of whether to implement such a measure is solely depended on fuel savings versus costs. This is not the case. Several studies have discussed barriers for implementation of fuel consumption and CO_2-emissions reduction measures (Faber et al., 2011; Maddox Consulting, 2012; Acciara et al., 2013; Rehmatulla & Smith, 2015; Tillig et al., 2015; Rehmatulla et al., 2017). Based on these, six barrier types have been identified and will be discussed in connection to the measures examined in this thesis.

4.5.1 Technological barriers

Technological barriers are related to many of the issues already discussed in this paper. Uncertainties around expected or actual effect of a measure, lack of operational data to back estimates and/or unattractive financial returns are typical technological barriers (Maddox Consulting, 2012). A concrete example of a technological barrier related to measures in this study, may be if a shipowner is concerned that the hull coating supplier’s claim that the coating will last for five years is too optimistic. In addition to this comes the problem of heterogeneity (Rehmatulla & Smith, 2015). Even if a technology may be cost-effective on average for a ship class, as several technologies in this study are, the class itself has owners with vessels of different sizes, routes, commodities, and other characteristics. A measure deemed cost-effective on average, may therefore still be cost-inefficient for some shipowners. Heterogeneity is discussed further in section 4.7.4.

4.5.2 Operational (physical) barriers

When a solution may not be used on a vessel due to either physical or operational reasons, this is considered an operational barrier. An example of this may be the Flettner rotor which needs a lot of deck space for installation. Container ships have the deck covered in cargo and may not install such a rotor. This is a typical operational barrier. Another example also related to container ships may be their inability to use kites, as the speed of the vessels are too fast for kite usage. Related to trim and draft optimizations, the shipowners often need to prioritize getting as much cargo as possible in order to maximize profits. In such cases, optimizing trim and draft is impossible. Due to the need for having the propeller properly submerged, this may even be the case in ballast for some vessels. This would also be an operational barrier.

4.5.3 Regulatory barriers

Regulatory barriers relate to the existing or potential implications of global, regional or local laws on the implication of a given measure (Maddox Consulting, 2012). In situations where several companies are running liner routes, it could be beneficial for the owners to collectively reduce speed and therefore also fuel consumption. However, such practice may end up being scrutinised by different competition authorities. Several coastal locations, with ports in Denmark and West Sweden as examples, have banned hull cleaning for vessel using copper-based hull coating, while propeller polishing is prohibited in Californian ports**.** For vessels frequenting these ports, this may limit their choices when it comes to coating type or polishing frequency.

4.5.4 Economical barriers

As seen from the discussion of marginal abatement costs previously, it is obvious that fuel price is an important aspect when considering the viability of different measures. The fuel price in shipping is very volatile, and it is difficult to predict what the future price will be (Faber et al., 2011). This volatility creates an uncertainty around fuel consumption reducing measures, and thus creates an economical barrier. Another economical barrier may be the investment cost in itself. If a measure is considered as having good effect, it may still be ignored due to large investment costs. This may be one of the reasons for the low implementation rate of air lubrication in this study. The barrier may become even larger as the vessel becomes smaller. If the cost of capital of a company is substantial and the owner needs to prioritize between projects, it may be that the introduction of cost-efficient, fuel reducing measures are ignored and more cost-efficient, non-fuel reducing measures implemented (Rehmatulla & Smith, 2015). If a vessel is only operating on a fixed route or area, it may be beneficial to implement specific optimizations giving the best effects in such conditions. The down-side of doing so, is that it also limits flexibility to either move or sell the vessel to a company operating on other routes or areas. The reduced flexibility may reduce resale value or future profits, and may also be viewed as an economical barrier.

4.5.5 Market failure barriers

There are several different market failure barriers, and many of them are directly linked to how the shipping economy works. Rehmatulla (2014) finds that this barrier type is the most important barrier to the implementation of energy efficient measures. Three of the most important market failure barriers will be presented here.

The problem of split incentives is very important for understanding some of the main reasons for certain shipowners not to invest in fuel consumption reducing measures. It is a classic principal-agent problem, where the one making the investment would not realize the benefit. There are several different contract types between a shipowner and a charterer. Two of these types are term/time charters and bare boat charters. With a time charter solution, the shipowner provides a fully crewed vessel to the charterer for a specific period. The cost of the vessel is paid by the shipowner, and the specific voyage cost like fuel, port and canal charges, by the charterer. In a bare boat charter, the shipowner only provides the vessel while the charterer handles crew. In such an arrangement the shipowner is only responsible for capital costs, while the charterer pays vessel and voyage costs. The split incentive therefore arises when the shipowner makes investment decision regarding the implementation of measures, while the charterer is the part getting their fuel costs reduced. A feasible solution could be that the charter rate for a more efficient vessel is higher than a less efficient one, thereby giving the shipowner the effect of his/hers investment. Unfortunately, data seem to indicate higher rates for more efficient vessel is not apparent (Ådland et al., 2017). This problem is a major market failure barrier, also pointed out during the survey and interviews. It could also be possible for the charterer to perfom the investment in order to reap the benefit of reduced fuel costs, but according to Rehmatulla et al. (2017), most time charter contracts are to short for the charterer to regain his/hers investment in the contract period. Another example of a split incentive issue is that shipowners often are unsure of how long they will own the vessel. The uncertainty in number of years to discount the investment, and the fact that a fuel efficient ship is not guaranteed a resale price premium may also become a barrier (Maddox Consulting, 2012).

The second market failure barrier is also related to the interaction between shipowners and charterers. It is connected to the contract type called spot or voyage charter, where the shipowner pays both vessel and voyage cost, and the contract is to transport a specific cargo on a specific ship from port A to port B. The problem arises when the vessel is approaching a highly congested port, where a long waiting time is expected. Under the current system, the shipowner has to arrive at port in a pre-determined time window to avoid being penalized by the charterer. However, if the ship arrives in this time window, but due to the congestion are unable to unload, the charterer has to pay demurrage to the shipowner after the pre-agreed lay-time is exceeded. Ideally the vessel should be able to slow down and time the arrival to when the port is ready to handle the cargo. This would decrease both fuel consumption and CO_2-emission. Once again, the contract situation between the shipowner and the charterer is unfortunate, as the shipowner has no incentive to slow steam. A possible solution to this problem is virtual arrivals, where the charterer and shipowner may agree on a speed reduction if receiving note from the port authorities about congestion (Jia et al., 2017).

The last market barrier failure to be discussed in this thesis is linked to the fact that shipping is a highly cyclical business (Faber et al., 2011). In so-called “boom-times”, shipowners are earning returns way above operational costs. In such periods shipowners are reluctant to take vessels out of business to perform installations, as the alternative cost, namely the lost earnings, is so high. Instead they have the incentive to operate at full speed to get as much business as possible, and disregarding increased fuel consumption and CO_2-emission. In “bust-times” shipowners may be reluctant to perform investments due to low earnings or low liquidity.

4.5.6 Administrative barriers

Administrative barriers are connected to situations where cost-effective solutions are not implemented due to management issues (Maddox Consulting, 2012). It may happen if a small company lacks the resources or personnel to identify, analyze and implement different measures. Shipowners with few vessels may experience high transaction costs as the they are unable to spread the cost of gathering and validating information over a large number of ships (Rehmatulla & Smith, 2015). It may be further complicated by the use of third-party managers, which may remove the shipowner from the day to day operation of his/hers vessels.

4.6 Managerial and regulatory implications

As discussed throughout this thesis, there are several measures which may be used to reduce fuel consumption and CO_2-emissions from shipping in more or less efficient ways. In the previous section, barriers for implementation of such measures were presented and discussed. In this section the possibility of managers, owners, regulators, and others to overcome these barriers will be examined. Several studies have previously identified some possibilities and implications like the works of Acciaro et al. (2012), Maddox Consulting (2012) and Jafarzadeh and Utne (2014).

4.6.1 Market-based measures

One option to incentivize ship owners and charterers to embrace more efficient vessels, is to introduce different market-based measures, and then let the different actors in the market adapt. One option which may be implemented is a form of CO_2-emission trading system. Shipping has been kept out of the emission trading system of the European Union, but if the industry itself is not able to present a CO_2-reduction plan that the EU finds sufficient it may be included in the future (The Maritime Executive, 2017). The economic sense behind this system is that a price is set on emissions, and companies may buy or sell emission quotas based on what they emit. Companies with less efficient vessels will need to buy more emission quotas, and the cost of running less energy-efficient vessels are therefore increased. This may incentivize both shipowners and fuel paying charterers to push for fuel reduction measures.

Another market-based measure may be port costs depending on fuel efficiency and emission rate. This is a measure that not necessarily must be implemented globally, and a country or region may set their own price schemes. If such a system is implemented in an attractive port this may lead to shipowners investing in fuel reduction measures if this is less costly than the increased port fees.

A final market-based measure might be a levy on bunker costs. Kosmas and Acciaro (2017) show that a tax on top of ordinary fuel cost would lead to a decrease in both speed and fuel consumption. As with all market-based measures, its effect depends on the inability of the shipowners to shift the increased cost over to their customers.

4.6.2 Incentivized or forced speed reductions

Reducing the speed of vessels is quite possibly the measure which has the largest potential of reducing fuel consumption, as discussed several times in this thesis. However, as seen in section 4.5.5., the split incentive problem between the shipowner and the charterer often makes speed reductions difficult to implement in practice. One way of eliminating this problem is through virtual arrival. If the port is congested when a vessel running a voyage charter approaches, both shipowner and charterer receive a message from the port, and a new arrival plan may be agreed upon when the port is less congested (Jia et al., 2017). This means the vessel may slow down and save both fuel and emissions, without the shipowner losing the compensation for the prolonged journey.

Another option to make sure that vessels slow steam is to enforce a regional or global speed limit. This might be done as an absolute value depending on vessel type, or as a percentage of design speed. Maddox Consulting (2012) claims that the solution is cost-effective as long as there is an over-capacity of ships in the market to make up for the increased demand. On longer terms the market will adapt by adjusting ship building and scrapping to the new demand under restrictions. The increased CO_2-emission with building and scrapping a larger fleet, as well as the increased emission by air transporting a greater amount of crew, makes Psaraftis (2011) claim that a speed limit is a bad solution. If speed reduction is the goal, increased bunker prices are better. There are also some questions regarding the legality of global speed limits, making this an unlikely measure to see implemented in the near future.

4.6.3 Energy-ratings and vessel certificates

Energy ratings and the ability to benefit more efficient vessel might be a good way of inspiring fuel reducing investments. In 2011, the Energy Efficiency Design Index (EEDI) was made mandatory for all new ships (International Maritime Organization, 2020). This index requires a minimum of energy efficiency for new vessels, and the emission limit compared to a reference value is tightened every five year.

For shipowners seeking to use their efficiency as a competitive advantage, evaluation by one or several of the independent shipping efficiency indices may be beneficial. An example of one such index is the Clean Shipping Index. Shipowners pay to get their vessels reviewed and get a certificate with a rating. A higher rating may lead to benefits, like lower port fees at some Swedish ports (Clean Shipping Index, 2020). One problem with such a voluntary review is the adverse selection, leading to only efficient ships opting for review. The fact that the shipowner pays to be reviewed, may also give the reviewer an incentive to provide a better rating to also get the renewal mission when the certificate expires.

An independent, mandatory rating scheme regulated by IMO or another international organization could incentivize investments. If large corporations and public procurement agencies listed energy efficiency as one of the evaluation criteria and gave benefit to vessels with higher ratings by more trades or higher rates, shipowners would have incentive to invest in fuel efficiency. Unfortunately, at the moment, fuel efficiency does not seem to affect the rates or trade amount enough compared to investment costs (Ådland et al., 2017).

4.6.4 Third-party investors and governmental support schemes

As seen during the analysis of marginal abatement costs, measures may be predicted to reduce CO_2-emissions and fuel consumption but still not be implemented. If the reason is mainly economical and the effect of the measure seems promising, governmental agencies may subsidize shipowners in order to reduce investment costs and make the investment economically viable. One example of this is the Port Authority of New York and New Jersey running a program which funded nearly 100% of the cost of new engines, while shipowners only covered installation costs (Faber et al., 2011). Another example is Enova SF, owned by the Norwegian Ministry of Climate and Environment. Over the last decade, Enova SF has paid more than NOK 1bn to support energy efficiency measures in shipping (Enova SF, 2020).

In later years, also third-party investors have begun to enforce stricter demands on shipowners seeking financing. The European Investment Bank launched in 2016 a green shipping financing program (European Investment Bank, 2016). Shipowners could seek up to 50% debt financing for building of new greener vessels, and 100% of the investment costs of retrofit components introduced to reduce fuel consumption and emissions. Other large banks have similar incentives, where loans to green operations give the shipowner benefits of lower interest rates and lower equity demands.

4.7 Uncertainties and limitations

During this research, some assumptions and simplifications have been made. In addition to this, the sample variety and sample size may provide some uncertainties in the conclusions drawn. This section discusses these possible issues.

4.7.1 Large influence of Norwegian shipowners

The purpose of this research was to compare the theoretical and actual effects of different retrofit measures, as well as the implementation rate of such measures. It is possible to claim that the majority of Norwegian shipowners responding, may lead to the data being skewed for both purposes. For the measurement of actual effects, this could be reasonable if all vessels owned by Norwegian shipowners only operated in and around the North-Sea, as the climate and weather may have led to different effects of differerent abatement measures. However, the responses to trading areas showed a fairly even distribution of ships operating across the seas. It may therefore be claimed that the possible overweight of Norwegian vessels would not influence the comparison between theoretical and actual effects. However, when considering the second purpose of the study, namely the implementation rate of the different measures, a claim of skewed data might be more reasonable. It may be claimed that Norway is a society with a high level of technological competence, focusing on climate issues and with CO_2-reduction as a vital part of decision making. If so, it may be that Norwegian shipowners are more likely to invest in CO_2-abatement measures, and that the data presented in this thesis regarding implementation of measures are too high compared to real life. In that case, the validity of the research may be reduced as the results are less generalizeable.

4.7.2 Sample size

According to United Nations (2019), a total of around 96,000 vessels were registered globally in 2019. Of this total, a litte less than 2,000 vessels were Norwegian-controlled, foreign-going vessels (Norwegian Shipowners' Association, 2020). Even if every member of the association responded to the survey, the sample size would be fairly small compared to the overall population. However, the participation was not limited to members of the Norwegian Shipowners’ Association, and many answers also originated from companies in other countries and regions. Even so, the sample size of this study is in the lower end of what is acceptable. Caution has to be taken when analyzing the data, and drawn conclusions should be conservative in regards to effects and cost-efficiency. This is even more important for measures which has a low implementation rate in the sample.

4.7.3 Additive effects

When considering the reported effect of the different measures, it is important to note that the effects are given as the isolated effect of the measure. Most companies have implemented more than one CO_2-abatement solution, and simply adding the effect of each one is unlikely to provide an exact estimate of the combined effect. As an example, if a shipowner decides to install two measures with isolated effect of 2% and 3% respectively, most likely the effect he will realize after the implementation is below 5%. This is also in accordance with the view from the Second IMO Greenhouse Gas Study (Buhaug, et al., 2009). Therefore, the marginal abatement cost curves and scenario analysis later have to be seen as simplifications.

4.7.4 Heterogeneity

Some simplifications and assumptions were done when calculating marginal abatement costs, and further influencing the marginal abatement cost curves and scenario analysis. A complete list of these assumptions may be found in section 4.3.1. The problem of heterogeneity is related to the generalizability of the data. Even if a technology may be cost-effective on average for a ship class, as several technologies in this study are, the class itself has owners with vessels of different sizes, routes, commodities, and other characteristics. Some shipowners may therefore experience a measure as cost-inefficient, even if the measure is considered cost-efficient for the average of the related vessel type (Rehmatulla & Smith, 2015). This discrepancy is likely to be greater for the largest and the smallest vessels in a vessel group, as these differs most from the average. Vessels traveling special routes or transporting special cargo may also experience greater differences.

4.7.5 Expert review

In order to increase validity, and making sure that the questions were measuring what they were intended to measure, the questionniare was reviewed by an expert on shipping and retrofit solutions. This expert review, as well as the usage of extensive literature review to construct answer intervals may increase the validity of the survey (Saunders et al., 2016).

5. Concluding remarks

The purpose of this master's thesis was twofold. The first part sought to find the actual fuel consumption and CO_2-reduction potential of different retrofit measures, and to compare them with effects found in the literature. Through interviews with actors in the business, 15 measures were identified and further examined. An extensive literature review was conducted to estimate intervals of the theoretically predicted effect of each measure. By use of a survey, actual effects of the measures were recorded from the companies which have implemented them. A key observation was that the actual effect of most of the retrofits solutions were in the lower interval, or even below the associated theoretical effect interval. It may also be noted that some measures had a higher average actual effect than theoretical effect, namely weather routing and trim and draft optimizations.

From the survey, data was also collected to indicate to which extent the different measures are being used across the fleet. It was found that weather routing, hull cleaning, speed optimization and trim and draft optimization were implemented by around 50% of the companies responding to the survey. A common characteristics is that they are fairly inexpensive in comparison with a lot of the other solutions. The measures least implemented were air lubrication, propeller retrofitting and wind propulsion. High investment cost may be a reason for the low implementation of both air lubrication and wind propulsion, while for propeller retrofitting a possible reason may be that the respondents had fleets with propeller already optimized to the current operational situation.

In the second part of the study the cost-effectiveness of the different measures were calculated. Based on both actual and theoretical effects and for different fuel cost, were marginal abatement cost curves created for four main vessel types. In total sixteen different curves were created. Weather routing, propeller polishing and trim and draft optimizations were found to be cost-effective for all vessel types, with both fuel costs considered and when calculating using either actual or theoretical effects. Four measures were found to be cost-ineffective at all scenarios. These measures were waste heat recovery, air lubrication, biofuel and wind propulsion. All these measures had a high theoretical reduction potential, but the investment and/or operational cost of them were very much higher than the other measures.

The marginal abatement costs were used to calculate the combined CO_2-reduction potential in “No regret” and “Zero cost”-scenarios. For the actual effects, it was found that the accumulated CO_2-reduction potential, using only cost-effective solutions was in the range of 77.5m – 127m tonnes per year depending on fuel price. By allowing for the introduction of measures that in themselves were not cost-effective until a point where the total abatement cost approached zero, it was estimated that the savings could increase to between 132m – 181.5m tonnes annually depending on fuel price. Such reductions are equivalent to 4.05% of the total EU-emissions of 2019.

Finally, some barriers for implementation of the measures were presented and discussed. The principal-agent problem, where the shipowner not necessarily reaps the benefit of his/hers investment is one of the main barriers. The volatile fuel cost causing uncertainties in investment calculations was also identified as important. Options for shipowners, regulators and governments in order to reduce these barriers included market-based measures as fuel tax and CO_2-trading schemes, speed reduction measures as virtual arrival and speed limits as well as energy-rating systems and government incentive schemes.

This thesis is based upon a group of interviews and a survey. As discussed previously, both the sample size and the sampling itself should lead to some caution regarding the results. Firstly, the small sample size may lead to the data being less generalizable and that single responses may be given too much weight. Secondly, the fact that a large part of the respondents are headquartered in Norway may lead to biases, if the answers and effects are varying geographically. Caution must also be taken when analysing the marginal abatement cost curves, as the influence of additive effects has not been considered.

Hopefully this thesis has shed some light on the possibilility of cost-effective solutions for CO_2-reductions. It has also highlighted the difference in theoretical and actual values, which need to be considered when investment decision are being made. The actors in the industry, both owners, charterers, regulators and other interests should be aware of the implementation barriers, and seek to provide incentives to overcome them, The shipping industry has to make large reductions in emissions in order to reach the goals for 2050. In order to get there, cost-effective, retrofit solutions will most likely play an important part.

5.1 Recommendations for future research

There are several ways in which the research done in this thesis may be built upon or improved. One branch of future research should continue exploring the actual effect of different retrofit measures, seeking to reduce the gap between theoretical and actual data. Such studies should also try to examine the additive effects of implementing several measures, and see how the implementation of one solution influence another. In order to do so, larger and more diversified samples must be examined. As most of the respondents were located in Norway, one angle may be to see whether effect and implementation rate varies from country to country or region to region. A larger sample may also open for analyzing vessels in finer groups and look at how vessel size or trading patterns may affect the effects seen.

Finally, one branch of future research may be to further examine the barriers for implementation of the different measures. An approach could be to examine the different solutions for reducing barriers and see whether some strategies have better effect than others.

6. References

Abouelfadl, A. H., & Abdelraouf, E. E. (2016). *The Impact of Optimizing Trim on Reducing Fuel Consumption .* Alexandria: Journal of Shipping and Ocean Engineering.

Acciaro, M., Hoffmann, P. N., & Eide, M. S. (2012). *Identifying and overcoming barriers to the implementation of emissions reduction measures in shipping.* Oslo: DNV.

Acciaro, M., Hoffmann, P. N., & Eide, M. S. (2013, February). The Energy Efficiency Gap in Maritime Transport. *Journal of Shipping and Ocean Engineering*, pp. 1-10.

American Bureau of Shipping. (2013). *Ship Energy Efficiency Measures Advisory.* Houston: American Bureau of Shipping.

American Bureau of Shipping. (2019). *Air Lubrication Technology.* Houston: American Bureau of Shipping. Retrieved April 14th, 2020, from https://ww2.eagle.org/content/dam/eagle/advisories-and-debriefs/Air%20Lubrication%20Technology.pdf

Avdeyev, B. A., & Vyngra, A. V. (2017). *Increase of operating efficiency of ship electrical generating plant with shaft generator.* Kerch: Kerch State Maritime Technological University.

Bengtsson, S. (2011). *Life Cycle Assessment of Present and Future Marine Fuels.* Gothenburg: Chalmers University of Technology.

Bouman, E. A., Lindstad, H. E., Rialland, A. I., & Strømman, A. H. (2017, May). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. *Transportation Research Part D: Transport and Environment*, pp. 408-421.

Buhaug, Ø., Corbett, J. J., Eyring, V., Endresen, Ø., Faber, J., Hanayama, S., ... (2009). *Second IMO GHG Study 2009.* London: International Maritime Organization.

Cambridge Dictionary. (2020). *Meaning of retrofit in English*. Retrieved May 25th, 2020, from Cambridge Dictionary: https://dictionary.cambridge.org/dictionary/english/retrofit

CCNR. (2012). *Possibilities for reducing fuel consumption and greenhouse gas emissions from inland navigation .* Strasbourg: Central Commission for the Navigation of the Rhine.

Chakraborty, S. (2019, October 4th). *What's The Importance Of Bulbous Bow Of Ships?* Retrieved April 28th, 2020, from Naval Architecture: https://www.marineinsight.com/naval-architecture/why-do-ships-have-bulbous-bow/

Clean Shipping Index. (2020). *Benefits*. Retrieved June 9th, 2020, from Clean Shipping Index Homepage: https://www.cleanshippingindex.com/benefits/

Corbett, J. J., Wang, H., & Winebrake, J. J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D*, pp. 593-598.

Eide, M. S., Longva, T., Hoffmann, P., Endresen, Ø., & Dalsøren, S. B. (2011, January). Future cost scenarios for reduction of ship CO2 emissions. *Maritime Policy & Management*, pp. 11-37.

Enova SF. (2020). *Tilskuddsliste*. Retrieved from Enova SF Homepage: https://www.enova.no/om-enova/om-organisasjonen/tilskuddsliste/?search=skip

Eskeland, G. S., & Lindstad, H. E. (2016). Environmental Taxation in Transport. *The International Journal on Green Growth and Development*, pp. 51-86.

European Investment Bank. (2016). EIB's Green Shipping Financing Programme. *7th Joint meeting of the Sub-groups on financing and competitiveness.* Brussels: European Sustainable Shipping Forum.

European Maritime Safety Agency. (n.d.). *Greenhouse gas*. Retrieved May 26th, 2020, from Greenhouse gas: http://www.emsa.europa.eu/main/air-pollution/greenhouse-gases.html

Eurostat. (2019). *Greenhous gas emission statistics - emission inventories.* Luxembourg: Eurostat.

Faber, J., Freund, M., Köpke, M., & Nelissen, D. (2010). *Can the current surplus of maritime transport capacity be turned into an opportunity to reduce GHG emissions?* Delft: Seas At Risk.

Faber, J., Wang, H., Nelissen, D., Russell, B., & St Amand, D. (2011). *MARGINAL ABATEMENT COSTS AND COST EFFECTIVENESS OF ENERGYEFFICIENCY MEASURES.* Institute of Marine Engineering, Science and Technology (IMarES).

Farnsworth, A. (2019, December 3rd). *Shaft generators enable emissions-free shipping.* Retrieved May 12th, 2020, from wartsila.com: https://www.wartsila.com/twentyfour7/innovation/shaft-generators-enable-emissions-free-shipping

Force Technology. (n.d.). *Force Technology Media - SeaTrim.* Retrieved from Optimal Trim Guidance: https://forcetechnology.com/-/media/force-technology-media/pdf-files/hydrodynamics/0-to-4000/3317-seatrim.pdf

Fylan, F. (2005). Semi-structured interviewing. In J. Miles, & P. Gilbert, *A Handbook of Research Methods for Clinical and Health Psychology* (pp. 65-76). Oxford: Oxford University Press.

Gennaro, G., & Gonzalez-Adalid, J. (2012). *Improving the Propulsion Efficiency by means of Contracted and Loaded Tip (CLT®) Propellers.* Athens.

Gilbert, P., Bows-Larkin, A., Mander, S., & Walsh, C. (2014). Technologies for the high seas: meeting the climate challenge. *Carbon Management*, pp. 447-461.

Glomeep. (2020). *Informational portal - Global maritime energy efficiency partnership*. Retrieved April 11th, 2020, from Technology groups: https://glomeep.imo.org/technology-groups/

Gougoulidis, G., & Vasileiadis, N. (2015). *An Overview of Hydrodynamic Energy Efficiency Improvement Measures.* Athens: The 5th International Symposium On Ship Operations.

Gunton, P. (2020, March 13th). *Jotun's HullSkater to revolutionise hull cleaning.* Retrieved May 14th, 2020, from ShipInsight: shipinsight.com/articles/jotuns-hullskater-to-revolutionise-hull-cleaning

Hai-long, S., Obwogi, E. O., & Yu-min, S. (2016, May 1st). Scale effects for rudder bulb and rudder thrust fin on propulsive efficiency based on computational fluid dynamics. *Ocean Engineering*, pp. 199-209.

Hapag-Lloyd AG. (2018, January 26th). *News & Lookout - Hapaq-Lloyd.* Retrieved April 20th, 2020, from How Vessel Trim Optimisation creates efficiencies: https://www.hapag-lloyd.com/en/news-insights/insights/2017/03/how-vessel-trim-optimisation-creates-efficiencies.html

Harrould-Kolieb, E., & Savitz, J. (2010). *Shipping Solutions: Technological and operational methods available to reduce CO2.* Washington: Oceana.

Hollenbach, U., & Reinholz, O. (2011). *Hydrodynamic Trends in Optimizing Propulsion .* Hamburg: Second International Symposium on Marine Propulsors.

ICCT. (2011). *Reducing Greenhouse Gas Emissions from Ships - Cost effectiveness of available options.* Washington: International Council on Clean transportation.

International Maritime Organization. (2020). *Energy Efficiency Measures.* Retrieved from Our Work: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx

International Maritime Organization. (2020). *Historic Background GHG*. Retrieved May 26th, 2020, from IMO - Historic Background: www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Historic%20Background%20GHG.aspx

Jafarzadeh, S., & Utne, I. B. (2014, May 1st). A framework to bridge the energy efficiency gap in shipping. *Energy*, pp. 603-612.

Jia, H., Ådland, R. O., Prakash, V., & Smith, T. (2017, July). Energy efficiency with the application of Virtual Arrival policy. *Transportation Research Part D: Transport and Environment*, pp. 50-60.

Kim, J.-H., Choi, J.-E., Choi, B.-J., & Chung, S.-H. (2014, September). Twisted rudder for reducing fuel-oil consumption. *International Journal of Naval Architecture and Ocean Engineering*, pp. 715-722.

Kosmas, V., & Acciaro, M. (2017, December). Bunker levy schemes for greenhouse gas (GHG) emission reduction in international shipping. *Transportation Research Part D: Transport and Environment*, pp. 195-206.

Levin, K. A. (2006, March 24th). Study Design III: Cross-sectional studies. *Evidence-Based Dentistry*, p. 2006.

Lin, S. (2012). *Greenhouse gas mitigation strategies - a ship operator’s perspective in the container shipping industry.* Nanyang: Nanyang Technological University.

Lindstad, H. E. (2013). *Strategies and measures for reducing maritime CO2 emissions.* Trondheim: Norwegian University of Science and Technology.

Lindstad, H. E., Asbjørnslett, B. E., & Jullumstrø, E. (2013). Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market. *Transportation Research Part D*, pp. 5-12.

Lindstad, H. E., Asbjørnslett, B. E., & Strømman, A. H. (2011, April 19th). Reductions in greenhouse gas emissions and cost by shipping at lower speeds. *Energy Policy*, pp. 3456-3464.

Lindstad, H. E., Eskeland, G. S., & Rialland, A. (2017, January). Batteries in offshore support vessels – Pollution, climate impact and economics. *Transportation Research Part D: Transport and Environment*, pp. 409-417.

Lindstad, H. E., Verbeek, R., Blok, M., van Zyl, S., Hübscher, A., Kramer, H., . . . Boonman, H. (2015). *GHG emission reduction potential of EU-related maritime transport and on its impacts.* Delft: European Commission.

Longhurst, R. (2010). Semi-structured Interviews and Focus Groups. In N. Clifford, S. French, & G. Valentine, *Key Methods in Geography* (pp. 103-115). London: SAGE Publications Ltd.

Lu, Y., Chang, X., & Hu, A.-k. (2016, April 1st). A hydrodynamic optimization design methodology for a ship bulbous bow under multiple operating conditions. *Engineering Applications of Computational Fluid Mechanics*, pp. 330-345.

Maddox Consulting. (2012). *Analysis of market barriers to cost effective GHG emission reductions in the maritime transport sector.* London: Maddox Consulting.

Miola, A., Marra, M., & Ciuffo, B. (2011, September). Designing a climate change policy for the international maritime transport sector: Market-based measures and technological options for global and regional policy actions. *Energy Policy*, pp. 5490-5498.

Mäkiharju, S. A., Perlin, M., & Ceccio, S. L. (2014, February 13th). On the energy economics of air lubrication drag reduction. *International Journal of Naval Architecture and Ocean Engineering*.

Norlund, E. K., & Gribkovskaia, I. (2013). Reducing emissions through speed optimization in supply vessel operations. *Transport Research Part D*, pp. 105-113.

Norwegian Shipowners' Association. (2020, April). *Medlemmer*. Retrieved from Om-oss: https://rederi.no/om-oss/medlemmer/

Norwegian Shipowners' Association. (2020). *Statistics and key figures*. Retrieved from Om oss: https://rederi.no/om-oss/statistikknokkeltall/

Norwegian Shipowners´ Association. (2019). *Maritime Outlook Report 2019 - Ocean Pioneers.* Oslo: Norwegian Shipowners´ Association.

Odfjell. (2020, February 21st). *Ten years of weather routing.* Retrieved May 23rd, 2020, from Our stories: https://www.odfjell.com/about/our-stories/ten-years-of-weather-routing/

Psaraftis, H. N. (2011, June 22th). *Slow steaming vs. speed limits.* Retrieved from ECCP II Ships / GHG 22-23/6/ 2011: https://ec.europa.eu/clima/sites/clima/files/docs/0036/slow_steaming_en.pdf

Rehmatulla, N. (2014). *Market failures and barriers affecting energy efficient operations in shipping.* London: UCL Energy Institute.

Rehmatulla, N., & Smith, T. (2015, December). Barriers to energy efficient and low carbon shipping. *Ocean Engineering*, pp. 102-112.

Rehmatulla, N., Hosseinloo, S. H., Smith, T., & Calleya, J. (2015). *The diffusion of energy effiency technologies in shipping.* London: Shipping in Changing Climates Conference 2015.

Rehmatulla, N., Parker, S., Smith, T., & Stulgis, V. (2017, January). Wind technologies: Opportunities and barriers to a low carbon shipping industry. *Marine Policy*, pp. 217-226.

Reja, U., Manfreda, K. L., Hlebec, V., & Vehovar, V. (2003). *Open-ended vs. Close-ended Questions in Web Questionnaires.* Ljubljana: Development in Applied Statistics.

Saunders, M., Lewis, P., & Thornhill, A. (2016). *Research Methods for Business Students.* Essex: Pearson Education Limited.

Schøyen, H., & Sow, H. (2015, November 15th). A decision making tool concering retrofit of shaft generator frequency converter. *Ocean Engineering*, pp. 103-112.

Sherbaz, S., & Duan, W. (2012, September). Operational Options for Green Ships. *Journal of Marine Science and Application*, pp. 335-340.

Silverstream Technologies. (2020). *Silverstream Home Page*. Retrieved April 12th, 2020, from About the Silverstream® System?: https://www.silverstream-tech.com/the-technology/

Smith, T., Newton, P., Winn, G., & La Rosa, A. G. (2013). *Analysis techniques for evaluating the fuel savings associated with wind assistance* . London: Low Carbon Shipping Conference.

Smith, T., O`Keefe, E., Aldous, L., Parker, S., Raucci, C., & Traut, M. (2014). *Third IMO GHG Study 2014.* London: International Maritime Organization (IMO),.

Statistics Norway. (n.d.). *Emission factors used in the estimations of emissions from combustion.* Retrieved May 20th, 2020, from ssb.no: https://www.ssb.no/_attachment/288060/binary/93858?_version=539789

Taljegard, M., Brynolf, S., Grahn, M., Andersson, K., & Johnson, H. (2014). *Supporting information for - Cost-effective choices of marine fuels in a carbonconstrained world: results from a global energy model.* Gothenburg.

Taylor-Powell, E. (1998). *Questionnaire Design: Asking questions with a purpose.* Madison: University of Wisconsin.

The Maritime Executive. (2017, November 12th). *E.U. Emissions Trading System Excludes Shipping For Now.* Retrieved June 9th, 2020, from The Maritime Executive: https://www.maritime-executive.com/article/eu-emissions-trading-system-excludes-shipping-for-now

Tillig, F., Mao, W., & Ringsberg, J. W. (2015). *Systems modelling for energy-efficient shipping .* Gothenburg: Chalmers University of Technology.

Traut, M., Gilbert, P., Walsh, C., Bows, A., Filippone, A., Stansby, P., & Wood, R. (2014, January). Propulsive power contribution of a kite and a Flettner rotor on selected shipping routes. *Applied Energy*, pp. 362-372.

United Nations. (2019, December 10th). *Merchant fleet*. Retrieved June 8th, 2020, from Development Statistics and Information Branch UNCTAD: https://stats.unctad.org/handbook/MaritimeTransport/MerchantFleet.html

Virtasalo, M., & Vänskä, K. (2011). *Achieving improved fuel efficiency with waste heat recovery.* Retrieved April 11th, 2020, from abb.com: https://library.e.abb.com/public/5f7cac28e876a9cbc1257a8a003cc6dc/ABB%20Generations_28%20Achieving%20improved%20fuel%20efficiency%20with%20waste%20heat%20recovery.pdf

Wang, H., & Lutsey, N. (2013). *Long-term potential for increased shipping efficiency through the adoption of industry-leading practices.* Washington: The International Council on Clean Transportation.

World Shipping Council. (2020). *Worldshipping.org*. Retrieved from CARBON EMISSIONS: http://www.worldshipping.org/industry-issues/environment/air-emissions/carbon-emissions

Wärtsilä. (2020). *Hybrid Solutions*. Retrieved May 6th, 2020, from www.wartsila.com: https://www.wartsila.com/marine/build/engines-and-generating-sets/hybrid-solutions#Products

Wärtsilä. (2020). *Shaft Generator*. Retrieved May 13th, 2020, from Power systems: https://www.wartsila.com/marine/build/power-systems/shaft-generator-systems/shaft-generator

Wärtsilä. (2020). *Wärtsilä Encyclopedia of Marine Technology.* Retrieved April 14th, 2020, from Air lubrication: https://www.wartsila.com/encyclopedia/term/air-lubrication

Yuan, J., Ng, S. H., & Sou, W. S. (2016, January). Uncertainty quantification of CO2 emission reduction for maritime shipping. *Energy Policy*, pp. 113-130.

Ådland, R. O., Alger, H., Banyte, J., & Jia, H. (2017, January). Does fuel efficiency pay? Empirical evidence from the drybulk timecharter market revisited. *Transportation Research Part A: Policy and Practice*, pp. 1-12.

Ådland, R., Cariou, P., Jia, H., & Wolff, F.-C. (2018, March 20th). The energy efficiency effects of periodic ship hull cleaning. *Journal of Cleaner Production*, pp. 1-13.

7. Appendix

7.1 Appendix 1 – Detailed information on abatement measures

More detailed information on the different abatement measures covered in the thesis is presented below. An aggregate discussion and overview is found in section 2.2

Hull retrofitting

When a hull is constructed, it is designed to be optimal for the speed-draught profile expected for the vessel. If this profile changes, it may be beneficial to redesign parts of the hull to increase the efficiency of the vessel (Glomeep, 2020). This may be done in many ways, like retrofitting either a bulbous bow, thrusters or optimizing the bilge keel. A bulbous bow is a horizontal extension of the bow just below the surface of the water (Faber et. al, 2011). The bulbous bow will create a wave, which if designed correctly, will have a destructive interference with the wave from the main bow (Chakraborty, 2019). This reduces the wave making drag on the ship, increasing fuel efficiency. Tunnel thrusters, also known as bow thrusters or transverse thrusters, help according to Wartsila (2020) by providing side force and simplyfing harbour manouvering and mooring. By adjusting the shape of existing thrusters, one may gain additional effect. The bilge keel optimizing entails to position the bilge keels the best way (Glomeep, 2020). Bilge keel optimizing has the largest potencial for vessels below 50,000 dwt.

For a vessel currently operating without a bulbous bow, Faber et. al. (2011) estimate an abatement potential of 10%. Gilbert et. al (2014) claim that the CO_2-reduction potential of a bulbous bow is around 9%. However, many ships already have a bulbous bow installed. In such cases it may be reasonable to replace the current bow with a new one, if the operational profile has shifted considerably. The effect of optimizing the bulbous bow is between 2-5% (Tillig et al., 2015; Glomeep, 2020). Lu et al. (2016) claim to have designed a bulbous bow which is optimal under several different conditions, saving up to 2.845%. Buhaug et. al (2009) consider the CO2-reduction potential of installing transverse thrusters to be between 0.9-4.2%, while Glomeep (2020) has a more conservative estimate of 0.5-1%. For the bilge keel optimization a reduction potential of 0.25-1% is reasonable (Glomeep, 2020).

A bulbous bow installation costs somewhere in the range of $350,000-$800,000 depending on the size of the vessel (Glomeep, 2020). The cost of optimizing thrusters is about $10,000. Miola et al. (2011) have estimated a negative, marginal abatement cost for both high and low emission reduction potential, meaning thrusters is a cost effective solution. Adjustment of the bilge keel is estimated to cost about $10,000, with costs for detailed design and docking not included (Glomeep, 2020).

Hull coatings

When vessels operate, organic growth may occur on the hull of the vessels. This growth increases the resistance between the hull and the water, and increased engine power and thus increased fuel consumption is needed to maintain a constant speed. By applying anti-foul hull coatings the resistance may be reduced by as much as 20-50% (Harrould-Kolieb & Savitz, 2010). The coating may either be self-polishing or being silicone-based, which creates a slippery surface where the growth cannot attach. The silicone-based type is the most expensive type. The effect of the coating reduces drastically over time and it is only applicable while the ship is in dry dock (Buhaug, et al., 2009). An interval of about 3-5 years between reapplying coating is considered normal.

As previously mentioned there are two main types of hull coating, where the silicone-based is the most expensive of the two. The effect on fuel consumption of the cheapest version is considered to be in the range of 0.5-2.0% (Buhaug, et al., 2009). The silicone-based type has a considerably better effect. Conservative estimates lie in the interval of 2-5%, but several studies estimate the effect to be between 5-10% (Buhaug, et al., 2009; Harrould-Kolieb & Savitz, 2010; Faber et al., 2011; Miola et al., 2011; Lin, 2012; Bouman et al. 2017). Research are currently being done on nanotechnological coatings predicted to have an effect of nearly 15%, but this is not confirmed numbers as of yet.

Hull coatings have a very short return on investment of less than a year (Harrould-Kolieb & Savitz, 2010). The cheapest coating type cost in a range of $10,000 for the smallest vessels to around $140,000 for the largest ones (Buhaug, et al., 2009). The silicone-based type ranges between $20,000-$600,000. Several studies have estimated the marginal abatement potential of hull coatings. Both Buhaug et al. (2009), Miola et al. (2011) and Wang and Lutsey (2013) find a cost range of -$150 to -$105/tonne, while other studies find the cost to be almost -$200/tonne (Faber et al., 2011; Lin, 2012). Maddox Consulting (2012) predict the abatement cost to be increasingly negative as time goes on, and estimates a cost of -$389/tonne in 2030.

Air lubrication

When a ship moves through the water, the friction between the water and the hull of the ship creates drag forces. These drag forces reduce the speed of the vessel, and the engine needs to combust more fuel to maintain the same speed as without the drag. According to Glomeep (2020) almost 50-70% of total resistance on ships is related to these drag forces. One way of reducing them is through air lubrication. Air lubrication is typically done by releasing microbubbles of air through nozzles at the front of the hull (American Bureau of Shipping, 2019). These air bubbles reduce the density of the water, and thereby also the friction between the water and the hull. Another positive effect is that the bubbles reduce noise pollution and vibrations from the engine (Wärtsilä, 2020).

According to the American Bureau of Shipping (2019), up until 2018 only 23 vessels had installed air lubrication systems, and Glomeep (2020) categorizes the technology as semi-mature. Because of this fairly low number of users, there is not much data recorded and most reports support themselves on estimates of the effect of the system. Silverstream Technologies (2020) estimate the fuel savings of the system to be 5-10%, depending on the vessel size. This is in accordance with much of the theoretical estimates given, where effects are considered to be between 1-15% (Buhaug, et al., 2009, Faber et. al., 2011, American Bureau of Shipping, 2019, Glomeep, 2020, Wärtsilä, 2020). The effect on bulkers and tankers are considered higher than on other vessels.

The cost of installing an air lubrication system varies between $0.7 million to $5.0 million depending on type and ship size (Faber et al., 2011). The price range is highest for LNG tankers, and for both oil tankers and bulk ships the installation cost is in the middle range of the cost estimate. Glomeep (2020) claims that the system will need less than three percent of the total ship power to operate. This may be compared to the increased fuel usage of 0.3-0.5 tonnes per day, which Faber et al. (2011) present. The 4-12 non-operative days needed to install the system must also be considered as a cost when calculating.

Propeller retrofitting

During the lifetime of a vessel, the operational conditions in which it operates can change. As the ship is usually designed to run at a pre-determined speed, parts, like the propeller, may not be optimal if the conditions change and for example slow steaming is needed (Glomeep, 2020). When such changes occur and seem to last, it may be beneficial to replace the current propeller with a more efficient model. The main area of focus in designing modern propellers is to restrict vortices (Gougoulidis & Vasileiadis, 2015). There are several different ways a propeller may be designed to accomplish this. Tip rake and Backwards Tip rake propellers use a tip on the end of the propeller to reduce friction. Kappel propellers utilize an extended, smoothly curving tip, while CLT-propellers have a finite chord and an endplate fitted at the tip (Gennaro & Gonzalez-Adalid, 2012). All these methods reduce the vortices formations, and increase propeller efficiency.

According to Harrould-Kolieb and Savitz (2010) it is possible to reduce fuel consumption by as much as 15% by retrofitting a more efficient propeller, but that 5-10% savings are more common. Several other studies also place the effect in the interval of 5-10% (Gennaro & Gonzalez-Adalid, 2012; American Bureau of Shipping, 2013; Gougoulidis & Vasileiadis, 2015; Lindstad, et al., 2015; Glomeep, 2020). CLT-propellers are expected to have a larger effect than tip rake propellers. The effect of a propeller retrofit is especially large on container ships and large vessels.

The cost of a propeller retrofit varies considerabely between ship types and sizes, but Lindstad et al. (2015) estimate a cost of between $250.000-$1,150,000. When analysing the marginal abatement cost of the measure, it is always profitable at a high level, 1000€/tonne fuel price.

The abatement cost is still negative for most ship types at mid-level fuel prices, and is also negative for several vessel groups for fuel prices as low as 250€/tonne. Other sources have also considered retrofitting costs, and Glomeep (2020) estimates a narrower interval of $400,000-$550,000.

Waste heat recovery

When fuel is combusted in the engine, a large portion of the energy provided from the fuel ends up as exhaust and heat, instead of providing propulsion for the vessel. It is common to estimate the energy loss percentage to be about 50-60% of the energy from the fuel (Virtasalo & Vänskä, 2011, Lindstad, et al., 2015). Part of the heat energy lost through exhaust may be recovered by waste heat recovery. Usually the process is done by leading the hot exhaust into either steam turbines, power turbines, or a combination of the two. In the turbines, parts of the thermal energy is converted to electrical energy (Glomeep, 2020). This energy may be used to either assist or replace auxiliary engines or to be led back to assist the main engine. The residual heat from the conversion of thermal energy to electrical energy may also be used on the vessel for hot water, heating etc.

The effect of waste heat recovery varies between both ship types and sizes. The larger the engine, the larger the heat exhaust, and therefore the larger the potential for waste heat recovery. Because of this, the range of the fuel saving potential by exploiting waste heat recovery varies throughout the literature. Reviewing the different estimates from the reports on the topic, reveals that the theoretical effect of waste heat recovery on fuel consumption may be somewhere between 1-10% (Virtasalo & Vänskä, 2011; Faber et al., 2011; Lin, 2012; Lindstad, et al., 2015; Tillig et al., 2015; Glomeep, 2020). This reduction in fuel consumption will consequently lead to a decrease in CO2-emissions, and Gilbert et. al (2014) estimates a decrease in emissions of up to 12%. This estimation concurs with the reduction in fuel consumption.

Waste heat recovery systems are fairly costly to fit and are often therefore not considered suitable for retrofit. Depending on the size of the engine and its effect, the cost of installing a waste heat recovery system may be between $2.1 million and $9.5 million (Faber et.al, 2011, Glomeep, 2020). According to Lindstad et al. (2015) waste heat recovery is not considered economically viable as a retrofit solution. However, combined with other technologies which provides more cost reductions than expenses, waste heat recovery may be retrofitted as well.

Shaft generator

The main idea behind a shaft generator is to utilize the main engine and the rotational motion of the propeller to generate electricity (Farnsworth, 2019). This electricity may be used on board the ship for propulsion engines, bow thrusters and other electrical machinery. The use of shaft generators may decrease the need for auxillary engines, and reduce maintenance and lubrication cost for remaining auxillaries (Glomeep, 2020). The models of shaft generators vary between the simplest, producing at a electrical frequency which may vary during the voyage due to speed, waves etc (Avdeyev & Vyngra, 2017). Newer models can produce at constant frequences with different speeds, which is an advantage for the supply of electricity to the ship.

Farnsworth (2019) estimates that running with a shaft generator installed may save around 1.2-1.5 mt/day of fuel running a container ship at vessel speed. Glomeep (2020) estimates a reduction of 2-5% of total ship consumption. When a vessel is slow steaming, a situation usually predicted to have a negative effect on shaft generator performance, Schøyen and Sow (2015) found an effect of 2-3% fuel savings.

Schøyen and Sow (2015) found the return on investment on a shaft generator retrofitted would be about 3.5 years. This correlates with Wärtsilä's (2020) claim of a 2-4 years return on investment. The cost of installing a shaft generator is around $400/kW, which leads to a total cost estimate of between $240,000-$600,000 (Glomeep, 2020).

Propulsion improving devices

Propulsion improving devices are modifications related to the propeller and the hull, intending to improve the ship's propulsion efficiency (Hai-long et al., 2016). The devices have usually either a pre-swirl or a post-swirl recovery approach. It is also possible to do modifications on the propeller or cap directly. The main goal of a pre-swirl device is to manipulate the flow of water, for example to give it a rotation opposite to the propeller rotation (American Bureau of Shipping, 2013). Such a rotational flow leads to the propeller requiring less kinetic energy to provide thrust. Pre-swirl devices include fins and stators, and are often combined with nozzles or ducts to further increase efficiency. According to Glomeep (2020) are post-swirl devices seeking to recover parts of the rotational energy from the propeller slip stream. Rudder bulbs, propeller boss cap fins, rudder thrust fins, post swirl stators and asymmetric rudders are just some of the possible post-swirl devices.

The American Bureau of Shipping (2013) estimates the effect in propulsion fuel consumption of both pre-swirl and post-swirl modifications to be between 2-6% each. This concurs with Harrould-Kolieb and Savitz's (2010) combined estimated effect of 5-10%, while Lin (2012) claims the emission reduction potential is between 5-15%. It is usual to consider the reduction potential for pre-swirl and ducts to be up to 5-6%, while propeller boss cap fins and rudder bulbs are estimated to be around 2% (Hollenbach & Reinholz, 2011; Kim et al., 2014; Hai-long et al., 2016; Glomeep, 2020)

Glomeep (2020) estimates the cost of pre-swirl devices and rudder bulbs to be between \$250,000-\$300,000, post-swirl fins between \$100,000-\$150,000 and ducts and other rudders to be between \$525,000-\$700,000. American Bureau of Shipping (2013) categorizes these cost as medium-low in comparison with other energy efficiency measures. The abatement cost of the propulsion devices discussed is negative, meaning the economic benefit from installing them outweighs the cost (Lin, 2012).

Hybridization

When a ship is designed, its engines are designed to run at a certain speed interval and a certain effect. This is the so called design speed of the vessel. However, for some shorter intervals the ship might need either more or less power than the optimal effect provides (Bouman et al., 2017). The effect of the engine outside its optimal interval is reduced, leading to a relative increase in both fuel consumption and CO_2-emissions. By installing batteries, the engine can continue to operate at optimal levels, even with fluctuating power needs (Lindstad et al., 2017). The battery is charged with the surplus energy in low-demand periods, and discharges to help the engine in high-demand periods. It is also possible to charge the batteries in ports, a so called plug-in hybridization solution (Glomeep, 2020).

Wärtsilä (2020) claims that their hybrid system has led to 15% decrease in fuel consumption, while Lindstad et al. (2017) has estimated that a hybrid power system with batteries gives a reduction of 6-8%. In the meta study of Bouman et al. (2017), hybrid power is found to have an effect of 2-45%, including the estimate of CCNR (2012) of up to 20%.

The cost of adding batteries to a ship is $600,000-$2,000,000, depending on the vessel and engine size (Lindstad et al., 2017; Glomeep, 2020). The estimated payback time of the installment is 12.5 years at a fuel price of $500/tonne, and 6.3 years at $1000/tonne. The cost of hybridization on container ships is much higher than on other ship types (Lindstad, et al., 2015).

Wind propulsion

In earlier times, wind propulsion was the main form of propulsion for ships (Smith et al., 2013). After the introduction of engines, the usage of wind power for commercial ships was almost eliminated. However, with the focus on reduction of fuel consumption, different measures of wind propulsion are regaining traction. The three methods discussed in this paper are fixed sails/wings, kites and Flettner rotors. Fixed sails is the solution reminding the most of historical sails. Mounted on one or more masts, the energy from the sail may reduce some of the propulsion power needed (Glomeep, 2020). The masts take up quite some space on deck, and is therefore not suitable for container ships. When using a kite solution, the kite is pulling the ship along using the power of the wind. A key difference between kites and sails, is the possibility to have the kite much further up in the air, where the wind is usually stronger (Traut, et al., 2014). Kites work best at vessels operating at 16 knots or lower, and therefore are only tankers and bulk vessels suitable for kite usage (Buhaug, et al., 2009). The Flettner rotor is an upright-mounted cylinder rotated by a motor. If the wind meets the cylinder at a 90 degree angel, the frictional drag changes the pressure in the front and back of the cylinder (Tillig et al., 2015). This pressure difference pushes the ship forward.

Sails have the best effect when slow steaming, and the reduction potential of fixed sails is according to Buhaug et al. (2009) 5% at 15 knots, but 20% at 10 knots. Combined with optimal weather routing the effect increased to 44% at 10 knots. The effect of kites obviously depends on the size of the kite, as well as the wind conditions in the areas the ship operates in. Faber et al. (2011) estimate a reduction in fuel consumption of about 3-7% for the smallest commercial vessels, up to about 10-20% for the largest vessels. An estimate between 5-20% seems to be a common guideline for kites (Buhaug, et al., 2009; Gilbert et al., 2014; Traut, et al., 2014; Glomeep, 2020). According to Traut et al. (2014) the fuel consumption of Flettner rotors increase almost linearly when adding more rotors to a vessel. Some studies have estimated the effect on fuel consumption of Flettner rotors to be as high as 25-35%, but most studies have an estimate of between 5-15% (Faber et al., 2011; Gilbert et al., 2014; Traut, et al., 2014; Lindstad et al., 2015; Tillig et al.,, 2015; Glomeep, 2020).

In general, the main issue with retrofitting wind propulsion is its long payback time (Tillig et al., 2015). Most shipowners has a preferred pay back time of 5-10 years, but with the fuel price of 2015, the pay back time for wind systems was nearly 15 years. The cost of installing fixed sails is in the range of \$170,000-\$300,000 (Glomeep, 2020). When considering the marginal CO_2-abatement cost for sails, Eide et al. (2011) find that it is considerably positive. This means that the cost of fuel saved is less than the investment cost of the sails. In addition to the installation cost, a kite system also has a yearly maintenance cost of about 5-15% of the purchase price (Faber et al., 2011). The purchase price varies between \$515,000 for the smallest kites, up to about \$3.5 million for the largest kites. Eide et al. (2011) finds the marginal abatement cost for kites to be around zero. The cost of a single Flettner rotor is between \$400,000-\$950,000, but is usually delivered in multiples of about \$1 million - \$3 million (Faber et al, 2011; Glomeep, 2020). The International Council on Clean Transportation (2011) claims the marginal abatement cost of a Flettner rotor was about -\$25 per tonne CO_2 at the 2011 fuel price level.

Biofuel

A way of reducing CO_2-emissions without actually reducing the fuel consumption, may be done by replacing the current fuel with a new one. Biofuels are types of fuel generated from biological materials. First generation biofuels are primarily produced from food, like grains and oil seeds, which may be processed into methanol (Bengtsson, 2011). Second generation biofuels are created from forest and plant residues, which can be transformed into biodiesel. The third generation of biofuels consists of microalgae, and according to Gilbert et al. (2014) this is the most promising option for shipping due to the possibility of cultivating and refining near ports. This technology is currently in early stages of development (Buhaug, et al., 2009). Depending on vessel adaptation and fuel type, the ship may run solely on biofuel, or on a combination between biofuel and marine diesel. Another positive effect by switching to biofuel is that the sulfur content is very low.

Lindstad et al. (2015) estimate that a combination of 10% biofuel and 90% diesel, will lead to a decrease in CO_2-emissions of 6%. Gilbert et al. (2014) predict that the effect of switching to biofuel being between 10-75%, while the meta study of Bouman et al. (2017) has an even wider estimate of 25-84%. The reason for the large intervals is the variation connected to the type of biomass being used.

Ships may use biodiesel without any big technical changes, but for other biofuels substancial investments must be undertaken (Faber et al., 2011). In 2014, Taljegard et al. (2014) calculated the cost of biofuel to be \$9.98/GJ, compared to fuel oil at \$8.03/GJ and liquid natural gas at \$8.36/GJ. The marginal abatement cost for changing to biofuels is around 200 Euro/tonne CO_2 reduced (Lindstad, et al., 2015).

Speed reduction

The design speed for bulk vessels is around 13-15 knots, while it is around 22-24 knots for large container vessels (Lindstad et al., 2011). This is the speed the engines are optimized to run at. However, by reducing this speed only a small fraction, it may lead to large reductions in fuel consumption. Speed and fuel consumptions are in fact related to a third power function, where a 10% decrease in speed leads to a 27% reduction in fuel consumption (Sherbaz & Duan, 2012). Considering that a vessel travelling at reduced speed will use longer time on a specific voyage, the net reduction from a 10% decrease in speed is a reduction of 19% in fuel consumption and CO_2-emissions (Harrould-Kolieb & Savitz, 2010). As the demand for ship services is constant or increasing, a reduction in speed will lead to a mismatch between supply and demand. This may be solved by adding more ships to the fleet, either by reclaiming lay-ups, or by building new vessels (Corbett et al., 2009). It may also be countered by building bigger ships which may transport more cargo, or also by optimizing port operations to reduce waiting times.

As mentioned, there is a distinct relationship between speed reduction and fuel consumption. This means that if a 10% decrease of speed leads to a 19% reduce in fuel consumption, a 20% decrease in speed leads to a 36% decrease in fuel consumption. One may be tempted to further decrease speed to save fuel, but there is a limit to how low load the engines may be run at without damaging them (Faber et al., 2011). According to the American Bureau of Shipping (2013), retrofits designed to reduce this lower limit on engine loads are in development. Harrould-Kolieb and Savitz (2010) claim that it is possible to reduce the CO_2-emissions by 30% below business as usual models across the fleet, only by reducing speeds and utilizing all laid-up vessels.

It is not easy to estimate the cost of speed reduction of an isolated vessel. If a company has ten equal ships which are running the same route, and then reduces the speed by 10% on all vessels, the cost will be the investment cost and operational cost by adding one additional vessel. By reducing speed by 20%, this cost will be doubled. Eide et al. (2011) claims that the marginal abatement cost by speed reduction is $85/tonne, while Buhaug et al. (2009) has an estimate of \$80-\$135/tonne at a fuel price of \$500/tonne. A fuel price below \$300/tonne gives no economical reasons for slow steaming (Lindstad, 2013).

Weather routing

When shipowners are planning routes for the ship to sail, it is not an option to just draw a straight line from port to port. In earlier days shippers utilized their own and their colleagues experience to choose routes with favourable weather and currents. Weather routing systems help to optimize the route of the ship by using real-time weather data, and presenting a route which may be both faster and safer than the alternatives (Maddox Consulting, 2012). The reduced time at sea, or the gain from avoiding to operate in rough weather and high waves lead to a reduction in fuel consumption. Due to less route flexibility, weather routing is less useful for ships operating in short sea shipping.

The potential savings related to weather routing systems are considered to be in the interval of 0.1-4.0% (Buhaug, et al., 2009; Harrould-Kolieb & Savitz, 2010; Faber et al., 2011; Lin, 2012; Wang & Lutsey, 2013). As a large portion of the world fleet already have installed such systems, the potential for a general reduction from current CO_2-levels will be in the lower end of the interval. Even so, Maddox Consulting (2012) estimates that the general reduction potential may be as high as 3.7% in 2020.

The cost of a weather routing systems are split in a licence purchase and a subscription fee (Glomeep, 2020). Both Buhaug et al. (2009) and Maddox Consulting (2012) use a subscription fee between \$800-\$1,600 p.a., but Glomeep (2020) uses a figure of about \$3,000 p.a. This may indicate that the price has risen recent years. The licence purchase is considered to be \$15,000. Buhaug et al. (2009) find the marginal abatement cost for a weather routing system to be from -\$160 to -\$100 depending on cost and effect. Eide et al. (2011) agree with the negative marginal abatement cost, but have a higher cost of about -\$70. There seems to be consensus of the opinion that weather routing is a measure to reduce CO_2-emissions and cost at the same time (Lin, 2012).

Trim and draft optimization

In earlier times, ships were designed to run at a specified speed, with a specified draft (Hapag-Lloyd AG, 2018). However, through the life of a vessel it may run on many different speeds and a lot of different drafts. With a trim and draft optimization software, one tries to adapt the ship to the different speed and draft conditions to reduce resistance and fuel consumption. The optimization can be done at port, where cargo loading planning can ensure a correct draft (Glomeep, 2020). It may also be done at sea, by shifting, or adjusting the levels of ballast water. According to Abouelfadl and Abdelraouf (2016), many shippers and shipowners still uses static trim and draft matrices to determine the optimal state. However, many software systems are now available which may take wind, weather, and sea state into account to reduce resistance even better.

The effect of trim and draft optimization depends partly on ship type (Glomeep, 2020). For passenger vessels the comfort of the passengers may reduce the trim possibilities, while tankers and bulk vessels may to a larger extent consider viscous friction more while storing cargo. Abouelfadi and Abdelraouf (2016) and Glomeep (2020) estimate around 5% reduction in fuel consumption. In the other end of the estimation interval are Miola et al. (2011) which estimate a CO_2-reduction potential of 0.65%. Other estimates are found in this interval, including estimates from producers of the software and companies already using it (Hapag-Lloyd AG, 2018, Force Technology, n.d.)

The cost of implementing a trim and draft optimization software is split in two. Firstly, you need to buy and install the software, and then you need to train the crew to being able to understand and react to the software’s recommendations. Glomeep (2020) estimates the combined cost to be between $15,000 to $75,000 for both software and training. There is no operational cost after the installation. Both Miola et al. (2011) and Lin (2012) claim that CO_2-abatement cost of such systems are negative at all fuel costs considered, making trim and draft optimization software systems a good investment in both an economical and environmental setting.

Hull cleaning

The process in which biological organisms are removed from the hull of the vessel is called hull cleaning. The organic growth happens whilst the ship is in operation, but is increased when travelling in warm waters or when idle in port (Maddox Consulting, 2012). Removing of the growth reduces the friction between the hull and the water, and thereby reduces fuel consumption. Hull cleaning may be done when the ship is at anchor or at some ports, and is performed by divers with specialized equipment. It is also possible to use automated cleaners, and the company Jotun claims that their HullSkater may inspect and clean a 10,000 square meter hull in just two hours compared to a diver which may clean 200-400 square meters per hour (Gunton, 2020). Hull cleaning is also done at drydock.

As mentioned, the reduction potential from hull cleaning comes from the reduction of friction between the hull and the water. This effect is in Buhaug et al. (2009) and Wang and Lutsey (2013) estimated to be between 1-10%, while Maddox Consulting (2012) and Glomeep (2020) has a narrower interval of 1-5%. Ådland et al. (2018) found that the effect of underwater cleaning was significantly less than cleaning at dry dock, with respectively savings of 9% and 17%.

Faber et al. (2011) found the cost of hull cleaning to be between $35-$45 per foot of the ship, based on overall length. Both Buhaug et al. (2009) and Glomeep (2020) have a more general interval of $5,000-$50,000 depending on the size of the ship and whether divers or robotic cleaners are used. Wang and Lutsey (2013) find the marginal abatement cost for hull cleaning to be -$175. There seems to be a broad consensus around hull cleaning as a measure with negative marginal abatement cost (Buhaug, et al., 2009; Faber et al., 2011; Maddox Consulting, 2012).

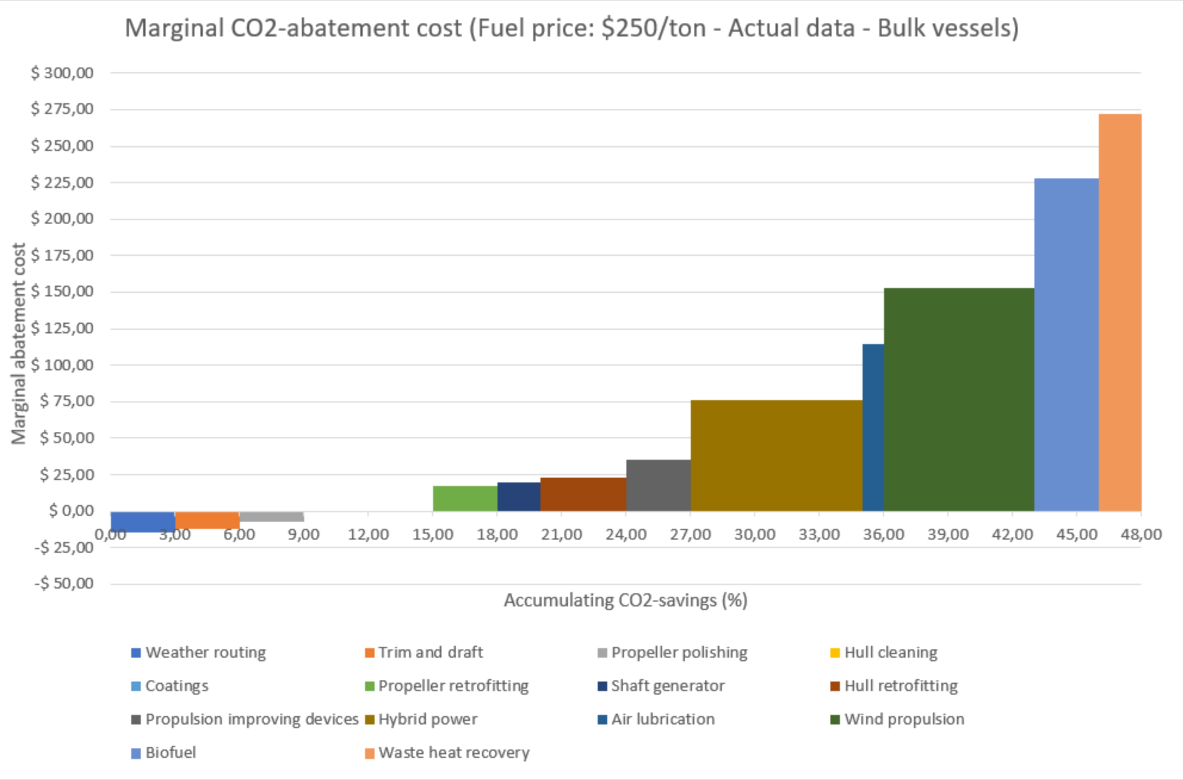
Propeller polishing

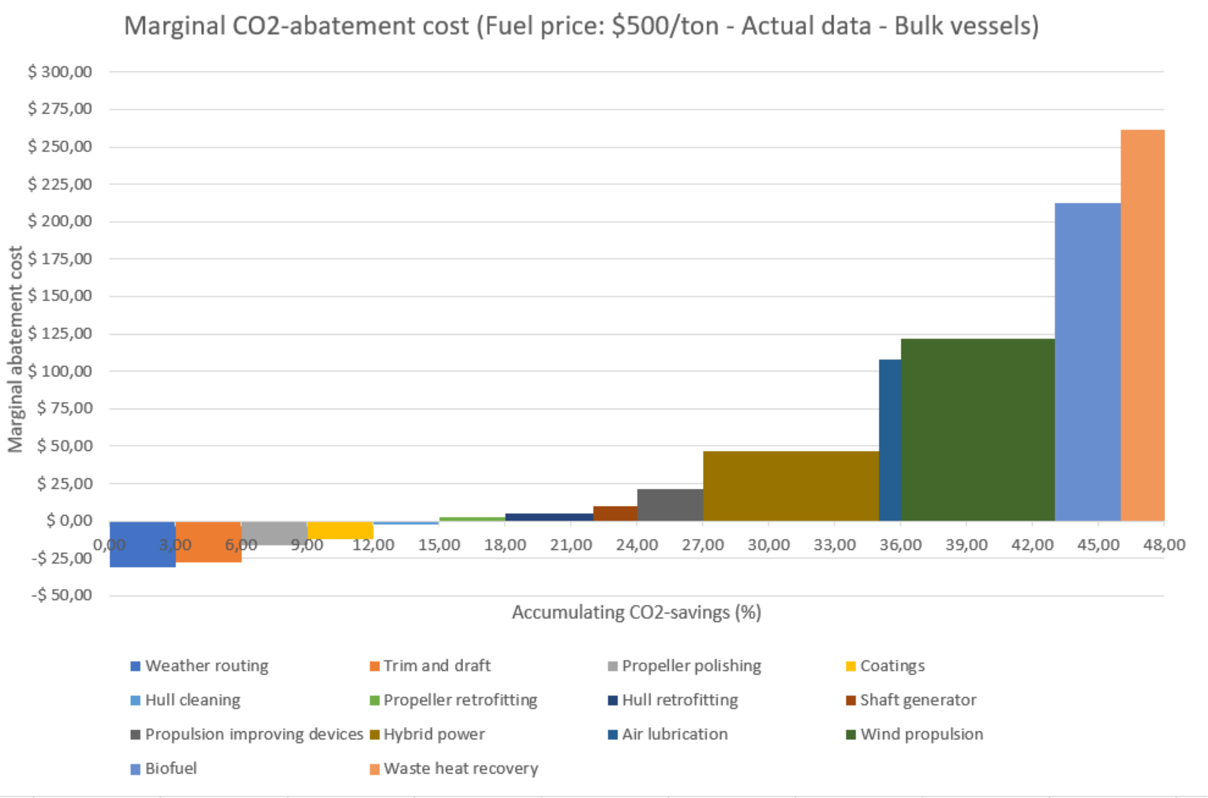
Similar to the hull, organic growth may also occur on the propeller. Propellers with significant organic growth may experience a loss in both frictional and rotational power (Sherbaz & Duan, 2012). Cleaning of the growth may happen at dry dock, or when at anchor by devices controlled by divers (Maddox Consulting, 2012). The propeller polishing may be done at regular intervals, or being done when needed. Glomeep (2020) claims a cleaning interval of six months is found to be optimal. In order to clean only when needed, a monitoring system is needed which will increase the cost of the measure.

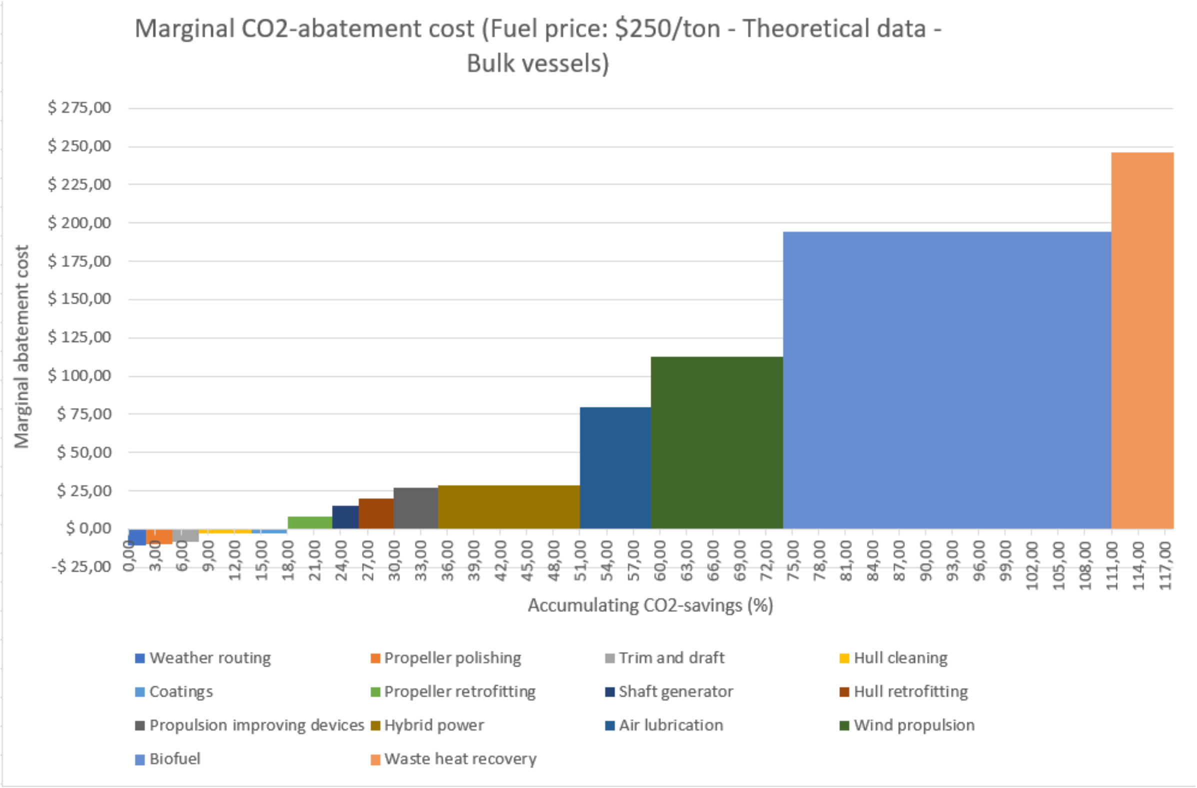
The effect of cleaning on a regular basis is less than cleaning when needed. If a vessel has been sailing in waters with higher growth than usual, cleaning more often is needed, and if it on the other hands has sailed in cold, low-growth water, the period between cleaning may be extended. For periodic cleaning, an estimated reduction in fuel consumption and CO_2-emissions is 1-5% (Buhaug, et al., 2009; Harrould-Kolieb & Savitz, 2010; Yuan et al., 2016). By doing cleaning only when needed this effect will increase to between 3-8% (Faber et al., 2011; Wang & Lutsey, 2013)

According to Faber et al. (2011), having a propeller polishing performed on a single screw vessel cost in the range of $3,000-$5,000. This concurs with the price range of Buhaug et al. (2009), but are way lower than the price range estimated by Glomeep (2020) and Maddox Consulting (2012) with $4,000-$8,000 and $6,000-$10,000 respectively. A system for monitoring the condition of the propeller will cost from about $10,000-$120,000 depending on vessel type and size (Faber et al., 2011). Wang and Lutsey (2013) have propeller polishing ranked as the measure with lowest marginal abatement cost of about -$215/tonne, meaning it is the measure best suited for reducing CO_2-emissions in an economical manner. This negative marginal abatement cost is also supported by Eide et al, (2011), Maddox Consulting (2012) and Yuan et al. (2016).

7.2 Appendix 2 – Collection of marginal abatement cost curves






Marginal CO2-abatement cost (Fuel price: $250/ton - Theoretical data - Bulk vessels)
Marginal abatement cost
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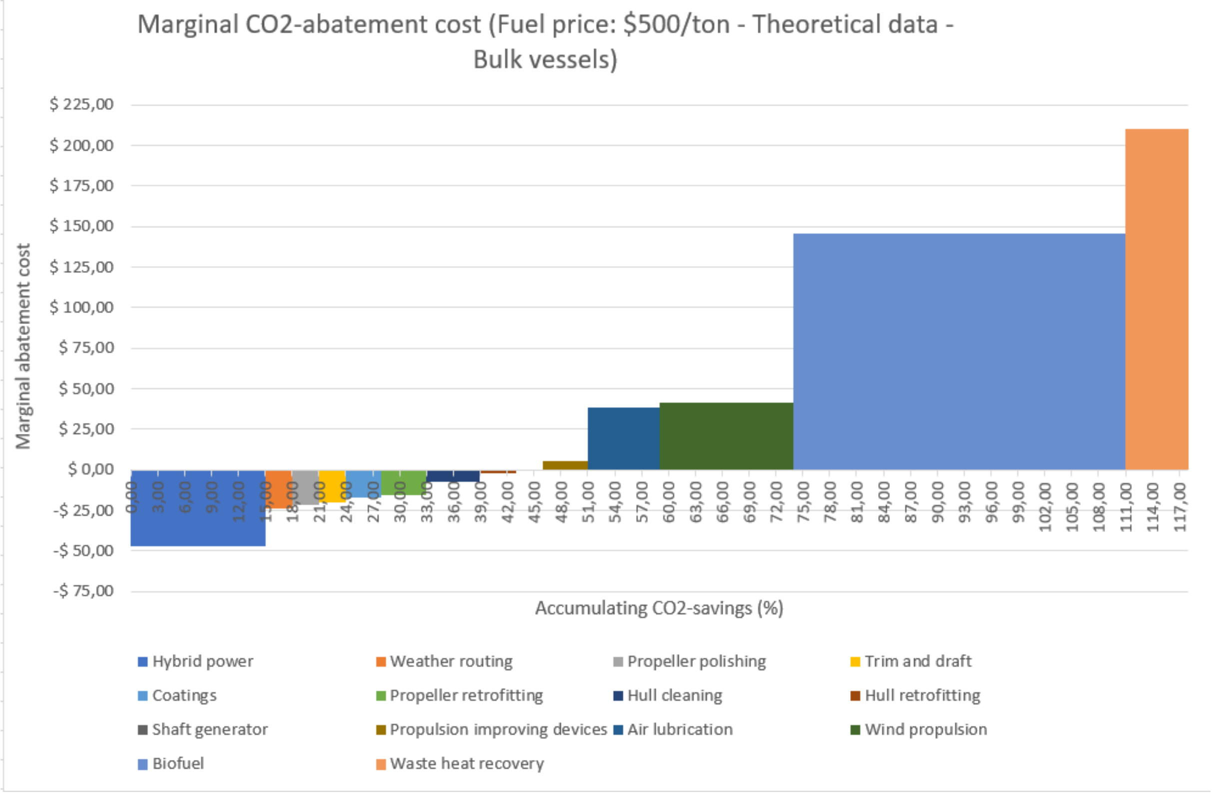
Accumulating CO2-savings (%)
Weather routing
Propeller polishing
Trim and draft
Hull cleaning
Coatings
Propeller retrofitting
Shaft generator
Hull retrofitting
Propulsion improving devices
Hybrid power
Air lubrication
Wind propulsion
Biofuel
Waste heat recovery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Accumulating CO2-savings (%)
Hybrid power
Weather routing
Propeller polishing
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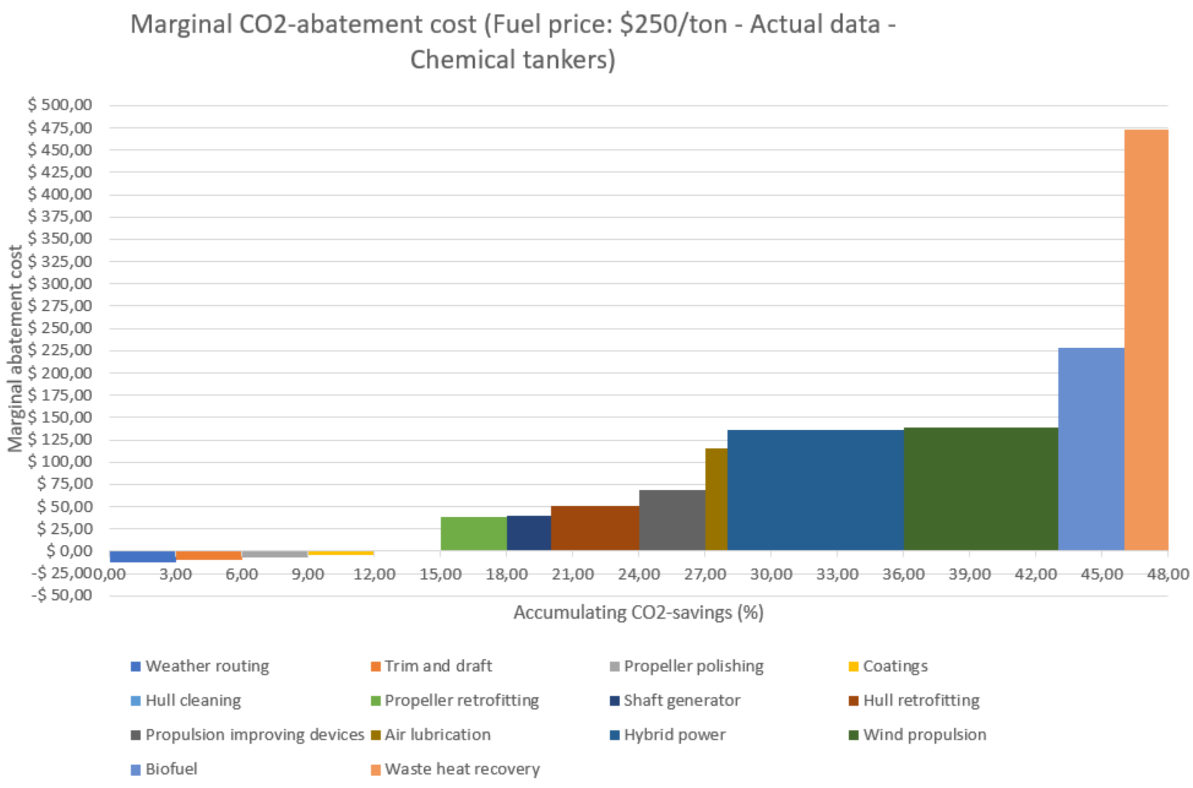
Propeller retrofitting
Hull cleaning
Hull retrofitting
Shaft generator
Propulsion improving devices
Air lubrication
Wind propulsion
Biofuel
Waste heat recovery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Accumulating CO2-savings (%)
Weather routing
Trim and draft
Propeller polishing
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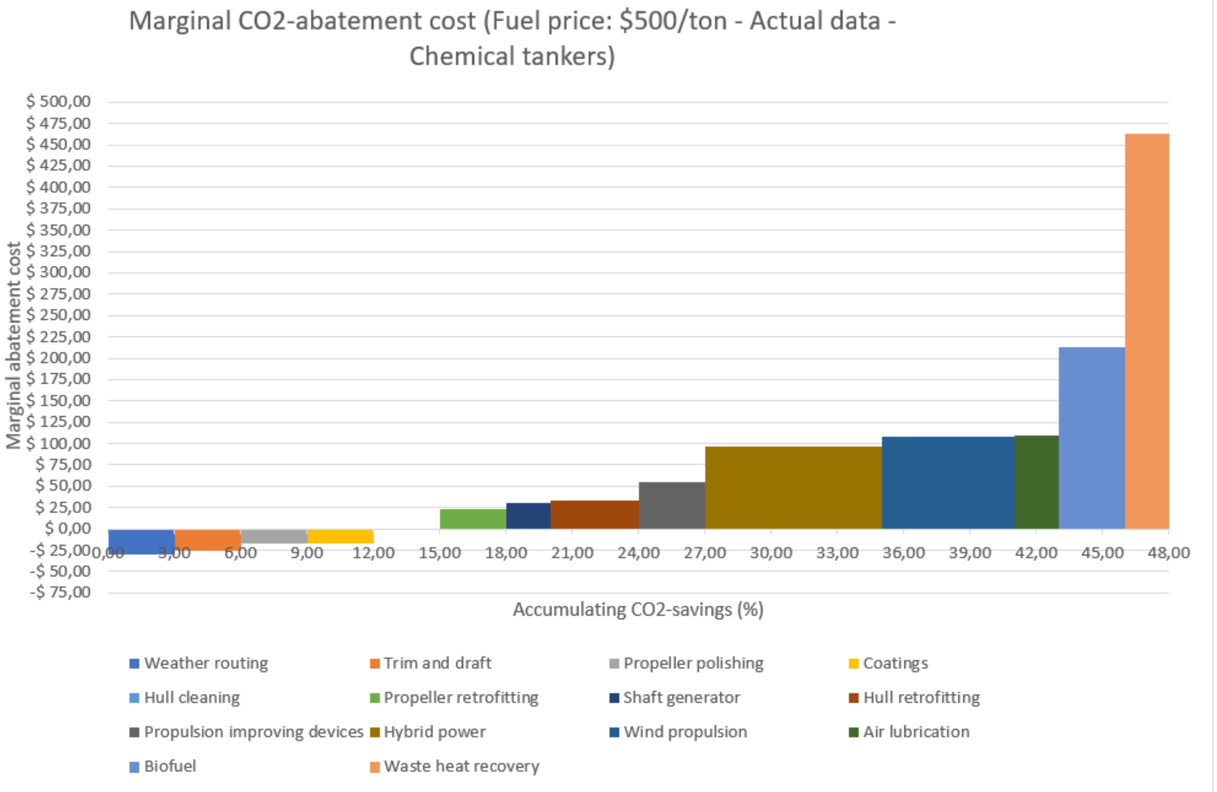
Propulsion improving devices
Air lubrication
Hybrid power
Wind propulsion
Biofuel
Waste heat recovery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Accumulating CO2-savings (%)
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Trim and draft
Propeller polishing
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Hybrid power
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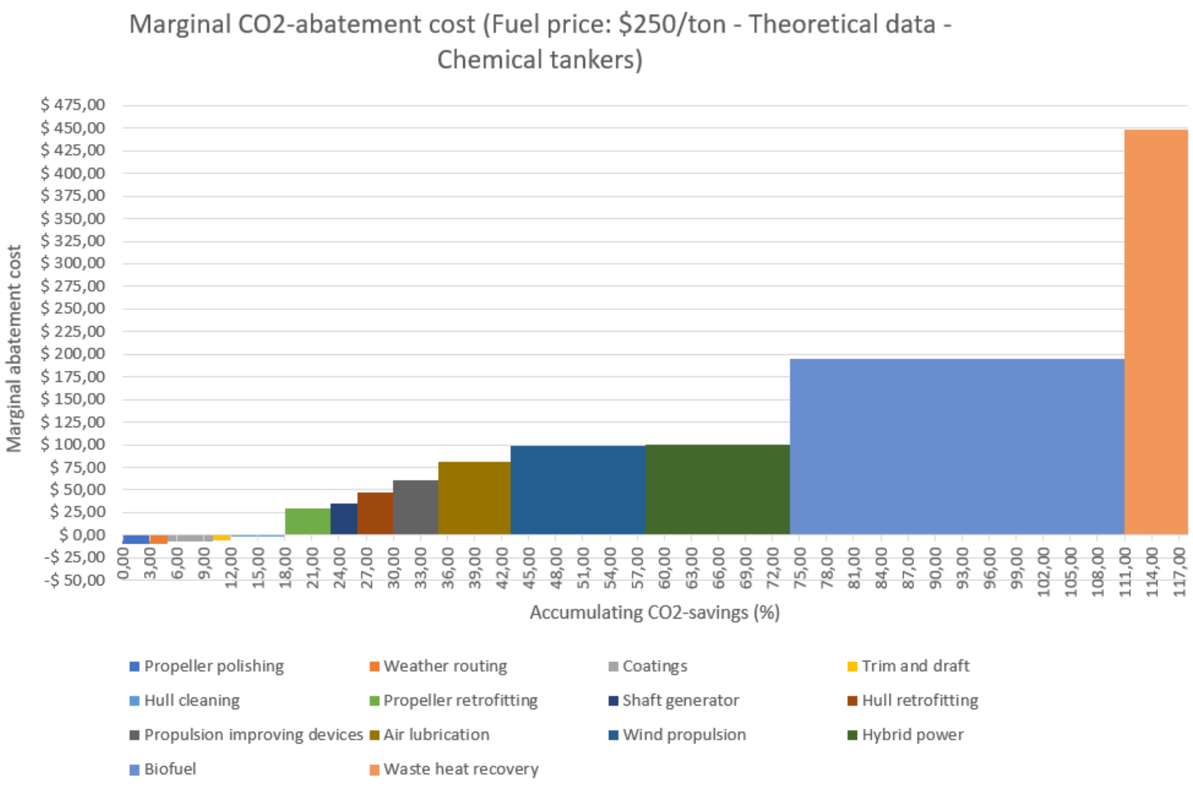
Waste heat recovery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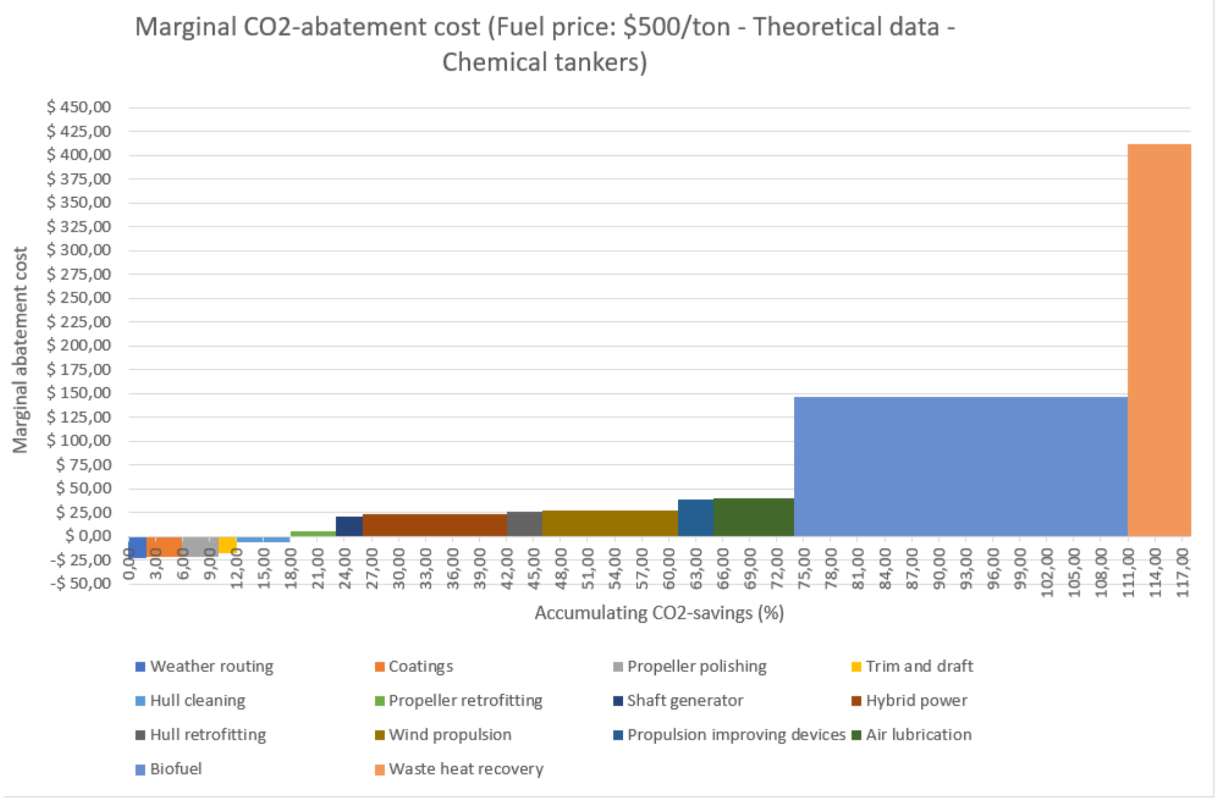
Accumulating CO2-savings (%)
■ Propeller polishing
■ Weather routing
■ Coatings
■ Trim and draft
■ Hull cleaning
■ Propeller retrofitting
■ Shaft generator
■ Hull retrofitting
■ Propulsion improving devices
■ Air lubrication
■ Wind propulsion
■ Hybrid power
■ Biofuel
■ Waste heat recovery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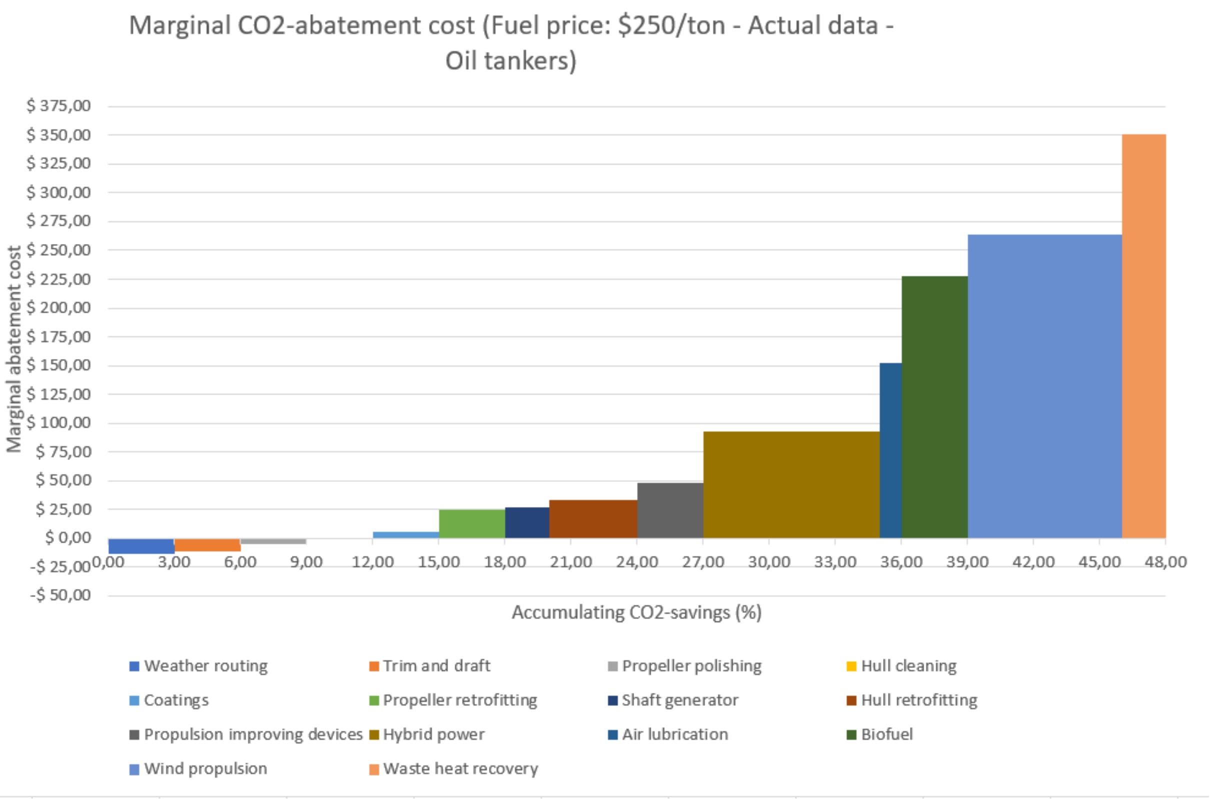
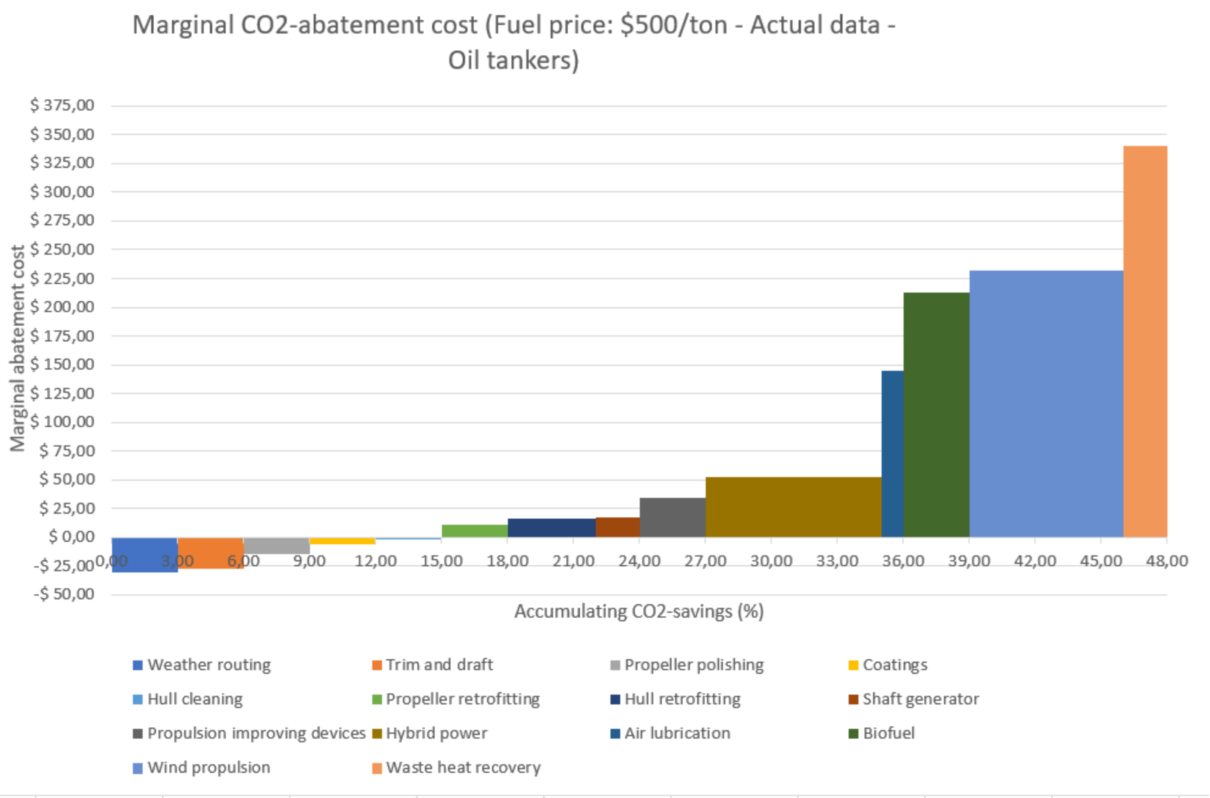
■ Waste heat recovery



Marginal CO2-abatement cost (Fuel price: $250/ton - Actual data - Oil tankers)



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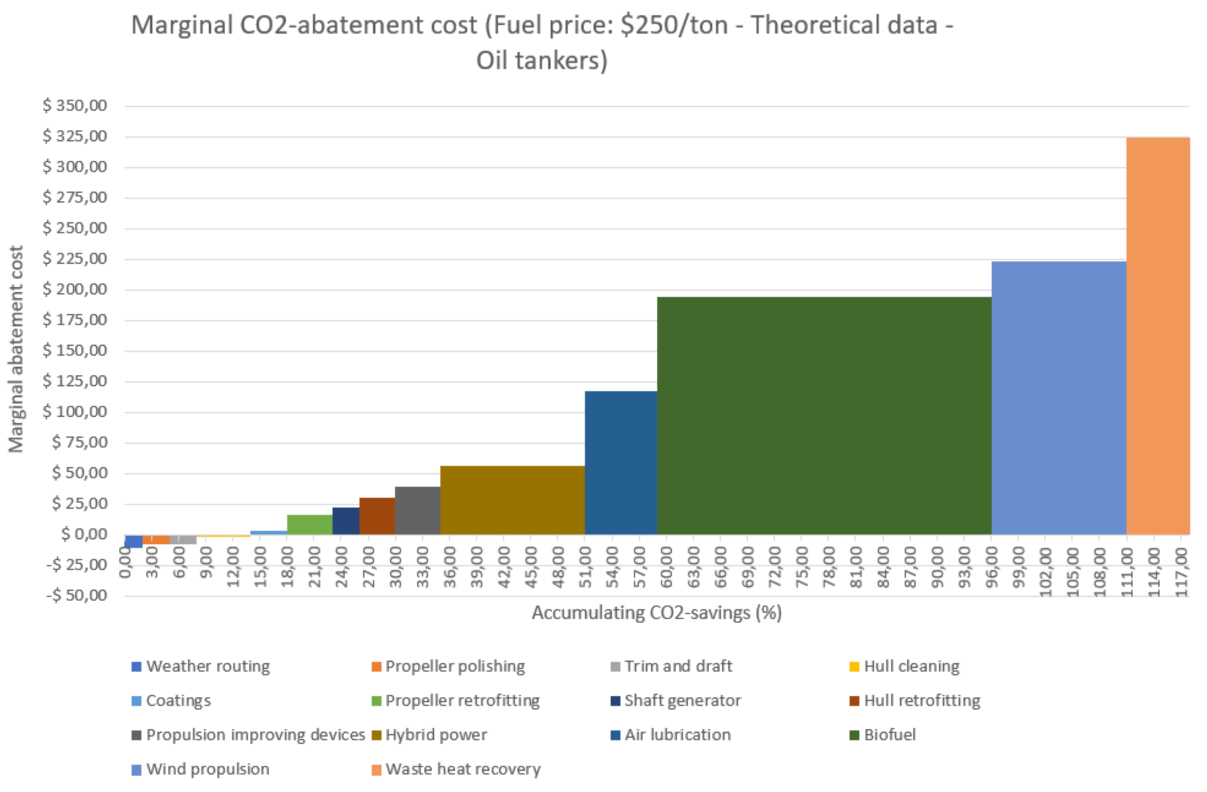
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Biofuel
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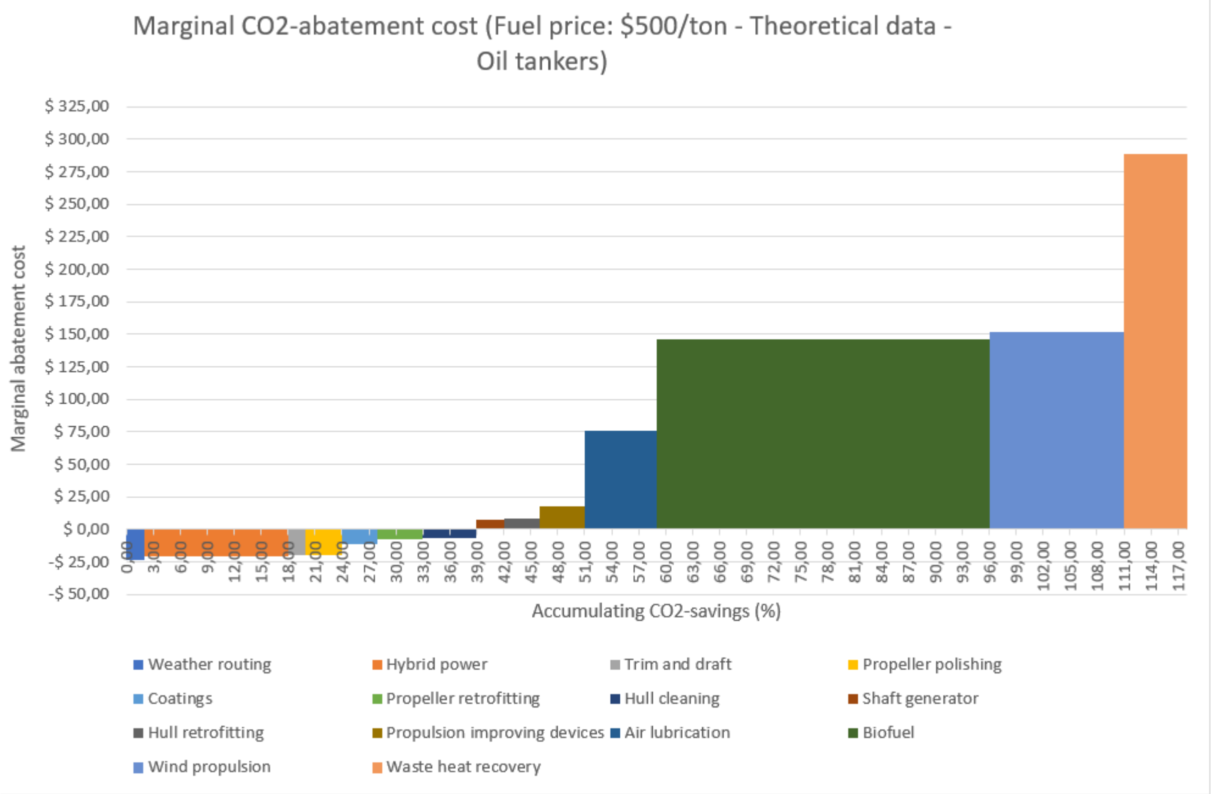
Waste heat recovery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Accumulating CO2-savings (%)
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Biofuel
Wind propulsion
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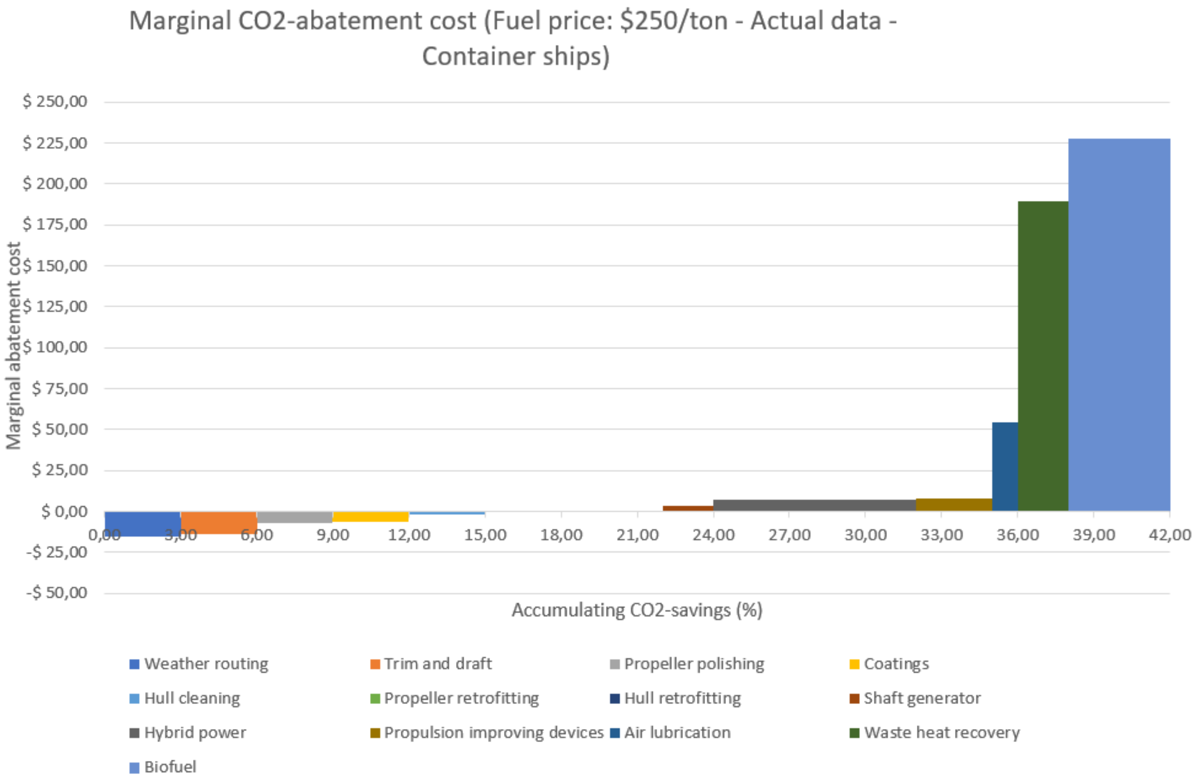
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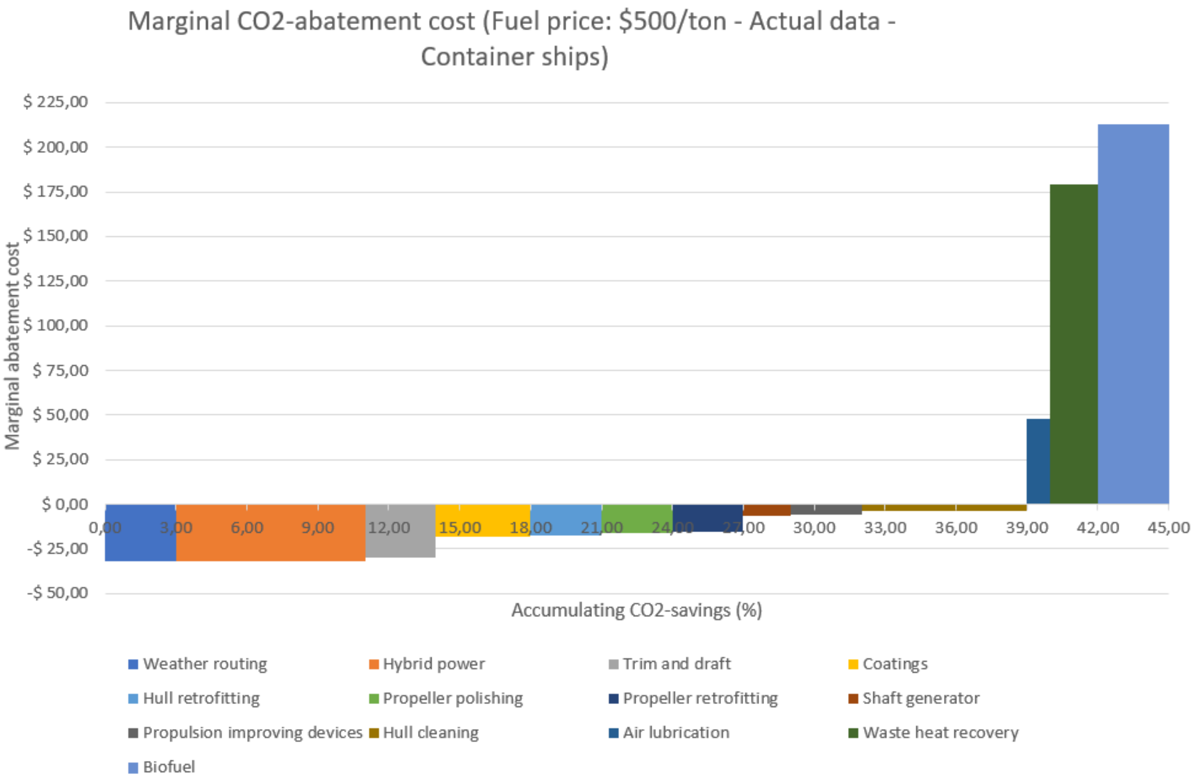
33,00
36,00
39,00
42,00
Accumulating CO2-savings (%)
Weather routing
Trim and draft
Propeller polishing
Coatings
Hull cleaning
Propeller retrofitting
Hull retrofitting
Shaft generator
Hybrid power
Propulsion improving devices
Air lubrication
Waste heat recovery
Biofuel


Marginal CO2-abatement cost (Fuel price: $500/ton - Actual data - Container ships)
Marginal abatement cost
$ 225,00
$ 200,00
$ 175,00
$ 150,00
$ 125,00
$ 100,00
$ 75,00
$ 50,00
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42,00
45,00
Accumulating CO2-savings (%)
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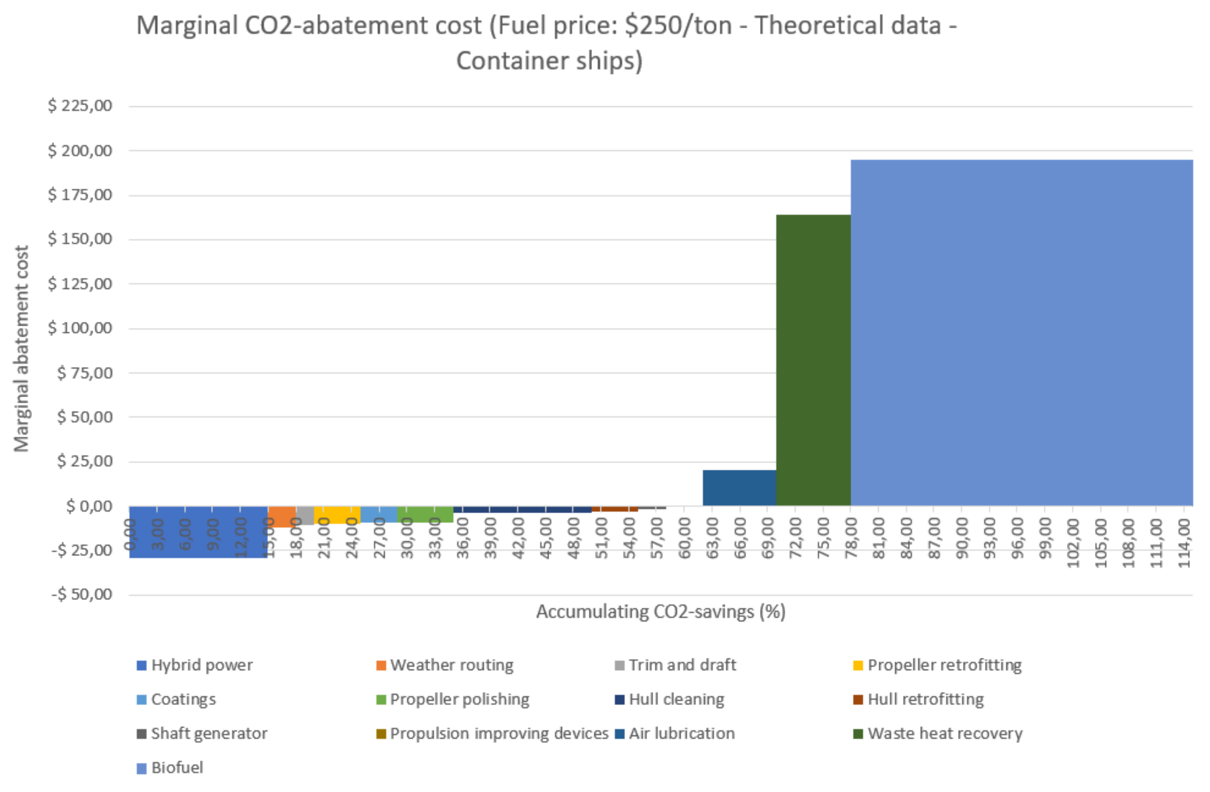
Marginal CO2-abatement cost (Fuel price: $250/ton - Theoretical data - Container ships)
Marginal abatement cost
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$ 200,00
$ 175,00
$ 150,00
$ 125,00
$ 100,00
$ 75,00
$ 50,00
$ 25,00
$ 0,00
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Accumulating CO2-savings (%)
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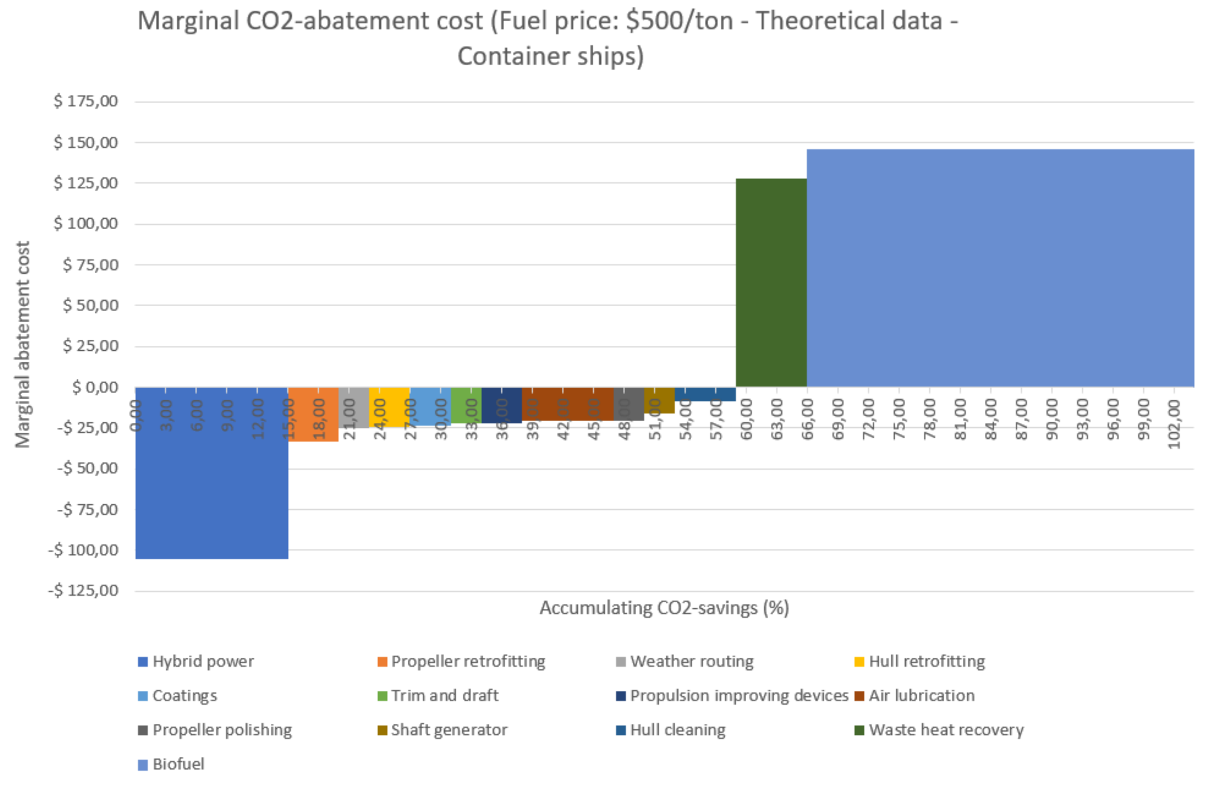
Biofuel


Marginal CO2-abatement cost (Fuel price: $500/ton - Theoretical data - Container ships)
Marginal abatement cost
$ 175,00
$ 150,00
$ 125,00
$ 100,00
$ 75,00
$ 50,00
$ 25,00
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Accumulating CO2-savings (%)
Hybrid power
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7.3 Appendix 3 – Examples of questions from the survey

Example 1:

Example of company-related, partially closed-ended question seeking to find categorical data.

Which types of ships are your company typically operating/owning?

- ☐ Tankers (1)
- ☐ Dry bulk (2)
- ☐ Container (3)
- ☐ Chemical tanker (4)
- ☐ Offshore (5)
- ☐ Other, please specify (6) ____________________

Example 2:

Example of closed-ended question seeking to examine the usage of different retrofit measures. The question is also used for sorting the coming questions, where a respondent answering either Yes or We are planning to do it, will be asked about their experienced or perceived effect of the measure. Respondents answering No, will be asked the reason for not implementing the measure.

<u>Usage of retrofit solutions related to hull and propeller</u>

	Yes (1)	No (2)	We are planning to do it (3)
Do you use high-efficiency anti-foul coating on your ships? (1)	○	○	○
Have you installed a system for air lubrication on your ships? (2)	○	○	○
Have you performed hull retrofitting (bulbous bow, thruster tunnel and/or bilge keel optimizing)? (3)	○	○	○
Have you had any propeller retrofitted? (4)	○	○	○
Have you retrofitted other propulsion improving devices (rudders, ducts, caps, fins etc)? (5)	○	○	○

Example 3:

Example of close-ended question seeking to find the effect of a measure. The intervals are validated using literature.

<u>Which effect on main engine fuel consumption do you see from the air lubrication system?</u>

○ No effect seen/estimated (1)

○ 0-1% (2)

○ 1-3% (3)

○ 3-5% (4)

○ 5-10% (5)

○ 10-25% (6)

○ > 25% (7)

Example 4:

Example of partially closed-ended question seeking to find reasons for not installing a measure.

<u>Why have you chosen not to install a system for air lubrication?</u>

☐ Not technically possible (1)

☐ Too expensive (2)

☐ Do not think it will reduce fuel consumption (3)

☐ Not familiar with technology (4)

☐ Age profile of vessels not suitable for investment (5)

☐ Other, please specify (6) ____