Application of greenhouse gas emission reduction technologies on a redesign of a multi-purpose heavy lift vessel

Master of Science Thesis

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BIGLIFT
KEY IN HEAVY LIFT

Thesis for the degree of MSc in Marine Technology in the specialization of Ship Design

Application of greenhouse gas emission reduction technologies on a redesign of a multi-purpose heavy lift vessel

By

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Performed at

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Preface

This thesis is the result of my graduation project conducted over the last nine months and marks the end of my studies in Delft. I initially started studying Marine Technology in Delft by thinking; “I like boats, I like physics and math, why not study them all?” During my years in Delft, I have learned that this was one of my best decisions in life as I became to enjoy it more and more over the years.

After finishing my bachelors’ degree, I have worked at a ship design company where I found ship design the most appealing part of Marine Technology. During my masters, I chose to follow more courses on naval architecture and was also able to find a graduation topic on this subject as well. This graduation project has made me more aware of how difficult it is for an entire industry to become more sustainable. The critical attitude of the maritime industry toward innovative technologies, the large costs associated with applying new technologies and the highly competitive nature make for a low innovation rate and the industry lagging behind in comparison to other industries.

This thesis aims to show how much emission reduction is possible for multi-purpose heavy lift vessels within the current industry and operations. It is evident from this thesis that when no drastic measures are taken, the climate goals will not be met. This means a different attitude during the design of new ships is needed, and more incentive to do so must be present. I hope that during my working life in the maritime industry, I can contribute to this change.

First, I would like to thank my supervisor Robert Hekkenberg for his support during my graduation. Despite a pandemic making that the two of us did not meet in person during the project, the digital meetings helped me a lot. Your valuable knowledge, critical attitude and feedback on the report have improved the results in this study. Further, I would like to thank Bart Maat and Max van den Berg for their supervision from BigLift/Spliethoff. Our discussions and meetings have helped me in appreciating the relevance of this study from an industrial perspective.

Thanks to my family for all the support during my studies, and for providing an audience for me to practise on. During tough periods you were always there to cheer me up. I would also like to thank my girlfriend Julia, your support, attention and presence helped me keep focus during my studies.

Tijmen Verburgh
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Abstract

Climate change due to excessive GHG emissions is a major problem, necessitating increasing worldwide awareness and action in the years to come. In order to live up to global agreements to mitigate climate change, contributions from all industries are needed, including the shipping industry. For BigLift Shipping B.V., a leading company in the heavy-lift shipping industry and a member of the Spliethoff Group, operating a fleet of multi-purpose heavy lift vessels, this holds as well. Their clients become increasingly more aware of the emissions associated with marine transportation and future GHG emission regulations will necessitate a change in the way their ships are operated. In preparation, they have initiated the present study into reducing GHG emissions for a next generation of their heavy-lift vessels. These should operate between 2025 and 2050, based on their current P-type series and able to execute the identical operational profile. Therefore the study was aimed to investigate how to obtain a maximum reduction of GHG emissions using technologies which do not negatively affect the ship design and operability.
This research question was approached by studying several GHG emission reducing strategies, with stepwise limitation of the number of feasible technologies, defining combinations of feasible technologies, and finally selecting from these the best performing combination of technologies.

First, a literature study was performed, leading to an initial selection of technologies which reduce GHG emission when applied to a redesign of the P-type. This initial selection was based on the criteria that the technologies are expected to be developed sufficiently by 2025 to be commercially available and applicable. A selection of fifteen technologies, which differ in their mechanisms of GHG emission reduction, was made. For all of these technologies, the additional information required to be able to assess their feasibility with the operational profile intended for the redesign has been listed.

In the second part of this study, the operational profile of the current P-type was analysed in detail using the operational data recorded by BigLift during actual voyages both sailing and in port. This data enables a detailed analysis of the operational profile, serving as a basis for the operations of the redesign. The insight gained from this analysis resulted in the elimination of eight technologies, being judged not to be feasible within the intended operational profile, and in the addition of two technologies, judged to be worthwhile to study further Thus, nine GHG emission reduction technologies remained for further assessment, namely: hull redesign and optimized engine, WHR-system, Flettner rotor, variable propeller frequency, cold ironing, fuel cell auxiliary powering, hybridisation and solar power.

As the operational profile of the redesign has been quantified, the assessment of these nine technologies could be based on this operational profile, allowing a more accurate estimation of the GHG emission reduction and costs. This was done in the third part of this study, where the individual performance was assessed first. Once insight in the individual performance was obtained, combinations of technologies were constructed. Seven concepts were created by combining technologies. Each of these concepts included a hull redesign and optimized engine. The assessment of the concepts was carried out based on the same performance indicators as were applied to the assessment of the individual technologies. The selection of the best performing concept was made based on the economic and emission performance, as well as the robustness of the concept. The latter was assessed by means of a sensitivity study, which aimed to quantify the influence of alternative assumptions to the concepts' performance. The selected best performing concept, with adequate robustness of the performance to possible future changes, was a concept employing the combination of a hull redesign and optimized engine, the addition of a Flettner rotor, frequency converter as well as cold ironing.

The last part of the study focussed on how the selected technologies could be applied to the redesign. From this, it was found that the Flettner had the most influence on the redesign, mainly in terms of stability requirements and cargo operations. This was not expected to significantly limit the operability of the redesign, this holds for the other applied technologies as well.
To conclude the study, the redesign was compared as accurately as possible to the current P-type. This was done based on one year's operational data from a P-type vessel. A model was employed to quantify the effect of the applied emission reduction technologies, taking into account the operational conditions. It was found that the total fuel consumption reduction while sailing would amount to 20.2%. Of this, 9.7% was due to the hull redesign, 7.2% was due to the Flettner rotor, 1.8% due to variable propeller speed and 1.5% due to the engine optimization. Taking into account the emission reduction in port by cold ironing, the total fuel consumption reduction in this model was 21.7% and the emission reduction was 20.6%. This was due to the emissions associated from the power production from shore being accounted for as well. With this emission reduction, the IMO goals for 2030 are not met. Recommendations were given on how this goal could be met by the addition of alternative fuels; in that respect, the most important characteristics for the application of drop-in fuels and LNG were discussed.

It was concluded that the research has successfully been executed; a combination of technologies capable of reducing GHG emissions by 20.6% compared to the current P-type was found and the application of these technologies and future further emission reduction has been outlined. Furthermore, it was concluded that all goals related to this study have been met. The current research method has resulted in an initial exploration of different ways of reducing GHG emissions, whereby the operability and design of the vessel is influenced the least. This has led to a result which is not revolutionary and is not expected to meet the IMO goals for 2030 and 2050. This shows that within the current industry, a combination of commercially and economically feasible technologies is not sufficient to reach the IMO goals.

It was therefore recommended to further study how the IMO goals could be met for a redesign of the P-type; by relaxing several constraints and criteria used in this study, a higher GHG emission reduction could be achieved. Furthermore, when the emission reduction is studied based on the carbon intensity, thus taking into account the transport work and a variable operational profile, more insight would be gained on how the IMO goals can be met and how the lowest carbon intensity for a redesign could be achieved. Such further research would also consider technologies having a high-impact on the ship design and operability, this would help in filling a literature gap.

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Introduction

One of the largest problems the world is facing right now is climate change. As climate change involves all nations of the world, the United Nations Framework Convention on Climate Change has come to an agreement to mitigate this problem. This agreement was ratified on 4 November 2016; 195 nations have signed the agreement. The goal of the agreement, known as the Paris Agreement, is: '*holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*' (UNFCCC, 2016). The most effective way of reaching this goal is to reduce global greenhouse gas (GHG) emissions drastically.

To reach the goals set out by the Paris Agreement, drastic action is needed from all industries, including the shipping industry. In their third GHG-study, the international maritime organization (IMO) estimates that the shipping industry accounts for an average of 2.8% of the Global CO_2-equivalent during the years 2007 to 2012 (Smith et al., 2014). This is for the largest part caused by intercontinental shipping, which is associated with large fuel consumption. The IMO has set out multiple goals in their Initial IMO strategy on reduction of GHG emissions from ships (IMO, 2018) to reduce the GHG emissions of the whole shipping industry. The most important goal is a reduction of 50% of the GHG emissions caused by shipping in 2050, compared to the 2008 levels. In order to anticipate to an increase in the shipping transport work, additional goals for GHG emission reduction for individual ships are formulated as well. The goal is that by 2030, the carbon intensity (mass of CO_2 emitted per unit cargo per mile transported) will be reduced by 40% and in 2050, by 70% of the 2008 value.

As the goals set out in the Paris Agreement and by the IMO are ambitious, additional regulations on shipping emissions are expected to be entering into force in the coming years. No widely accepted technical solution to reduce a ship's emissions by 70% has yet been found that is also feasible in the current shipping industry. Most technologies which reduce emissions are not sufficiently developed yet, or are too expensive to be economically feasible. This is why, in the coming years, a lot of research will need to be carried out on which solution enables the shipping industry to reach the climate goals.

For different ship types, with different operational and mission profiles, the most feasible technology to reduce emissions can be significantly different. For example, for a ferry sailing on a fixed route, the application of batteries can be a feasible solution to reduce emissions. For an ocean-going container ship however, applying batteries to reduce emissions could be a completely infeasible solution due to the large battery capacity need. This is why research has to be carried out for each specific ship type to indicate the best fitting emission reduction technologies.

One of the ship types for which this research has yet to be carried out is the multi-purpose heavy lift vessel. These vessels generally do not operate on a fixed sailing schedule or route, and have a largely varying operational profile due to different cargo. This results in different drafts and sailing speeds. These aspects influence the selection of the most feasible emission reduction technology and thus need careful consideration while executing this research.

Since additional emission regulations are expected for these ship types as well, the industry wants to stay ahead of these regulations. Thus, ship operators will need insight in which types of solutions could be implemented to comply with these future regulations, and they therefore benefit from further research.

BigLift Shipping B.V., member of the Spliethoff Group, in Amsterdam is one of the companies which want more insight in the best way of complying with the IMO goals for their fleet of multi-purpose heavy-lift vessels. This is why they initiated the present study that has been carried out during nine months as a masters' thesis for the TU Delft master program 'Marine Technology'. The supervisor of the project from the TU Delft was Dr. Ir. R.G. Hekkenberg, associate professor at the department Ship Design, Production & Operations. The supervisors representing the company were Ing. Bart

Maat, project engineer at BigLift Shipping B.V. and Ir. Max van den Berg, performance coordinator and data analyst at the Spliethoff Group.

Research context

The research that has been carried out for BigLift Shipping focusses on reducing the greenhouse gas (GHG) emissions by redesigning one of their vessels, the P-type. The redesign should not apply solutions with high-impact to the operational profile and the arrangement, because the current flexibility in operations and dimensions of the P-type are favourable. An important part of the research was to get insight in how these requirements set by BigLift limit the feasibility of several emission reduction technologies. In short, it can be stated that the main goal is to investigate how much GHG emissions can be produced using off-the-shelf technologies that have a low-impact on the ship redesign.

The redesigned vessel should serve BigLift from 2025 to 2050. This period will be the basis for different scenario's for the future, with assumptions on developments in technology, additional emission regulations, fuel types and bunkering infrastructure. In terms of design freedom, the main criteria is that the hold volume and deck area should be roughly the same as with the current P-types. The main dimensions can be altered when this is deemed necessary to enhance the overall efficiency, but only to the extent that the current way of operating remains feasible. A redesign should be able to serve the same market, being capable of transporting the same cargo types and volumes, of reaching the same ports and being able to sail the same distances. In terms of speed, deviations from the current speeds may be accepted for the sake of reducing GHG emissions. The main research question therefore is as follows:

'Which combination of technologies can best be applied to the redesign of BigLift's P-type in order to reduce GHG emissions as much as possible within the current industry and operational profile, and how would a concept design with these technologies perform compared with the current design?'

Some general information on the currently operated P-type will be given, as this vessel series shall be the basis for the redesign process. Once insight in the currently operated P-type is given, the report goal and structure will be shortly described.

The current P-type operated by BigLift and Spliethoff is a series of nine ships, all built between 2009 and 2012. The vessels have a length overall of roughly 169 m, a breadth of 25 m and a design draft of 9 m. The P-type has a deadweight capacity of nearly 20000 tonnes and a hold volume of 26300 m^3, enough to transport 912 twenty foot containers. The vessels have favourable characteristics for their use by BigLift, as all of them are equipped with cranes able to hoist heavy loads. The two main cranes on the portside of the vessel are able to carry 700 t, and the crane on the bow is able to hoist 180 t. Three of the P-type vessels have a reduced portside crane capacity of 400 t instead of 700 t. Furthermore, the deck and hold arrangement and foldable hatch covers enable the P-types to carry other sorts of cargo as well, including bulk and containers. One of Spliethoff's P-types, the Poolgracht, is shown in figure I.1.

The versatility in cargo type makes the P-type very suitable for the operating profile intended by BigLift. This is because the heavy-lift market is mostly unidirectional; being that some area's in the world mostly require heavy-lift cargo (like Northern-America and Australia), whilst others mainly produce heavy-lift cargo (like India and China). This means that when a heavy-lift transport has been completed, most of the times no such cargo is taken back. Yet, the versatility of the P-type allows other types of cargo to be taken back, thus avoiding return ocean-voyages with an empty ship, increasing the profitability of these vessels. This is a definite advantage over its competitors in this market, as the return voyage of most competitors is empty sailing, thus only incurring additional costs. The P-type, operating as a multi-purpose vessel with heavy-lift capabilities, is therefore a good candidate for a redesigned next generation of heavy-lift vessels for BigLift.

Figure I.1: An example of Spliethoff's P-type, the Poolgracht, transporting heavy-lift cargo.

Furthermore, the P-type operates based on market demand, meaning that no standard voyages or liner services are carried out. Instead, the P-type sails where it finds the demand for cargo. This means that voyages are carried out all over the world and that a dedicated office department optimizes the profit made on these voyages by utilizing the ships to their fullest capacity. This way of operating demands a variable operational profile in terms of speed and draft.

The variability in speed is imposed by the fact that heavy-lift cargo voyages usually are not demanding in terms of speed. As slower speeds make for reduced accelerations of the cargo, acceleration limits are even important criteria for most heavy-lift voyages. Thus, when shipping heavy-lift items, the speeds are mostly reduced and not near the maximum speed of the P-type. On the other hand, return voyages with bulk or general cargo generally are strict in terms of arrival date, meaning that the speed of the vessel is usually higher. When making a return voyage in ballast, the speed depends on the start date of a new voyage or the optimal speed for the lowest fuel costs.

From personal communication with the supervisors from BigLift and Spliethoff, it is concluded that in terms of sailing time, the P-type sails 40% in ballast, 40% shipping heavy-lift cargoes and 20% with bulk or general cargo items. These percentages will be verified during the research. The differences in cargo transported make for a variety in draft as well, since the heavy-lift items are mostly critical in terms of size, not in terms of their weight. This means that the draft when transporting these items is not near the maximum draft and usually ballast water is taken in to achieve the desired draft and stability. When sailing fully ballasted, the draft is usually between 6.5-7.5 meters. The deepest drafts are usually reached when sailing with bulk or general cargo, as these cargoes are mostly critical in terms of deadweight.

The P-type has an endurance of 40 days at a speed of 13,5 kn. This makes for the range of the vessel to be 12960 nm or 24000 km. The bunker capacity is 1200 ton and bunkering is performed based on the voyages of the vessel. A dedicated bunkering desk seeks to find the best bunker fuel prices along the route of the vessel. Bunkering is usually performed at larger ports, since this is where the best bunker prices are generally found. Since the P-type vessels are operating very flexible in terms of operating area and trade routes, worldwide availability of fuel is critical in order to support this way of operating.

Because the P-type operations described above are most representative for the future operations of BigLift, this vessel type has been chosen as a basis to perform research on reducing GHG emissions.

Report goal

This report will describe the research that has been carried out on GHG emission reduction for a redesign of the P-type. It aims to provide a clear overview of which subsequent steps have been taken during the study, and to show the reader how the best performing combination of technologies to reduce GHG emissions has been identified.

Furthermore, the report aims to serve as a reference for similar studies into GHG emission reduction, as readers can gain insight in how this problem has been identified, how the number of feasible alternatives has been reduced and how the most feasible or best performing alternative has been selected.

For BigLift and Spliethoff, this report aims to describe which GHG emission reduction solutions are most appropriate in the short-term, and could serve as a basis for future research into GHG emission reduction for other ships operated by them or for more in-depth research into a redesign of the P-type.

The final important goal of this report is to show compliance with the study goals needed to obtain the Master of Science degree in Marine Technology.

Report structure

The report will follow the structure as decribed in the following. This is graphically presented in figure I.2. First of all, the research is defined; a literature study has been carried out in order to define the problem, obtain insight in the research that has already been carried out and perform a literature gap analysis. The results of the literature study will be discussed in this section as this defines the research that was carried out.

When the research has been clearly defined, the initially selected GHG emission reduction technologies will be presented in section 1. This will form the basis of the further research, as the best performing combination of feasible technologies will be selected from these technologies.

In section 2, the operational profile will be analysed. This is done for two important reasons; to provide a reference of the current operations and GHG emissions of the P-type and to formulate the constraints which limit the number of technologies that are feasible within the operational profile.

In the third section, the emission reduction and economic performance of the remaining technologies on the defined operational profile are estimated. From this, combinations of technologies are made which are assessed on their combined performance as well. The result of this section is a selected final concept which is a combination of GHG emission reduction technologies that is deemed to be the best performing on a redesign.

In the fourth section, the selected concept is analysed further. The application of the selected technologies is discussed in more detail, and a comparison of the expected performance of this concept with the current P-type is carried out. Finally, recommendations on future research on this concept are given.

The report ends with the final conclusions and discussions on the present study. The last section is dedicated to providing recommendations for future research.

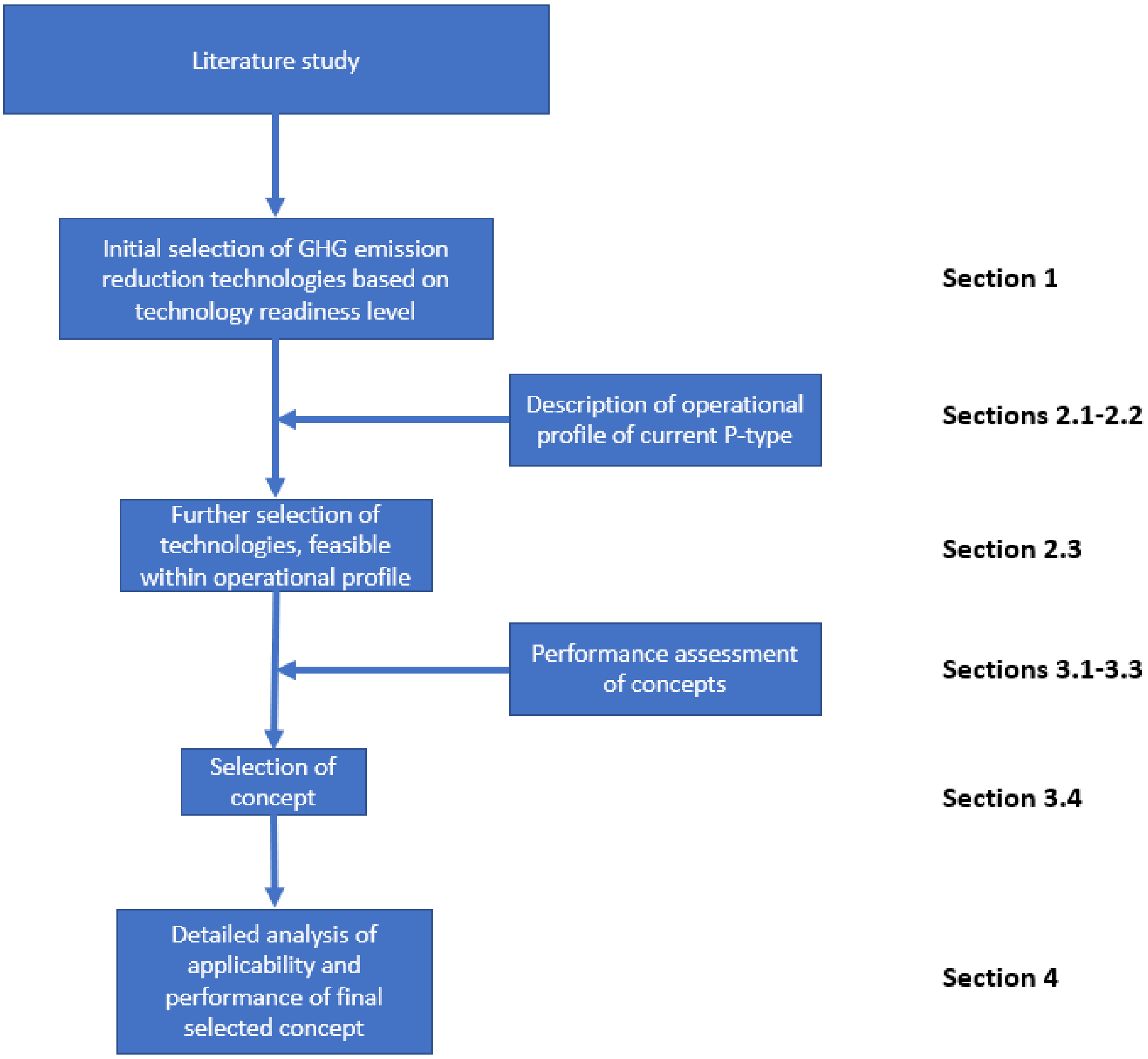

Figure I.2: Scheme of the present study

Research definition

In this section, the research is defined. This section is the result of a literature study that was performed at the start of this project. The most important findings from the literature study that have contributed to the present strategy of research on GHG emission reduction for the P-type will be discussed.

First of all, the problem addressed by the research will be defined. After this, the gap indicated in the studied literature is addressed. From this gap and the studied literature, the research goals can be formulated. The associated research questions are presented after this. At last, the scope of the research and the approach to answering the research questions is shortly described.

Background

One of the largest problems the world is facing right now is climate change. Therefore, the United Nations Framework Convention on Climate Change has come to an agreement to mitigate this problem. This agreement was ratified on 4 November 2016 and 195 nations have signed the agreement. The goal of the agreement, known as the Paris Agreement, is: '*holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*' (UNFCCC, 2016). The most effective way of reaching this goal is to reduce global greenhouse gas (GHG) emissions drastically.

In order to live up to the global agreements to mitigate climate change, the European Parliament has set its own goals in reducing greenhouse gas emissions. The aim of the European Parliament has been outlined in the 'European Green Deal', which states that efforts will be made to achieve a climate-neutral European society by 2050. Furthermore, they call for 'an ambitious Climate Law with a legally binding domestic and economy-wide target for reaching net-zero greenhouse gas emissions by 2050 at the latest, and intermediate EU targets for 2030 and 2040' (European Parliament, 2020). This shows that from a global political perspective, the need to reduce GHG-emissions is urgent and incentives to enforce this reduction are currently being developed.
To reach the goals set out by the European Union and the Paris Agreement, drastic action is needed from all industries, including the shipping industry. The International Maritime Organisation (IMO) has set out its own goals to reduce GHG emissions from shipping. These goals are stated in the 'Initial IMO strategy on reduction of GHG emissions from ships', and are as follows;

1. 'Carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships
2. Carbon intensity of international shipping to decline: to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008
3. GHG emissions from international shipping to peak and decline:
   to peak GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008' (IMO, 2018)

All three goals are quite coherent with one another, although each goal may have a different solution or different impact on the shipping industry. For instance, a maximum annual fleet growth of only 0.4% is allowed to reach the third goal whilst complying with the second goal (de Jong & de Jong, 2020). The three goals may invoke three different approaches.

It can be concluded that global and local politics are striving to reduce GHG emissions from shipping to mitigate climate change. Goals for the shipping industry have clearly been formulated and regulations have been introduced in the past years to enforce shipping companies to operate their ships more environmentally friendly. Several aiding tools for shipping companies have been set up as a start towards reducing maritime GHG emissions. However, with only the current regulations, the climate goals of the IMO and the UNFCCC will probably not be met. This means that more strict measures are needed in the coming years to reduce GHG emissions from ships. It can be expected that in the period up to 2050, international politics will have an increasing influence on the shipping industry's way of operating. Moreover, additional GHG emission limits are expected to enter in effect in the coming years.

Furthermore, the clients of BigLift became increasingly aware of the emissions associated with the transportation of their cargo. More often clients want to know how much CO_2 is emitted to the environment for their voyages with BigLift. This means that next to increasing focus of politics and expected upcoming regulations, the societal pressure for shipping companies to reduce their emissions increases. Future clients may opt for BigLift over their competitors when BigLift can show that their transports have a lesser impact on the environment. Such a 'green' company image is expected to be beneficial for future commerce.

Currently, much research is being conducted in the field of reducing maritime GHG emissions. This includes studies into ship efficiency improvements, alternative fuels and exhaust gas post-treatment (Bouman et al., 2017). A lot of this research is government funded, showing the political influence in this field. From the number of ongoing studies on this topic, it can be concluded that the industry is highly active in searching for technologies to reduce GHG emissions, but rapid innovations are not yet present and the number of actual solutions is still very limited. This is mainly due to the fact that solutions are not commercially viable, either due to the high associated costs, the high impact on the operability of the ship, the large impact on ship design and cargo carrying capacity or due to the fact that no regulations exist for the usage of some emission reduction technologies.

The background for reducing GHG emissions in shipping has been defined from multiple perspectives, and it can be concluded that the political and societal awareness for reducing GHG emissions from shipping is increasing. This will result in more stringent GHG emission related regulations in the coming years for shipping operators.
As the shipping industry is characterised by high levels of competition and large investment costs involved with technological development, a wrong investment decision could result in a loss of market position. This is why shipping operators are generally conservative with respect to innovations. This means that only technologies that have been proven feasible and commercially attractive are considered. To accelerate the reduction of the GHG emissions from shipping, more incentives for ship operators to change their current way of operating are needed. This could be achieved by the introduction of new regulations or market-based measures which make for a more level-playing field for the shipping operators.

Research relevance

As the background for the research is now known, the gap identified in the literature study can be presented. From this, the relevance of the research will be presented and the research goal and associated research questions can be formulated. Note that the following are the conclusions from the separate literature study conducted prior to this thesis, which means that references to the specific studies can be found in the literature study report and are not given in this overview.

It has been noted that most major studies on GHG emission reduction focus on a projection of future emissions for a large number of vessels in a fleet model. These studies show whether compliance with the 2050 goals of IMO can be achieved, but provide very little insight in the practical issues when applying the emission reduction measures on a ship. Furthermore, as these studies consider fleets, the distinction between the performances of GHG emission reduction technologies in different ship types is in most cases unclear. Next to that, the technical and economical characteristics and the impact on the operations of the vessel due to applying a certain emission reduction technology are not or only very shallowly discussed.

In the studies based on single ships, the focus seems to be more on the choice between certain GHG emission reduction technologies. This means that the technologies are qualitatively compared based on their influence on the operations, costs and design of the individual ship. It was observed that only very little attention was given on the application of these technologies. This is because the main criteria involved in the decision between GHG emission reduction technologies are the costs and the performance in terms of emission reduction. Other criteria which are frequently used in the comparison between the emission reduction technologies are safety, technology readiness level (TRL) and availability. The impact on the ship design and operations is difficult to quantify with a single parameter, which is why this is often not included in the comparison of technologies. Furthermore, it is seen in various studies involving a single ship that when the best emission reduction technology is chosen, the effect on the ship design and operations are not quantified, but merely qualitatively discussed. In several studies where this has been quantified, it involved merely low-impact solutions in terms of naval architecture, being operational measures or efficiency-improving measures. Where solutions were proposed which have a high impact on the ship design, such as the application of alternative fuels, this was in most studies merely touched upon and the focus remained on comparing the alternative fuels based on other criteria.
From both types of studies it is concluded that a literature gap exists in the application of GHG emission reduction technologies on a ship, in terms of influence on the ship's design and operation.

In terms of vessel type, little to no case studies of emission reduction technologies are applied to general cargo or multipurpose ships. Instead, most of the case studies where the GHG emission reduction potential is studied have been applied to container ships, bulk carriers and oil tankers. This makes sense as these ship types are the top three polluters as shown in IMO's third GHG study (Smith et al., 2014). Furthermore, as these ship types often operate on a certain freight route with preset ports and speed, the application of GHG emission reduction technologies can be assessed with a lot less uncertainty with respect to the operational profile and thus the eventual reduction potential. This provides studies with more firm conclusions drawn regarding the performance of GHG emission reduction technologies. Thus a gap exists in the literature on reducing GHG emissions for multipurpose or general cargo ships.

Furthermore, current literature mainly focusses on the application of a single GHG emission reduction technology. Some studies have been found in which a combination of technologies has been assessed, however, the interaction of the technologies with one another and the synthesis of these solutions in terms of the ship design and operation were neglected. This makes sense, as most of the studies had the goal of assessing the performance of a single emission reduction technology or alternative fuel; therefore the combination of technologies could cloud the results and make it unclear what the exact contribution is of a single solution to the total performance. Only the study of Schwartz et al. (2020) combined different GHG emission reduction technologies and showed the effect on the costs and the combined CO_2 reduction. However, it is unclear why the combination of these technologies has been chosen. A literature gap with respect to the application of a combination of GHG emission reduction can thus be identified.

From the literature gaps mentioned above, it is clear that the present study could contribute to filling this gap by applying a combination of GHG emission reduction technologies which have a large influence on the ship design and operability on a multi-purpose general cargo vessel. Some remarks on why such a study is relevant are given in the following.

The most prominent reason why the present research is relevant, is the fact that general cargo/multi-purpose ships are the fourth largest polluting ship types and fuel consumers (Smith et

al., 2014). Most studies that have been conducted on this topic, are based on the top three polluting ship types. This makes sense, as for these three ship types, a certain emission reduction for reach vessel has a larger overall contribution due to the number of vessels for which this reduction holds. This means that in absolute terms, the impact of reducing emissions on multi-purpose ships does not provide the highest overall reduction of the shipping sector's emissions, when compared to the top three polluting ship types. Nevertheless, providing a study which shows the most promising ways of mitigating GHG emissions for ships of this type and the effects on their design and operations would have significant benefits to future research and eventually the total of shipping GHG emissions. Overall, a reduction of GHG emissions from general cargo ships of 70% compared to the 2012 levels would reduce the annual GHG emissions of shipping by nearly 48 million tons of CO_2 (Smith et al., 2014).
In terms of scientific relevance, it is unclear whether the reported GHG emission reduction potential from different technologies for a certain ship types are also true when applied to a multi-purpose ship. The research on the P-type would enable such a comparison with the current literature and could help in providing insight in whether or not these results can be translated to other ship types.

In addition to this, assessing the performance of a selected combination of emission reduction technologies could show that the impact on the ship's design and operation can be limited and may be feasible. For instance, alternative fuels on their own have a very high impact on the volume and weight of the ship in order to store the same amount of energy in fuel. This might lead to the conclusion that these are not yet feasible. However, by combining an alternative fuel with several efficiency improving technologies, this effect may be mitigated such that the application of this combination of technologies may be feasible. This is why research into the combination of emission reduction technologies may be relevant for the shipping industry.

Next to the relevance in terms of filling a literature gap, some industrial relevance is also associated with conducting the present study. For BigLift, one of the major companies in heavy-lift shipping, this could boost their image as being a frontrunner in more sustainable shipping in this sector. This might also provide incentive for future clients concerned with sustainable shipping to opt for BigLift instead of one of their competitors. This study might also provide a source of information on how other vessel series of BigLift or the Spliethoff Group can be designed for less GHG emissions. This study may provide an incentive to conduct the same sort of research into other series of their fleet which are to be redesigned.

Finally, another important aspect why the present study is relevant, is that BigLift has an ethical obligation to conduct research into more sustainable shipping. From an ethical standpoint, the developed countries have more accountability for climate change and thus are more obligated to reduce their GHG emissions. As the origins of BigLift date back to 1973, the company has emitted significant amounts of GHG to the environment and this has contributed to their current position as a heavy-lift shipping company. This means that when compared with other, smaller shipping companies, BigLift has a larger obligation to reduce the emissions of their fleet. This study provides a first step in exploring the options to reduce GHG emissions and is thus relevant from an ethical perspective as well.

Research goals

The main goal of this study is to obtain more insight in which combination of GHG emission reduction technologies can best be applied to a redesign of the P-type to be built in 2025, with the highest reduction of emissions that is feasible. As 'best' and 'feasible' can be measured by a variety of criteria associated with the performance of the design, selecting the most appropriate criteria for this is a subgoal related to this main goal.

The application of a combination of GHG emission reduction technologies can be beneficial for the impact on the ship design and operability, since a combination of different technologies can make for reduced consequences of a single emission reduction technology. This has not been extensively studied and it is thus a goal to gain more insight in the benefits of applying a combination of technologies to a redesign. This goal shall play a crucial role when selecting a combination of GHG emission reduction technologies.

The last goal of the research is to provide recommendations for the implementation of the GHG emission reduction technologies on the redesign of the P-type; how can the chosen technologies be implemented when the vessel is newly built? How can emissions be reduced further in the future and how does this impact the performance of the redesign? This last goal shall be met when evaluating the 'future-proofness' of the redesign.

Research questions

As the main goal and subgoals of the research have been presented, the research questions which will aid in meeting these goals will be formulated in this section. The main research question associated with the main goal of the research is the following:

'Which combination of technologies can best be applied to the redesign of BigLift's P-type in order to reduce GHG emissions as much as possible within the current industry and operational profile, and how would a concept design with these technologies perform compared with the current design?'

To help answer the main question, several sub-questions have been formulated which are also to be answered:

1. Which GHG emission reduction technologies are feasible in terms of technology-readiness-level and prospected development in the period up to 2050?
    a. Which criteria should be adopted to measure the definition of feasibility used in this part of the study?
2. Which GHG emission reduction technologies are feasible within the operational profile of a multi-purpose vessel?
    a. What does the operational profile and power plant profile of the P-type look like?
    b. Which criteria with respect to the GHG emission reduction technologies follow from the operational profile?
3. How does the operational profile of the P-type influence the feasibility of emission reduction technologies?
4. What is the best performing combination of GHG emission reduction technologies from the remaining alternatives?
    a. Which performance indicators are associated with this assessment?
    b. Which performance indicators have the most influence on the selection of the best alternatives?
    c. How can the alternatives be assessed on these performance indicators?
5. How does the redesign of the P-type with the chosen combination of GHG emission reduction technologies compare to the original vessel?
    a. What are the most significant differences in terms of ship design?
    b. What are the most significant differences in terms of operability?
    c. How does the redesign perform in terms of costs?
    d. What recommendations with respect to even further emission of the vessel can be made?

Scope of research

As the goal of the study and the research questions to be answered are now clear, the scope of the study will be discussed. This is done in order to set boundaries in which the research shall take place and to ensure that the focus of the study remains on achieving the research goals and answering the research questions.

The study will focus on reducing the GHG emissions, meaning that it is not a goal in this research to reduce local emissions such as sulphur oxides (SO_x), nitrous oxides (NO_x) and particulate matter (PM). However, as for some local pollutants regulations with regard to the maximum allowed emissions exist, these may be of influence when a GHG emission reduction technology would still not meet the requirements in terms of local emissions. This may then lead to additional technologies to be implemented to comply with these regulations, thus influencing the overall performance and should be taken into account. Nevertheless, reducing local emissions is not a research goal and assessment of the alternatives shall not be based on this.

The study will focus on the implementation of GHG reducing technologies. However, the number of technologies under study shall be limited to those technologies that prove feasible within the operating period and the operational profile of the vessel. Combinations of technologies will be investigated. Yet, this shall not be a combination of more than four technologies in order to avoid the solution becoming too complex and introducing to many uncertainties with respect to the performance of the combination of solutions. A combination of too much solutions would also obscure the effect a single solution has on the overall performance.

Furthermore, the GHG emissions that will be the focus during this study will be those emitted from the tank of the vessel to the propeller. This means that when assessing the performance of GHG emission reduction technologies, only this will be of interest. When assessing alternative fuels however, it has become clear from the literature that during the production process large amounts of greenhouse gases can be emitted. When studying alternative fuels, the well to tank emissions should thus be taken into account to avoid an unfair comparison of different alternative fuels.

As stated earlier, only technologies that are feasible within the operational profile and the current industry are considered. This will be an important requirement throughout the study as this influences which technologies are studied further. During the study, limits on the applicability of GHG emission reduction technologies will be imposed resulting from the operational profile or the costs associated with the application of such technologies.

Approach

In the following, the scheme of the study will be discussed. This was visually presented in figure I.2 in the introduction. Distinct parts of the study will be introduced and the approach to these parts will be focused on.

In each part a specific research goal will be met through answering the associated research questions. When all parts are completed, the main research question can be answered and the main research goal will be met. In the descriptions below, the approach to each part of the study will be discussed and the associated research questions and goals will be stated.

Part 1: Selecting technologies

In the first part of the study, a set of different GHG emission reduction technologies will be selected. This will be done based on the literature study that was conducted prior to executing this research. From this, the most promising GHG emission reduction technologies with an appropriate level of development are selected. These technologies will be the basis for the remainder of the study and from this set of technologies, a best performing combination is selected. The result of this part is a list of initially selected technologies and the answering of sub question 1 of the research.

Part 2: Operational profile analysis

In the second part of the research, a detailed study with respect to the operational profile of the current P-type will be conducted. This will be done in order to select the most feasible GHG emission reduction technologies. The goal of this part of the research is to get insight in the typical operations, utilisation, efficiencies, fuel consumption and emissions of the current design. This study will provide insight in why the vessel produces emissions, how the performance of a technology may best be measured and how the operational profile poses limits to the feasibility of an emission reduction technology.
This analysis will be based on the operational data that BigLift has gathered from the P-type vessels. From this data, a typical operational profile will be constructed. This will serve as a basis for the power plant operational profile. This will give insight in where the most CO_2-emission reduction can be achieved and will help in deciding on the best performing combination of technologies. Next to this, the voyages of the P-type will be studied including the cargo carried and the ports that are called at.

An important step taken after the operational profile has been analysed is the reduction of the selected technologies from the first part to only those which are feasible within the operational profile of the current P-type. This is because an important requirement of the redesign is that the current way of operating can be maintained.

Thus, this part of the study should result in insight in the operations and operational profile of the vessel and additional criteria for the choice of an emission reduction technology. Sub questions 2 and 3 of the research can be answered after this part.

Part 3: Concept selection

In this part of the study, the individual performance of the remaining technologies will be assessed, based on the constructed operational profile, in order to provide more reliable estimates of the emission reduction and economic performance of the technologies. This assessment will be performed relative to the current P-type vessels, thus only taking into account increases or decreases in fuel consumption, emissions and costs due to the applied technology. First, it will be investigated which performance indicators need to be considered for this assessment. After the performance indicators have been selected, the alternatives will be evaluated on these indicators.

From these results, combinations of technologies are constructed, which are assessed as well on the same performance indicators. Next, a concept selection is performed, based on an additional sensitivity study, which aims to point out which combination of technologies is most robust to changes in future scenario's or assumptions done.

The result of this part of the study will be that the best performing combination of GHG emission reduction technologies is identified. Next to this, an insight in the performance indicators and criteria that were used in this assessment is gained. As this part of the research will provide the basis of the redesign of the P-type, emphasis will be given on how the alternatives were assessed and why the selected alternative is indeed the best. After completion of this part of the research, sub-question 4 can be answered.

Part 4: Analysis of selected concept

As the combination of GHG emission reduction technologies that performs best has now been identified, this selected concept is analysed further to show a proper proof of concept. This will be done to an extent in which the impact of the combination GHG emission reduction technologies can be measured or qualitatively addressed. As it is a main goal of the study that this selected concept can be compared with the current P-type, it is important that the implementation of GHG emission reduction technologies can be quantified more accurately than was done in the previous part of the study.
In addition to the finalized concept and the comparison with the current vessel, this part will consist of an evaluation of the emission reduction performance of the redesign and recommendations will

be made on how the emissions can be reduced further. This will be based on whether the IMO's 2030 climate goal can be met.

The result of this part will thus be a detailed overview on how the ship and its operations are affected by the combination of technologies and an evaluation on how the IMO 2030 goal can be met. After the completion of this part of the research, research sub-question 5 can be answered.

With the approach to the study now clearly formulated, the research that has been executed following from this approach is described in the following sections.

Section 1: Selected technologies

This first section describes the first part of the study and is the result of the literature review that has been performed prior to the study. This section starts with an overview of the selected GHG emission reduction technologies and their most important characteristics and concludes with an overview of the information needed from the operational profile analysis for each technology. The latter is of importance because, for further assessment of the feasibility of these technologies, specific information on the compliance with the operational profile needs to be known. Finally, a conclusion on this section is formulated.

1.1 Overview of selected GHG emission reduction technologies

The literature study found numerous technologies and operational measures which reduce GHG emissions in different ways. From all of these technologies, only some were considered for application on a redesign of the P-type. These have been selected based on their technology readiness level (TRL) and expected future development. The main criteria for this selection were that only technologies with a TRL of 6 or higher were considered and that it is expected from the information available that these technologies are sufficiently commercially developed by 2025 to be applied to a redesign. Both of these criteria have drastically reduced the number of considered GHG emission reduction technologies.

In table 1.1 below, an overview of the selected GHG emission reduction technologies are given. The most important characteristics of these are given in order to compare the technologies. The selected alternative fuels are presented in section 1.2.

Table 1.1: Overview of selected GHG emission reduction technologies

Technology/ measure	GHG emission reduction potential	Impact on costs	Impact on ship design	Impact on ship operations	TRL	Future outlook
Economies of scale	5.5%, based on transport work	Higher operational expenses (OPEX) and capital expenses (CAPEX) due to ship enlargement	Moderate: Mainly increase in overall size	High, larger dimensions make for larger cargoes	9	Depending on shiptype
Slender hull concept	10-15%, depending on decrease in block coefficient	Length increase is roughly the same as increase in CAPEX a, decrease in fuel costs	Moderate: the most impact on the design is found in the bow area	Moderate, Mainly different behavior in waves, probably more deck area for cargo	6	Viable technology which is expected to find more uptake for different shiptypes
Resistance reduction (Hull coating)	3-10%, depending on the type of coating	Fuel costs decrease with 3-10%, increase in CAPEX is unknown, but expected to be moderate	None	Minimum, may affect dry-dock schedule	7	Viable technology, continuous development expected in near future
Propeller flow optimization	3-25%, depending on aftbody shape	Fuel costs decrease with 3-10%, additional CAPEX unknown,	Minimal, only stern area and propeller	Moderate, a certain draft at the stern and a trim range may	9	Expected to see uptake in newbuilds, as technology is

		estimated to be around 200 kEUR	may be influenced slightly by applying an energy saving device.	be needed to ensure proper functioning		proven to be cost-effective. This holds mostly for ships which operate mostly at a fixed draft and speed
Waste-heat recovery	8 %	Reduction of fuel costs of 8%, CAPEX increase between 1800-4000 EUR per kW output of WHR system	Minimal, little additional space in engine room. No significant change in engine room when auxiliary boiler is replaced	None	9	Integration of bottoming cycles with conventional diesel engines is expected to be more extensively applied in newbuilds
Cold ironing	3-10%, depending on electricity mix on port's grid	Reduction in OPEX depending on fuel and electricity price difference. CAPEX estimated to be 100 kEUR	Minimal, some additional space needed for transformers and grid connection	Little, crew needs to be trained to operate high-voltages. May influence choice of ports	8	Expected to see more uptake in the nearby future, as local regulations may lead to ports striver for better environmental performance
Solar power	Highly case sensitive, not expected to be higher than 10%	Highly case sensitive	Little, additional electric machinery and batteries need to be placed in the ship	None	9	Expected to be more applied for certain ship types in specific operating areas
Wind-assisted ship propulsion	4.2-12.9%	Reduction in fuel costs between 4.2-12.9%, CAPEX for Flettner rotor between 400 and 950 kEUR	Moderate, additional space and local strengthening is necessary.	Moderate, route planning may have to be based on wind. Sailing of the ship is different and more heeling is encountered	9	Limited uptake of this technology for ocean-going vessels is expected due to high investment costs and possibly long payback periods
Hybridization	Case sensitive, not expected to be higher than 20%	Reduction in fuel costs which is dependent of the variation in terms of energy demand. CAPEX	Moderate, engine room needs power take off/in	Little, engine is operated differently and crew needs to be trained to	9	Is already applied more and more in newbuild ships. Mostly used for short-sea

	for deep-sea vessels	for batteries are between 150-450 EUR/kWh	system and probably a large amount of batteries	cope with this system		vessels, not expected to see large uptake for deep-sea vessels in nearby future
Fuel cell systems	Depends on fuel cell type and used fuel, ranges between 2-100%	Reduction in fuel costs when using conventional fuels due to higher energy conversion efficiency. CAPEX increase of possibly 400% compared to conventional engine	Significant, larger tank volumes may be needed depending on fuel used. Electrical propulsion system is necessary and more space for fuel cell is needed due to lower power density	Can be significant, if fuels are used which are not widely available. Crew needs to be trained to safely handle fuel cell systems. Start-up and transient response of the system may be coped with by different way of operating	4-8	Fuel cell systems are expected to develop rapidly in the coming years, driven by the need to use alternative marine fuels and stricter emission regulations. In the nearby future the expected use of fuel cells may be limited to short-sea ships due to the relatively low power density of the system
Slow steaming	1-35%	Reduction in fuel costs, possibly reduced CAPEX for newbuilds due to smaller engine	Moderate, hull form and propeller may be altered, less fuel capacity needed	Significant, voyages take longer, profitability decreases when not increasing fleet size	9	Expected to be adopted by more shipowners when energy efficiency design index (EEDI) regulations become more stringent as a short-term solution
Voyage Optimization	11-19%	Reduction of fuel costs with 11-19%, OPEX increases due to additional work in terms of voyage preparation. CAPEX increase is very little, since only some shore-based software is needed	None, ship arrangement can maintain exactly the same	Moderate, ship voyages may take longer. Furthermore, more distance may be covered to avoid bad weather	9	Is already being applied by many ship owners, route planning based on weather forecasts has become the standard and optimizing the capacity of the fleet of vessels is common practice

Draft-Trim optimization	5-8.7%	Reduction in fuel costs of 5-8.7%, additional CAPEX of between 15-75 kEUR due to software and control systems on board	None, assuming that ballast tank configuration can remain the same	Minimal, location of cargo may need to be altered and loading of cargo may take more time to prepare	9	Is being applied by some shipping companies, not expected to see enormous uptake. Development of computational fluid dynamics may decrease investment costs
Condition-based maintenance	3-12%	Reduction in fuel costs of 3-12%, additional OPEX due to more frequent cleaning, depending on ship size and maintenance interval	None	Minimal, cleaning may take place during loading or unloading of the ship, thus not influencing the operations at all	9	Condition-based maintenance is studied more the past years, it is expected that for certain ship types maintenance will not be carried out on a regular basis but based on the condition of the vessel

From table 1.1, it is found that a variety of different types of GHG emission reduction technologies have been presented. Most of the technology readiness levels are above 7 and all technologies are feasible in terms of their prospected technology readiness by 2025. Furthermore, the considered technologies achieve GHG emission reduction via different mechanisms. Some technologies reduce the power need for the redesign, others gain energy from the environment and others are efficiency improving technologies. Having this variety in technologies will aid in constructing feasible combinations of technologies.

1.2 Overview of selected alternative fuels

In table 1.2 below, the most important characteristics of the alternative fuels selected from the literature study are listed. Again, the selection of the alternative fuels has been based on the expected availability in 2025 and whether it is expected that regulations will be in effect for sailing on these fuels in 2025. Furthermore, the following selected fuels were the ones most frequently studied in the literature on alternative fuels as a means of GHG emission reduction for shipping.

Table 1.2: Overview of selected alternative fuels and their most important characteristics

Alternative fuel	Energy density		GHG emission reduction potential	Impact on ship design	Impact on costs	Safety and regulations	Availability and future outlook
	GJ/t	GJ/m^3					
LNG	53.6	22.2	20-30%, depending on feedstock and methane slip	Large, increase in tank volume of 100%. Extensive safety precautions for fuel pipes and engine rooms needed. ICE are feasible for LNG, fuel cells are in development	Reduced fuel costs, CAPEX increase between 10-20%	Higher flammability risk, more safety measures to be applied. Regulations are in effect to safely use LNG as a fuel, more specific regulations are in development	Bunkering infrastructure evolving rapidly, rapidly increasing fleet of LNG-fueled vessels
Hydrogen	120.2	8.5	Highly dependent of feedstock, ranging from increase by 65% to decrease by 80%	Very Large, increase in tank volume of 600%. Extensive safety precautions are necessary to handle hydrogen. ICE technology is not available yet. Fuel cell technology is available	Increased fuel costs by factor 2, increased CAPEX by up to 100% due to high fuel tank and fuel converter costs	Extremely flammable gas, extensive safety measures and gas detection to be applied. Regulations are not yet developed for using hydrogen as fuel, but these are in development	No infrastructure is present, although natural gas grid can be used. Hydrogen is produced worldwide and used in chemical sector. Hydrogen is not expected to see large uptake in deep-sea shipping in the foreseeable future
Ammonia	18.6	12.7	Highly dependent of feedstock, can be up to	Large, increase in tank volume of around 250%. Safety precaution to	Fuel costs increased by factor 2.3. Estimated increase in	Toxicity hazard of ammonia is more significant	Ammonia is produced worldwide for land-based application,

			69% for ammonia produced from renewable energy	reduce risk on ammonia leakage. Fuel converters using ammonia are still in development	CAPEX for ICE is 70 %. Additional CAPEX for storage and piping is unknown	than flammability hazard. No current regulations for using ammonia as a fuel. No literature found on development of regulations regarding ammonia as a fuel	infrastructure and production are present. Specific bunkering infrastructure needs to be developed. Ammonia is seen as a promising carbon-free fuel for deep-sea shipping
Methanol	19.5	15.5	Highly dependent of feedstock, methanol from natural gas increases GHG emissions by 10%. Only from renewable energy or biomass a reduction is expected	Moderate, increase in tank volume of around 150%. Storage tanks can be the same as conventional fuel tanks. ICE for methanol are commercially available. Piping needs to be double walled and additional safety measure are applied due to low-flashpoint	Fuel costs increase with 150%. CAPEX for piping and storage increase with 75% and use in ICE remains the same costs. Application of fuel cell increases CAPEX of fuel converter by 300%	Flammability hazard of methanol is higher than when using conventional fuels. Toxicity is a risk to human health. Current regulations enable usage of methanol as a fuel and the IGF code is being developed to more clearly assess the measures to be taken to use methanol as a fuel	Methanol is available worldwide as a primary feedstock for the chemical industry. Bunkering infrastructure is not yet present but can be achieved at relatively low costs. Methanol is not expected to see large uptake with current production paths leading to high GHG emissions over the life cycle. More incentive is needed to produce more sustainable methanol at an attractive price
Biofuels	varies	varies	19-88%, varies per type of fuel and feedstock	Little to none, biofuels can be used as drop-in fuels, having the same properties as their fossil counterparts.	Higher costs than conventional fuels, up to 3 times more expensive expected to drop in the	Safety concerns of biofuels are the same as their fossil counterparts, although some of the	Biofuels are produced sufficiently to enable part of the shipping sector to sail on biofuels. For the

				This doesn't affect the ship design	future. Little to no increase in CAPEX.	biofuels are less toxic and flammable. Drop-in biofuels have no specific regulations, ISO standards on biofuel quality are needed	bunkering infrastructure the current infrastructure can be used. Biofuels are not expected to see large uptake unless strong incentives in terms of GHG regulation are introduced.

1.3 Overview of information needed from operational profile

From the previous two parts, a list of GHG emission reduction technologies was presented. As these were obtained from literature on different ship types or for a fleet of vessels, the specific applicability to the P-type and the performance based on the actual operational profile for the P-type is unknown. For each of the listed GHG emission reduction technologies, more information on the operations of the P-type is needed in order to be able to evaluate the GHG emission reduction potential and whether or not this technology is feasible in a redesign. Therefore, the goal of this part is to identify which data from the operational profile is needed for each technology in order to provide more reliable predictions on the feasibility of that technology.

The selected GHG emission reduction technologies from the previous section will each be discussed in order to find the specific questions that need to be answered from an operational perspective. This will be done by recapitulating the physical principle which is the basis for the GHG emission reduction and which variables influence the GHG emission reduction potential. Further, the question needs to be answered whether this reduction can also be achieved in a redesign of the P-type. For each individual technology, the required information on the operations of the P-type to answer this question will be defined.

The approach described above was performed for each GHG emission reduction technology/measure identified in parts 1.1 and 1.2, and is presented in appendix A. In appendix A, a full overview of these considerations for each of the selected technologies is presented. A summary of the specific questions and required data resulting from this approach is presented in this part. Finally, all of the alternative fuels were combined, as the specific questions to be answered and the required data are similar for all alternative fuels.

In table 1.3, a summary of the specific questions and the required operational data listed in appendix A.1 to A.16 is given.

Table 1.3: Summary of questions and required data for the GHG emission reduction technologies, as were described in full in appendix A.

GHG emission reduction technology/ measure	**Questions with respect to operational analysis**	**Operational information required**
Economies of scale	Can additional hold volume be filled with the cargo P-type is intended for? Can the same ports be called at with larger ship dimensions?	Analysis of hold and deck utilization Analysis of trade routes and ports which limit main dimensions

	Can the same routes be sailed with larger ship dimensions?	
Slender hull concept	Can both ways of reducing the block coefficient be applied? Is the reduction of the wave making resistance effective for the operational speed range? Which sea states are most frequently encountered?	Analysis of hold and deck utilization Analysis of trade routes and ports which limit ship length Analysis of operational speed range Analysis of encountered waves and wave direction
Resistance reduction (Hull coating)	What type of coating is currently used? How much does the fuel consumption decrease after applying a new hull coating?	Current type of coating used Fuel consumption before and after a dry dock where a coating has been applied
Propeller flow optimization	What is the variation in draft, trim and speed? What type of propeller is currently used?	Analysis of operational speed range Analysis of operational trim and draft range Information on currently used propeller
Waste-heat recovery	How much power can be extracted from the exhaust gases? How can this amount of power be used efficiently on the ship?	Fuel consumption of main engine for various load levels Auxiliary power demand and hotel power consumption
Cold ironing	What is the power need during port visits? What are the current emissions associated with this? How much time is spent in larger ports?	Data on the energy consumption during port calls GHG emission factor of power produced by the P-type during port calls Data on time spent at which ports
Solar power	What is the usable area for solar panels? How can the additional power be used efficiently?	Data on general arrangement and deck layout Data on cargo deck utilization Information on auxiliary and hotel power demand
Flettner rotor	What is the distribution in apparent wind direction and speed? What is the area in which a Flettner rotor can be placed? Can the voyages be optimized for maximum Flettner rotor performance?	Data on encountered wind speed and directions Data on deck layout and crane operating radii Information on current way of voyage planning
Hybridization	What is the fluctuation in power demand during sailing and in port? What is the estimated battery capacity needed?	Data on power plant operational profile Data on current fuel consumption vs. engine load
Fuel cell auxiliary power	What is the power demand of the auxiliary power system? What is the variation of auxiliary power? How much energy needs to be stored for auxiliary purposes?	Data on auxiliary power demand over time Data on fuel consumption for auxiliary power purposes
Slow steaming	What is the current way of depicting the speed of a voyage? Can the same markets be served when sailing at lower average speeds? How much can the speed be reduced?	Analysis of operational speed range Analysis of speed variation for single voyages Information on required speed for various voyages Information on minimum speed requirements
Voyage Optimization	What is the current standard of voyage planning for the P-type?	Information on current way of voyage planning (personal communication)
Draft-Trim optimization	What is the operational trim and draft range? How much flexibility in the draft and trim is present when loaded with cargo? What is the current practice in terms of draft and trim when in ballast?	Data on the variation in draft and trim Data on the loading conditions and draft & trim philosophy when making loading plans Data on the draft and trim used when sailing empty

Condition-based maintenance	Can hull and propeller maintenance be performed during loading and unloading operations? What is the current practice of hull and propeller maintenance? What is the interval in which this maintenance is executed? What is the difference in fuel consumption before and after executing maintenance?	Data on the time needed for loading and unloading Information on the current practice and interval of hull and propeller maintenance Fuel consumption before and after a dry dock where maintenance has been performed
Alternative fuels	What is the current amount of energy stored in bunkers? How much can the sailing range of the redesign be reduced and how does this effect the operability? How much time is spent at larger ports? What is the time interval between visits to the identified larger ports?	Data on bunker capacity Data on bunkering interval and amount of bunkers taken in Data on distance sailed between port calls Data on fuel consumption during voyages Data on routes sailed Data on time spent at which ports

1.4 Conclusions

In the first part of this study, various GHG emission reduction technologies have been presented. These have been selected based on the literature study, that showed which technologies are most promising in terms of their GHG emission reduction potential, technology readiness level (TRL) or expected future development.

Furthermore, the required operational data and specific questions that are to be answered for these technologies have been formulated. This will be applied in the next section, where the operational profile is analysed and the GHG emission reduction technologies will be discarded when incompatible with the operational profile.

At the conclusion of the first part of this study, the first research sub-question can be answered:

1. *Which GHG emission reduction technologies are feasible in terms of technology-readiness-level and prospected development in the period up to 2050?*
   These are the GHG emission reduction technologies listed in tables 1.1 and 1.2.

   a. *Which criteria should be adopted to measure the feasibility used in this part of the study?*
   Two criteria are of importance; the current TRL and whether it is expected that this technology will go through a rapid development within the next five years. The TRL of some technologies are low, however, they are not discarded as it is expected that the TRL will increase in the coming five years, making them applicable to the redesign of the P-type. The main criterion is that only technologies with a TRL of 6 or higher were considered and that it is expected from the information available that these technologies are sufficiently commercially developed by 2025 to be applied to a redesign.

Section 2: Operational profile analysis

The following chapter will focus on the operational profile of the current P-type. This will be done for several reasons. First, insight in the operational profile of the current design is needed, as the redesign is required to maintain the original operational profile. Furthermore, by inspecting the operational profile in a general sense, additional potentially usefull GHG emission reduction technologies can be identified which were not considered during the literature study. Also, insight in the operational profile will aid in discarding the GHG emission reduction technologies which are considered non-feasible within this profile.

The first part of this section will describe which data sources have been used in the operational profile analysis and which information has been extracted from this data.

The second part consists of the actual analysis of the operational data. This includes the data that is needed in order to draw conclusions on the applicability of the GHG emission reduction technologies. In this part, insight in the operational profile is gained.

In the third part, the applicability of the selected GHG emission reduction technologies will be discussed based on the specific questions stated for these technologies. This will reduce the number of feasible technologies.

In the final part, a summary will be given and the sub-questions of the research associated with this section are answered.

2.1 Available operational data

This part of the second section will consist of an overview of the available data sources, the data attributes, the data resolution and reliability of the data.

As has been stated, the operational data of the current P-type will be analysed in order to draw conclusions on the applicability and effectiveness of the GHG emission reduction technologies which are to be applied to a redesign of the P-type. This is because the main requirement for the redesign is that the same way of operating needs to be maintained and the same market is to be served.

Spliethoff currently owns five P-14 type vessels and three P-8 type vessels. The only difference between these vessels is their crane capacity, which for the P-8 type is 2x 400 t instead of 2x 700 t for the cranes on the portside of the vessel. Apart from this, they serve the same markets, operate with the same speeds and handle the same types of cargo, albeit that the P-types are able to transport cargo items with a higher individual weight. This is why no distinction between these types has been made in this study, with the exception of the power demand for the cranes; for this, the 700t cranes have been used.

The sources of operational data can be divided into four groups, which shall be discussed separately due to their different characters.

The first group of data is the data that is physically measured on board of the ship and transmitted to a database where all data points are stored. The content of each data point will be addressed shortly. Every five minutes, a data point is added to this, and currently over 230.000 data points are stored for five P-type vessels. Not all of the five vessels have the same amount of data points stored, some of the vessel have only started logging their operational data since June 2020, while the earliest data point in the set dates back to September 2019. Information on the routes sailed is also documented; the voyages of the different vessels since they started logging the data are shown in figure 2.1. The total amount of logged data for all four vessels spans 826 days of which nearly 400 sailing days in which a distance of 107000 nm was sailed.

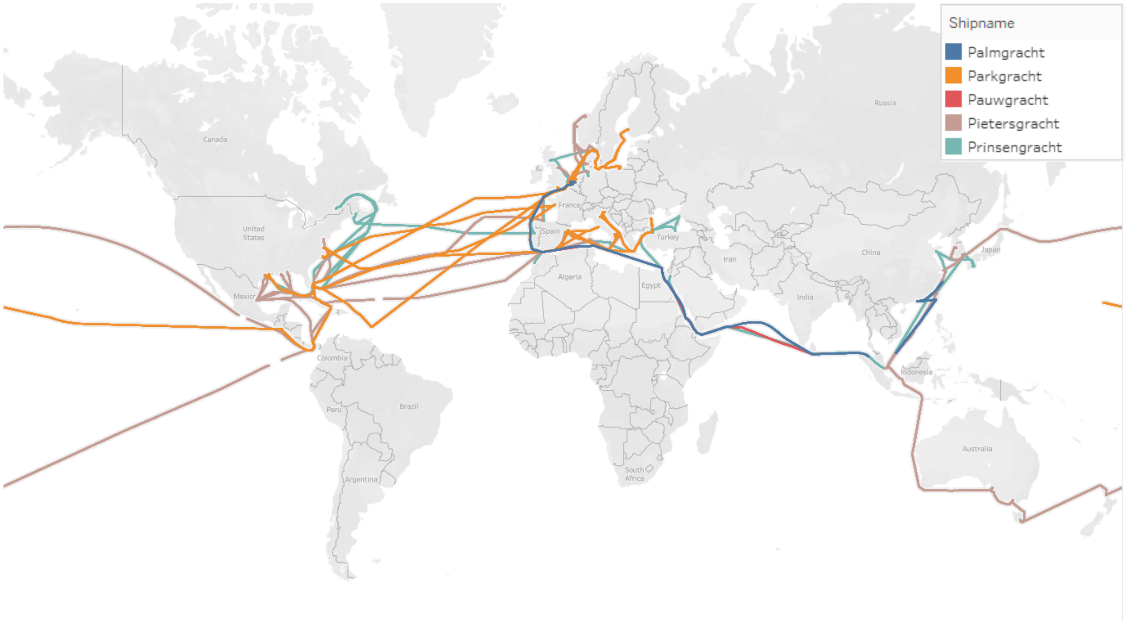

Figure 2.1: World map with routes sailed for the different P-type vessels since their first data log

The contents of each data point consists of different variables. The variables which are measured are the speed over ground, the location coordinates, the ship heading and the fuel consumption of the main engine. The reported values are averaged during a five minute interval. Furthermore, weather data is added to the data points based on the location and time. The added data is the absolute wind direction and speed, the absolute wave direction and total wave height and absolute current direction and speed. From these variables and the measured variables, the apparent wind speed and direction is calculated, as well as the relative wave direction and the speed through water. Additionally, some variables are added from reports of the ship, such as the trim and mean draft, the miles travelled, the voyage (port of departure - port of arrival) and the fuel consumed (per type of fuel) over the documented period. All datapoints including all variables have been exported to an Excel file, where the processing and data analysis has been carried out.

The second group of data is a combination of different data sources and is based on the monitoring, reporting and verification (MRV) reports of all P-type vessels in the year 2019. This means that the data has a much lower resolution than the measured data, as a single data point represents a complete voyage. The voyage is defined as the time between the arrival at a port up until the arrival at the next port, thus including the loading of new cargo and/or unloading of cargo of the previous voyage. In total, 153 voyages for seven P-type vessels are documented covering a time of 1803 days, in which a distance of 230000 nm has been sailed. All data is manually reported by the crew of the vessels, including the time of arrival and departure at a port and associated bunker levels.
From the noon, arrival and departure reports which have been submitted by the crew, the average sailing speed (speed over ground) and the aft and fore drafts have been added to this data set. Furthermore, the location of the port, the amount of bunkers taken in and distance between ports have been added to this data. The bunkers are split between heavy fuel oil (HFO), which is used in the main engine and marine gas oil (MGO), which is used in the generator sets on board and used in the main engine when sailing in a sulphur emission control area. All P-type vessels are to be equipped with a scrubber to comply with the SO_x-emission regulations, but during the period for which data is available, these were not yet installed.

From these variables, the days at sea, at port and associated fuel consumption per type are calculated. The average sailing speed is calculated from the total distance and sailing time, as well as the fuel consumption per nautical mile.

Finally, data on the cargo carried was added manually by inspection of the stowage plans for the voyages. The dataset now also includes the cargo weight and volume. An estimation of the utilisation of the hold and deck per voyage is made from the stowage plans. This has been added to all 153 voyages, in order to get insight in the utilisation of the vessel's cargo carrying capacity. Furthermore, the type of cargo carried has been added to this dataset.

The third group of data sources is technical documentation on the P-type vessels, which date back to the launching date of the vessels. This includes technical drawings, such as a general arrangement, engine room arrangement, shaft line drawings etc. Furthermore, instruction manuals and general information on the machinery on board of the P-type vessels is available, such as the propeller, shaft generator, main engine and auxiliary engines. This group of data also proved to be a valuable source of information on specific details regarding the operations of such machinery and the arrangement of the vessel.

The fourth and last group of data can be summarized as personal communication. This includes e-mail conversations with the crew on board the P-type vessels and conversations with the supervisors from BigLift and Spliethoff and with various people from different departments within the Spliethoff Group.

From these four groups of data, insights from different perspectives on the operations of the currently operated P-type vessels have been acquired. This has proven to be valuable information for the analysis of the operational data.

2.2 Operational profile analysis

In this part, the available operational data will be analysed. This is done according to the specific questions posed in appendix A, as summarized in section 1.3. With graphs, tables and figures, conclusions on the operational profile of the current P-type will be drawn. In this part, no conclusions on the applicability or estimated performance of the identified GHG emission reduction technologies will be drawn, as these will be presented in the third part of this section.

In order to provide a structured analysis, the data analysis is performed based on the subject of operation under investigation. The broad subjects have been based on the summary of required data and specific questions in section 1.3. The following subjects have been identified and will each be discussed in detail in the stated order;

- Cargo transported; cargo type, volume and weight
- Draft and Trim
- Loading conditions
- Operational speed
- Propulsion
- Auxiliary powering
- Operational environment
- Voyage planning
- Arrangement
- Maintenance
- Bunkering
- Emissions

2.2.1 Cargo transported

GHG emission reduction technologies involving economies of scale or other emission reduction technologies are likely to impact the available cargo volume. Insight in the amount of cargo transported and the cargo types transported is needed to draw conclusions on the applicability of these emission reduction technologies.

The cargo transported by the P-type can be classified into five groups; heavy-lift, project, general cargo, bulk and yachts. The distinction between heavy-lift and project cargo is that for a transport to be categorized as a heavy-lift type, the individual weight of one of the loaded cargo items exceeds 200 ton. Usually, for project and heavy-lift type transports, a significant amount of break-bulk type cargo is loaded as well. In order to provide an insight in the amount of time and distance the vessel sails empty, ballast is added as a cargo type as well in figure 2.2.

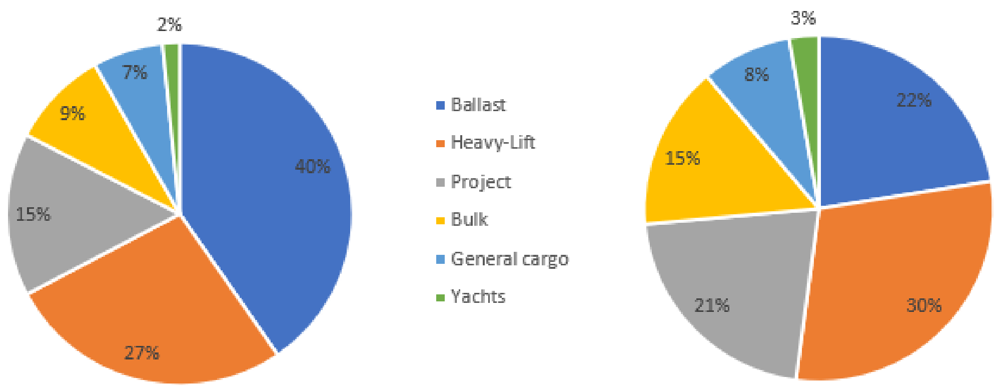

Figure 2.2: Cargo type transported as a percentage of time (left) and as percentage of distance sailed (right)

It can be concluded from the cargo type distribution that the P-14 indeed operates mostly on the focus markets of BigLift, being heavy-lift and project cargoes. Furthermore, it is seen that for a large percentage of time and distance, the vessels sail in ballast conditions. As 2019 was the first year for BigLift operating these vessels, the first voyages where the vessels were relocated or sailed to a dock are included in the ballast voyages. It is thus expected that the percentage of sailing in ballast is to decrease the coming years.

For each cargo type, the capacity used in terms of volume and deadweight was analysed as well. This was done based on the data available from 153 voyages. Furthermore, by visual inspection of the stowage plans for the voyages where this was available, an estimation of the utilisation of the cargo hold volume and deck area as a percentage of the total volume/area available has been made. For general cargo voyages, the stowage plans were not available. This utilisation data is shown in table 2.1, the averages are based on the weight or volume of cargo taking into account the amount of miles this cargo was transported. This means that a longer voyage contributes more in the average value than a short voyage, making for a weighted average based on the transport work.

Table 2.1: Capacity utilisation per cargo type

	Average cargo weight [t]	Average cargo volume [m^3]	Average deadweight utilisation [%]	Average volume utilisation [%]	Average estimated hold utilisation [%]	Average estimated weatherdeck utilisation [%]
Heavy-Lift	3477	17818	17	68	62	54
Project	2815	14962	14	57	68	61
Bulk	14112	8470	71	32	48	0
General cargo	10784	11037	54	42	-	-
Yachts	1254	-	6	-	30	100

The differences between the utilisation values that are calculated from the available data and estimated by visual inspection of the stowage plans are quite significant for some cargo types. This can be explained by the fact that the cargo volume data is based on their outer dimensions, which makes for an overestimation of the total used volume. Furthermore, the estimation of the volume utilisation has been based on 2D stowage drawings, which limit the accuracy of the occupied volume estimation.

Nonetheless, it is seen that the focus cargo types are more critical in terms of their volume than in terms of their weight. Furthermore, from the average values, it is found that in general, the full capacity of the vessel is never nearly reached. The only exception are when the P-types are transporting yachts, which are stacked on the main deck and for the two voyages analysed, the deck was fully used.

Furthermore, only in four voyages of all voyages analysed, the vessel was fully loaded in terms of its volume and deck capacity. In general, the averages listed in table 2.1 above represent the utilisation of the vessel quite accurately. The conclusions with respect to the applicability of GHG emission reduction technologies following from the insights on cargo capacity utilisation are dealt with in section 2.3.

2.2.2 Draft and trim

The draft and trim data was analysed as well in order to get an insight in the loading profile of the vessel. This information is valuable for the applicability of different emission reduction technologies, such as draft-trim optimization and propeller flow optimization. This information is based on the departure reports of the vessel where the draft aft and fore are reported by the crew of the P-types. To show the variation of the draft and trim per type of cargo, the data is presented as a boxplot per cargo type in figure 2.3 and 2.4 below.

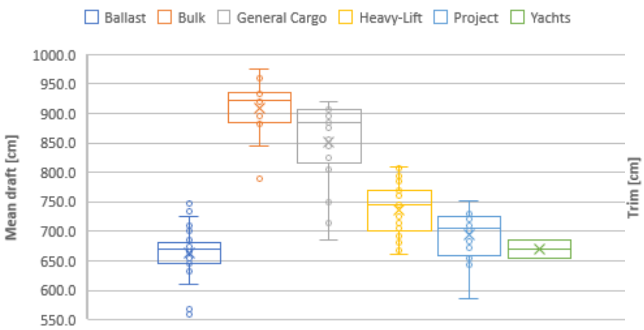

Figure 2.3: Mean draft variation per cargo type

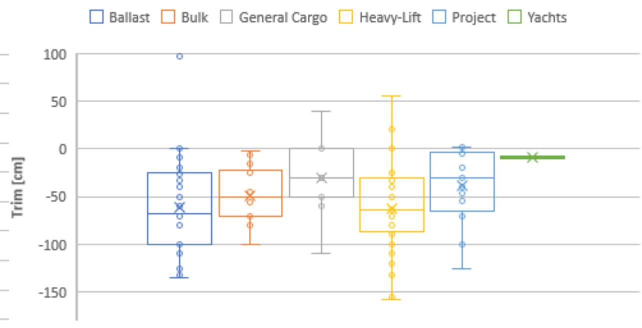

Figure 2.4: Trim variation per cargo type (negative values indicate a trim by stern)

It can be seen that the averages of the mean drafts for the various cargo types are in good correspondence with the mean cargo weights in table 2.1. For the cargo types with the lowest mean cargo weights, the lowest drafts are reported and vice versa. Furthermore, it is seen that the operational draft range is quite wide, ranging from 9.5 m when carrying bulk or general cargo to less than 6.5 m when in ballast. It is again seen that for heavy-lift and project cargoes, the mean draft is lower as the cargo items are more demanding in terms of their volume than in terms of their weight.

In the operational trim variation data, again a large spread is observed. Especially for heavy-lift voyages, the trim variation is large. This can be accounted to the need for most ballast tanks to be filled in order to keep the metacentric height within the acceptable limits, and the trim is therefore a result of the loading conditions, rather than a criterium. Furthermore, from inspection of the stowage plans of heavy-lift cargo voyages, it was found that the placement of the cargo items is restricted in possibilities due to their size or due to the unloading sequence. Therefore, the cargo cannot always be placed in a position optimal for the trim of the vessel.

As figures 2.3 and 2.4 above show the variability per voyage, this does not fully cover the variation in time sailed at a certain draft, as the sailing time per voyage can vary greatly. In order to also analyse the draft and trim variation in terms of sailing time, the dataset with the measured data was used to construct figures 2.5 and 2.6. In these figures, the same variability is seen in terms of the operational draft and trim. Furthermore, it is found that only for 31% of time, the draft is above 800 cm. From figure 2.6, it can be derived that for 70% of time, the trim is between 80 cm over stern and less than 0. In terms of the variability, it is still concluded that a fixed design point in terms of draft and trim is absent, caused by the flexibility in cargo types and amount of cargo transported.

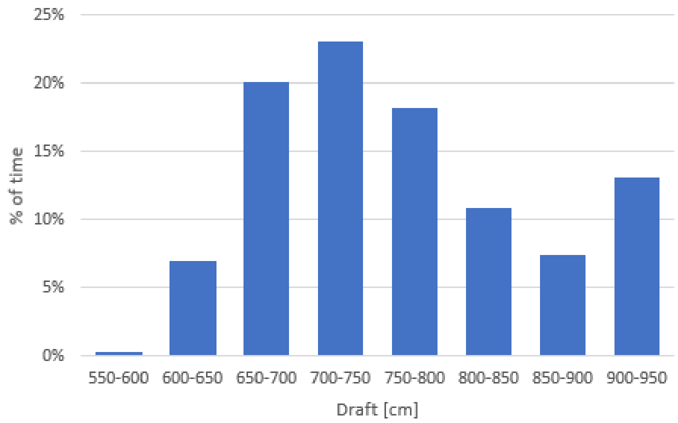

Figure 2.5: Draft distribution over time during sailing

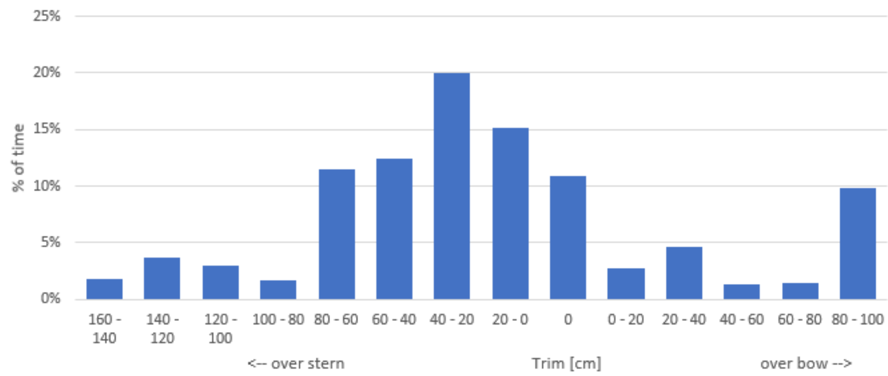

Figure 2.6: Trim distribution over time during sailing

2.2.3 Loading conditions

An analysis has also been made of the loading conditions while sailing with different types of cargo. This analysis is based upon inspection of the cargo stowage plans made by various engineers from BigLift and by personal communication with several of these engineers. Insight in the loading conditions is needed to assess the applicability of draft-trim optimization as a GHG emission reduction measure.

It was found that the most limiting criterium when preparing the loading conditions is the metacentric height (GM). Especially when sailing with heavy deck cargoes with high vertical centres of gravity, during the lifting of cargo over the hatch coaming and at the maximum reach overboard, the metacentric height becomes limiting. This is why the full double bottom ballast capacity is frequently used in order to increase the GM to exceed the minimum required value. Furthermore, most of the side ballast tanks are also utilised, often to their full capacity, in order to provide the additional anti-heeling moment to be able to limit heeling of the vessel during lifting. Even this capacity can still be insufficient when lifting heavy loads with an already partially filled vessel, as the GM during lifting could be lower than required. In order to cope with this, a stability pontoon is kept on board of the P-types, which can be lowered in to the water and connected rigidly to the vessel to be able to increase the GM when the loading condition requires this.

Thus, the loading conditions for heavy-lift and project cargoes, which are shipped for the most amount of time and distance, do not offer much flexibility with respect to the trim and draft as most ballast capacity is utilised. The current P-type design is highly suitable to be able to carry these cargoes. In a redesign, it is expected that the same ballast capacity is needed when not altering the crane capacities or principle dimensions.

Another conclusion which can be drawn on the loading conditions in terms of draft and trim, is that the floating position of the vessel is usually a result of the cargo stowage, and not a criterium itself. This holds when the vessel is loaded near its maximum capacity or when transporting cargo items with large dimensions. When the vessel is (partially) empty, or sailing with bulk cargo or yachts, enough flexibility in the ballast arrangement is present to be able to achieve a desired trim and draft, while complying with the stability criteria.

2.2.4 Operational speed

It is of importance to study the operational speeds to assess the applicability of both slow steaming and the application of a slender hull form as an emission reduction technology.
The operational speed analysis is performed with multiple data sources, as this data is available and this provides more insight. The first analysis with respect to the operational speed was carried out based on MRV-dataset which was supplemented with noon-report data. The speeds shown in this dataset are the average speeds during a voyage, as the vessel did not sail the entire voyage at this constant speed. The distribution of the average speeds are shown by a boxplot graph per cargo type transported in figure 2.7.

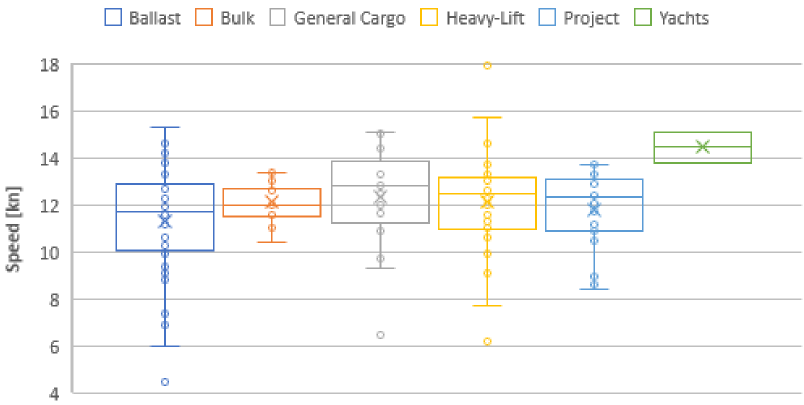

Figure 2.7: Speed distribution per cargo type

It can be seen that the average speed is around 12 kn, except for when transporting yachts (note that the latter data is based on just two voyages). Furthermore, it can be seen that the spread in average speed is quite large when sailing in ballast and when shipping heavy-lift cargo. The vessel is designed to sail at speeds of 17 knots, yet it can be seen that this speed is only exceeded in one voyage. This means that in practice, the vessel is already applying some sort of slow steaming with respect to the intended use when designed. This will be discussed in more detail under 'propulsion'. Some outliers in the speed distribution of very low speed are noticed as well, these refer to short voyages, where the speed was reduced to avoid waiting for a berth.

As figure 2.7 indicates the average speed of a voyage, the occurring operational speeds over time during a voyage can differ from the speed actually attained. This is because the average speed has been calculated from the distance and the number of days sailing and can thus include the time waiting for a berth. From the measured dataset, the percentage of time a certain speed over ground is sailed can be derived. This has been performed for speed intervals of 0.5 kn over the operational speed range and the resulting graph is shown in figure 2.8. It is found that the operational speed distribution resembles a normal distribution with the mean around 13 kn.

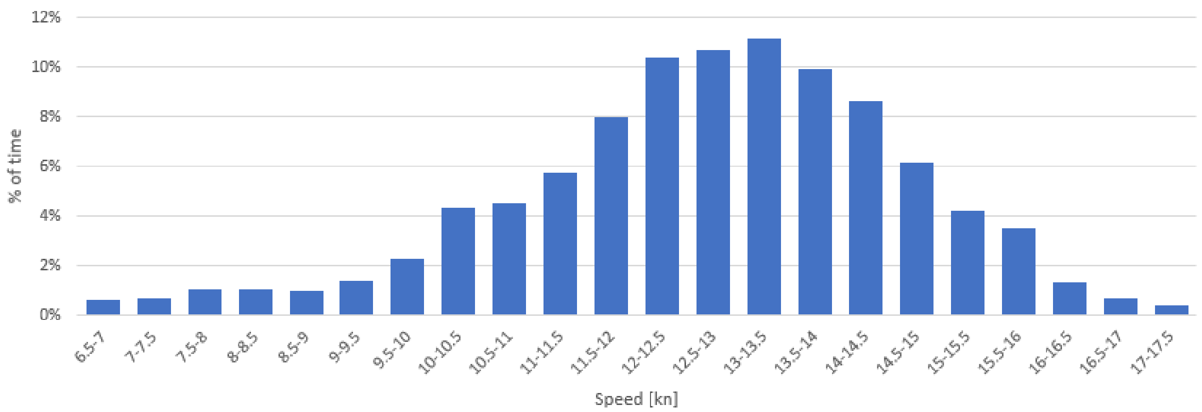

Figure 2.8: Distribution of measured speed over ground

The speed of the vessels is not often prescribed by contract with the cargo owner, however the latest arrival date is specified so a certain minimum speed will need to be attained in order to avoid penalties. When the vessel arrives early and can start unloading already, more voyages each year can be performed and the profitability can thus be increased. However, a trade-off exist in setting the operational speed, as sailing faster increases the fuel costs disproportionally. This is why the speed is depicted in terms of a maximum consumption per day, which can be seen in figure 2.9. In this figure the measured fuel consumption is set out against the speed through water, and grouped based on the encountered sea state. It is more appropriate to show the fuel consumption against the speed through water, due to the encountered currents. This will be discussed further under 'operational environment'. It can be seen that some data points are on the same horizontal line between consumptions of 1000 and 1500 kg/h. This means that a fixed fuel consumption is attained for that voyage, and the speed through water is thus secondary and drops when encountering heavy sea states. Of all data recorded on the fuel consumption of the P-type, 41% is in the mentioned consumption range. The practice of sailing on a certain defined fuel consumption is also confirmed by the operational instructions given to the P-type vessels, which are often instructed to sail at a fuel consumption of 30 tons of fuel per day, which amounts to 1250 kg/h.

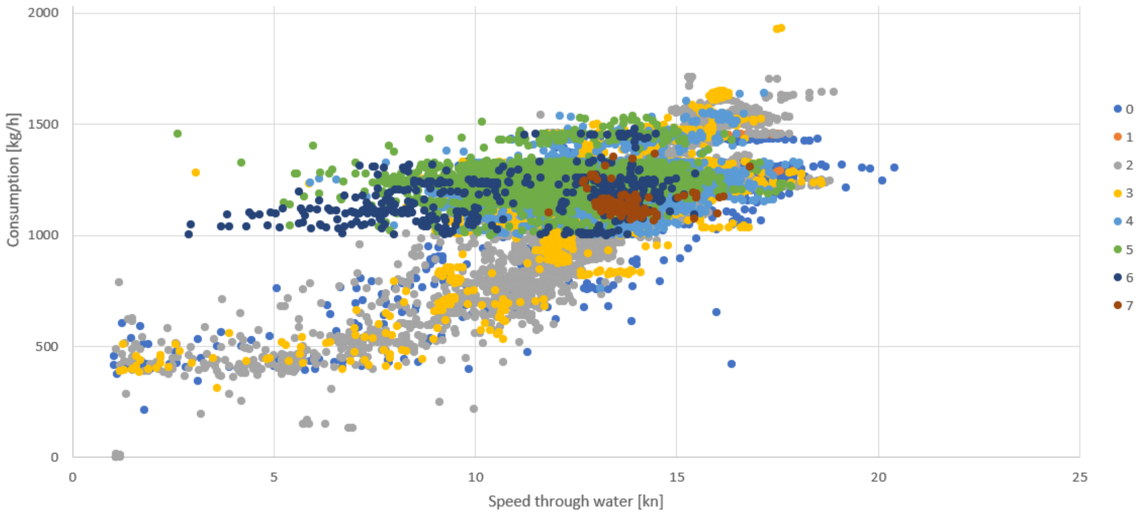

Figure 2.9: Fuel consumption against speed through water per sea state

Next to the fixed consumption, a regular speed-power curve is found in figure 2.9 for the lower speeds at lower sea states, in which the disproportionate relation between fuel consumption and speed is seen. However, this curve is not sharply pronounced as a variety of drafts, trims and different conditions of the hull and propeller are influencing the fuel consumption at a certain speed as well.

Looking at figure 2.9, it can be seen that the regular operational speed ranges between 9 and 16 knots. Using the vessels waterline length, this makes the operational Froude numbers ranging between 0.118 and 0.210. In this region of Froude numbers, the viscous resistance is dominant over the (added) wave resistance in terms of their contribution to the total resistance (Larsson and Raven, 2010).

2.2.5 Propulsion

Some general information on the propulsion system has been studied in order to get more understanding on the propulsion of the current P-type and to assess the applicability of GHG emission reduction technologies such as waste-heat recovery, hybridization or fuel cell systems.

The current propulsion system is a direct driven, geared controllable pitch propeller of 5.1m in diameter. The application of a controllable pitch propeller (CPP) is suitable for a vessel with varying propeller load due to varying drafts and ship speeds. Furthermore, as the P-types are equipped with a shaft generator which requires a constant shaft speed, the propeller speed is also constant. To accommodate with this, the pitch can be altered to change the delivered thrust. Operating a CPP increases the frictional losses due to the propeller hub and blade roots being larger than conventional propellers. Still, due to the varying propeller load, the time-averaged efficiency of the CPP is higher than would be the case for a fixed-pitch alternative.

The propeller is driven by a constant speed, four stroke diesel engine, capable of delivering an output power of 9800 kW at maximum continuous rating (MCR). From the shop test documentation, it is found that the engine efficiency ranges from 38.8% at low engine loads to 45.9% at higher loads. This is also depicted in figure 2.10 below, where the specific fuel oil consumption (SFOC) is also shown for various engine loads.

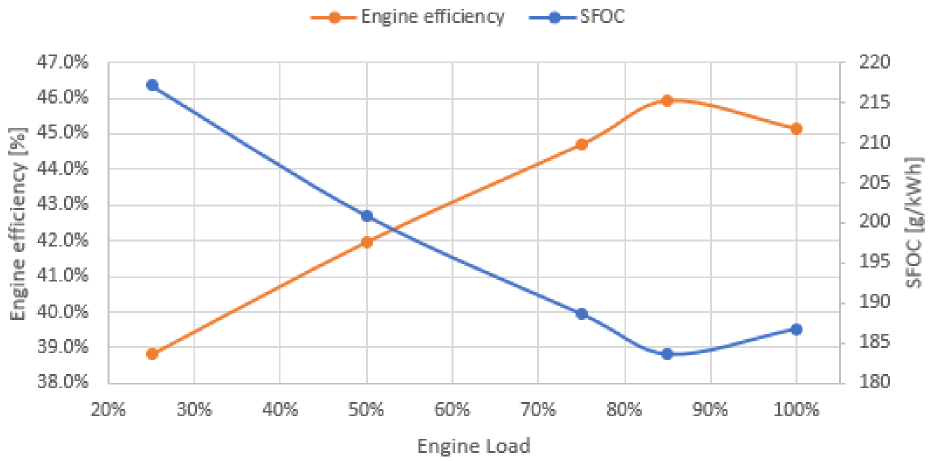

Figure 2.10: Main engine performance graph

With the aid of figure 2.10, the engine load distribution while sailing can be constituted. This is because the fuel oil consumption rate is measured, and with use of the specific fuel oil consumption the engine output power, and thus load percentage can be calculated. This has been done for all data points during the 400 days of data while sailing and leads to the engine load distribution depicted in figure 2.11. Since the engine load is concentrated between 50 and 80%, the distribution is shown for this range with a smaller interval in figure 2.12.

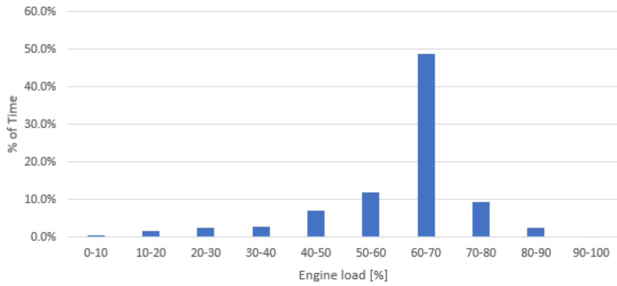

Figure 2.11: Main engine load distribution

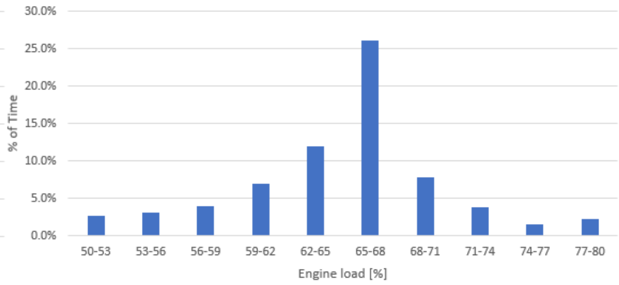

Figure 2.12: Main engine load distribution for most occurring loads

The figures show a large concentration of data points at main engine loads between 65 and 68%. This can be explained by what was previously found under 'operational speed' when discussing the speed-fuel consumption data. As the vessels are instructed to sail with a consumption of 30 ton HFO per day, the load of the main engine comes down to 66.5% using the specific fuel oil consumption data in figure 2.10. It is thus concluded that for a large percentage of time, the load of the engine is fairly constant. With respect to the design point of the vessel, it is also observed from the engine load profile that slow steaming is applied. When the vessel operates on the design speed of 17 kn, the main engine load is around 90% of MCR, at which point the lowest SFOC is found.

Furthermore, by inspection of the measured fuel consumption it is seen that the engine load is not highly fluctuating and is centred around 66.5%. Using figure 2.10 it is found that the engine efficiency for this nominal working point is 43.7%, and the engine delivers an output power of 6517 kW, while consuming 14.9 MW based on the associated fuel consumption and theoretical lower heating value. From the load profile of the main engine, conclusions can be drawn on the applicability of emission reduction technologies focussing on the main powering.

For the propeller, it is known that the propeller operates at a constant rpm and the thrust delivered is varied by changing the pitch of the propeller. In terms of efficiency, it would be more beneficial if the propeller speed could be varied as well as in that case, for each operational condition of the propeller the most optimal working point can be achieved. This is not done since the shaft generator requires a constant speed in order to be able to provide electricity at a constant frequency. The open water efficiency of the propeller from model tests ranges from 0.53 to 0.59, from the combinator curve associated with the CPP, it is found that a variable propeller speed could increase the open water efficiency of the propeller. Applying technologies which enable a variable propeller speed could be a means to reduce GHG emissions as well, this is discussed further at the end of this section.

2.2.6 Auxiliary powering

In order to assess the applicability of various selected GHG emission reduction technologies such as hybridization, fuel cell systems and cold ironing, the auxiliary powering of the current P-type was studied.

For the auxiliary powering of the P-types, no data is measured. Only the consumption of MGO during sailing or port calls is documented. MGO is only used in the generator sets dedicated for the auxiliary powering, so an impression of the energy consumed by this system can be acquired from this data. This would result in averages over several days of operation, which gives a poor data resolution. To be able to assess GHG emission reduction technologies focussing on the auxiliary powering, an alternative approach in finding the load profile of this system is needed.

An approach was found by getting insight in the main power consumers which are served by the generator sets, and estimating the duration of the average usage of these consumers during the operations of the P-type. This information has been gathered from personal communication with the 3rd engineer of Palmgracht, a P-type vessel (B. Weergang, e-mail communication, 28-07-2020).

First of all, it was found that the generator sets are not active while sailing, as the auxiliary power and hotel consumption are then supplied by the shaft generator. The average power extracted from the shaft generator at sea is around 400 kW, however this fluctuates depending on the outside environment and the time of day. As no more data is available on this, it is assumed that during the daytime, the shaft generator delivers 440 kW of power for auxiliary and hotel purposes, and during the night-time this amounts to 350 kW. This additional load on the main engine by the shaft generator is already included in the engine load distribution depicted in figures 2.11 and 2.12.

When entering the port, two of the generator sets are switched in stand-by for redundancy reasons. The bow thruster is supplied with power by the shaft generator during manoeuvring. During port calls, the power demand fluctuates heavily, depending on which operations are performed and the environment in which this takes place. This is why an average daily operational profile of the auxiliary system during port calls needs to be established. The powers of the individual systems have been supplied by the Palmgracht engineer and the average daily duration and time used for these systems have been estimated. Furthermore, the time during the day when the system demanding electric power is used is estimated, based on a typical port day when loading or unloading of cargo is performed. The resulting operational profile of the electrical system is shown in figure 2.13; this has been verified by the crew of the vessel as representing the average power demand of a typical port day where loading or unloading is performed.

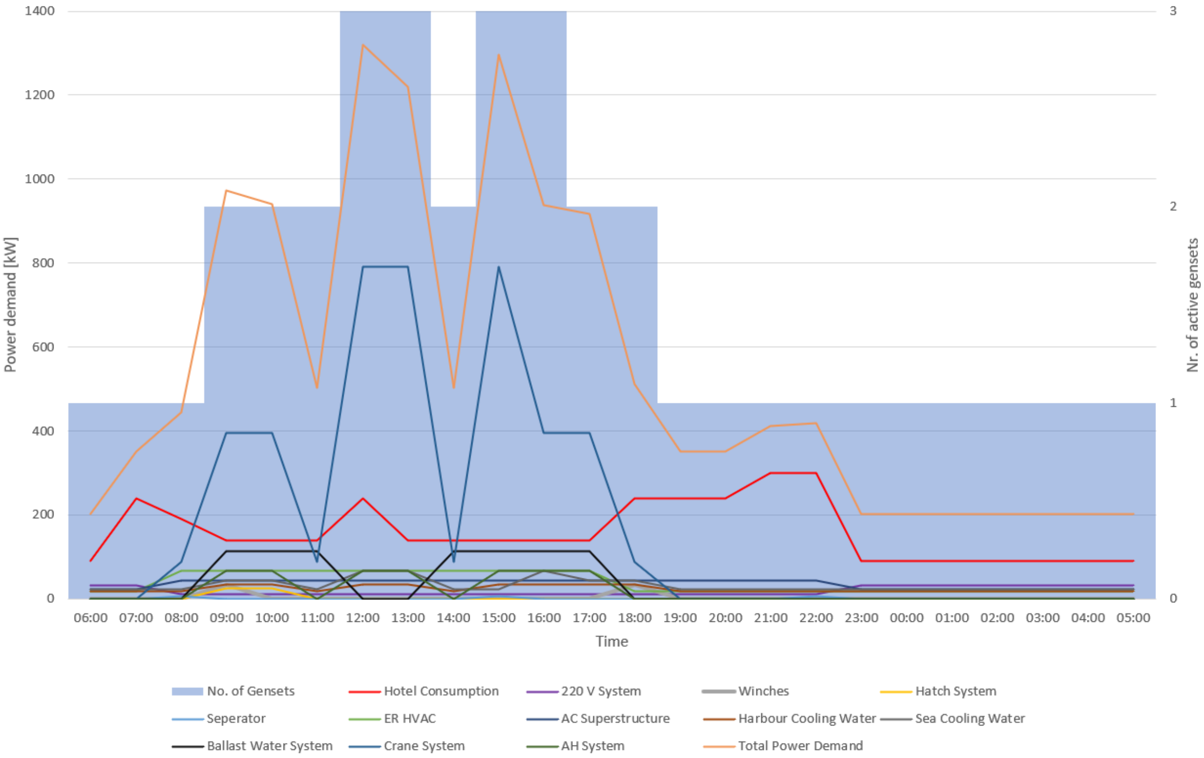

Figure 2.13: Estimated electrical power demand by auxiliary systems during an average port day

Some remarks on the operational profile of the electrical power system can be made. First of all, the output of all electrical consumers are averaged over one hour. Due to this averaging, the variability of the power demand is not represented accurately, as this varies much more and incidental use of systems for shorter periods of time cannot be captured. Furthermore, each type of loading differs in the extent to which the cranes are used, how much power they demand, how much ballast water is needed, and what duration the anti-heeling (AH) system operates. From the email conversation it became clear that the variability of the power demand for the electrical system is significant, and that it can even be noted from the power gauge when the chef starts preparing the lunch. The operational profile in figure 2.13 should thus be seen as representative in terms of average values and tries to capture the power demand variability during a typical port day.

Furthermore, some systems which are mostly active during the first and last day of (un)loading, like the hatch system and winches, are included, but averaged over the amount of days a port call usually takes. Furthermore, from the information received from the 3rd engineer, it is known that when a crane is active, a second generator set is put in standby, to be able to cover the power demand if the first generator fails. This system of redundancy is also practised when two cranes are active; in that case the third generator is also put in standby. Furthermore, the power management system for the electrical loads activates an additional generator if the demanded power exceeds the power delivered by the then active generator sets.

From figure 2.13, it can be seen that the highest power demands originates from the crane system, the ballast water system, and the hotel consumption. Furthermore, it is noted that during the working day two generator sets are active and when both cranes are used a third generator set is put in standby. The power delivered by the generators corresponding to figure 2.13 in terms of a percentage of the maximum load is given in figure 2.14 below. When a generator set is in standby, the load is set to 10%.

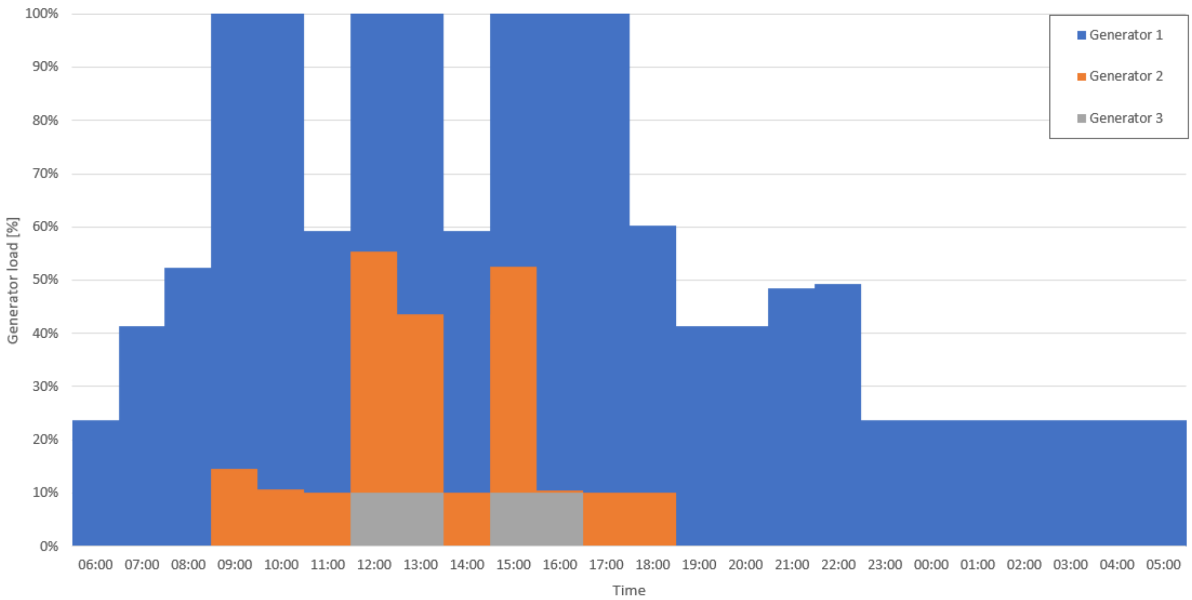

Figure 2.14: Generator load profile during typical port day where (un)loading is performed

There are three identical generator sets on board of the P-type vessels, each capable of delivering 850 kW electrical power at 440V at MCR. The performance of the generator set for different loads is depicted in the performance graph in figure 2.15. It can be seen that the overall efficiency is much lower than that of the main engine, as the conversion from mechanical energy to electrical energy in the generator is already included in the efficiency. Furthermore, it is seen that for higher loads, the efficiency is rather constant, however, for low loads the efficiency drops with nearly 6%.

By combining the loads of the individual generator sets from the assumed profile in figure 2.14 and the performance graph in figure 2.15, the fuel consumption for each hour on an average port day can be calculated. The resulting daily average consumption is 3.84 tons MGO. In order to check whether the assumed average operational profile during a port day where (un)loading is executed is correct, the MRV data set is used. In this data set, the MGO consumption per port day is calculated for each of the voyages recorded. The average consumption of all voyages where loading and unloading of cargo has been performed is 3.95 tons MGO per day. As these values are in correspondence, the operational profile is assumed as accurate enough to capture the typical average profile of the auxiliary powering during a port day where (un)loading is performed.

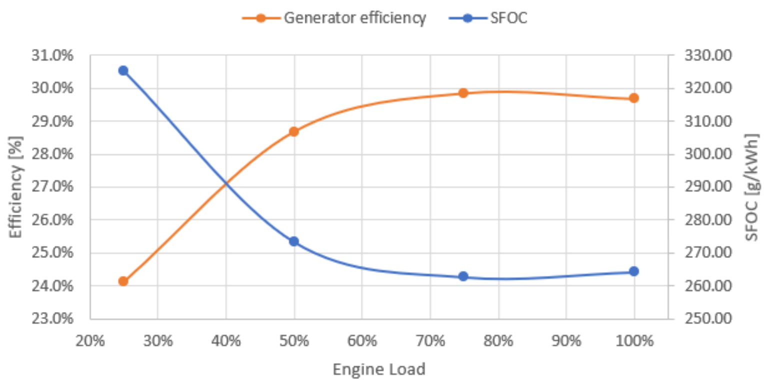

Figure 2.15: Performance graph of generator set

2.2.7 Operational environment

The operational environment is analysed in this subsection. This is done to provide a background for assessing the expected performance of GHG emission reduction technologies such as a slender hull form and the application of a Flettner rotor.

The encountered wind, waves and current have been analysed. All these data are analysed for the vessel attaining a speed over ground of more than 2 kn, in order to exclude berth changes or drifting at anchor from the analysis. The distribution of the encountered wave conditions relative to the direction of the vessel while sailing are shown in figures 2.16 to 2.22 below. Note that the wave heights shown here are the total wave heights, thus the significant wave height from wind and swell waves combined.

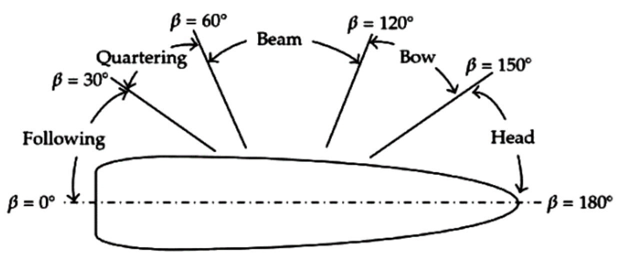

Figure 2.16: Definition of relative wave directions

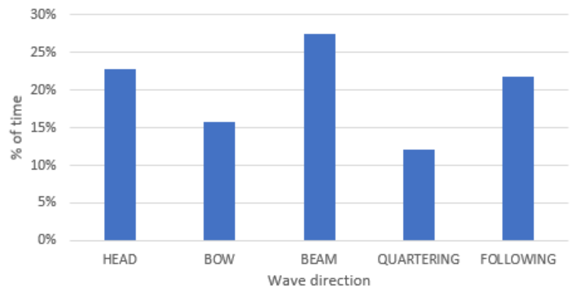

Figure 2.17: Wave direction occurrence

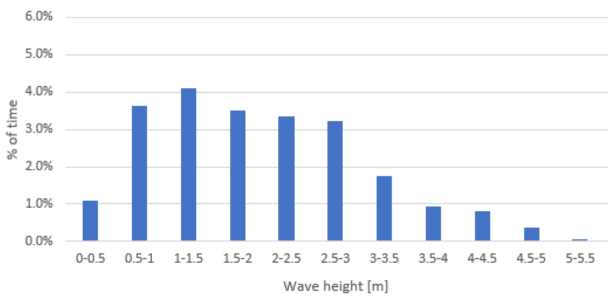

Figure 2.18: Wave height distribution for head seas

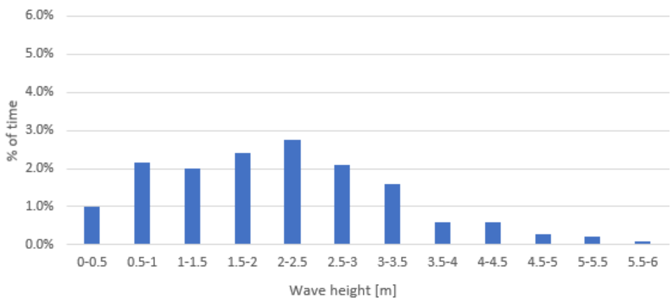

Figure 2.19: Wave height distribution for bow seas

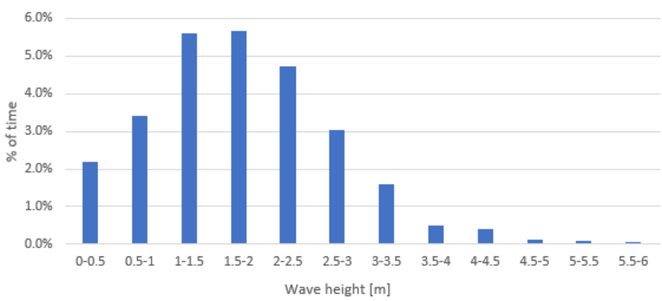

Figure 2.20: Wave height variation for beam seas

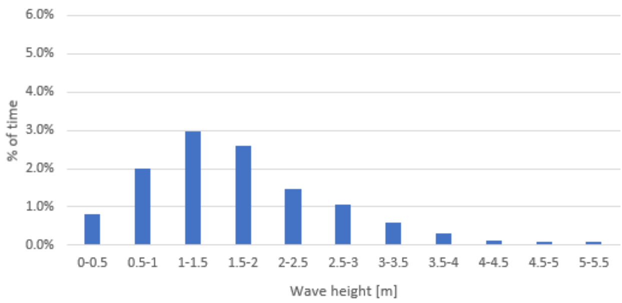

Figure 2.21: Wave height variation for quartering seas

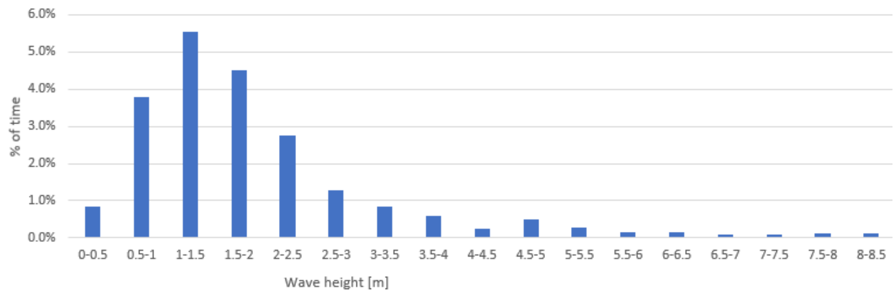

Figure 2.22: Wave height variation for following seas

From figure 2.17, it is seen that, in general, quartering and bow seas are encountered for a lesser percentage of sailing time. This can be explained by the combined roll/pitch motion these wave directions cause on the vessel, which are highly uncomfortable for the crew, especially with higher waves. These wave directions are assumed to be avoided when this is possible by alteration of the vessels course. Furthermore, it can be seen in figures 2.17 through 2.22 that wave heights above 3.5m are mostly encountered in in following and head seas. Furthermore, the highest waves are encountered from the aft of the vessel, as this is the most comfortable encountering direction for large waves. If these sea states are encountered at any other direction, the vessel's course is altered to avoid heavy ship motions and large speed loss.

In figures 2.23 and 2.24 below, the apparent wind direction distribution and speed are depicted. It was found that the largest percentage of time the apparent wind is in head direction, and the largest wind speeds are found in this direction. This is obvious, as the apparent wind speed is constructed from the true wind direction and speed, as well as the ships' speed and heading, which is always from true head direction. This explains why, in figure 2.24, the average wind speeds from any other relative direction are lower than from head direction, as the sailing speed influences the apparent wind speed data. The reason to depict the apparent wind data instead of the true wind data is that the apparent wind is of more importance for wind-assisted ship propulsion systems such as the Flettner rotor.

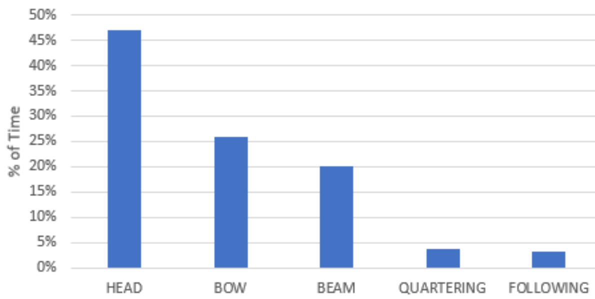

Figure 2.23: Apparent wind direction distribution

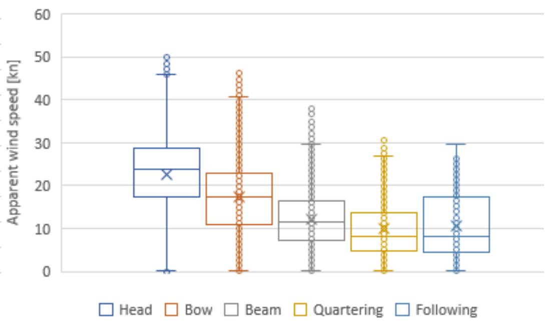

Figure 2.24: Apparent wind speed distribution

Finally, in terms of environmental data, the current distribution in longitudinal ship direction was analysed. This is depicted in figure 2.25, where a positive current speed means that the vessel is encountering head currents. It can be seen that only for 2.4% of the time sailing, no current is present. Furthermore, the distribution between negative and positive current is nearly even, albeit that for positive currents, higher current speeds are encountered. It can be concluded from the graph that from the perspective of resistance and propulsion , the speed through water is a better measure than the speed over ground, as in some cases the difference between these can be up to 4 kn.

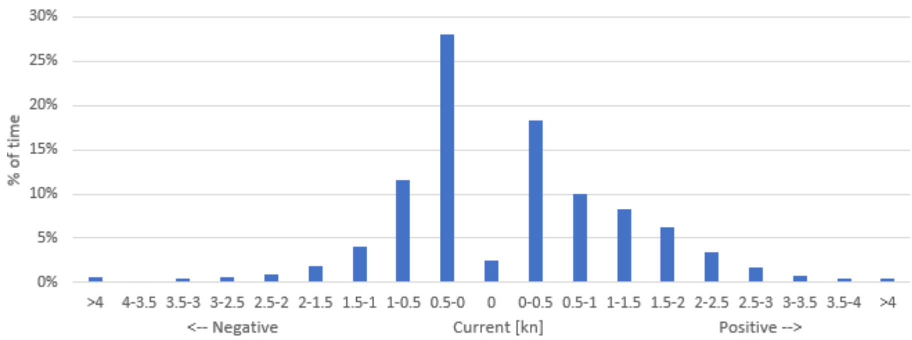

Figure 2.25: Longitudinal current distribution

2.2.8 Voyage planning

For the evaluation of many emission reduction technologies, it is needed that a more thorough analysis on the current way of voyage planning is executed, which includes the routes sailed and ports called at. From personal communication with one of the supervisors, it became clear that, in the current method of voyage planning, a capacity optimization is applied to some extent. In practice, this means that, whenever a cargo which does not fully use the P-types hold volume is transported over a long distance (intercontinental), cargoes of other clients which need to be transported to or from the same region are carried during this voyage as well. Thus, in general small detours are made in order to ensure that the capacity of the ship is used to its fullest potential, optimizing the income per voyage.

Furthermore, extensive weather routing is also applied in planning the ocean voyages, especially when sailing with heavy-lift and project cargoes, as these voyages are associated with acceleration limits imposed by the cargo rigging limits. This means that some conditions at sea need to be avoided. For this purpose, a weather routing program, employing a Monte-Carlo simulation based on historic weather data per location and time of year, is used. This program calculates the probability of exceeding the acceleration limits for a certain sailing route, concluding whether rerouting is needed. The weather routing program is currently based on acceleration limits and the shortest possible distance, without taking the added fuel consumption due to speed loss or added resistance into account. Since the beginning of 2020, sailing within an emission control area (ECA) for sulphur emissions should be taken into account as well, as it could sometimes be economically beneficial to sail a longer total distance and spend a longer time outside of an ECA to be able to combust HFO in the main engine.

Furthermore, in terms of voyage planning it is required for the 'economies of scale' technology to get insight in the routes sailed and the ports called at. The focus of this analysis is on whether certain limitations in main dimension exist, and whether a ship redesigned with larger dimensions would still be able to call at the same ports and sail the same routes as the original P-type.

Limitations on the shipping routes usually exist at canal passages, such as the Panama and Suez canal. The P-type vessels make use of these passages, as can be seen in figure 2.1. After gathering information on the limitations these canals pose with respect to ship dimensions, it was concluded that even when all main dimensions are doubled in value, a redesign would still be able to complete these passages.

Regarding the dimension limitations in the ports call at, it is possible such limits to maximum size restrict the increase in ship dimension in a redesign. The limits in terms of main particulars for different ports are logged within an internal database. From the MRV data it can be seen which ports have been called at during the year 2019 for all P-type vessels. It was found that the berths now called at pose a limit for the length at 175 m (Moerdijk), the maximum draft at 7.6 m (Mumbai) and the maximum breadth at 26 m (Moerdijk). Thus an increase in main dimensions in a redesign would necessitate a change of berths at which is now called at for a handful of ports.

Finally, the time spent at larger ports was analysed. This is of interest for the GHG emission reduction technologies ‘Cold ironing’ and ‘Alternative fuels’ as only the larger ports are expected to facilitate cold ironing and bunkering of alternative fuels in the future. For this analysis, all ports listed in the MRV dataset for all P-type vessels during the year 2019 were classified as being large ports or not. From this data, it was found that on average, 62.8 days per year are spent in large ports. In terms of time, 40% of time in port is spent in larger ports. Also, a large variation was observed between continents in the amount of time spent in larger ports and the frequency at which a large port is called at. It was found that the time between port visits which are identified as large ports can vary from weeks to months.

2.2.9 Arrangement

Although the arrangement of the vessel cannot be seen as operational data on the P-type, it needs to be studied at this point in order to assess the applicability of the remaining emission reduction technologies. By inspection of the stowage plans and when analysing the utilisation of the P-types, insight has been acquired on the usage of the vessel’s arrangement during operations. From this, it was seen that the design of the current P-type is optimized to be able to carry a maximum amount of cargo and to provide a flexible arrangement to be able to transport varying cargo types.

This can also be seen in appendix C, in which the general arrangement of the P-type is given. In the entire space between the forward bulkhead of the forward hold and the aft bulkhead of the main hold, no void spaces or unused deck is present. The only available room to apply additional technologies can be found on top of the wave breaker at the bow and at the superstructure aft. It is expected that when redesigning the vessel, the area forward and aft of the cargo holds are most favourable for applying new technologies, taking into account the requirement of a minimal effect on the operability of the vessel and the ability to transport large cargo items.

2.2.10 Maintenance

Regarding maintenance, the required data especially concern the maintenance of the hull and propeller. Here, maintenance can decrease GHG emissions by reducing the frictional resistance. In order to get insight in the current practice of maintenance, information has been gathered from the technical services department of BigLift (Technical department, personal communication, 4-08-2020), which is responsible for the maintenance works on the P-type vessels.

Currently, the P-type vessels are dry-docked twice every five years. During the dry-dock the hull is grinded by sandblasting and a new coating is applied. This takes on average 8 days, depending on the location where this is performed. The coating applied is a biocide auto-polishing coating, which can last for over two years when the vessel isn’t idle for longer periods of time. Should the latter occur, biological growth on the hull surface can build up very fast. This can affect the fuel consumption drastically. When this reaches an unacceptable level, the hull and propeller are typically cleaned by divers. It takes about a working day to remove the growth, but this also has a negative effect on the quality of the coating on the hull surface.

In order to get insight in the performance gain after a recoating has been applied, the fuel consumption data over 3 months before and 3 months after a coating has been applied has been analysed. This is visually represented in the speed-consumption graph in figure 2.26. It can clearly be seen that the point cloud has shifted to the right after the dry-dock, meaning that on average, a higher speed through water is achieved for the same fuel consumption rate. On average, this amounts to 10% speed increase for the same fuel consumption over the entire speed range. Over the operational speed range from 9 to 15 kn, this amounts to 11% on average.

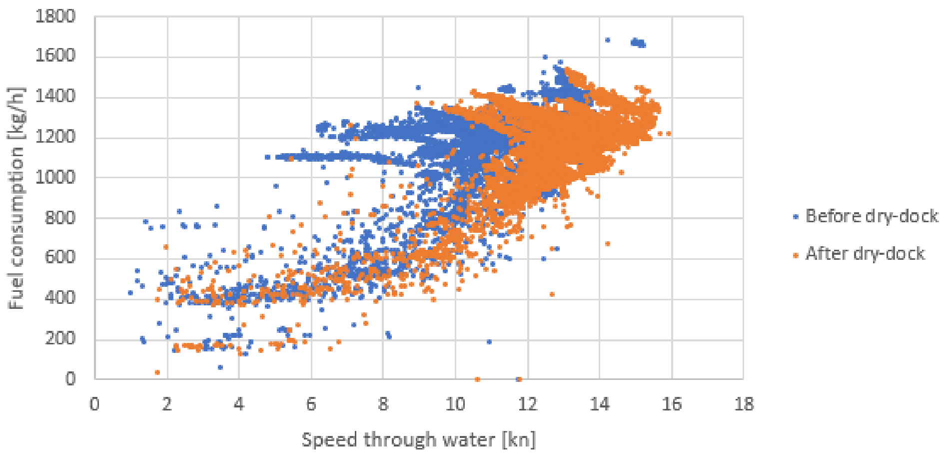

Figure 2.26: Speed-fuel consumption graph for before and after a dry-dock where a recoating was performed.

By comparing the speed increase to the fuel oil consumption baseline, it can be concluded that the fuel oil consumption decrease, when the same speed would have been sailed, would amount to 16.4%. However, it is seen that in practice this gain is translated in a higher average speed of the vessel, since the speed is based on the fuel oil consumption as was discussed under 'operational speed'.

Of note is the fact that this graph showing a significant decrease in fuel oil consumption, was based on a vessel which had been idling for a significant amount of time prior to the 3 months before the data shown in the graph. This means that the same impressive performance increase after recoating should not be expected in ships with regularly cleaning or recoating of the hull.

2.2.11 Bunkering

In analysing the bunkering of the P-types, it should be known what the average fuel oil consumption of these vessels is, what the range between bunkering roughly is and what the current practice of bunkering is. This information is valuable to assess the applicability of alternative fuels.

At first, it is noted from the general arrangement plan of the P-types that the bunkering capacity is 1300 ton HFO and 200 ton MGO. As stated earlier, the HFO is used for the main engine and thus for propulsion purposes, whilst the MGO is mainly used for the generator sets and thus for auxiliary and hotel purposes.

In terms of average fuel consumption, this can also be analysed by using the MRV-dataset on the daily MGO and HFO consumption, while in port and while at sea. The variability of this data is shown by boxplot in figure 2.27 below.

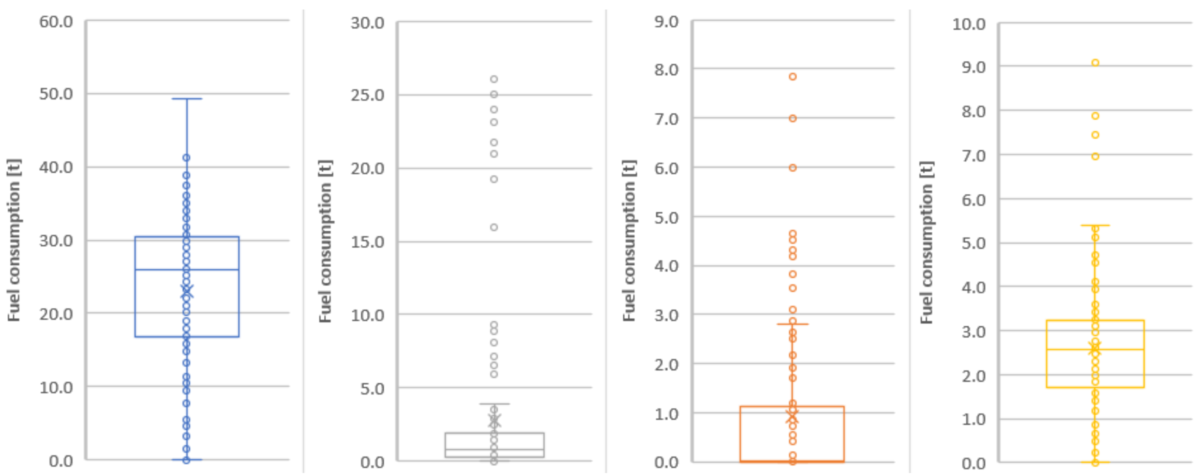

Figure 2.27: Daily fuel consumption boxplots, from left to right: HFO at sea, MGO at sea, HFO in port and MGO in port

The 3rd quartile of the consumption for HFO at sea can be seen to be around 30 ton HFO per day. This corresponds with the maximum consumption the vessels are instructed to sail at, which has been discussed under 'operational speed'. Furthermore, it is noted from the very low median and quartile values for the daily MGO consumption at sea, that indeed the generator sets (which operate solely on MGO) are not used. The values above the maximum can be explained by the fact that for the area around Denmark, the main engine consumes MGO instead of HFO in order to meet the local sulphur emission limits. In general, it can be said that the daily consumption of MGO at sea is (nearly) zero, which can be confirmed by the very low median value.

As for the consumption in port: it has been stated that the main engine is not active when in port, therefore around 50% of data recorded on HFO consumption in port is equal to zero. For the other 50% of data, the daily consumption of HFO in port varies but is not significant. This can be accounted to maintenance works on the main engine for which it needs to be running or due to quay changes during the port visit for which the main engine is activated. The last possible explanation is measurement errors in the bunker levels or bunker notes which show a higher delivered amount than what was actually delivered. For the MGO consumption during port calls, a large variability of consumption is found. This can be ascribed to the fact that the MGO consumption during port calls where only a crew change or bunkering is performed is taken into account in this data, as well as port calls where the cranes, ballast and AH system are active during almost the entire day. This corresponds with the variability in auxiliary power demand, as had been discussed under 'auxiliary powering'.

The average values for the daily consumption are depicted in figure 2.27 as well by a cross, the values corresponding to the figures are 22.94, 2.76, 0.92 and 2.69 ton/day. For the average value of the daily MGO consumption in port, this average also takes into account port calls with a different goal than (un)loading. For this reason it does not correspond to the average used in 'auxiliary powering'. Furthermore, in calculating the range of the P-type, a higher HFO consumption is used. This is set at 30 tons of HFO per day, as this usually is the operating fuel consumption, with the speed following from this. With the measured data, the speed over ground corresponding to a fuel consumption of 30 ton per day can be found. As this varies significantly due to encountered weather, draft and fouling of the hull, the average value of the speed is taken for fuel consumptions between 29.5 and 30.5 tons per day. The resulting corresponding speed is 12.78 kn. With this speed, the range can be calculated using the bunker capacity and daily consumption of 30 tons HFO. Thus the endurance is 43 days and the corresponding range is nearly 13200 nm.

To evaluate whether this range is necessary for the operations of the P-type, the MRV data on the voyages was used. From this, the amount of bunkers taken in was analysed; the spread in the amount of bunkers taken in is shown in figure 2.28.

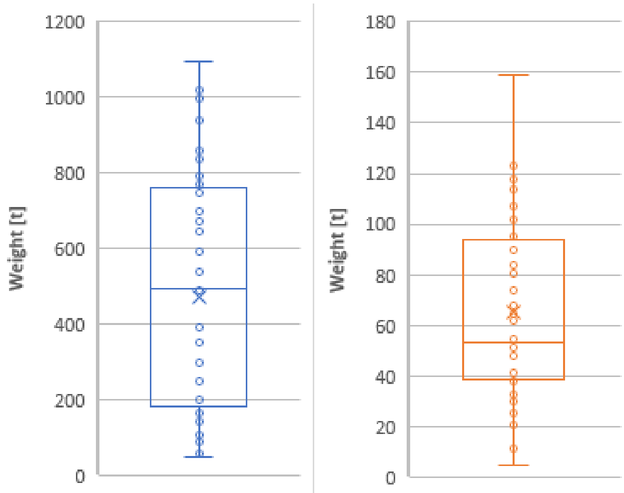

Figure 2.28: Mass of HFO (left) and MGO (right) bunkered

The amounts taken in were found to vary greatly per port where bunkering was performed and the amount of bunkers needed for the next voyage. It was observed that when bunkering in larger ports in Asia, more bunkers were taken in. This is most likely due to more attractive bunker prices and the fact that the bunker levels are already quite low since the vessel has sailed from Europe or America to Asia. Only a small amount (< 200 t) of HFO is bunkered when this was necessary for the next voyage and the prices are not attractive.

In order to conclude on whether the range is needed, the voyages for which over 1000 tons of HFO were bunkered were analysed. These are typically intercontinental voyages of more than 5000 nm and the highest consumption during a voyage was 966 ton of HFO. This corresponds to an ocean voyage across the Pacific of roughly 9000 nm. Other voyages with a very high fuel consumption were found to be also a crossing of the Pacific from Panama to Australia. From the analysis of other voyages with high fuel consumption due to the length of the voyages, it was concluded that bunkering on route at a large port is theoretically possible. This makes the limiting range of the P-type a crossing of the Pacific, which means that a reduction of the required range is possible for a redesign, as the current range is 13200 nm.

2.2.12 Emissions

As a last analysis of the operational profile, the current GHG emissions associated with the operations of the P-type vessels were studied. This was done based on the conclusions already drawn on the fuel consumption, cargo carried and distance sailed. The results of this analysis will also be the baseline of the current P-type with respect to its emissions.

The relevant information with respect to the CO_2-emissions is shown in table 2.2 below. The MRV dataset has been used which also included the bunkering information over the year 2019. As some of the P-types were taken into operation that year, some vessels have limited data available. For the calculation of the CO_2-emissions, the guidelines as set out in the documentation on the energy efficiency operational index (EEOI) (MEPC, 2009) have been followed. A distinction is also made between all voyages and loaded voyages, to show the effect of sailing in ballast.

Table 2.2: CO_2-emission results for all P-type vessels

						All voyages			Loaded voyages		
Shipname	**Days recorded**	**Distance sailed [nm]**	**HFO used [ton]**	**MGO used [ton]**	**Transport work [t · nm]**	**CO_2-emissions [t]**	**EEOI [g CO_2 /t·nm]**	**kg CO_2 per nm**	**CO_2-emissions [t]**	**EEOI [g CO_2 /t·nm]**	**kg CO_2 per nm**
Paleisgracht	184.4	23779	2931	319	2.21E+08	10150.8	45.9	426.9	8197.1	37.0	344.72
Prinsengracht	201.1	32465	3101	329	6.41E+07	10711.6	167.0	329.9	9532.3	148.6	293.62
Pietersgracht	322.6	36429	3511	602	2.66E+08	12863.6	48.4	353.1	8126.5	30.6	223.08
Poolgracht	294.6	43261	4592	478	1.43E+08	15834.5	110.9	366.0	12513.6	87.7	289.26
Pijlgracht	269.9	40070	4452	388	2.68E+08	15110.3	56.4	377.1	12241.2	45.7	305.50
Pauwgracht	242.9	30881	3533	355	8.09E+07	12140.1	150.1	393.1	8901.4	110.1	288.25
Parkgracht	288.3	23019	2506	374	3.35E+07	9004.0	268.8	391.2	4448.5	132.8	193.26
Combined	**1804**	**229904**	**24626**	**2845**	**1.08E+09**	**85814.9**	**79.7**	**373.3**	**63960.7**	**59.4**	**278.21**

The results of the above analysis have been verified using the MRV database of the European Maritime Safety Agency (EMSA, 2020b). In this database, the emission data of all vessels above 3000 GT which have called at European ports in 2019 and 2018 are accessible. Vessels of similar characteristics which serve equal markets have been investigated in this database; it was concluded that the above results are as expected for these types of vessels, albeit that the emissions of the P-type are somewhat higher than vessels of similar characteristics. The latter may be accounted for by the fact that the above emissions analysis also includes relocation of the newly acquired vessels. As this was the first year of operating the P-type vessels, this may have led to a reduced capacity utilisation and thus less transport work for the same amount of GHG emissions.

As all analyses on the operational profile of the P-type vessel, necessary for defining a more limited set of feasible GHG emission reduction technologies, have been carried out and discussed, the third part of this section can be proceeded with.

2.3 Conclusions on GHG emission reduction technologies

The following part will focus on answering the questions stated for each emission reduction technology in section 1.3 and appendix B. From this, conclusions can be drawn on the applicability of these technologies. This will lead to a reduction of the number of feasible technologies, based on the operational data for the P-type vessels. This process will be performed for each technology separately. At the end of this section an overview of the remaining technologies will be given.

2.3.1 Economies of scale

Using the analyses performed in section 2.2 on 'Cargo transported', 'Draft and trim' and 'Voyage planning', the questions below can be answered.

- *Can additional hold volume be filled with the cargo P-type is intended for?* No, from the capacity utilization analysis and personal communication, it was clear that the current hold volume and deadweight capacity cannot always be filled. This means that when increasing the ship size, this will not lead to a reduced carbon intensity; the amount of transport work would not increase since the additional volume is not expected to be utilized to the same extent. Furthermore, for the focus markets of BigLift, project and heavy-lift cargo, it was concluded that the current cargo hold dimensions are suitable for these markets. If the vessel is to be filled with larger cargo items, it would operate in a different market segment and internal competition with higher capacity ships within the BigLift fleet would occur. For bulk items and general cargo, economies of scale could be effective to reduce emissions per transport work, however, these are not the focus markets for the redesigned P-type.
- *Can the same ports be called at with larger ship dimensions?* No, the current information on the ports called at in 2019 showed that the quays that are used now are in some cases exactly fit for the current P-type dimensions. An increase in ship dimensions would be possible, however this would result in berthing at a different quay for some cases.
- *Can the same routes be sailed with larger ship dimensions?* Yes, only canal passages limit the main dimensions on the ship routes. As these canals are also suitable for ships that are twice the present main dimensions, an increase in ship dimensions would not affect the routes that are sailed.

In conclusion, the choice was made not to take 'economies of scale' into account as a GHG reduction technology in a redesign of the P-type, due to the expected inability to utilise the full capacity of a redesign with larger dimensions, which would increase the carbon intensity.

2.3.2 Slender hull concept

Using the analyses performed in section 2.2 on 'Cargo transported', 'Voyage planning', 'Operational speed' and 'Operational environment' the questions below can be answered.

- *Can both ways of reducing the block coefficient be applied?* Yes, it would be possible to lower the hold volume slightly, as the hold volume is rarely used to its full capacity. Furthermore, from section 2.3.1, it was concluded that a small increase in ship dimensions does not significantly affect the operations in terms of ability to call at the same ports and to sail the same routes.
- *Is the reduction of the wave making resistance effective for the operational speed range?* Moderately, from Larsson and Raven (2010), it was found that for the range of Froude

numbers the vessel sails at, the wave making resistance is not the largest component to the total resistance. However, the wave making resistance still contributes significantly to the total resistance and especially to the added resistance when sailing in waves. This means that reducing the added wave resistance is still worthwhile; especially for the higher sea states the reduction of added wave resistance would have a significant overall effect.

- *Which sea states are most frequently encountered?* The most frequently encountered relative wave direction is beam waves, for which wave heights between 1.0m and 2.5m are most occurring. This corresponds to sea state 4. For the head and bow seas, which are most relevant in terms of reducing added wave resistance, it is found that the occurring wave heights are generally slightly higher. Sea state 4 is again encountered most frequently, however sea state 5 is also occasionally encountered from head and bow direction.

In conclusion, it is found from the operational analysis that this GHG emission reduction technology is still deemed effective and applicable for a redesign of the P-type. However, during the subsequent parts of this study, this technology was seen as a general hull form optimization. This could include making the bow more slender. The shift in focus with respect to the hull form optimization stems from the fact that the current P-type vessels do not sail at the speeds they have been designed for. A resistance reduction can therefore be expected by optimizing the hull form for the operational speeds.

Furthermore, from a recent article by Dallinga et al. (2020) on the optimization of the bulbous bow for added resistance in waves, it was found that current computing techniques enable evaluation of the added wave resistance and optimization for the added resistance. The results of their study imply that the design of a bulb is a compromise between its benefits in calm water and a disadvantage in waves which depends on the targeted route. This is to be investigated by future research.

2.3.3 Hull coating

Using the analyses performed in section 2.2 on 'Maintenance' the questions below can be answered.

- *What type of coating is currently used?* Currently, a biocide auto-polishing coating is applied which can last for over 2 years when the vessel doesn't idle for too many consecutive days.
- *How much does the fuel consumption decrease after applying a new hull coating?* This depends on the interval between the previous coating or hull cleaning, thus the amount of fouling present at the time of recoating. For a heavily fouled ship, the resistance reduction can be up to 16.4%. However, when regular hull cleaning is applied and the interval of renewing the hull coating is fixed, it is expected that this reduction will be no more than 5%.

In conclusion, it was found that applying special hull coating can improve the energy efficiency by some percent. However, there is still a lot of uncertainty on the costs and the expected performance of these coatings. Furthermore, as a sufficiently performing coating type is already applied, only applying novel types of coating could possibly make a difference in comparison with the current P-type. This means that this technology is not eligible for a redesign. However, more frequent cleaning of the hull after longer periods of idling can be considered when evaluating a final concept.

2.3.4 Propeller flow optimization

Using the analyses performed in section 2.2 on 'Draft and trim', 'Operational speed' and 'Propulsion' the questions below can be answered.

- *What is the variation in draft, trim and speed?* The variation in draft is quite large, with operational drafts ranging from 650 to 950 cm. However, it is found that for the largest percentage of time sailing, the drafts are between 650 and 800 cm. In terms of operational trim, a larger variation is found from the analyses. The operational trim ranges from 150 cm by stern to 100 cm over bow, while the most occurring trim range is between 80 cm over stern and level trim. For the operational speed, it was concluded that the operational speed

varies greatly per voyage, encountered weather and even draft and trim as the speed is usually depicted by the fuel consumption.
- *What type of propeller is currently used?* Currently, a CPP propeller is used and the propeller speed is kept constant, while the pitch is altered to meet the desired speed.

This type of emission reduction technology will not be considered further during this study. This is due to the absence of a fixed propulsion point for the propeller to operate at, as the variability of draft, trim and speed make for a whole range of propeller working points. Since a design point is needed to optimise the flow into the propeller, it is expected that applying this technology to a redesign of the P-type would result in overall very low or even counterproductive emission reduction potentials. Next to that, this technology is more suitable for a refit of an existing vessel, since propeller flow optimization can be carried out by stern shape optimization during the redesign process.

2.3.5 Waste-heat recovery

Using the analyses performed in section 2.2 on 'Propulsion' and 'Auxiliary powering' the questions below can be answered.
- *How much power can be extracted from the exhaust gases?* From the efficiency of the main engine at the nominal operating point, it was found that around 1.2 MW of power can be recovered. This has been assumed based on the study by Zhu et al. (2020), who estimated that 8% of the total input power could be recovered by applying state-of-the-art waste heat recovery technology. For the auxiliary engines, the amount of potential power to be extracted is not worthwhile in terms of GHG emission reduction.
- *How can this amount of power be used efficiently on the ship?* Only when this power can be stored or be used for the propulsion by a PTI-system, this technology is deemed effective. This is because, on the current P-type, an economiser makes use of the exhaust gases of the main engine to provide additional powering, however this power is not used (fully) by the auxiliary system and cannot be stored or put into propulsion. From personal communication with the technical department at BigLift (Technical department, personal communication, 4-08-2020) it was concluded that with the current design, the extracted power cannot be put to good use. For a redesign, they advised to use the additional gained power for propulsion, as this was the most efficient use of the extracted power from their perspective.

It can be concluded from the above that waste-heat recovery should not yet be discarded, as it could constitute an effective efficiency improving technology. Recent application of waste-heat recovery shows a fuel consumption reduction of more than 5% (Buitendijk, 2020). This GHG emission reduction technology is thus taken into account in further phases of this study.

2.3.6 Cold ironing

Using the analyses performed in section 2.2 on 'Auxiliary powering', 'Voyage planning', 'Bunkering' and 'Emissions' the questions below can be answered.
- '*What is the power needed during port visits?* This varies greatly depending on the reason for the port call. When (un)loading is performed during a port call, the average power demand is nearly 550 kW, however this fluctuates heavily during the day and peak power demands of over 1300 kW can occur. If only bunkering or a crew change is performed, the associated power demand is much lower and doesn't fluctuate as much.
- *What are the current emissions associated with this?* The fuel consumed in port is MGO, as the generator sets only operate on this type of fuel. With the average MGO consumption in port, the average amount of port days per year and the emission factor for MGO, the total amount of CO_2-emissions due to the power needed in port amounts to 1314 ton. This is 7.6% of the total CO_2-emissions per year.
- *How much time is spent in larger ports?* This information is needed as it is assumed that in most larger ports, shore side electricity will be available when the redesign becomes

operational. From inspection of the ports called at in the MRV dataset, it was found that 62.8 days per year are spent in large ports where shore side electricity is expected to be the available in 2025.

To assess the applicability of cold ironing, the associated emission reduction was calculated first. This was done by retrieving the average specific emissions of electricity generation all over the world. From the website of the International Energy Agency (2019), it was found that the worldwide average was 475 g CO_2/kWh for 2019. From the information on the generator sets and by use of the assumed operational profile, it was found that the specific emissions for electricity generation by the generator sets equals 915 g/kWh. With these figures, it can be calculated that by applying cold ironing, 252 ton CO_2 can be saved annually. This equals an emission reduction potential of 1.5%. Although this emission reduction potential is quite small, the investment and the effect on ship design to enable cold ironing is relatively small. This makes this GHG emission reduction technology quite effective to be able to reduce the ship's emissions with a few percent. For this reason, it was chosen to not discard this technology, however, no primary focus will be given to it either in the following.

2.3.7 Solar power

To assess whether the application of solar panels is feasible within the operational profile of the P-type, the analyses performed in section 2.2 on 'Cargo transported', 'Auxiliary powering' and 'Arrangement' were used to answer the following questions:

- *What is the usable area for solar panels?* Solar panels can be placed at the superstructure and at the structure at the bow which prevents green water from entering the holds. For the latter, the technical feasibility is to be analysed. In total, an area of almost 390 m^2 can be used for solar panels. The average output during daytime of a solar panel is 200 W/m^2 (Hammarlund et al., 2017), which means that, on average, 78 kW of power can be saved during daytime.
- *How can the additional power be used efficiently?* The additional power can be used effectively by using it for auxiliary or hotel purposes or storing it in batteries. Since the amount of power generated by the solar panels is very small relative to the output power of the main engine, it is not expected that this power can be used effectively for propulsion purposes.

From the above, it was concluded that solar power would not be the primary subject of primary research in a further stage, because the emission reduction potential is very low due to the small area where solar panels can be placed. Only in a final concept design, the application of solar power can be re-evaluated to reduce emissions slightly more.

2.3.8 Flettner rotor

Using the analyses performed in section 2.2 on 'Operational environment', 'Arrangement' and 'Voyage planning' the questions below can be answered.

- *What is the distribution in apparent wind direction and speed?* It is found that the most frequently occurring wind direction is head wind, and the largest wind speed spread is found for head winds. For apparent head winds, which occur for nearly 50% of the sailing time, a Flettner rotor has a counterproductive effect on the fuel consumption. The most effective additional thrust is delivered by the Flettner rotor when the apparent wind is from beam direction, which is the case for 20% of the sailing time; however, lower wind speeds and thus lower thrust is found from these directions. For all other directions, thrust can be generated, however this is associated with a drifting moment that is to be compensated by rudder forces.
- *What is the area in which a Flettner rotor can be placed?* From the arrangement, it is found that the best placement is at the bow of the ship, on top of the green water cover structure. This corresponds to the literature studied (Berendschot, 2019; Lu & Ringsberg, 2020), which

shows increased performance of a Flettner rotor when placed at the bow. Furthermore, at this location, the Flettner rotor does not experience shielding effects of other ship structures and has the least impact on the crane operating area.

- *Can the voyages be optimized for maximum Flettner rotor performance?* Yes, since it was concluded that the operational speed is not fixed for most voyages, the voyage planning can be based on an optimization of the added thrust by the Flettner rotor. Furthermore, weather routing is already applied, which means that the route sailed can be altered in response to the encountered environment.

From the above it is concluded that the Flettner is to be taken into account in further phases of research into a redesign of the P-type, as it is feasible within the operational profile, and the GHG emission reduction found from literature can be significant. However, from the analysis of apparent wind direction, it is noted that it would be beneficial if the Flettner rotor could be lowered. This would reduce the amount of added drag when faced with head winds and avoid obstruction of the crane operating area.

2.3.9 Hybridization

Using the analyses performed in section 2.2 on ‘Propulsion’ and ‘Auxiliary powering' the questions below can be answered.

- *What is the fluctuation in power demand during sailing and in port?* During sailing, the power demand does not fluctuate significantly enough for hybridization technology to be effective, as the propulsion power demand does not show large fluctuations in short periods of time. However, for the power demand in port, it is found that this is highly fluctuating and varies greatly per type of port call and cargo that is to be loaded or unloaded. For the auxiliary powering while in port, hybridisation thus seems very suitable.
- *What is the estimated battery capacity needed?* Based on the average power demand from the operational profile of the auxiliary power in figure 2.13, it was found that when applying the batteries for peak shaving purposes, a constant power generation of 550 kW results in an energy capacity of 6.3 MWh for the batteries. This includes a margin to avoid a too high cycle depth, as this deteriorates the battery lifetime. This battery capacity can be used during peak power demands. If a purpose other than peak shaving is to be served, the battery capacity need would be different. Based on current commercially available batteries (EMSA, 2020a), a weight of roughly 34 tons of batteries, corresponding to a volume of roughly 11 m^3 would be needed to provide 6.3 MWh of battery capacity. This additional battery weight is deemed to be applicable in a redesign.

Thus, hybridization seems a very promising emission reduction technology which can be applied to the auxiliary power system in a redesign of the P-type vessels. The specific application of hybridisation is to be investigated further, however it can be proven that for hybridization of this system, the impact on the ship design and operations are minimal. Next to this, it was found that generator sets are often in standby to provide redundancy in case the power delivering generator set fails. This is the case when the cranes are used and also when manoeuvring. This back-up power source can be provided by batteries when hybridization is applied. For these reasons, hybridization of the auxiliary system is beneficial. In terms of GHG emission reduction, it is expected that the effect is very little. Yet, a recent article claims that a reduction in operational expenses can be expected when applying hybrid technology (Bruins, 2019).

2.3.10 Fuel cell auxiliary power

To assess the feasibility of fuel cell auxiliary powering, the analyses performed in section 2.2 on ‘Auxiliary powering’ and ‘Bunkering’ have been used to answer the following questions:

- *What is the power demand of the auxiliary power system?* The auxiliary power demand at sea can be delivered by the shaft generator, is around 450 kW without much variation.

When in port, the demand fluctuates strongly, depending on the cargo that is to be (un)loaded and the amount of crane operations associated with this.

- *What is the variation of auxiliary power?* The spread in power demand can be up to 1000 kW, however, rapid fluctuations of power demand are not expected to exceed 400 kW.
- *How much energy needs to be stored for auxiliary purposes?* Based on the current design, the MGO is solely consumed by the generator sets delivering the power for auxiliary and hotel purposes. The current bunkering capacity of MGO is 200 ton, which amounts to 8.54 TJ of energy. However, it is expected that the MGO capacity can be reduced, as the bunkering frequency of MGO is much lower than HFO, which could indicate that a lower capacity and more frequent bunkering for MGO is possible. On the other hand, when an alternative fuel is applied, a larger capacity provides flexibility in operations when this fuel is not widely available.

The application of fuel cell auxiliary power is not discarded, however, the technical applicability is to be investigated further. The application of a fuel cell system in combination with an alternative fuel for auxiliary and hotel purposes could reduce GHG emissions by 7.6% if a fuel is used which doesn't produce net GHG emissions. It is unclear whether the fluctuating demands of power can be met by a fuel cell system. However, a combination with hybridization technology as was described above could be applied. It is not expected that this technology will be of importance during the remainder of the study, due to the large impact on the ship design, low GHG emission reduction potential and large associated costs. The following phases of this study will have to prove this.

2.3.11 Slow steaming

In order to assess whether slow steaming is a feasible GHG emission reduction measure within the operational profile of the P-type, the questions formulated in the first part of this section will be answered below, using the analyses performed in section 2.2 on 'Operational speed' and 'Voyage planning'.

- *What is the current way of depicting the speed of a voyage?* This is based on contractual agreements with the cargo owner, where an arrival window is agreed upon. This defines the speed range which can be sailed. For most cases, an optimization of the associated costs and profits (for instance demurrage) is carried out which prescribes the optimal speed to be sailed. When no cargo is booked and the vessel is relocated, the speed is generally lowered to reduce fuel consumption.
- *Can the same markets be served when sailing at lower average speeds?* No, as heavy-lift and project cargoes are the focus markets for the P-type vessels, and these cargo items are often critical for the project, longer transportation times would mean that these markets cannot be served. Furthermore, large earnings are made with demurrage, which means it sometimes is economically beneficial to arrive before a berth is available. When slow steaming is applied, it is expected that the vessel is incapable of reaching high speeds to be able to collect demurrage, meaning that a substantial share of income is lost.
- *How much can the speed be reduced?* Only when sailing in ballast with no subsequent voyage, slow steaming could be applied. For this, the speed can be reduced to a level where a safe voyage is still ensured. This depends on the weather which is expected to be encountered and the location of sailing.

In conclusion, this technology is not feasible within the operational profile of the P-type vessels. From the analyses performed in section 2.2, it was concluded that, with respect to the design point of the vessel, slow steaming has already been applied, as the design speed of the vessel is around 3 kn higher than what is currently sailed with. This has also been discussed under 2.3.2. Even further reduction of speed will not be investigated in a redesign, as this would influence the operability to such extent, that competitors using vessels able to reach higher speeds would be favored over the redesign.

2.3.12 Voyage optimization

To assess the applicability of this GHG emission reduction measure, the following question is answered using the information discussed in section 2.2 on 'Voyage planning'.

- *What is the current standard of voyage planning for the P-type?* A capacity optimization is already carried out, as well as weather routing, to ensure the voyages of the P-type are as efficient as possible. Furthermore, the operational department tries to limit sailing in ballast as much as possible by finding suitable cargoes for return voyages.

This GHG emission reduction measure is discarded from further study, as the voyages of these vessels are already optimized in terms of weather routing and capacity utilization.

2.3.13 Draft-trim optimization

Using the analyses performed in section 2.2 on 'Draft and trim' and 'Loading conditions' the questions below can be answered.
To be able to answer the questions below, the contents under 'Draft and trim' and 'Loading conditions' of the previous part have been used.

- *What is the operational trim and draft range?* The variation in draft is quite large, with operational drafts ranging from 650 to 950 cm. However, it is found that for the largest percentage of sailing time, the drafts are between 650 and 800 cm. In terms of operational trim, a larger variation is found in the analyses. The operational trim ranges from 150 cm by stern to 100 cm over bow, while the most frequent occurring trim range is between 80 cm over stern and level trim.
- *How much flexibility in the draft and trim is present when loaded with cargo?* For heavy-lift and project cargo transports, not much flexibility in the draft and trim is present, as the ballast tanks are often used to their full capacity to comply with stability criteria. The trim and draft is more a result of the cargo loaded rather than an objective. When loaded with bulk, for instance, usually deeper drafts are attained and more freedom in terms of trim and draft is present.
- *What is the current practice in terms of draft and trim when in ballast?* The draft and trim varies slightly when sailing in ballast, although the draft is almost always between 650 and 700 cm. The trim, however, varies significantly; yet, the most occurring trims are between 25 and 100 cm over stern. It cannot be concluded from the data that a specific trim is to be achieved when sailing empty. However, the freedom to do so is present, as it was observed that a large range of trims can be achieved while in ballast.

In conclusion, this GHG emission reduction measure is not applicable to a redesign, as it was found that the current design does not show a large freedom in draft and trim when sailing with cargo of the focus markets. In a redesign, additional ballast capacity would have to be arranged to provide this freedom in draft and trim, which would be counterproductive. This means that only for ballast voyages, a resistance reduction due to draft-trim optimization is expected. If it is assumed that for all ballast voyages, the fuel consumption is reduced by 5% due to the application of this technology, this would make for a yearly CO_2-emission reduction of 0.9%. As a large effort is associated with achieving an optimal draft and trim for all voyages, this small emission reduction potential implies that the application of this technology is not worthwhile during the further study.

2.3.14 Condition-based hull and propeller maintenance

To assess the applicability of this GHG emission reduction technology, the analyses performed in section 2.2 under 'Maintenance' were used to answer the following questions:

- *Can hull and propeller maintenance be performed during loading and unloading operations?* Hull and propeller cleaning can be performed whilst (un)loading of the vessel. This can either be performed by divers, or with hull cleaning robots.

- *What is the current practice of hull and propeller maintenance?* During dry-docking, the hull is sandblasted and a new coating is applied. Furthermore, the hull and propeller are occasionally cleaned when the ship is heavily fouled.
- *What is the interval in which this maintenance is executed?* A fixed time interval of roughly 2.5 years between dry-docking is applied. Hull and propeller cleaning is executed when the vessel has been idle for a longer period of time, causing the fouling on the hull and propeller to reach an unacceptable level.
- *What is the difference in fuel consumption before and after executing maintenance?* From the operational data, it was calculated that this is 16.4%. This figure probably misrepresents the average reduction of fuel consumption, since this was calculated for a very heavily fouled hull of one vessel which wasn't dry-docked for a long period of time. It is assumed that on average, the fuel consumption reduction is around 8%.

From the above, it can be assumed that the current practice of maintenance on hull and propeller is already adequate. A more frequent cleaning of the hull and propeller could pose a benefit with respect to the GHG emissions, however, it is also expected that this effect is very limited. For this reason, this GHG emission reduction technology is not considered during the remainder of the study.

2.3.15 Alternative fuels

To assess whether the application of alternative fuels fits within the operational profile of the P-type vessels, the questions below were answered, using the analyses performed in section 2.2 on 'Bunkering':

- *What is the current amount of energy stored in bunkers?* The maximum bunkering capacity is 1300 ton HFO and 200 ton MGO, which amount to an energy capacity of 55.5 TJ and 8.5 TJ respectively.
- *How much can the sailing range of the redesign be reduced and how does this effect the operability?* The range can be reduced from 13200 nm to 9000 nm, as the limiting range is a crossing of the Pacific. The associated reduction of bunker capacity is from 1300 ton to 1000 ton. The range reduction effects has very little effect on the operability, as it was noted that in 75% of the occasions that bunkering was performed, the amount of HFO bunkered was less than 800 ton. Furthermore, it was found that only when a Pacific crossing is performed, the bunker consumption reaches 1000 tons. For other voyages consuming this amount of fuel between departure and arrival, it was noted that bunkering in between at a large port is possible.
- *How much time is spent at larger ports? What is the time interval between visits to the identified larger ports?* From the analysis of the ports called at in the MRV dataset, it was found that, on average, 62.8 days per year are spent in large ports. The time interval between these visits varies greatly per area where the vessel is situated at that time.
  As it is expected that alternative fuels will be available only at the larger ports, the time interval between these ports was expected to be of interest. However, this has proven to be of less significance. Instead, the fuel consumed between visits to these larger ports is of significance. It was found that this also varies greatly, but can sometimes be over 1300 tons. The latter indicates that a large port should be called between the large ports, in order to bunker an alternative fuel. This has a large effect on the operability, as for some areas, like Africa and some parts of Asia, large ports are located at great distances from each other. This means that in the voyage planning, care should be given to assure that the fuel is available on the route and if a greater distance will probably need to be sailed.

From the above, it can be concluded that the sailing range can be reduced. This would make the applicability of alternative fuels more feasible from a technical perspective. However, from an operational perspective, the application of alternative fuels on the P-type would have drastic effects, as it is expected that, if alternative fuel bunkering is available by 2025, it would only be available in

large ports. Therefore, a large storage capacity of this fuel would be needed to enable to operate in more remote areas where no large ports are present.
As operability and flexibility in operations is a key factor for the commercial success of the P-type vessels, and the most important criterion for a redesign of the P-type is that the way of operating stays mostly unaffected, the application of alternative fuels does not seem to be feasible, as this would very negatively influence the operability of the redesign.
Furthermore, as a lot of uncertainty exists concerning costs, availability and safety of alternative fuels, the choice has been made to avoid the application of alternative fuels as much as possible in the further stages of the present study. Thus, the amount of GHG emission reduction achievable with the technologies that have not been discarded will be investigated first, focussing on a concept without the application of alternative fuels. However, it is expected that without the application of alternative fuels, the IMO goals for the carbon intensity of ships in 2030 and 2050 will not be met. Therefore, it can be investigated at a later stage what type and how much alternative fuel has to be applied to meet these goals, and to assess its influence on the operational profile, design and costs.

2.4 Conclusions on operational analysis

As all questions formulated in the first part of this section have been answered, conclusions on the feasibility of the GHG emission reduction technologies can be drawn and the feasible technologies are summarized. Furthermore, as the operational analysis has been completed, the sub questions related to this part of the study can now be answered. First, an overview of the discarded technologies will be given, after that, the remaining technologies will be listed. Finally, the sub questions will be answered before closing this section.

In table 2.3, the GHG emission reduction technologies deemed to be not feasible within the operational profile of the P-type have been listed. Furthermore, the reason why these technologies are not considered during further research is recapitulated.

Table 2.3: Discarded GHG emission reduction technologies

Discarded GHG emission reduction technology/ measure	**Reason for discarding**
Economies of scale	It is expected that a redesign with a larger cargo carrying capacity would not be sailing with the full capacity utilization, but lower, which would increase the carbon intensity
Hull coating	GHG emission reduction potential is small, good types of coating are already used currently, much uncertainty with respect to costs and performance of novel coatings
Propeller flow optimization	Due to the absence of a fixed propulsion point for the propeller to operate at, it is expected that applying this technology to a redesign of the P-type would result in overall very low or even counterproductive emission reduction potentials
Slow steaming	Not feasible within the market the P-type operates in, lower speeds would have a negative effect on market position and profitability.
Voyage optimization	Is already applied to some extent, which is why the expected GHG emission reduction is very low and not worth investigating at this stage
Draft-Trim optimization	Not enough freedom in trim and draft when loaded with the focus cargo types. For the voyages where this freedom is present, the expected overall GHG emission reduction is very low, and thus not worth investigating at this stage.
Condition-based maintenance	Already applied to some extent, only a more frequent cleaning of the hull and propeller could pose a benefit with respect to the GHG emissions. However, it is also expected that this effect is very limited
Alternative fuels	Drastically reduces the operability and flexibility of the vessel, high uncertainty with respect to the availability. Unavailability in remote areas would require a large fuel storage capacity in order to ensure that these areas can still be served. Expected to be reconsidered at a later stage in order to meet GHG emission reduction goals, however these will be alternative fuels having a low impact on the ship design and operability.

With the listed eight GHG emission reduction technologies now being discarded, eight other emission reduction technologies remain. Some of these are expected to be more promising and more effective than others after having conducted the operational analysis. The GHG emission reduction technologies which will be focussed on during the next phases of research are:

- Slender hull concept/Hull redesign
- Waste-heat recovery
- Wind-assisted ship propulsion
- Hybridization
- Fuel cell auxiliary power

Two technologies are not discarded, but will not be the primary subject of the present study, due to the expected low emission reduction potential. However, these technologies can be applied in order to reduce the emissions with a few percentages in order to meet the IMO goals. The following GHG emission reduction technologies belong to this category:

- Cold ironing
- Solar power

Two additional technologies that have not been listed previously are included in the further study. These are engine optimization and the ability to sail with a variable propeller speed. These are included as the operational profile analysis had pointed out that the current P-type operates on a sub-optimal engine load for most of the time, increasing the overall fuel consumption. Furthermore, the propulsion analysis has shown that due to the variability in propeller loading, an efficiency gain is expected when being able to sail with a variable propeller frequency. This is currently not done as the shaft generator operates at a fixed frequency.

The main goal of this section was to eliminate the GHG emission reduction technologies which are not applicable to a redesign of the P-type. This goal has been reached in this section, so the sub questions related to this part of the research can now be answered:

2. *Which GHG emission reduction technologies are feasible within the operational profile of the P-type?*

   The following GHG emission reduction technologies are feasible within the operational profile: Slender hull concept, Waste-heat recovery, Wind-assisted ship propulsion, Hybridization, Fuel cell auxiliary power, Cold ironing and Solar power.

   a. *What does the operational profile and power plant profile of the P-type look like?*

      As this cannot be fully captured within several sentences, reference is made to section 2.2. In short, the operational profile is characterized by cargo flexibility, a narrow operational speed range, draft and trim variability, a worldwide operating area, constant propulsion power and a highly fluctuating auxiliary power demand in port.

   b. *Which criteria with respect to the GHG emission reduction technologies follow from the operational profile?*

      In general, the main criteria that follow from the operational profile are that the same markets can be served, the same routes can be sailed and the flexibility in operations is not negatively impacted. More specifically, it has been found that the speed is not to be diminished, the main dimensions are not to be increased too much and the emission reduction technology is not to reduce the range of sailing below a specified minimum.

3. *How does the operational profile of the P-type influence the feasibility of GHG emission reduction technologies?*

   With the operational profile, a more substantiated estimation on the effectiveness of certain emission reduction technologies can be made. This means the feasibility of emission reduction technologies is influenced by the operational profile in such a way that more confidence is acquired to be able to discard technologies. Furthermore, as the operational profile of the current P-type is the basis for the intended operations of a redesign, emission reduction technologies which would greatly affect this profile in a negative sense are considered infeasible.

With the answers to the sub questions above, this part of the research on the operational profile and the feasibility of GHG emission reduction technologies within this profile can be concluded. In the following section, the merits of the remaining technologies will be studied in greater detail.

Section 3: Concept selection

In this section, concepts will be created from the remaining technologies. Concepts are defined here as a combination of GHG emission reduction technologies applied to the operational profile of the P-type described earlier. First, the remaining emission reduction technologies will be assessed individually on their GHG emission reduction and economic performance. After an overview of the individual performances has been presented, the second part of this section will be dedicated to choosing combinations of technologies that are to be assessed on their emission reduction potential and economic performance. After the concepts have been analysed, a sensitivity analysis is performed in section 3.3. This will aid in the concept selection as a measure of how robust the concepts are to changes in the performance estimation. At last, the concept that will be studied further is selected.

3.1 Individual performance

In this paragraph, the individual performance of the remaining emission reduction technologies will be assessed. First, the performance indicators will be introduced. After this, the assumptions associated with the calculation of the performance of the technologies will be dealt with in subsections 3.1.2 to 3.1.9. The paragraph is concluded with an overview of the performance of the emission reduction technologies.

For the creation of concepts, it is important to have a better understanding of the individual performance of the emission reduction technologies. This will be assessed in this subsection. For each of the technologies, a calculation of the fuel consumption reduction and emission reduction will be performed based on the operational profile of the P-type which has been established in the previous section. The assumptions that have led to the emission reduction estimation will be elaborated upon as well.

Next to this, the investment associated with the application of these technologies will be assessed for each technology as well. In this, the CAPEX and OPEX of the technologies will be estimated for their application on a redesign of the P-type and the value of the investment will be calculated as well.

But first, the performance indicators used and assumptions underlying these indicators will be described.

3.1.1 Performance indicators

In general, the analysis is carried out based on the average values of the operational profile of the current P-type vessels. The effect of an emission reduction technology will be assessed relative to these values. The use of average values and the use of a relative comparison is chosen as for the goal of this part of the study, this is deemed sufficiently accurate and efficient. This means that for the results presented throughout this section, all are relative to the average annual CO_2 emissions of the current P-type.

In terms of the economic analysis of both the concepts and the individual technologies, an analysis method associated with the quality of an investment is deemed most suitable. This is because the different technologies all have different associated capital expenses, operational expenses and different fuel cost reduction. Furthermore, an analysis method in which the sensitivity to fuel price can be accounted for is suited as it is known that the profitability of emission reduction technologies is sensitive to changes in the fuel price.

Alexandridis et al. (2018) state that shipping investment valuation methods most used in the industry are the calculation of the net present value (NPV), the internal rate of return (IRR), the payback period and the height of the CAPEX. These values can be used to compare the alternatives and gain a better understanding in the relative economic performance of the alternatives. Only the NPV, the payback period and the CAPEX will be used to value the economic performance of the technologies and concepts. The calculations and assumptions associated with the three performance indicators will be discussed below.

The Net Present Value method is an investment appraisal technique based on discounted cashflows. It is used to express the present value of an investment by calculating today's value of expected cash flows minus todays value of the investment. The formula associated with this is found below:

$$NPV(T=t) = -CAPEX + \sum_{i=0}^{t} \frac{Cashflow\ in\ year\ i}{(1+WACC)^i} \quad (3.1)$$

Based on the average operational lifetime of newbuilt vessels for the Spliethoff group, the investment time duration has been set at 25 years. From formula 3.1, it is seen that the CAPEX of (a combination of) technologies influences the NPV, since a large CAPEX requires a larger cashflow each year for the NPV to be positive and thus make the investment worthwhile.

Furthermore, the CAPEX also has an influence on the weighted average costs of capital (WACC). This is clear from the expression used to calculate the WACC:

$$WACC = \frac{D}{E+D} * r_D + \frac{E}{E+D} * r_E \quad (3.2)$$

In this formula, D is the value of the debt used in the investment, E is the own equity used in the investment and r_D and r_E are the 'costs' of debt and equity respectively. It can be seen that the costs of equity and the costs of debt are weighted over the debt and equity ratio of the total investment and the summation of these two make for the WACC. The WACC can be seen as the weighted required return rate of an investment (Alexandridis et al, 2018).

In this assessment, the following is assumed with regards to the WACC; when the CAPEX increases for the application of a certain technology on a ship, the amount of debt used to invest in this increases as well, when assuming a constant amount of own equity to be invested. This means the height of the CAPEX also influences the debt ratio of the investment and thus the WACC. This is accounted for by assuming that application of technologies with a CAPEX above 2M€ have their surplus fully financed from debt with an interest rate of 3%. For the part of the CAPEX below 2M€, a 40% share of own equity is used. The resulting WACC for part of the CAPEX below 2 M€ is 5.4%, based on personal communication with the director of BigLift (A. Hubregste, personal communication, October 13, 2020), information given in the study of Smits (2016) and formula 3.2 above. The surplus has a fixed WACC of 3% and the resulting total WACC for investments above 2 M€ will be given for each technology. This is calculated by taking a CAPEX-weighted average over the different WACC figures, as in formula 3.2.

The NPV at year 25 is used as a measure to compare the different alternatives, as the highest NPV at year 25 will make for the most profitable investment. However, as the CAPEX influences the NPV, another measure to be included in the economic assessment is the payback period. This is to account for (a combination of) technologies with a large CAPEX and with a high annual cost savings. This may result in a large NPV at year 25, however it still takes a long time to have sufficient cost savings to justify the initial investment. Furthermore, the payback period is an important characteristic in the commercial environment of shipping, where short payback periods are highly favoured over long-term profitability.

With the aid of the NPV at year 25, the payback period and the height of the CAPEX, the alternatives can be assessed on their economic performance. These calculations will be done both for the individual technologies as well as the concepts that are created.

As a last parameter for the assessment, the emission reduction and costs are combined into one figure, the Marginal Abatement Costs (MAC). This figure expresses the costs of emission reduction over the amount of emissions reduced and the corresponding unit is €/ton CO_2. There are multiple ways to calculate the costs associated with emission reduction (Schwartz et al., 2020; van den Berg, 2018), but in this assessment, the NPV at year 25 is used. This value is divided over the amount of

CO_2 emissions reduced in this 25 years and in this way, the MAC is calculated. A negative value of the MAC indicates that emissions are reduced profitably.

A last important remark with respect to the performance assessment is made; the fuel costs reduction is based on the average fuel price recorded for the current P-type during the year 2019. This is a price for HFO and MGO of 380 €/ton and 500 €/ton respectively. As the fuel price can be highly varying and volatile, the sensitivity to changes of +30 and -30% in fuel price is shown for each of the (combinations of) technologies as well.

In the following subsections, each of the individual technologies will be assessed, where attention will be given specifically to the assumptions made to be able to calculate the fuel consumption and emission reduction potential. These results as well as the values for the economic indicators will be discussed in the following subsections. An overview which combines the results of the different technologies will be presented in subsection 3.1.10.

3.1.2 Hull redesign and optimised main engine

For the application of hull redesign and an optimised main engine to the operational profile of the P-type, several assumptions with regard to the resistance reduction have been made. Based on comparative studies (Lindstad et al., 2019; Jung and Kim, 2019), internal documentation on resistance data for a bow modification and communication with BigLift employees, an assumption on the resistance reduction over the operational speed range can be made.

The first major assumption that can be drawn from the previous section is that the operational speeds center around 13,5 knots and that speeds above 14,5 knots are sailed for roughly 17% of the time. From communication with BigLift personnel, it is noted that the influence of limiting the speed to 14,5 knots is little, as the vessels are rarely instructed to sail at speeds above 14,5 knots. This means that in some sense, slow steaming is applied with respect to the original design of the P-type, as these vessels were designed to sail at an operational speed range of 16 to 17,5 knots. The first assumption is that the design speed of a redesign is 13,5 knots at CSR, with a maximum speed of 14,5 knots at MCR.

The second assumption has been drawn from studies into slender hull concept and studies into redesigning a ship for slow steaming (Tez et al., 2014; Faber et al., 2017; Lindstad et al., 2015). This assumption is that at a speed range from 12 to 13,5 knots, the resistance reduction with respect to the original P-type is 10%. For speeds lower than 12 knots, the resistance reduction is greater, estimated to be 12% on average. For the speed range from 13,5 to 14,5 knots, the resistance reduction is estimated to be 5%. With the aid of the operational speed distribution from figure 2.8 from the previous section, the time-weighted average of the resistance reduction was estimated to be 9.6%. This weighted resistance reduction includes the effects of designing the vessel for the encountered sea states, as it was shown in the previous section that the P-type operates regularly in higher sea states, in which a slender hull form can decrease the added resistance. Furthermore, a resistance reduction for a redesign of a vessel that was designed in 2008 is expected to be around 10% due to the more accurate resistance prediction programs and developments in hull form optimization since the previous design was made. A more accurate prediction of the fuel consumption reduction by slow steaming for a redesign of the P-type will be executed in the next section.

The third assumption is that, since the resistance and maximum speed have both been reduced, a significantly smaller engine can be installed which matches the design speed. This means that the optimal operating point of the engine matches with the design speed range, in order to achieve an as low as possible average SFOC. The main engine power can be lowered from the current P_B of 9.8 MW at MCR to the estimated P_B of 7 MW at MCR for the redesign. It was found from manufacturers data that current diesel engines which are able to deliver this power, have an overall SFOC of 176 g/kWh at ISO conditions (Wärtsilä, 2019). In order to account for actual working conditions, the SFOC at the optimal engine load is estimated to be 182 g/kWh. As no data on the engine performance for different load levels is available, the engine performance characteristic of figure 2.10 of the previous section is used and altered for the optimal SFOC of 182 g/kWh. It is assumed the optimal SFOC corresponds to the most occurring engine load. Taking the time average of the newly found SFOC, the new SFOC for a theoretically matched engine is calculated to be 185 g/kWh. For reference, the time-averaged SFOC of the current P-type main engine was computed to be nearly 199 g/kWh.

Applying the above assumptions, the fuel consumption reduction and associated emission reduction potential of the hull redesign and optimised engine can be estimated. For this, it is first calculated what the annual energy need during sailing is, with the use of the average annual fuel consumption during sailing and the average SFOC. This turns out to be 22.8 GWh of energy produced by the main engine, used for propulsion only. Assuming no change in the drive efficiencies, applying the resistance reduction of 9.6% on average, and taking into account the average SFOC of the optimised engine, an annual fuel consumption reduction of 749 ton is estimated. This is a fuel consumption reduction of 13.5%. Using an emission factor of 3.1144 ton CO_2/ton HFO and 3.206 ton CO_2/ ton MGO (MEPC, 2009), the total annual emission reduction is 2337 ton $CO_{2,}$ which amounts to an emission reduction potential of 13.5%.

In terms of the economic assessment of hull redesign and optimised main engine, the influence on the CAPEX and OPEX relative to the current P-type is estimated. First, the increase in CAPEX is estimated. The additional costs for a hull design study focussing on reducing the resistance in operational environment for the most occurring speed range is estimated to be 1 M€. This includes model trials, CFD analysis and design costs for properly matching the engine optimal working point to the most occurring operational load. As the optimised engine can be reduced in size, the CAPEX of the engine for a newbuild is lower than the original P-type engine. The costs for a main engine have been estimated to be € 270/kW (Kim et al., 2020), and the 2.8 MW reduction results in a CAPEX reduction of 756 k€. The total CAPEX is thus 244 k€ for this emission reduction technology. Whether these costs are actually additional costs for a redesign will be discussed in the following paragraph.

In terms of the change in OPEX relative to the current P-type, the only two factors that influence the OPEX are reduced maintenance of the engine and reduction of fuel costs. For the maintenance, it is expected that a smaller engine which works more optimally and significantly less in part-load will have a reduced maintenance need and thus smaller costs. The reduction of maintenance costs annually is estimated to be 15 k€ (Kim et al., 2020). With the fuel consumption reduction estimated and the fuel price estimation, the annual fuel costs reduction is nearly 290 k€.

As the CAPEX and OPEX have been estimated, the remaining three indicators can be calculated from this. The NPV calculation has been performed for the reference fuel price and the estimated WACC of 5.4%, as the total CAPEX is below 2 M€. The NPV at year 25 amounts to 3.8 M€ and the sensitivity of the NPV calculation for a difference in fuel price of ± 30% is presented in figure 3.1, where the NPV over time is depicted. It can be seen in this graph that the payback period for this emission reduction technology is less than 1 year.

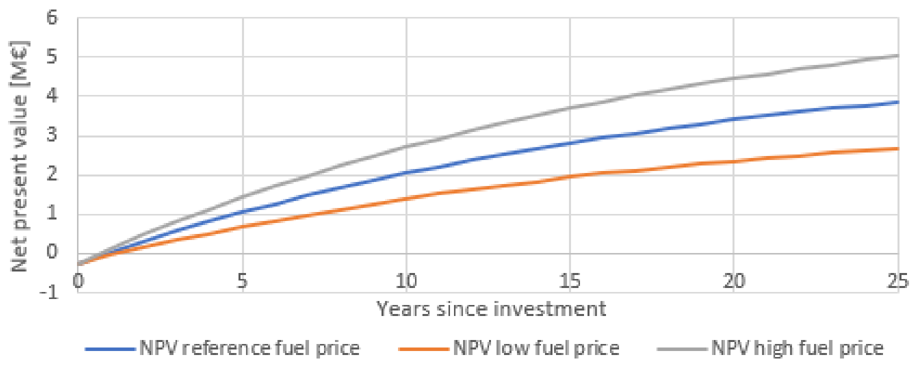

Figure 3.1: NPV over time and sensitivity to fuel price for hull redesign and engine optimization

The last parameter that is calculated to assess the combined emission and economic performance is the MAC. This is calculated to amount a value of – 66.1 €/ton CO_2. The minus sign indicates that emissions are reduced profitably.

3.1.3 Waste-heat recovery

The estimations and calculations made to assess the emission reduction and economic performance of the application of waste-heat recovery systems on a redesign of the P-type will be dealt with in this subsection.
From the previously studied literature, it has been found that the application of an Organic-Rankine Cycle to convert waste-heat to electric energy is a cost-effective way to reduce fuel consumption to provide auxiliary powering. From the previous section, it was concluded that in the current design of the P-type, the energy generated from waste-heat cannot be used efficiently. However, in a redesign, the energy extracted from waste-heat during sailing could be used for auxiliary purposes such as engine room ventilation, hotel purposes and other electricity needs that have their power delivered by the shaft generator in the current design.

It has been estimated, using personal information from the on-board technicians, that the average power supplied by the shaft generator is 400 kW. The assumption that this power can be delivered by the main engine exhaust gases has already been proven in the previous section. Here, it was concluded from the literature that, when highly-efficient WHR-systems are applied, over 1000 kW of power can be generated from the exhaust gases. Based on this information, it is assumed that a simpler WHR-system is able to provide the average 400 kW and the peak power demand of around 500 kW.

As this energy is not produced by the main engine, the total energy consumed by the shaft generator is subtracted from the total energy need during sailing. Furthermore, an increase in the main engine's SFOC of 5 g/kWh is taken into account. This originates from an increase in the pressure of the exhaust gases, which negatively influences the SFOC of the main engine (Mondejar et al., 2018).

With the time-averaged value for SFOC of 190 g/kWh and the annual propulsion energy demand of 22.8 GWh, the annual fuel consumption reduction equals 614 ton or 11.1%. The associated CO_2 emission reduction is 1916 ton, making for a reduction percentage of 11.0%. Note that these values also assume a main engine that is optimised in comparison with the current main engine, as this would be the case in a redesign.

In terms of the economic analysis, some assumptions related to the CAPEX and OPEX of WHR-systems have been made. The CAPEX for a complete WHR-system and installation has been estimated from values found in literature, and is estimated to be 5000 €/kW output of the system (Chun et al., 2020; Casisi et al., 2020 ; Mondejar et al., 2018). This value has been conservatively estimated due to the estimated high performance of the system, also in off-design conditions. The sensitivity of the CAPEX of WHR-systems on the economic performance will be studied later in this section. The resulting CAPEX for a 500 kW WHR-system is 2.5 M€, however, the CAPEX for a shaft generator can be subtracted from this, as all auxiliary power is now produced by the WHR-system. This results in a decrease of 540 k€, based on a shaft generator specific price of 400 $/kW (GLOMEEP, n.d.) and a maximum shaft generator output of 1.2 MW based on technical documentation on the current P-type. The total CAPEX is thus 1.96 M€.

In terms of the OPEX, the added maintenance and operation costs are estimated to be 27 k€ based on the study of Chun et al. (2020). The reduction of OPEX due to the fuel consumption reduction based on the average 2019 fuel price is 238 k€, leading to a total OPEX reduction of 211 k€.

The resulting NPV at year 25 amounts to 892 k€ for the reference fuel price, calculated with a WACC of 5.4%. The sensitivity of the NPV for this emission reduction technology to the fuel price is depicted in figure 3.2. In this figure, the payback period is found to be between 13 and 14 years for the reference fuel price.

As a last parameter for the comparison of the individual technologies, the MAC is calculated. The value amounts to -18.6 €/ton CO_2 reduced.

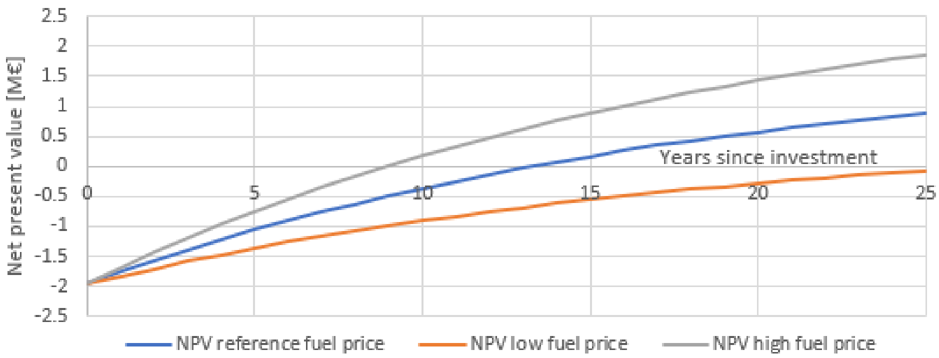

Figure 3.2: NPV over time and sensitivity to fuel price for application of a WHR-system

3.1.4 Flettner rotor

The calculation of the performance indicators, as well as its associated assumptions, for the application of a Flettner rotor on a redesign of the P-type will be dealt with in this subsection.

The first assumption which was made is that, when applying a Flettner rotor, a weather routing program optimising for the highest thrust delivered by the rotor is applied as well. From this assumption and the analysis of the encountered environment during sailing in the previous section, it is deduced that wind conditions which enable use of a Flettner rotor are present at 50% of the time sailing. For the assumption on the fuel consumption reduction when the wind conditions allow use of a Flettner rotor, use is made of literature on design and operation of wind-assisted ship propulsion (van der Kolk, 2020; Berendschot, 2019). Based on the results of both studies, the fuel consumption reduction is estimated to be 15% on average for the 50% of the time when the wind allows use of the rotor. The total fuel consumption reduction therefore amounts to 7.5% during sailing, in accordance with the results of a confidential study performed by Norsepower for the Spliethoff group. This estimation will also be subject to the sensitivity study that is to be performed later in this section.

With the above assumptions, the annual total fuel consumption reduction is expected to amount to 371 ton or 6.7%. The associated emission reduction is 1158 ton of CO_2 saved annually, amounting to a reduction potential of 6.7% as well.

For the economic analysis of the application of a Flettner rotor to a redesign of the P-type, the increase in CAPEX and relative reduction of OPEX have been estimated as well. The unit costs of a Flettner rotor vary significantly, however, for larger units the price ranges from 0.5-1 M€. In this study, a conservative estimation has been made, with estimated unit costs of 0.9 M€ with an additional 0.5 M€ CAPEX for the design, construction and installation costs. The total CAPEX therefore amounts to 1.4 M€. This has been compared with data from the available literature and manufacturers' data, and seems a reasonably conservative estimation of the CAPEX for this technology.

The influence on OPEX is a reduction of 129 k€ annually, which includes an estimated 15 k€ additional service and maintenance costs for the rotor. The fuel consumption reduction thus makes for a OPEX reduction of 144 k€ annually, taking into account the reference fuel price.

Using above estimates of CAPEX and OPEX, the NPV at year 25 results in 341 k€ for the reference fuel price and a WACC of 5.4%. The sensitivity to a 30% higher and lower fuel price is depicted in figure 3.3, where it can be seen that the payback period is just short of 17 years for the reference fuel price.

The MAC for the application of a Flettner rotor equals -11.8 €/ton CO_2 using the assumptions above.

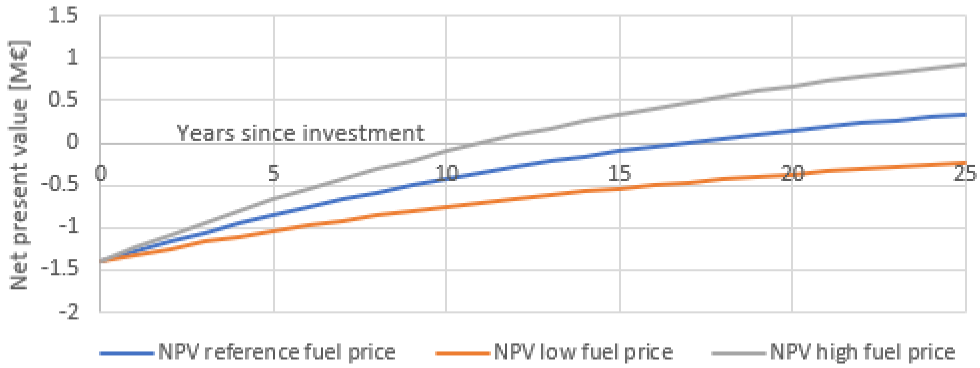

Figure 3.3: NPV over time and sensitivity to fuel price for application of a Flettner rotor

3.1.5 Frequency converter/variable propeller speed

The assumptions and calculations related to the theoretical implementation of a frequency converter to the shaft generator, which allows a variable propeller speed, will be dealt with in this subsection.

This technology was not listed as an emission reduction technology in section 1. However, in the previous section, in was found that an emission reduction could be achieved when sailing at a variable propeller frequency in a redesign of the P-type. This is especially the case when sailing more in off-design conditions for the propeller, which would for instance be the case when wind-assisted ship propulsion is applied. Furthermore, from the operational profile analysis, it was concluded that off-design speeds are sailed at for around 50% of the time.

Being able to sail with a variable shaft and engine frequency in off-design conditions, increases the efficiency of both the propeller, as the optimal combination of propeller speed and pitch can be selected (combinator mode), as well as the engine efficiency as it is optimally loaded. From propulsion data of an earlier study into a redesign of the propeller for the P-type, it was estimated that the propeller efficiency for off-design speeds could be increased up to 10% when being able to sail with a variable frequency. This holds especially for lower speeds. It was assumed that, on average, the increased propulsive efficiency by enabling combinator curve due to the absence of a shaft generator or the addition of a frequency converter for the shaft generator is 7% for off-design conditions. As these are encountered for around 50% of the time, the overall fuel consumption reduction during sailing due to the application of a frequency converter is 3.5%.

The resulting annual fuel consumption reduction is 173 ton or 3.1%. The associated CO_2 emission reduction is 541 ton, also amounting to a reduction potential of 3.1%.

The CAPEX of applying a frequency converter for the shaft generator, which enables sailing on a variable propeller frequency is estimated from a similar study by Schøyen and Sow (2015). In this study, the total installation costs for a frequency converter applied to a 360 kW shaft generator were estimated to be 131 k€. With this data, and the maximum power of 600 kW that needs to be produced by the shaft generator for a redesign, the CAPEX of the installation and system were estimated to be 300 k€.

For the OPEX, it is estimated that this is annually 2% of CAPEX. This equals an increased costs of 6 k€ per year. The fuel consumption reduction results in a annual fuel cost reduction of 67 k€ per year.

The resulting NPV is calculated using a WACC of 5.4%, as the CAPEX is below 2 M€. The NPV at year 25 is 526 k€, indicating a profitable investment. The evolution of NPV over time and sensitivity to fuel price changes is depicted in figure 3.4 below. In this, it can be seen that the payback time is just short of 6 years for the reference fuel price.

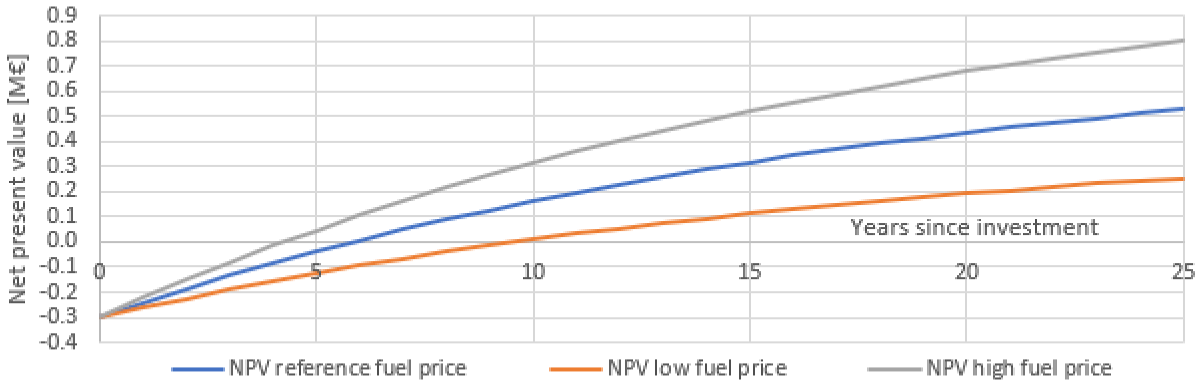

Figure 3.4: NPV over time and sensitivity to fuel price for application of a shaft generator frequency converter

The MAC for this technology is -38.9 €/ton CO_2 reduced.

3.1.6 Cold ironing

For the assessment of the application of cold ironing to a redesign of the P-type, the assumptions and data underlying the calculation of the performance indicators for both emission reduction and economic performance will be described next.

First of all, all ports that have been visited during the sample period of data for all P-type vessels have been analysed. In this analysis, it was estimated whether these ports in 2025 are expected to be able to deliver shore-side electricity. From this analysis, it was computed that on average, 168.5 ton of MGO is used annually for a single ship in ports which are expected to deliver shore-side electricity by 2025. From this, using the average SFOC of the auxiliary generator sets of 299 g/kWh, it is computed that the yearly energy consumption in these ports is 564 MWh. Assuming that this power is now delivered fully by shore-side electricity, the fuel consumption reduction is thus 169 ton or 3.0%. The average specific emissions worldwide related to electricity production is 475 g/kWh (IEA, 2019). With this figure, the CO_2 emission reduction equals 273 ton or 2.1%.

For the CAPEX of this technology, the total system costs for a system with a comparable maximum capacity were estimated to be 450 k€ in the study by Sáenz (2019). This estimate has been compared with the information on the website of GloMEEP (n.d.) and seems to be in the correct order of magnitude for the total installation costs.

In terms of the OPEX, the annual maintenance costs have been estimated as 0.5% of CAPEX. Furthermore, the electricity price for the use of shore side electricity has been estimated to be 0.11 €/kWh (IEA, 2020). This makes the yearly additional OPEX to be 65 k€. The reduced fuel consumption lead to a yearly cost reduction of 84 k€.

With the aid of above estimations of CAPEX and OPEX, the NPV can be calculated. This is depicted in figure 3.5, where it can be seen that the payback period is higher than 25 years for the reference fuel price, using a WACC of 5.4%. The NPV at year 25 equals -183 k€.

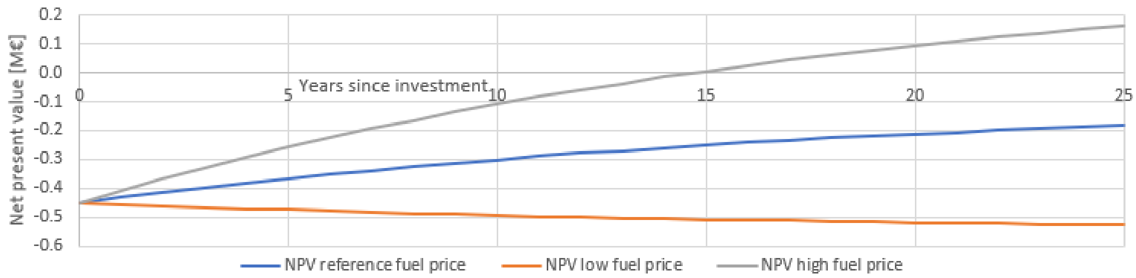

Figure 3.5: NPV over time and sensitivity to fuel price for application of cold ironing

As the NPV for a reference fuel price is negative, the investment for the application of this technology as a sole GHG emission reduction technique is not recommended. However, in combination with other technologies it may be worth the investment, this will be elaborated further in section 3.2.

Finally, the MAC for the application of this technology to a redesign of the P-type were calculated to be 26.8 €/ton CO_2 reduced.

3.1.7 Fuel cell auxiliary power

The assumptions and calculations made to evaluate the performance indicators for the application of a fuel cell system for the auxiliary powering of a redesign of the P-type will be dealt with in this subsection.

The most important underlying assumption is that the use of fuel cells for the auxiliary powering enables an electricity production with a much higher efficiency than conventional generator sets. Furthermore, as alternative fuels had been previously discarded due to the expected limited worldwide availability, it is assumed that these fuel cell systems should be able to convert conventional fuels such as MGO or (in a later stage) LNG. This means that high-temperature fuel cell systems should be applied, as these can most efficiently reform MGO or LNG to the elements that are used within the fuel cell. A benefit of having a fuel cell system installed is the relatively easy adaptation to alternative fuels should these become more readily available during the operational life of the vessel.

From several studies on high-temperature fuel cells, able to convert these conventional fuels, it was concluded that the highest thermal efficiency is obtained by solid-oxide fuel cells (SOFC) (Reurings, 2019; van Biert et al., 2016). These are very expensive, however, it is assumed that the increased efficiency outweighs the additional costs when compared to, for instance, a high-temperature proton exchange membrane fuel cell (HT-PEMFC). It has been assumed that an average efficiency of 50% can be achieved for a SOFC serving as auxiliary powering unit (van Biert et al., 2016). Furthermore, the auxiliary fuel cell should be able to serve the average auxiliary power demand of 400 kW, thus replacing a single generator set. This means that only when the auxiliary power demand in port is higher than the peak value of 500 kW, the remaining generator sets are used. In the previous analysis of the operational profile, it was estimated that this occurs for 30% of the time when loading or unloading is performed, however this does not occur when only bunkering or a crew change is performed during port calls. Taking these assumptions into account and using the average efficiency of a conventional generator set of 28.1%, the average auxiliary power efficiency time-averaged when a single SOFC is applied equals 45.6%.

Subsequently, the resulting fuel consumption reduction is calculated. The energy need during port calls annually is on average 1.0 GWh. Using the above estimated new combined annual efficiency, the fuel consumption reduction equals 131 ton or 2.4%. This is a reduction of nearly 50% of the MGO consumption in port. The associated emission reduction is 420 ton of CO_2 reduced, a reduction potential of 2.4%.

The economic performance of this technology is estimated using the data found in literature as well. The CAPEX for the total costs of applying a SOFC-system is estimated to be 4.95 k€/kW (Kim et al., 2020), resulting in a CAPEX increase of 2.97 M€. However, as the fuel cell system replaces a generator set, a reduction of 0.3 M€ is applied (Kim et al., 2020). The total CAPEX is thus 2.67 M€.

In terms of OPEX, Kim et al. (2020) estimate the annual maintenance and operating costs of a SOFC-system to be 1% of CAPEX, making for an increase in OPEX of nearly 30 k€ per year. The reduction of fuel consumption results in an annual cost reduction of 65 k€ per year using the reference fuel price.

As the CAPEX and OPEX have been estimated, the NPV can be calculated. The WACC is computed based on the method explained at the beginning of this section and equals 4.8%. The resulting NPV over time is depicted in figure 3.6, making for a NPV at the 25th year of -2.15 M€ for the reference fuel price. The payback period is non-existent, as it can be seen that the NPV-curve flattens out.

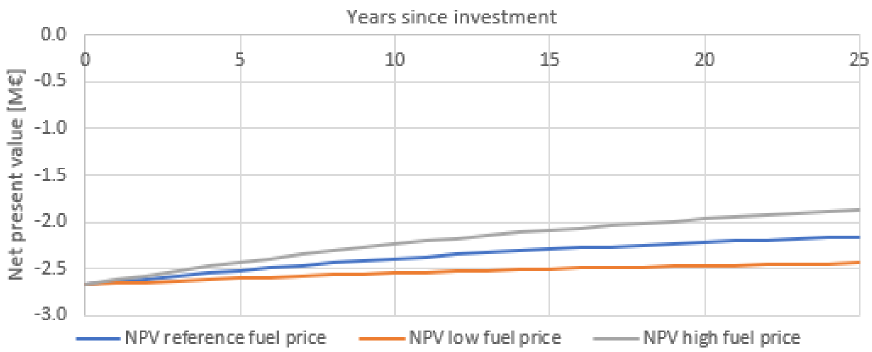

Figure 3.6: NPV over time and sensitivity to fuel price for the application of a fuel cell system for auxiliary powering

The MAC for the used WACC and reference fuel price is 205 €/ton CO_2 reduced.

3.1.8 Hybridization

The evaluation of the emission and economic performance of applying hybridization to a redesign will be dealt with in this subsection, including the associated assumptions and estimations.

In the previous section, it was already assumed that the most effective and feasible way to apply hybridization is to apply this for peak shaving of the auxiliary powering system when (un)loading in port, as this is where the highest power fluctuations are found. A sufficiently large battery package enables the generator sets to always operate at their optimal SOFC. From the previous computations that have been performed in subsection 2.3.10, it was calculated that a battery capacity of 6.3 MWh is needed for peak-shaving purposed during loading and unloading. As peak-shaving enables the generator sets to run in optimal conditions, it was assumed that all energy demand can now be generated with an overall generator SFOC of 262 g/kWh instead of the average 299 g/kWh. This results in a fuel consumption reduction during loading and unloading of 0.40 ton MGO per day. From the operational profile analysis, it was found that in each year, the P-type spends on average 97 days in port performing (un)loading. This results in a yearly fuel consumption reduction of 39.5 ton, or 0.7%. The associated CO_2 emission reduction is 127 ton per year, amounting to a reduction potential of 0.7% as well.

The CAPEX of applying hybridization for the total system, including converters, rectifiers and a switchboard is adopted from the study by EMSA (2020a). In this study, the total system costs are estimated to be 684 €/kWh battery capacity. As this is deemed a reliable estimate, the total system costs are calculated from this using the calculated needed battery capacity, which yields an increase in CAPEX of 4.3 M€. As peak shaving enables a single generator set to supply the auxiliary power, a decrease in CAPEX for two generator sets is applied as well. This is also because the battery pack serves as an additional back-up power source when needed, which makes an additional generator set obsolete. Using the estimate of CAPEX for a generator set in the study by Kim et al. (2020), the total CAPEX is reduced to 3.7 M€.

The OPEX for the battery pack and associated machinery is assumed to be equal to that of two generator sets, which means no additional operating or maintenance costs are present. The only influence on OPEX is the reduced fuel consumption, which makes for a reduction of 19.7 k€ per year.

With the influence on CAPEX and OPEX now known, the NPV calculation can be carried out. The WACC applied is 4.3%, as the surplus of CAPEX above 2M€ is fully financed by a loan at a debt cost of 3%. The NPV at year 25 is still highly negative; -3.46 M€. Furthermore, from figure 3.7, where the NPV is depicted over time, it is seen that the payback period is non-existent; the technology by itself cannot be a justified investment from an economic point of view.

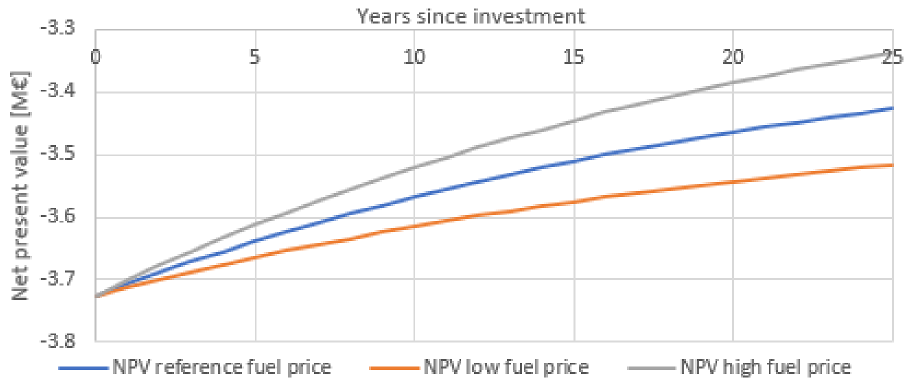

Figure 3.7: NPV over time and sensitivity to fuel price for the application of hybridization

The MAC associated with this technology for a reference fuel price is -1083 €/ton CO_2 reduced, since the costs are very high and the CO_2 emission reduction is quite low (0.7%).

3.1.9 Solar power

The calculations that have been performed to assess both the emission reduction and economic performance of applying solar panels to a redesign of the P-type will be presented in this subsection.

From subsection 2.3.8, it was estimated that on average, 78 kW of power can be generated during daytime. The underlying assumption is that 390 m^2 of solar panels can be placed on the deckhouse and wave breaker in a redesign. To estimate the fuel consumption reduction, it was assumed that on average, 40% of days have a cloud coverage sufficiently low to enable this 78 kW and that on these days, this power can be delivered for 10 hours per day. This leads to an additional 'free' energy of 113.8 MWh per year. During sailing, this translates to a fuel consumption reduction of 12.9 tons of HFO and in port this translates to a reduction of MGO consumption of 14.7 tons. Annually, a fuel consumption reduction of 0.5% is achieved with this. Using the emission factors in the guidelines by MEPC (2009), the CO_2 emissions reduction equals 87.1 ton or 0.5% annually.

For the economic performance, the total system and installation costs were estimated to be 2.79 €/W output (GloMEEP, n.d.). With this estimation, the total system CAPEX are estimated to be 218 k€.

In terms of OPEX, the maintenance and operation costs for solar panels were estimated to be 0.5% of CAPEX, leading to an increase in OPEX of just over 1000 € annually. The reduction in fuel consumption leads to an annual OPEX decrease of 12.2 k€.

The resulting NPV calculation is performed for a WACC of 5.4% and is depicted over time in figure 3.8, where the sensitivity to a fuel price change of ± 30% is made visible as well. The NPV at year 25 equals -66.7 k€ for the reference fuel price. This means the investment for this single technology is not economically worthwhile for the expected operational lifetime of the redesign. This is also concluded by the payback time, which is over 25 years.

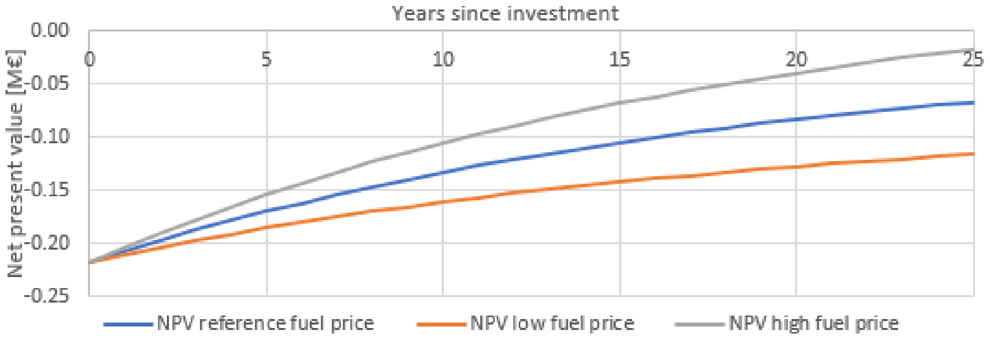

Figure 3.8: NPV over time and sensitivity to fuel price for the application of solar panels

MAC for this technology for the reference fuel price are -30.6 €/ton CO_2 reduced.

3.1.10 Overview

As all technologies have now been assessed based on their expected emission reduction performance and their economic performance, an overview of all distinct technologies is given in table 3.1 below. A clear trend is observed between larger reductions in fuel consumption (and thus in emission) and the economic performance; this obviously is related to the fact that the investment has a shorter payback time when the technology has a larger fuel consumption reduction, as more fuel costs are then reduced annually as well.

Table 3.1: Overview of emission reduction performance and economic performance

Technology	**Fuel consumption reduction**		**CO_2 Emission reduction**		**CAPEX increase [k€]**	**OPEX increase [k€]**	**Fuel cost reduction [k€]**	**NPV T=25y [k€]**	**MAC [€/t CO_2]**	**Payback period [y]**
	ton	**%**	**ton**	**%**						
Hull redesign & optimized engine	749	*13.5*	2337	*13.5*	244	-15	290	3860	-66.1	<1
Waste heat recovery	614	*11.1*	1916	*11.0*	1960	27	238	892	-18.6	13-14
WASP/Flettner rotor	371	*6.7*	1158	*6.7*	1400	15	144	341	-11.8	16-17
Frequency converter	173	*3.1*	541	*3.1*	300	6	67	526	-38.9	5-6
Cold ironing	169	*3.0*	273	*2.1*	450	65	84	-183	26.8	-
Fuel cell auxiliary power	131	*2.4*	420	*2.4*	2671	30	65	-2156	205.3	-
Hybridization	40	*0.7*	127	*0.7*	3726	-	20	-3427	1083	-
Solar power	28	*0.5*	87	*0.5*	217	1	12	-67	30.6	-

Next to the overview presented in table 3.1, a visual representation of the combined emission and economic performance is depicted in figure 3.9 below.

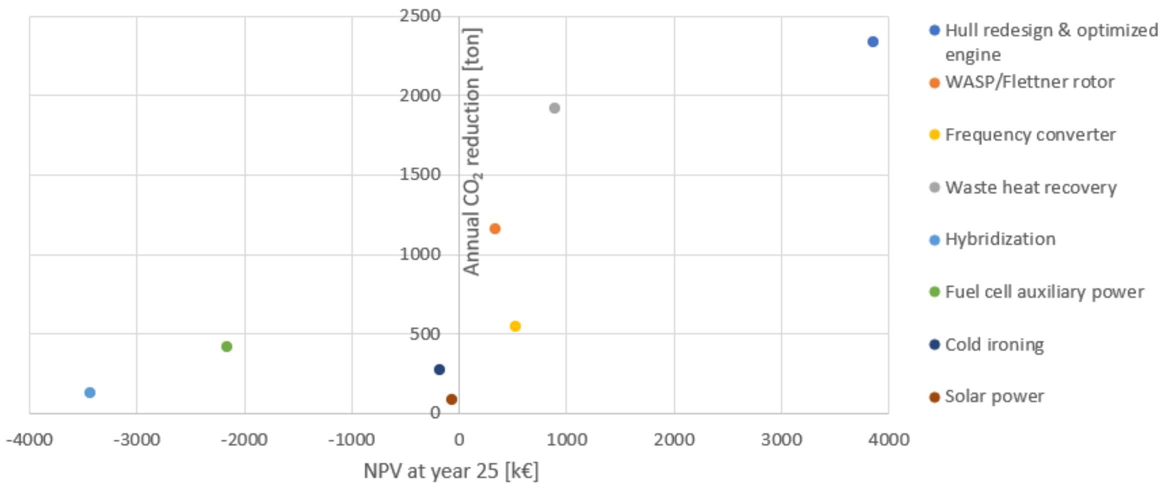

Figure 3.9: Overview of emission and economic performance for all analysed technologies

From figure 3.9, it can be quickly observed that the best performing technology is the hull redesign and optimization of the main engine. Furthermore, it could be concluded from an economic perspective that all technologies which have a negative net present value at year 25, should be discarded. However, the combination of one or more of these technologies with a technology having a higher NPV, could compensate for the negative NPV and still amount to considerable additional CO_2 emission reductions. The combination of technologies will be dealt with in the next paragraph.

Furthermore, as the data depicted in table 3.1 and figure 3.9 are the result of several assumptions with variable reliability, the sensitivity of these results will be checked against changes in these assumptions. This will be dealt with in section 3.3, where the sensitivity of the performance of the different concepts to changes in the underlying assumption will be studied.

3.2 Concept performance

In this paragraph, concepts will be created by combining the technologies that were assessed in the previous part of this section. First, some general remarks and assumptions on the creation of concepts will be given, next the concepts will be presented. Additional information on the calculation of the economic and emission performance of the concepts will be given, after which the results are presented.

First of all, an important assumption is made from the results of the individual performance. It is observed that a hull redesign and optimization of the main engine contributes to a significant CO_2 emission reduction at a low CAPEX. A critical note should be made with respect to this CAPEX; are these actually additional costs due to the application of emission reduction technologies? As this analysis focusses on the relative differences due to the application of emission reduction technologies on a redesign, it could also be concluded that in every redesign, costs are made with regards to a resistance reduction study. Furthermore, for each redesign, the most optimal engine will be properly matched. It is thus questioned whether this technology is actually an additional technology to the redesign or whether this would hold for each redesign. After consultation with the supervisors from BigLift and Spliethoff, it was concluded that the CAPEX is indeed considered to belong to the cost of new build of vessels. Nevertheless, the CAPEX of 244 k€ is still considered, to be on the conservative side as additional costs in computational studies for resistance minimization are likely to occur. Another consequence of the decision that hull redesign and engine optimization is not an additional technology, is that this will be considered for each concept.

The identified inaccuracy with respect to the emission reduction resulting from slow steaming needs to be studied in more detail, as this technique will be applied to a chosen final concept. This will be performed in the next section.

Now, combinations of the individual technologies will be made to create the concepts. From subsection 3.1.10, it became clear that the only three remaining technologies (next to hull redesign and engine optimization) that are profitable on their own are waste-heat recovery, application of a Flettner rotor and application of a frequency converter. Combining these technologies with technologies which are not profitable on their own, could make for a net profitable investment whilst increasing the CO_2-emission reduction. The following concepts have been created; a short explanation is given why these specific combinations of technologies are of interest. In order to avoid creating concepts that are too complex, the amount of technologies combined in a concept is limited to 3.

A. *Flettner rotor + Frequency converter.* The combination of these technologies stems from the fact that application of a Flettner rotor induces a lower propeller load. This means that sailing on a combinator curve (and thus with a variable propeller frequency) could enhance the propulsive efficiency for a larger amount of the time during sailing, as the occurrence of off-design conditions increases.
B. *WHR-system + Hybridisation.* The combination of a WHR-system with hybridisation originates from the ability to store excess energy recovered from the exhaust gases in batteries. Working the other way round is also possible: when too little energy can be extracted from the waste-heat, the energy can be supplied by the batteries.
C. *WHR-system + Cold ironing.* This combination of technologies originates from concept B. Since hybridisation is associated with high CAPEX, an alternative concept which also reduces emissions in port was created. The solution is cold ironing combined with a WHR-system
D. *Fuel Cell Auxiliary powering + Hybridisation.* From the previous section, it was found that the auxiliary powering is characterized by large power fluctuations during loading and unloading. These have to be absorbed by the fuel cell system. Data from the literature indicate that not all

fuel cells are able to follow the power demand. Therefore, hybridisation combined with fuel cell auxiliary powering to deal with these power fluctuations.

E. *Flettner Rotor + WHR-system.* For this concept, only technologies having negative marginal abatement costs are combined. From 3.1.10, it is clear that this is a combination of a Flettner rotor, a frequency converter and a WHR-system. However, as the frequency converter is applied to a shaft generator, and the shaft generator becomes obsolete when applying a WHR-system, only the Flettner rotor and WHR-system remain.
F. *Flettner Rotor + Frequency converter + Cold Ironing.* This combination is an extension to concept A, as cold ironing enables reduction of emissions in port as well and is associated with moderate CAPEX.
G. *All compatible technologies*. These are a Flettner rotor, a WHR-system, hybridisation, cold ironing and solar panels. The application of a frequency converter is not useful, as the WHR-system makes the application of a shaft generator obsolete. Furthermore, no fuel cell system is applied as cold ironing, hybridisation and the use of a WHR-system make the need for more efficient auxiliary power generation obsolete. This combination exceeds the maximum amount of combined technologies, yet is added in the performance analysis to gain insight in the maximum emission reduction using the considered technologies.

With these seven concepts, the performance analysis is carried out. First, some remarks need to be made on the limitation of concepts to these seven that have been presented.

Most importantly, the CAPEX of several technologies makes it undesirable to combine these technologies. For instance, combining a WHR-system with hybridisation *and* a fuel cell auxiliary powering would amount to an additional CAPEX for the redesign of over 8 M€. A significant fuel cost reduction annually would allow an investment to be paid back within the operational lifetime, however, this is not expected for these combinations. Combinations of technologies having a combined additional CAPEX of higher than 8 M€ are therefore not studied.

The mechanism of GHG emission reduction also plays a role in the creation of concepts. Some technologies focus on reducing the emissions while sailing, whereas others reduce emissions while in port or focus on reducing the emissions associated with the auxiliary powering. In order to avoid the technologies having a negative impact on one another, combinations of technologies which all focus on a different mechanism for GHG emission reduction have only been considered.

Finally, some remarks on the inclusion of solar panels in the concepts. The application of solar panels is most effective for concepts where batteries are installed, as excess solar power which cannot be used directly can be stored in the batteries. This means solar panels could have been applied to concepts B and D. This was not done, as it was expected from the previous section that this would not have a large benefit with respect to the economic performance or the emission reduction performance. Solar panels have only been applied to concept G, in which all technologies are considered together.

Concepts A to G have been assessed on their emission reduction and economic performance using the average values from the operational profile and the assumptions made in section 3.1.2 to 3.1.9. In appendix B, more detail on the performance assessment of the concepts is given. Furthermore, additional assumptions and remarks regarding the calculation of the combined performance of emission reduction technologies have been made in this appendix. An overview of the results of appendix B is given in the following, which will be discussed and a conclusion on the concept ranking will be given. An overview of all the performance indicators for all concepts is given in table 3.2 below. For reference, concept H is added, in which only the hull redesign and engine optimization is applied.

Table 3.2: Overview of performance indicator values for all analysed concepts. Note that all concepts include hull redesign and optimized engine in redesigned P-type vessel

Concepts	Fuel consumption reduction		CO_2 Emission reduction		CAPEX increase [k€]	OPEX increase [k€]	Fuel cost reduction [k€]	NPV T=25y [k€]	MAC [€/t CO_2]	Payback period [y]
	ton	%	ton	%						
A: Flettner rotor + Freq. conv.	1159	20.8	3615	20.8	1944	21.0	448	3842	-42.5	5-6
B: WHR + Hybridisation	1207	21.7	3769	21.7	5930	27.0	471	1153	-12.2	18-19
C: WHR + Cold ironing	1336	24.0	3915	22.5	2654	91.5	536	3729	-38.1	7-8
D: Aux. fuel cell + hybridization	1323	23.8	4132	23.8	6101	63.4	518	1162	-11.2	19-20
E: Flettner rotor + WHR	1451	26.1	4528	26.1	3604	44.0	561	4200	-37.1	8-9
F: Flettner rotor + Freq. conv. + Cold ironing	1327	23.9	3888	22.4	2394	85.5	532	3901	-40.1	6-7
G: All compatible technologies	1694	30.5	5034	29.0	7998	109.6	679	1289	-10.2	19-20
H: No additional technologies	749	13.5	2337	13.5	244	21.0	290	3680	-63.0	0-1

The data from table 3.2 indicate that the CO_2 emission reduction of the different concepts does not differ too much, whilst the NPV at year 25 and the CAPEX of the concepts can vary significantly. By comparing the MAC's in this table, concepts A and F are found to generate the most profit per ton of CO_2 reduced. However, concept E, which has lower MAC, has a significantly larger emission reduction and has the highest NPV at year 25. In figures 3.10 and 3.11, the NPV over time and the performance of the concepts are also presented graphically.

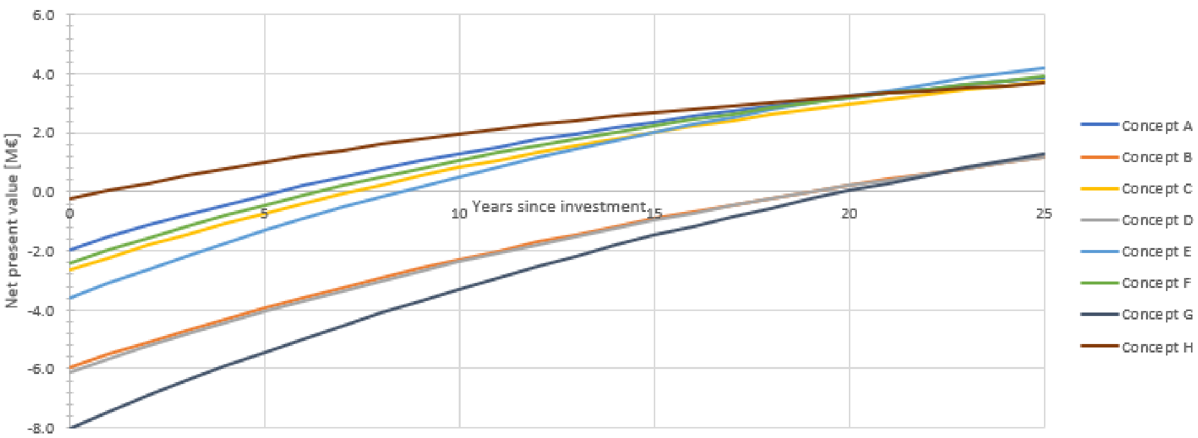

Figure 3.10: NPV over time for all concepts

It can be concluded from figure 3.10, that for the concepts where hybridisation is applied (B, D and G), the CAPEX is much higher, which negatively influences the NPV at year 25. From the inclination of the curves in this graph, it can be deduced that these concepts are generally comparable to the other concepts in terms of their annual payback, so it is solely the high CAPEX which makes for its unfavourable economic performance. Concept G has the highest annual return, and with the low WACC associated with this concept, the inclination of the curve that describes the NPV over time of concept G is the steepest.

When only considering the data in figure 3.10, it might be concluded that concepts B, D and G are to be discarded as the CAPEX is much higher, which makes for a long payback period and low NPV at year 25. However, when also looking at the emission reduction performance, it is found that two of these concepts (D and G) are among the three concepts with the highest CO_2 reduction. This can be clearly observed in figure 3.11. Of note, figure 3.11 also shows that concept E seems to be the best compromise between the economic performance and emission reduction.

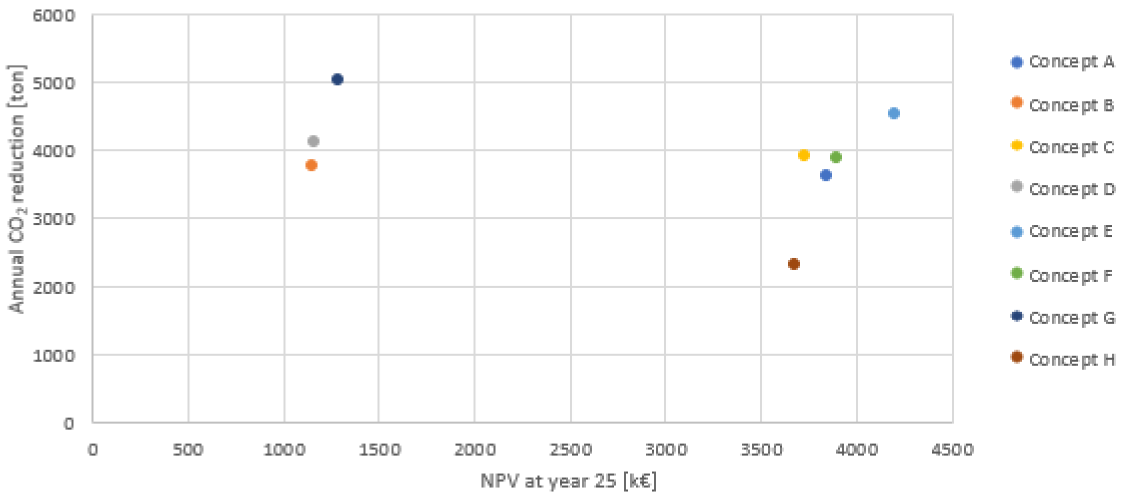

Figure 3.11: Overview of emission and economic performance of analysed concepts

Summarizing from table 3.2 and figures 3.10 and 3.11 it seems that the most promising concepts overall are concepts E and F, as these have the highest NPV at year 25, have moderate CAPEX and a large emission reduction. It is expected that these concepts will be of interest in the next part of the study, where the sensitivity analysis will need to point out which of the concepts E and F is most robust to changes in the future performance.

3.3 Sensitivity analysis

As the performance analysis made in the previous paragraph is based on estimations on future performance or prices, the selection of a concept for further study could be influenced by changes in these assumptions. It is important for the concept selection to know how alternative assumptions influence the performance of the concepts, as this indicates how robust the concepts are. Therefore, before selecting a final concept, a sensitivity analysis on the performance estimation of the concepts will be done.

The sensitivity analysis will be performed based on different cases, in which underlying assumptions on the emission reduction potential and costs of the technologies applied in the concepts will be altered. The cases will first be introduced, after which the sensitivity of the concepts to these cases is studied. This will be studied for all concepts, not only for concept E and F which were previously identified as the most favourable. Finally, conclusions will be drawn from the results of this analysis, which will aid in the concept selection to be performed in the next paragraph.

3.3.1 Introduction of cases

The cases introduced in the following will form the basis of the sensitivity analysis. A case is defined as an alternative assumption on the costs or performance of the emission reduction technologies. The following cases are considered to be of importance to the concept selection and deemed to represent possible future scenario's.

The cases will be presented in table 3.3 below, where a description and the variation of a relevant parameter for the performance analysis is given. Furthermore, the cases are numbered for future reference. Solar panels will be excluded from the analysis, as these are solely applied to concept G and the sensitivity of this concept to changes in the performance of solar panels is expected to be minimal and less relevant.

Table 3.3: Overview of cases for the sensitivity analysis

Case	*Description*	*Change of variable*
1	Estimated resistance reduction for the redesign cannot be met	Instead of 9.6% reduction of sailing energy need, this is 5%
2	Engine redesign cannot be optimized to estimated extent	Increase of average SFOC from 180 g/kWh to 185 g/kWh
3	WHR-systems are more developed and widely used	CAPEX and OPEX of WHR-systems decrease by 30%
4	WHR-system cannot deliver power demand	Average output of WHR is only 200 kW, instead of 400 kW
5	Flettner rotors are more developed and widely used	CAPEX and OPEX of Flettner rotors decrease by 30%
6	Flettner rotor cannot be used to the estimated extent	Sailing energy demand reduction of 4% instead of 7.5%
7	Efficiency of variable propeller speed is lower than estimated	Instead of a 3.5% reduction of sailing energy, this only makes for a reduction of 1.5%
8	Frequency converters are more expensive than estimated	CAPEX and OPEX of frequency converters increase by 50%
9	Cold ironing is always done with subsidized green energy	No emissions associated with shore power, OPEX decrease of 50%
10	Cold ironing is not as widespread as estimated	Decrease in number of port days where cold ironing is used by 40%.
11	Fuel cell systems become more developed and widely used	CAPEX and OPEX of fuel cell systems decrease by 30%.
12	Fuel cell systems need less battery capacity for load variation	Hybridization need for combination with fuel cells decreases by 50%.
13	Fuel cell systems are more efficient than estimated	Average efficiency of fuel cell system increases from 50% to 60%.
14	Batteries are more developed and widely used	CAPEX and OPEX of batteries and associated equipment decrease by 30%
15	Batteries are used more extensively	Increase in fuel savings and emission reduction potential from 0.7% to 2%.
16	Vessel productivity decreases	Only 150 days sailing instead of 208, reduction of sailing days are now idling (only hotel consumption)
17	Vessel productivity increases	Increase of days sailing from 208 to 250, larger percentage of ports where (un)loading is performed
18	Future fuel price change (CO_2-tax, price drops)	For a range from -40% to +70% fuel price, the sensitivity to the payback period of the concepts is studied

Using the above set of 18 cases, the sensitivity of the assessment of the performance of the concepts will be studied. For some of the above cases, it is expected that it will not make for a large difference in the relative performance of the concepts. This is for instance expected for the first two cases, as these influence all concepts in roughly the same way. However, comparing the sensitivity to the individual performance of the concepts with one another can still give interesting results for these cases. On the other hand, several cases are expected to have a large influence on the concept performance. These are for instance the cases associated with the CAPEX of batteries and fuel cell systems, as it was noted that the high CAPEX associated with these technologies leads to their unfavourable economic performance. In the following subsection, it is studied whether these cases indeed have a large influence on the performance of the concepts.

3.3.2 Sensitivity to cases

For all of the introduced cases, the most significant changes in the performance of the concepts will be described. Furthermore, when the case changes the optimal concept in terms of the combined economic and emission performance, this will be noted as well. First, the cases and results will be studied separately, in which a more detailed description of the change in concept performance is given. Finally, an overview of all major effects of the cases will be given.

The sensitivity is studied based on the ranking of the concepts relative to each other, the sensitivity to the annual CO_2 reduction and the sensitivity to the NPV at year 25. Only for case 18, an additional performance indicator is used to show the sensitivity in a more appropriate manner.

The ranking of the concepts will be studied using figure 3.11. In this figure, the concept with the highest NPV at year 25 and highest annual CO_2 reduction will be at the top-right position in the graph. The concepts which are closest to the top-right position will be ranked the highest.

Furthermore, the sensitivity to the NPV at year 25 and the CO_2 emission reduction will be studied for all cases. This will be based on the absolute change in NPV and the absolute change in CO_2-emission reduction. All concepts will be compared with their reference values presented in subsection 3.2.

Case 1: Estimated resistance reduction for the redesign cannot be met

The sensitivity of the overall ranking to this case is very little; it results in an overall shift down and to the left of the points in figure 3.11. No change has to be made in the conclusions on the relative performance of the concepts.

A drop of 3.5% to 3.1% of the emission reduction percentage is observed. The most sensitive to this case for the emission reduction are concepts B and C, and the least sensitive are concepts A and F. The differences between the concepts are minimal.

In terms of the NPV, Concept D now has a NPV of 0 at year 25. Concepts B and D are most sensitive to this case in terms of their NPV, which is expected as these concepts have the lowest WACC, which means a decrease of fuel costs has a higher effect on the NPV than other concepts. The NPV of concept A is least sensitive to this case.

Case 2: Engine redesign cannot be optimized to estimated extent

The result of this case is again an overall shift left-down in figure 3.11. No change in ranking is observed.

Concept A and F are most sensitive to this case for the emission reduction, concepts E and G show the least sensitivity to the emission reduction. All emission reduction percentages are decreased with around 1.8%, and the differences between the concepts are minimal.

For the NPV at year 25, concepts B and D are most sensitive to this case. Concepts A and E are least sensitive to this case for the NPV at year 25.

Case 3: WHR-systems are more developed and widely used

This case results in concepts B, C, E and G to be shifted to the right in figure 3.11 due to an average increase in NPV at year 25 of 500 k€. This is shown in figure 3.12 below, where the shift is indicated with an arrow. Concept E becomes even more favourable in this case and concept C surpasses concept F in NPV at year 25. The concept of which its NPV is most sensitive to this case is G, the concept that is least sensitive is concept C. This is also noted from figure 3.12, where the arrow lengths indicate the sensitivity of the concepts.

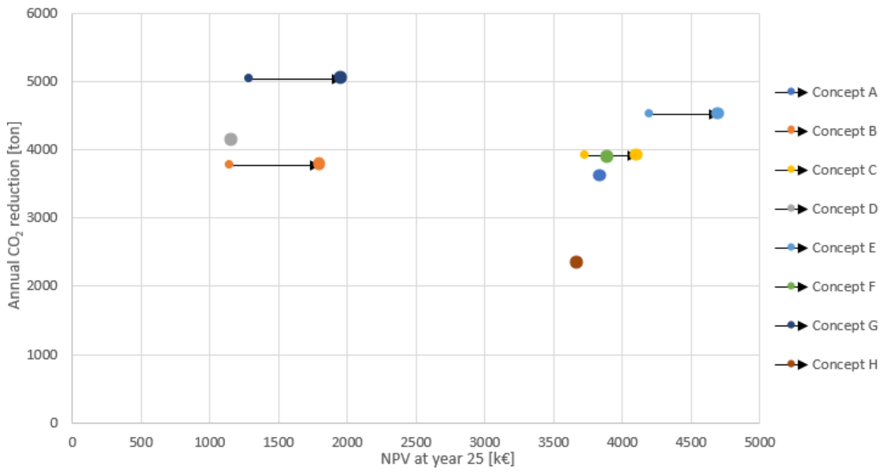

Figure 3.12: Sensitivity of concepts' performance by application of case 3

Case 4: WHR-system cannot deliver power demand

The power supply of the WHR-system in this case is 200 kW on average, half of the reference value of 400 kW. The loss in power is compensated by the generator set, which delivers the power with the average SFOC of 299 g/kWh. This means that MGO consumption and CO_2 emissions increase, as well as an occurrence of additional fuel costs.

This case changes the ranking significantly; concept F now becomes most favourable, and concept D now has the highest emission reduction potential. This is shown in figure 3.13 below, where the influence on the ranking is seen clearly. Even when the power demand which can be delivered by the WHR-system would be 300 kW, concept F still is favoured over concept E as it has a 1 M€ higher NPV and only 0.8% less emission reduction.

The emission reduction sensitivity to this case is equal for all concepts affected; the drop in emission reduction potential is 5.7%.

The NPV at year 25 drops for all four concepts using WHR technology with 2.3 M€ on average, resulting in a negative NPV for concepts B and G. The most affected is concept G and the least affected is concept C.

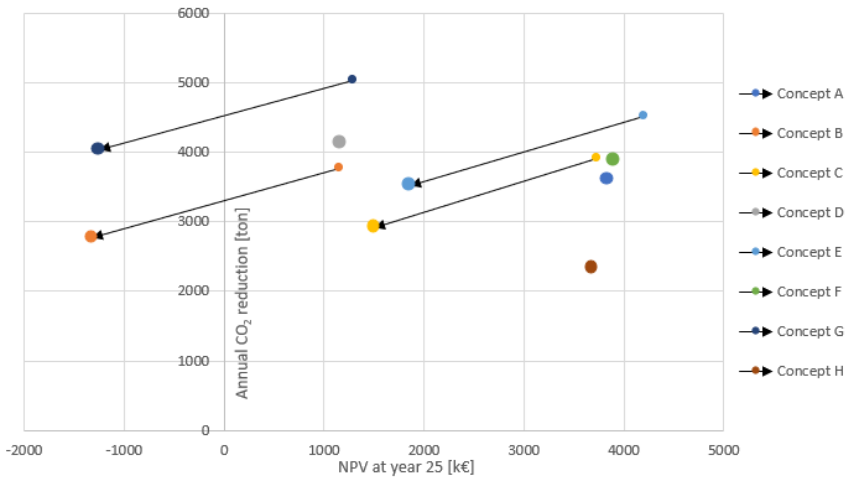

Figure 3.13: Sensitivity of concepts' performance by application of case 4

Case 5: Flettner rotors are more developed and widely used

This case only affects concepts A, E, F and G. The most favourable concept is still concept E, however, concept A now has a higher NPV than concept F.

In terms of the NPV, concept A gains the most for this case, while concept F gains the least. This explains the difference in their rank on economic performance.

Case 6: Flettner rotor cannot be used to the estimated extent
This case influences the ranking significantly; concept C now has the highest NPV at year 25, and the emission reduction potential of concept C is now only 1.2% less than concept E. This means that concept C is now one of the better performing concepts, which is shown in figure 3.14.

All affected concepts are equally sensitive to this case with respect to the emission reduction; the emission reduction potential of all affected concepts drops with 2.3%.

The NPV of all affected concepts decreases with around 750 k€, the most affected is concept G, the least affected is concept A.

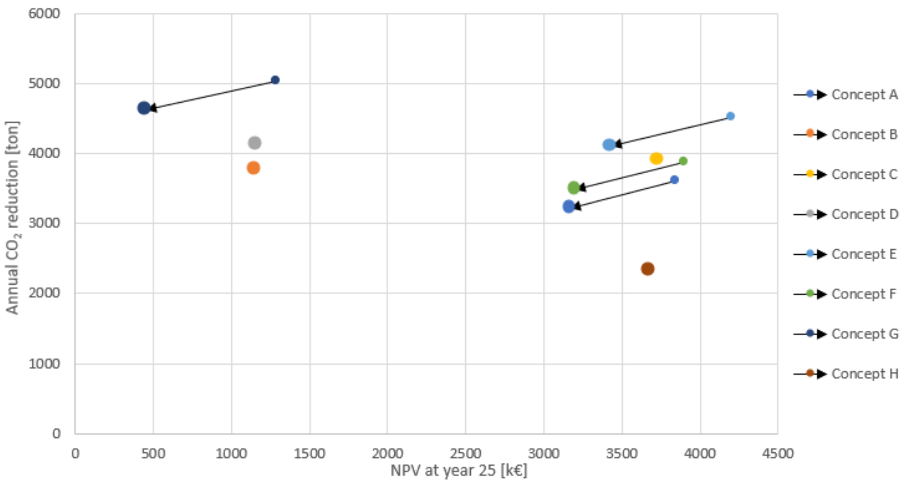

Figure 3.14: Sensitivity of concepts' performance by application of case 6

Case 7: Efficiency increase of variable propeller speed is lower than estimated
All concepts using this technology are equally affected by this case, and the relative ranking of the concepts is thus unaffected.

The emission reduction potential of all concepts drop equally by 1.3% due to this case. The NPV of all concepts drop by around 420 k€, concept A has the lowest drop, concepts B, D and G have the highest drop. This can be ascribed to the difference in WACC.

Case 8: Frequency converters are more expensive than estimated
The ranking is influenced by this case in such way that concept E becomes more favourable from an economic perspective. This is since concepts A and F have their NPV decreased with 177 and 103 k€ respectively. Concept A is thus most sensitive to this case in terms of NPV.

Case 9: Cold ironing is always done with green energy, port subsidies for green energy use
This influences the ranking in such way that concepts C, F and G are shifted upwards and to the right in figure 3.11. The highest NPV at year 25 now corresponds with concept F, and concept F now only differs with 2.2% (instead of 3.7%) from concept E in terms of their emission reduction potential. This means that concept F is now also among the most favourable concepts.

The sensitivity of the emission reduction to this case is constant for the three concepts; the emission reduction potential increases with 1.5%.

The NPV of all concepts increases by around 470 k€, concept G shows the highest increase, while concept F shows the lowest increase. This difference is due to the WACC.

Case 10: Cold ironing is not as widespread as estimated
This case influences the ranking slightly; concepts C, F and G now perform worse in terms of the NPV at year 25. This means concept A now has the second-highest NPV, which means it becomes more

favourable. Concept E is still deemed most favourable, since the difference in emission reduction potential between E and G is now only 2.3%, whilst the difference in NPV is almost 3.5 M€.

The sensitivity to the emission reduction of the concepts for this case is for all concepts equal; a drop of 0.6% is observed for all concepts.

The sensitivity to the NPV at year 25 is for the three concepts fairly equal; the NPV of concepts C, F and G drop with 484 k€, 475 k€ and 550 k€ respectively.

Case 11: Fuel cell systems become more developed and widely used
This case influences concept D by a sharp increase of the NPV at year 25 of nearly 1 M€. This does not influence the concept ranking.

Case 12: Fuel cell systems need less battery capacity for load variation
This case only affects concept D again, as this is the only concept where this technology is applied. The NPV at year 25 for this concept is now increased with 1.8 M€, however, this is not sufficient to influence the ranking in such way that the most favourable concepts are identified differently.

Case 13: Fuel cell systems are more efficient than estimated
This case does not influence concept D in such a way that the most favourable concept differs from the reference case. The emission reduction potential of concept D is increased by 1.6% and the NPV of concept D is increased with nearly 700k€.

Case 14: Batteries are more developed and widely used
This case affects concepts B, D and G significantly in terms of their economic performance. All concepts have their NPV at year 25 increased by 1150 k€. This makes concept G more favourable, as the NPV is now nearly 2.5 M€. Furthermore, the payback period for concept G is decreased from 20 to 16 years, which influences the investment decision significantly.

Case 15: Batteries are used more extensively and in more modes
This case again affects concepts B, D and G in both their emission reduction and their NPV at year 25. All concepts have their emission reduction percentage increased with 1.4%. The NPV increase of concepts B, D and G is 540 k€, 586 k€ and 598 k€ respectively. The sensitivity of concept G to this case makes this concept more favourable. This is because the emission reduction now is 30.3%, and the payback period is decreased from 20 to 18 years.

Case 16: Vessel productivity decreases
The lesser productivity case also takes into account that the fuel consumption and emission reduction reference values similarly change when the vessel becomes less or more productive. This means that for these cases, a new set of reference values is computed and with the aid of these, the fuel consumption reduction and emission reduction (potentials) can be calculated.

This case affects all concepts, but not to an equal extent, which is why the ranking is affected by this case. This can be best demonstrated using figure 3.15, in which the changes in the combined performance graph are made visible. The large dots are the new values for the concepts, and the arrows show the relative change with respect to the reference case. The length of the arrows can be used as a rough measure to show the concept's sensitivity to a decrease of productivity. It can be seen that concept E is most sensitive to this case, and concept F and H are least sensitive.

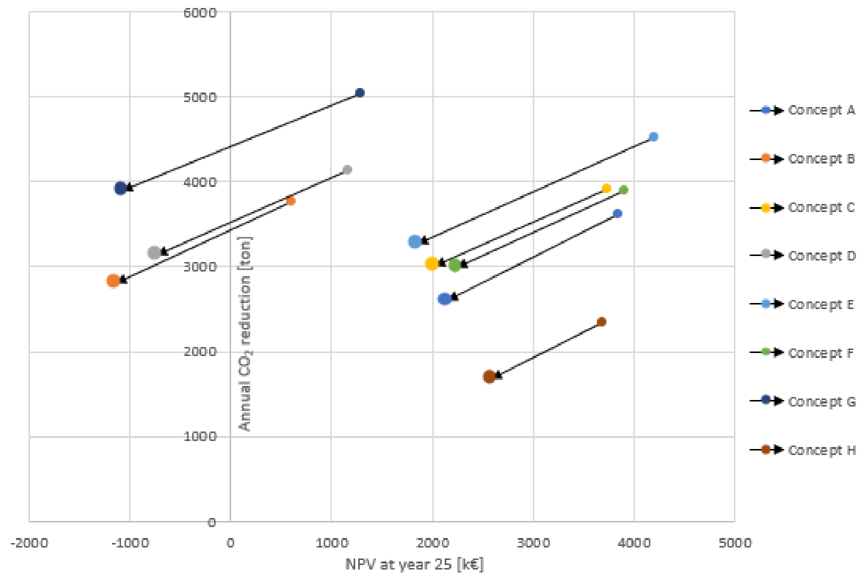

Figure 3.15: Sensitivity of concepts' performance to case 16, with a decrease of 58 sailing days annually

From figure 3.15, it is noted that concept F becomes the most favourable in terms of the NPV at year 25. This also holds when the productivity is decreased by 28 sailing days, instead of 58 as was shown in the graph above. Nevertheless, the higher emission reduction of concepts E still makes the concept selection for this case undecisive, as it could be chosen that higher emission reduction prevails over the NPV at year 25.

Case 17: Vessel productivity increases
Just as in case 16, with increased productivity the reference values also change; for example, the annual fuel consumption increases by 15%. This has been taken into account when assessing the performance of the concepts when case 17 is applied.

Again, this case affects all concepts, and also changes the ranking of the concepts. This is shown in figure 3.16 where both economic and emission performance of all concepts is visualized. In this figure, it is noted again that concept E is most sensitive and concept F is least sensitive to this case. Furthermore, concept E is in this case undoubtedly the best performing concept, as its NPV is nearly 1 M€ more than concept F, which is second best, and it has the second highest emission reduction.

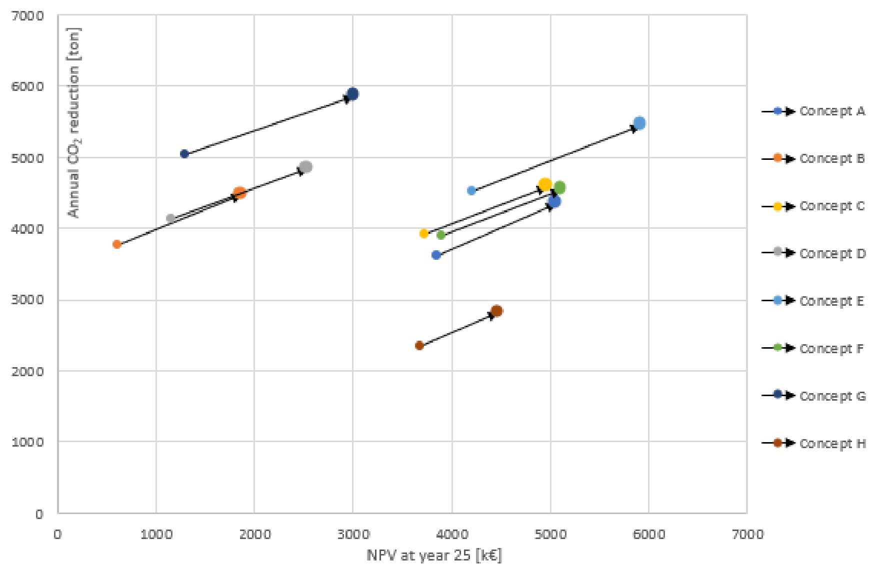

Figure 3.16: Sensitivity of concepts' performance to case 17, an increase of 42 sailing days annually

Case 18: Future fuel price change (CO_2-tax, price drops)
The sensitivity to this change is best visualized by a graph which shows the payback period against the fuel price, as this is deemed more intuitive than the NPV at year 25. This is depicted in figure 3.17, the red vertical line is the reference HFO price of 380 €/ton. The HFO price is varied from 225 €/ton (-40% compared to reference) to 650€/ton (+70% compared to reference), and the MGO price follows the same relative increase or decrease. From the graph, it can be seen that concepts B, D and G are most sensitive to fuel price changes, whereas the other concepts are even profitable over the 25 year period for a 40% drop of fuel price. The payback time of concept A is least sensitive to changes in the fuel price.

The sensitivity to the NPV at year 25 of the concepts was studied as well, concept A was found to be the least sensitive to fuel price change and concept G the most sensitive.

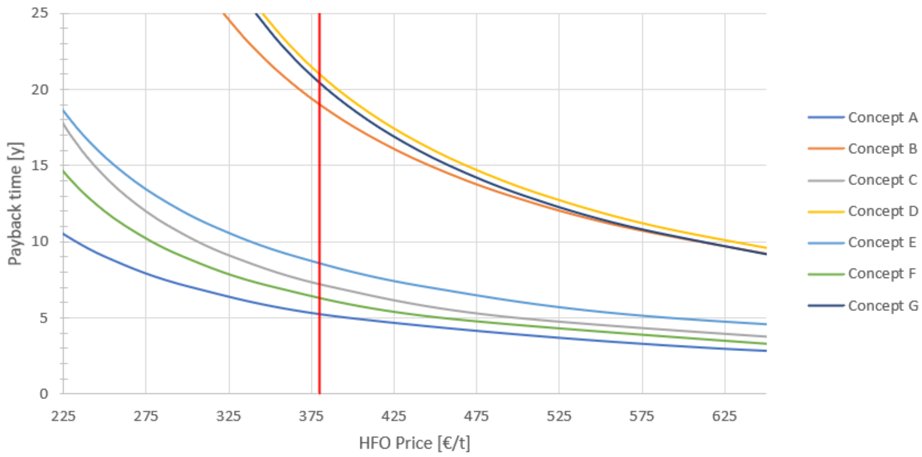

Figure 3.17: Sensitivity of payback time to fuel price

In table 3.4 below, an overview of the sensitivity analysis is given for all cases.

Table 3.4: Overview of results for sensitivity analysis

Case	Change of parameter	Sensitivity to:		
		Ranking	**Emission reduction**	**NPV**
1	Resistance reduction is 5% instead of 9.6%		All decrease with 3.4%	Most: B and D Least: A
2	SFOC of redesign increased by 5 g/kWh		All decrease with 1.8%	Most: B and D Least: A and E
3	WHR costs decrease by 30%	C becomes more favourable		Most: G Least: C
4	WHR can only deliver half of the required power	F becomes most favourable	All decrease with 5.7%	Most: G Least: C
5	Flettner rotor costs decrease by 30%	A becomes more favourable		Most: A Least: F
6	Flettner fuel cons reduction is 4% instead of 7%	C becomes most favourable	All decrease with 2.3%	Most: G Least: A
7	Fuel consumption reduction of variable shaft speed is 1.5% instead of 3.5%		All decrease with 1.3%	Most: B Least: A
8	Frequency converter costs decrease by 30%	E becomes more favourable		Most: A Least: F
9	Cold ironing has no associated emissions, OPEX cold ironing decreases with 50%	F becomes more favourable	All increase with 1.5%	Most: G Least: F
10	Cold ironing only 60% of estimated time	A becomes more favourable	All decrease with 0.6%	Most: G Least: F
11	Fuel cell costs decrease by 30%			NPV of concept D increases with 1 M€.
12	Battery capacity for fuel cell systems decreases by 50%			NPV of concept D increases with 1.8 M€.
13	Fuel cell efficiency increases from 50% to 60%		D increases with 1.6%	NPV of concept D increases with 700 k€
14	Battery costs are reduced by 30%			B, D and G all increase with 1150 k€
15	Battery emission reduction potential is increased to 2.0%		All increase with 1.4%	Most: G Least: B
16	150 sailing days instead of 208	F becomes most favourable	Most: E Least: F	Most: E Least: F
17	250 sailing days instead of 208	E becomes most favourable	Most: E Least: F	Most: E Least: F
18	Fuel price change from -40% to +70%			Most: G Least: A

3.3.3 Conclusions

In this subsection, general conclusions on the results of the sensitivity analysis will be drawn, based on the results presented in the previous subsection. The cases and their results with respect to the sensitivity of the concepts' performance will be discussed, and conclusions are drawn regarding which of the concepts is in general the most or least robust.

First of all, table 3.4 is inspected. In this table, it is observed that the ranking of the concepts is affected for nine cases. For two of these cases, concept F becomes the most favourable. Only for case 6, concept C becomes the most favourable. For all other cases, concept E is ranked the highest, and the other concepts have changed in ranking.

Furthermore, from table 4, it is noted that a different sensitivity with respect to the emission reduction is only observed in cases 16 and 17, in which concept E is most sensitive to both cases, and concept F is least sensitive. This will be discussed in more detail later in this subsection.

For the NPV, much more differences between the sensitivity of the concepts is observed. From table 4, it is noted that the most sensitive to the cases in terms of the NPV is concept G, which was indicated as most sensitive for 7 cases. The least sensitive is concept F, which was indicated least sensitive for 6 cases. Concept A is the least sensitive after concept F, being indicated as least sensitive 5 times. The sensitivity to the NPV is also influenced by the WACC; when the WACC is lower, future cashflows are less discounted for and impact in these future cashflows have a higher influence on the NPV at year 25 than concepts having a higher WACC. This corresponds with the results found here; concept G has the lowest WACC, concept A and F have the highest WACC.

From table 4, a general overview of the concepts' sensitivity against a variety of cases is presented and general conclusions on the sensitivity to ranking, emission reduction and NPV of the concepts relative to each other can be drawn. However, some cases will be dealt with in more detail in order to provide more information on the robustness of concepts and to study cases which are probable to occur in the future.

Next to above observations, combinations of cases which are likely to occur in the (far) future are studied. The main goal for studying this is to ascertain to what extent these combinations of cases cause a different ranking.

The first combination of cases that is studied is the combination of case 9 and an alternative of case 10, as case 9 depicts the situation where ports focus on supplying green energy to the ships at an attractive price due to subsidies. When this would be the case, it is expected that more ports will follow this example as the demand for green energy in ports would increase. This is why a combination of case 9 with an increase in the number of ports that can supply green shore side electricity of 20% is also considered as a sensitivity case.

This combined case affects concepts C, F and G as can be seen in figure 3.18 below. It is

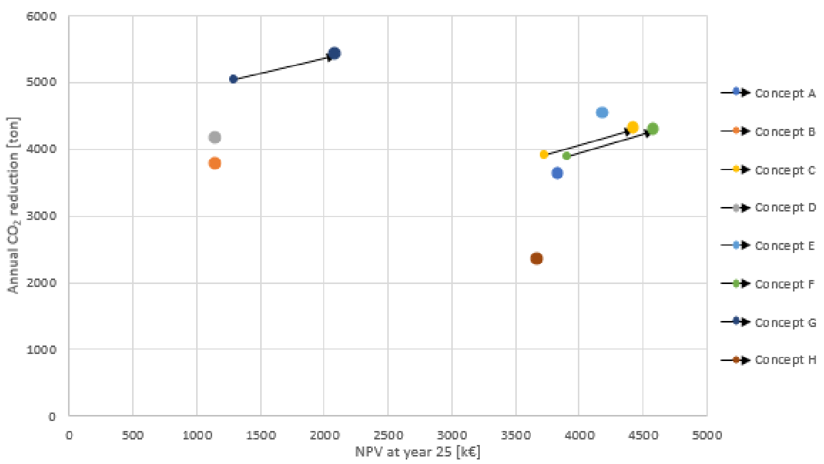

Figure 3.18: Sensitivity to concepts' performance for increased use of green port electricity

observed that concept F now becomes the most favourable in terms of NPV and the emission reduction potential is now only 1.5% less than that of concept E. Furthermore, concept C becomes more favourable. All three concepts have their emission reduction increased with 2.2% and all of these concepts' NPV are increased with 700-800 k€. Most sensitive to NPV at year 25 is concept G, least sensitive is concept F.

It can be concluded from this combined case that if cold ironing becomes more widespread and port authorities are incentivized to reduce emissions in port, concept F and concept C become more attractive.

Another interesting combination of cases is the combination of cases 11, 12 and 13. All of these are associated with fuel cell systems, and the prospect is that these will become more and more developed in the coming years. The combination suggests a cost reduction of the system with 30%, reducing the necessary battery capacity for power demand variations by 50% and an increase of the average efficiency from 50% to 60%. The effect for concept D, the only concept which employs this technology, is made visible in figure 3.19 below. It is observed that the NPV at year 25 increases with over 3 M€ and is now the most favourable in terms of NPV. Furthermore, the emission reduction is increased from 23.8% to 25.4%. As a result of the cases, the CAPEX of concept D is now lower than concept E. This would imply that concept D becomes most favourable for the combination of these cases. It is not probable that fuel cell system development achieves the situation of cases 11, 12 and 13 combined at short notice, but this could possibly occur during the operational life of the redesigned P-type.

It can be concluded that only when the above combination of cases occurs, concept D becomes the most favourable. However, it is not likely that this occurs within 5-10 years, which is why this combination of cases does not influence the present concept selection.

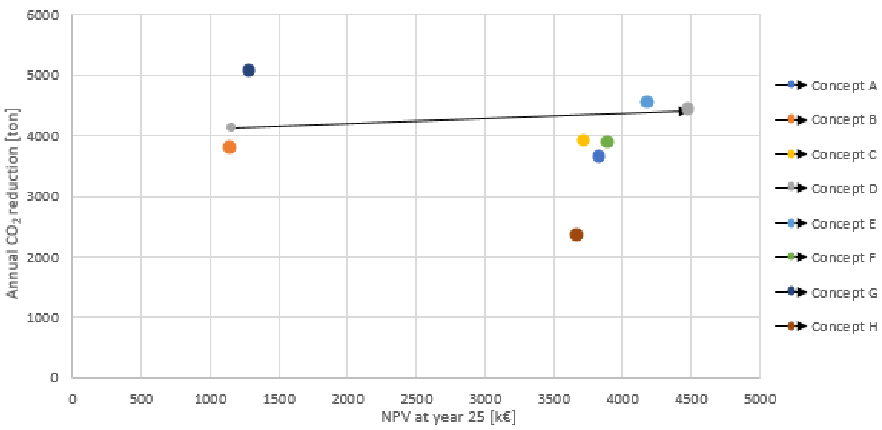

Figure 3.19: Sensitivity to concepts' performance for combination of cases 11, 12 and 13

The final combination of cases that is of interest before concluding the sensitivity analysis is the combination of sensitivity cases 14 and 15, both affecting concepts which have batteries applied. As it is known that batteries are developing quickly, it is likely that in the coming years, the costs will decrease and the usage possibilities of the batteries will increase. This is why this combination was studied as well.

The result of combining case 14 and 15 is depicted in figure 3.20. It is found that the combination of cases does not cause a change in ranking of concepts, and that the increase in NPV at year 25 of 1.7M€ is not sufficient for concepts B and D to become competitive with the other concepts. For concept G, the increase in NPV and emission reduction makes for a more favourable concept. However, the CAPEX associated with this technology for this combined case still is 6.7 M€. It is concluded that even when batteries are rapidly developing in the short term, concepts B, D and G do not become more favourable than the other concepts that were analysed.

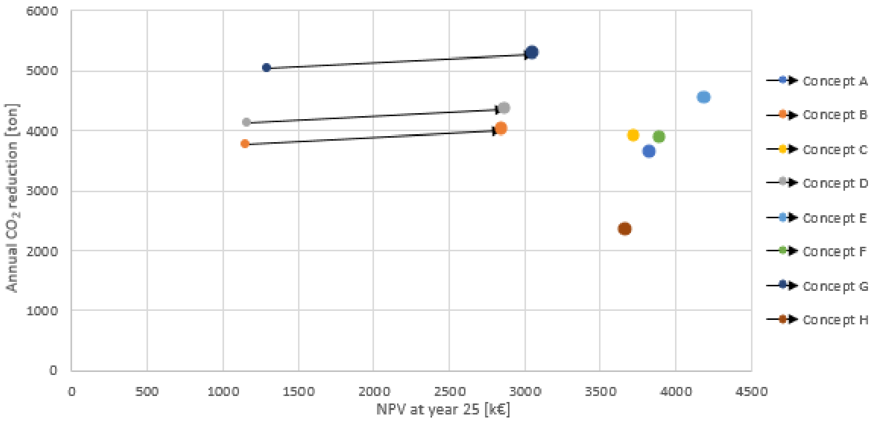

Figure 3.20: Sensitivity to concepts' performance for combination of cases 14 and 15

To conclude the sensitivity analysis, its goal is first recapitulated: 'To know how alternative assumptions influence the performance of the concepts'. Furthermore, the robustness of the concepts to probable changes in the assumptions will be used in the final concept selection. This is why a comparison between the concepts E and F, identified earlier in section 3.2 as most favourable, will be made using the results of this paragraph.

For the comparison of concepts E (Flettner rotor + WHR-system) and F (Flettner rotor + Frequency converter + Cold ironing), multiple cases of the sensitivity analysis are of interest, as these affect both or one of the concepts. These are cases 1 till 10, 16, 17 and 18. First, the cases which affect both concepts are studied to compare the sensitivity of concept E and F.

For cases 1, 5 and 6, concept F is least sensitive to changes. Concept E is however more robust to case 2. For cases 16 and 17, in which the expected productivity of the concepts is altered, concept F is clearly more robust than concept E. This is an important finding, as the heavy-lift shipping industry can be volatile; changes in vessel productivity are likely to occur as the cargo supply is not always constant. This fact highly favours a concept that is more robust to such changes. For reference, with a decrease of 50 sailing days, concept E shows a decrease of emission reduction potential by 2.4%, where this is only 0.7% for concept F. For case 18, concept E is more sensitive to fuel price changes than concept F. The above cases show that concept F is more robust than concept E to cases that influence both of the concepts.

Cases 3 and 4 (affecting the WHR-system's costs and performance) influence only concept E and cases 8, 9 and 10 influence only concept F. These cases are interesting for the comparison between concepts E and F as well, as these show how sensitive the different technologies applied are to changes.

Case 3 influences the concept choice, as concept E becomes more favourable in terms of NPV and the CAPEX reduces significantly. However, case 4 is more interesting, as the redesign and the application of a WHR-system could result in less than expected power generation. When the power generation is 300 kW instead of 400 kW, the emission reduction decreases from 26.1% to 23.2% and the NPV at year 25 decreases by 640 k€, which will make concept F most favourable. This shows that concept E is very sensitive to changes in the performance of the WHR-system.

Case 8, 9 and 10 influence the frequency converter and cold ironing technologies, which are applied to concept F. Case 8 is of very little influence on concept F, as it only decreases the NPV at year 25 by 3%. Case 9 is likely to occur and positively influences concept F. When comparing case 10 with case 4, both cases aim at a reduced performance of an applied technology. When both performances are reduced by the same percentage, say 50%, it is observed that concept F is less sensitive to this performance reduction than concept E.

Concluding on the comparison of the robustness of concept E and F, it can be stated that, in general, concept F provides a more robust concept.

3.4 Concept selection

In this paragraph, the best performing concept will be chosen from the concepts analysed in the previous paragraphs. This was already narrowed down to a choice between concept E and F. This choice will be based on the economic and emission reduction performance, but also on the results from the sensitivity analysis from the previous paragraph and some general considerations as well.

Recapitulating on paragraph 3.2, where the performance of the concepts was presented, it was concluded that concepts E and F are most favourable in terms of their emission reduction and economic performance. This is mainly due to these concepts having the highest NPV at year 25, have moderate CAPEX and a large emission reduction. Furthermore, the payback time for the additional investment associated with the application of the emission reduction technologies in these concepts is favourable. In table 3.5 below, concepts E and F are compared with each other.

Table 3.5: Comparison of performance of concepts E and F

Concepts	Fuel consumption reduction		CO_2 Emission reduction		CAPEX increase [k€]	OPEX increase [k€]	Fuel cost reduction [k€]	NPV T=25y [k€]	MAC [€/t CO_2]	Payback period [y]
	ton	%	ton	%						
E: Flettner rotor + WHR	1451	26.1%	4528	26.1%	3604	44.0	561	4200	-37.1	8-9
F: Flettner rotor + Freq. conv. + Cold ironing	1327	23.9%	3888	22.4%	2394	85.5	532	3901	-40.1	6-7

From the table, it is noted that concept E has a 3.7% higher annual emission reduction, and a 300 k€ higher NPV at year 25. If the concept selection would be solely performed based on these two performance indicators, the choice for concept E would be obvious. However, the CAPEX and payback period is also of importance for the concept selection. It is observed from the table that concept F has 1.2 M€ less CAPEX, and a 2 year less payback period. Both of these differences make for an investment with less risk when compared with concept E. This is thus an important advantage of concept F when the selection is not only based on emission reduction potential and NPV at year 25 solely. The selection of the concept thus depends on which criteria are deemed more important; the economic and emission reduction performance or the investment risk? As the concept selection is not based on this trade-off alone, this trade-off will be discussed after other relevant comparisons between concepts E and F are made.

In order to allow a complete comparison between concepts E and F, the results of the sensitivity study are included in this comparison as well. From subsection 3.3.3, it became clear that concept F is more robust to changes in the (economic) performance of the technologies. More importantly, it was shown with case 16 and 17, in which the future productivity of the redesign is varied, that concept F is far less sensitive to these changes than concept E. Thus, in terms of robustness, concept F is favoured over concept E.

Next to these 'measurable' characteristics of concepts E and F, some qualitative comments can be made with respect to the concepts which are also of importance in the concept selection:

- Concept F can also reduce emissions in port, whilst concept E only employs technologies which reduce emissions at sea. This makes for more impact, both in emission reduction and economic performance when less days are spent at sea. This was shown by case 16 in the sensitivity analysis.
- The frequency converter and machinery associated with the use of cold ironing in concept F is considered less complex than the WHR-system applied in concept E. This is important, as the complexity of the technology can be indicative of the extent to which this technology will be employed and operated correctly. If the emission reduction technology is more

simple, correct operation will be more likely and the technology will be more easily implemented by the crew of the vessel.
- The employment of cold ironing in concept F could offer a strategic marketing advantage, as port authorities and clients are pleased to report that a certain amount of emissions is reduced due to the supply of green electricity to the vessel. This creates a marketing value, as both parties benefit from presenting a green image to their (future) clients. This 'green partnership', which cold ironing enables, is absent for concept E.

All of the relevant differences between concept E and F have been discussed and all information on both of these concepts has been presented, the concept choice was made in cooperation with the supervisors from BigLift and Spliethoff. Based on their perspectives on the industry in which BigLift operates and their knowledge on past investment decisions, a conclusion on above comparison could be made.

Concept F was selected as the favourite concept. The most important reason for this is that concept F (Flettner rotor + Frequency converter + Cold ironing) provides a decent emission reduction, at a lower risk, and with simpler and more strategic technologies than concept E. The lower CAPEX and shorter payback period of concept F outweigh the higher NPV and emission reduction of concept E, as this reduces the risk associated with the investment. Furthermore, the results of the sensitivity study also show less risk; concept F is more robust to future changes than concept E. Lastly, concept F is also favoured due to the applied technologies being more simple.
By concluding this part of the study, the following sub-question of the study can now be answered:

4. *What is the best performing combination of GHG emission reduction technologies from the remaining alternatives?*
   The best performing combination of GHG emission reduction technologies is a combination of a hull redesign and engine optimization, a Flettner rotor, a frequency converter and cold ironing.
   a. *Which performance indicators are associated with this assessment?*
      The performance indicators used to assess this are the CO_2 emission reduction potential, the NPV at year 25, the additional CAPEX due to the technologies, the payback time, robustness of the concept and the MAC.
   b. *Which performance indicators have the most influence on the selection of the best alternatives?*
      These are the emission reduction potential, the robustness of the concept, the payback time and the CAPEX. It can be concluded that based on these four characteristics, concept F was favored over concept E.
   c. *How can the alternatives be assessed on these performance indicators?*
      This has been done in a relative sense; meaning that the influence the combinations of technologies has on the original P-type are accounted for to estimate the performance of a redesign. This means that the assessment is based on additional costs and reduced emissions with respect to the average operational profile of a P-type vessel. This average operational profile was conducted using the contents of section 2. This holds for all mentioned performance indicators except for the robustness of the concepts. This was assessed based on a sensitivity study using multiple scenarios in which the underlying assumptions to calculate the performance of the concept were varied.

The selection of concept F partly answers the main research question: *'Which combination of technologies can best be applied to the redesign of BigLift's P-type in order to reduce GHG emissions as much as possible within the current industry and operational profile, and how would a concept design with these technologies perform compared with the current design?'.* However, some additional research with respect to this concept will be performed in the next section, where the comparison between the currently operating P-type will be done as well.

Section 4: Analysis of selected concept

In this section, the final part of the study is described. This part will focus on providing a clear overview of the selected concept and will focus on the general effects of applying the GHG emission reduction technologies on the redesign of the P-type.

First, an overview of the selected concept will be given, where the implementation of GHG emission reduction technologies to a redesign will be qualitatively discussed.

In the second part of this section, a more accurate calculation of the emission reduction is performed based on actual operational data of a currently operated P-type. From this calculation, the performance of the concept is compared to the current P-type and the remaining part of the main question can be answered.

The third part of this section focusses on discussing the measures to reduce GHG emissions even more for the redesign. This will focus mostly on how to reach the IMO 2030 goals by applying a carbon-neutral drop-in fuel and what the effect on the operations and the operational costs are.

Finally, some general conclusions and recommendations for further development of the redesign are given.

4.1 Application of emission reduction technologies

As concept F was selected as the best performing combination of feasible GHG emission reduction technologies, this concept is studied further. Concept F consists of a combination of technologies, each of these technologies are discussed in terms of their implementation on the concept design. The most important consequences of the implementation are presented, and it will be focused on how these can be accounted for during the further design process.

4.1.1 Hull redesign

The hull redesign applied to the selected concept focuses on reducing the added resistance in waves, by means of a more slender bow form. Furthermore, as lower speeds will be sailed than with the current P-type, a resistance reduction due to the hull design being optimized for lower speed is expected. Both of these changes to the outer hull form could influence the arrangement of the vessel. For instance, when the block-coefficient is to decrease, this would mean a reduced cargo carrying capacity when not increasing the main dimensions. However, it has been shown in section 2.3 that a slight reduction of cargo carrying capacity and a slight increase of main dimensions is acceptable, as this is not expected to pose limits on the operability of the redesign. For these reasons, it is assumed that only the bow form change has a larger impact on the design. Upon inspection of the current arrangement of the bow area, it is found that a more slender bow form reduces the capacity of the forward hold, several stores, water ballast tanks and leaves less space for the bow thruster. It is expected that this can be accounted for in a later stage of designing, and otherwise the bow area needs to be extended to ensure sufficient capacity for the rooms affected. It is concluded that no severe show stoppers are expected for the application of a hull redesign optimized for less added wave resistance and optimized for lower speeds.

4.1.2 Engine optimization

An optimization of the main engine is also applied to the redesign. This optimization mainly means that the optimum engine working point is properly matched to the most occurring design load. It was already stated in section 3.1.2 that a reduction of the engine power of nearly 3 MW can be expected. As this makes for a smaller sized engine, this does not pose limits on the physical implementation of this technology. It will be expected though that this will pose limits on the speeds that can be reached, this is discussed in section 4.2.

Another important consideration is that engine optimization is for a large part a trade-off between the lowest specific fuel oil consumption and an acceptable level of local emissions such as NO_X, PM and black carbon (BC) as these emissions are influenced by the combustion conditions

(GLoMEEP, n.d.). This is to be studied in a later stage, as possibly additional technologies need to be applied to comply with regulations for local emissions.

4.1.3 Frequency converter

Applying a frequency converter behind the shaft generator is not expected to have a large influence on the ship's design, as judged from supplier data: the required frequency converter dimensions are expected to be less than 2x1x2.2m (LxBxH). This can easily be placed in the engine room, especially since additional space to place this equipment will become available with the smaller sized engine. The physical implementation of a frequency converter to the redesign is not expected to have large consequences for the arrangement of the redesign.

4.1.4 Cold ironing

The physical application of cold ironing does not influence the arrangement of the redesign. This is because during the design stage, the additional machinery and upgraded switchboards can already be accounted for and no large increase in equipment dimensions is expected. The only real influence is the connection point at the ship side or on deck to connect to the shore cable, however, sufficient freedom in the placement of this connection point is available and this also does not pose consequences for the general arrangement.

The only real concern with the application of cold ironing on the redesign is whether the shore-supply is able to handle the large power fluctuations when loading or unloading is performed. It has been shown in section 2.2.6 that power peaks of 1200 kW can occur when two cranes are operated simultaneously, while the average power demand is mostly below 500 kW. It is expected that some shore connections cannot handle these power fluctuations, and the auxiliary generator sets on board the ship need to be activated to account for these power peak demands. In order to avoid an overoptimistic estimate of the performance of this technology, this is accounted for in the comparison with the current P-type in section 4.2.

4.1.5 Flettner rotor

The application of a Flettner rotor to the redesign of the P-type is expected to have the largest consequences for the ship design. The most important consequences will be dealt with in this subsection.

First of all, the Flettner rotor is to be placed at the bow, which limits the visibility from the bridge. To ensure this is not a show stopper for the redesign, the applicable regulations with respect to bridge visibility was checked. From the regulations in SOLAS Chapter V (IMO, 1980) on the Safety of Navigation, regulation 22 section 1.2 provides clarity on this. In this section, the following is stated: "*No blind sector caused by cargo, cargo gear or other obstructions outside of the wheelhouse forward of the beam which obstructs the view of the sea surface as seen from the conning position, shall exceed 10°. The total arc of blind sectors shall not exceed 20°. The clear sectors between blind sectors shall be at least 5°. However, in the view described in .1 (forward of the bow to 10° on either side), each individual blind sector shall not exceed 5°;*" As the Flettner rotor is placed at the bow on the centreline of the vessel, the blind sector it causes may not exceed 5°. As the distance from the bridge to the centre of the Flettner rotor is 120 meter, it can be calculated what the maximum rotor diameter can be in order to comply with this regulation. This results in a maximum rotor diameter of 10.5 m. None of the commercially available Flettner rotors have a diameter near this value. Bridge visibility obstruction is thus not an obstacle for the application of a Flettner rotor.

Secondly, the height of the Flettner rotor can be a problem in terms of operability. The current air draft of the P-type is 37.7 m for a draft of 8.1 m. Since the Flettner rotor is placed at the bow on top of the wave breaker, the maximum air draft is increased depending on the Flettner rotor height. The limiting height of navigational routes sailed at by the P-type is 57.9 m, which is due to the bridge over the Panama Canal. This makes for a maximum rotor height of 43.7 m, when the rotor is not designed to be tiltable. This can easily be maintained, as the maximum height of most commercially available rotors is 30 m.

As the limits to the dimensions of the Flettner rotor are now known, the dimensions of the applied rotor can be selected. From supplier data (Norsepower, 2018) it was found that the largest rotor dimensions also cause the largest fuel consumption reduction. This is why a rotor of 30 m high and a diameter of 5 m was selected in the present description. The weight of this rotor is 49 tons and the placement of the rotor is demonstrated in figure 4.1. For this position of the rotor, the forward crane has an impact on the performance of the rotor, as well as cargo that is carried on top of the forward hold hatch covers. This is because the size of these items make for a range of wind directions where shielding of the wind to the Flettner rotor is present, which influences the flow of wind to the Flettner rotor and deteriorates its performance. However, from the top view in figure 4.1, it is observed that the wind angles for which this occurs are between 145° and 180°. For these apparent wind angles, the Flettner rotor performance is already severely reduced. This is why it is expected that this effect does not pose practical limits on the applicability of the Flettner rotor.

The last physical limit the Flettner rotor poses at the indicated position is the freedom in movement of the forward crane. In a redesign, this crane could either be relocated to a place where the crane reach does not intersect with the Flettner rotor, or cargoes (un)loading with the forward crane is to be restricted to certain movements to avoid collision with the Flettner rotor.

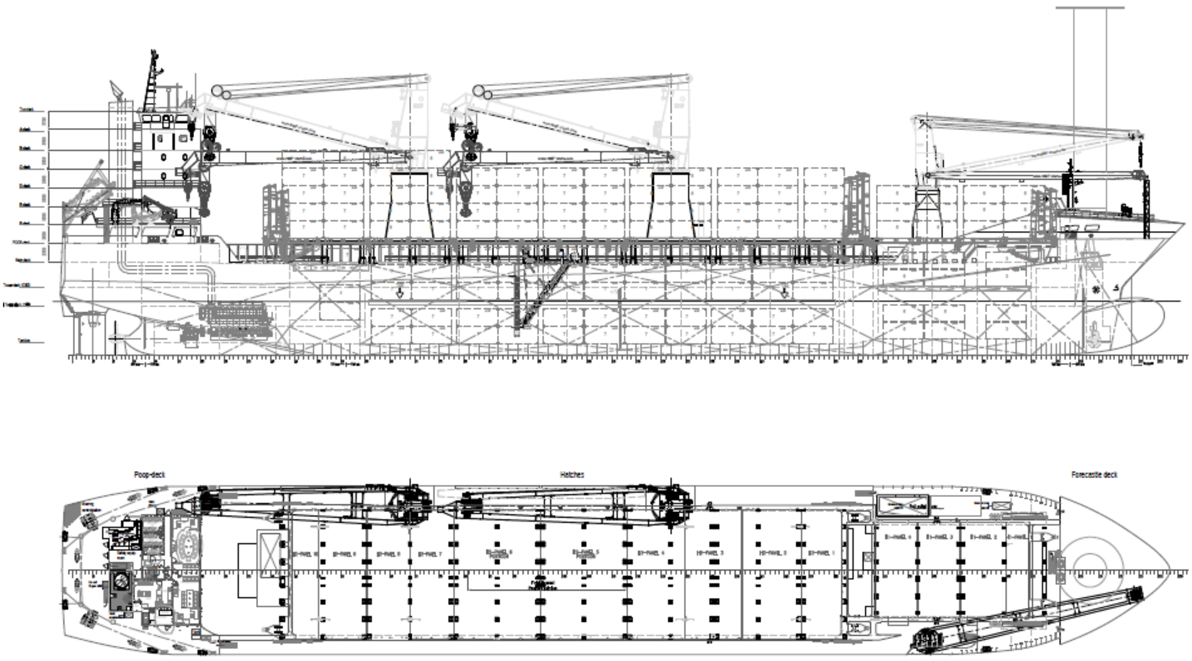

Figure 4.1: Concept general arrangement of the redesign with Flettner rotor position

Next to the physical limits the Flettner rotor poses, the application of the Flettner rotor influences the stability of the redesign as well. The most important considerations will be dealt with in the following.

The weight of the rotor being placed at a high vertical position impacts the stability of the redesign. The consequences for this can be shown to be little; from the stability information on the current P-type, it was found that for ballast conditions, the VCG is 8.74m for a displacement of 23415 tons. When assumed that the VCG of the Flettner rotor is at one-third of its height, the increase in total VCG of the vessel in this condition is only 5 cm. For loaded conditions, this is even less. The 5 cm increase does not pose limits on the stability requirements and can be accounted for during the design process with a possible slight increase of ballast water capacity.

Another consequence for the stability stems from the larger lateral wind area, which influences the stability requirements. From the code on intact stability (IMO, 2008), one of the stability requirements is the result of wind acting on the side of the ship, for which the vessel's lateral area is one of the parameters used in this calculation. This requirement is also known as the weather criterion. The increase in lateral area is roughly 150 m^2, making for a lateral area increase of 4% when not loaded with special cargo, and 3.4% when loaded with cargo with a large wind area. This small percentual increase is found not to be of large influence, as the weather criterion is currently very easily met, even when loaded with special cargo. The influence on the steady heel angle due to side wind is accounted for in the performance comparison in the next paragraph.

It can be concluded that the application of a Flettner rotor at the bow of the redesign does not influence the stability of the redesign in such a way, that drastic changes to the design or ballast water configuration are needed to account for this.

4.2 Performance compared to current P-type

In this part, the comparison with the current P-type is made, based on operational data. First, the underlying assumptions and methodology used in the comparison are explained. Subsequently, the results for the concept and the current P-type are compared, and remarks on the specific performance of the technologies will be made.

4.2.1 Methodology

The comparison of the selected concept to the currently operated P-type is the final part of the study needed to fully answer the main question. This comparison needs to be accurate enough to generate reliable results, but also simple enough to provide insight in the way the results are obtained and in the individual performance of the concepts. The performance calculations done in section 3 were based on yearly averages of operational data for multiple P-types. Furthermore, based on these averages, some assumptions have been made which may have been either too pessimistic or optimistic. In order to provide more accurate results for the selected concept, a calculation which involves more parameters influencing the concept's expected performance needs to be carried out.

To meet these requirements, it was chosen to base this comparison on real-time operational data for one of the P-type vessels. These are the data that have been described in section 2.1. For the performance comparison, the on-board data measured for each 5 minutes is used, as well as the voyage data which consists of the data on the voyages and ports called at. The main reason for using this data is that it is readily available and can offer a much more detailed calculation of the fuel consumption reduction due to the applied technologies. In this data, the operational environment is included as this also influences the fuel consumption of the vessel. Thus using the measured operational data in the comparison will provide better insight in the influence of the operational environment on the performance of the GHG emission reduction technologies applied to the concept. Especially the performance of the Flettner rotor can be estimated more accurately by using the measured data.

In the following, the model that was made to assess the performance of the concept in terms of fuel consumption reduction is described for all applied technologies. A distinction is made between the fuel consumption reduction while sailing and while in port, as only the application of cold ironing reduces the fuel consumption while in port. How the latter is accounted for by the model will be dealt with at the end of this subsection. First, the model used to estimate the reduced fuel consumption while sailing will be discussed.

Hull redesign

In order to account for the resistance reduction by the hull redesign, the effective towing power of the current P-type ($P_{E,old}$) needs to be known, as this relates most directly to the hull resistance. With the use of the formulas described in the book of Klein Woud and Stapersma (2002), the $P_{B,old}$ can be related to $P_{E,old}$ using the transmission and propulsive efficiencies (η_{TRM} and $\eta_{D,old}$). The $P_{B,old}$ can be estimated from the measured fuel consumption rate ($\dot{m}_{f,old}$) and the specific fuel oil consumption for various engine loads, as has been described under section 2.2.5: 'Propulsion'. The value for η_{TRM} has been estimated at 0.95 due to the use of a gearbox. The value used for $\eta_{D,old}$ is 0.625, this has been obtained from results from model test for the P-type corrected to full scale. This value has been assumed to be constant for all ship speeds and propeller loads, while in fact this varies for these parameters. With the above described method, $P_{E,old}$ can be calculated for each data point.

The assumptions made with respect to the resistance reduction due to the hull redesign have previously been described in section 3.1.2. These were based on the expected resistance reduction due to a combination of two effects. The first origin for resistance reduction is that due to the current P-type hull being designed for higher speeds, the resistance at the speeds it now operates at is higher than if the hull was designed to originally sail at these speeds. The second effect is due to the application of a more slender bow form, which reduces the added resistance in waves. Both effects make for an overall reduced resistance and are dependent on the encountered wave conditions and the speed of the vessel.

It has been chosen not to increase the level of detail of the resistance reduction calculation, as this would make for a much more complex model with a lot more associated assumptions. It is not expected that this would increase the significance of the results accordingly within the available time. This is why the resistance reduction due to the hull redesign has been based on the assumptions listed in section 3.1.2. This means that based on the actual speed, a resistance reduction associated with this speed will be accounted for, and lower speeds will have a higher resistance reduction. $P_{E,new}$ is thus found by multiplying $P_{E,old}$ with (100 – x) where x is the speed-dependent resistance reduction percentage.

As the effective power for propulsion for the redesign can now be estimated for each operational data point, the other fuel consumption-reducing technologies can be accounted for as well. These are the Flettner rotor, the ability to sail at variable propeller speeds and optimization of the main engine. First, the method used to predict the performance of the Flettner rotor is described.

Flettner rotor

In order to increase the accuracy of the fuel consumption reduction estimation, it has been chosen to base the estimation of the performance of the Flettner rotor on the actual weather conditions encountered, as these are available. However, in order for the model not to become too complex, some assumptions were done with respect to the added resistance from a drift angle, rudder action and heeling angle due to application of the Flettner rotor. In search of a methodology that matches these requirements, the study by Tillig and Ringsberg (2020) was found. In their study on wind-assisted ship propulsion with Flettner rotors, they extended an already existing performance prediction model with a module for the Flettner rotor. They have based their calculations on real-scale experimental data and it was proven that their predictions correspond quite well with the real-scale data. Therefore their method has been applied in the comparison of the selected concept with the current P-type.

With their method, the lift and drag coefficients of a Flettner rotor are expressed as polynomials depending on the spin ratio. The spin ratio is the ratio between the apparent wind speed and the rotor's tangential speed at the surface (Tillig and Ringsberg, 2020). With these coefficients, the lift and drag force induced by the Flettner rotor can be calculated from the rotor frontal area (D x h), the apparent wind speed, the apparent wind angle and the spin ratio. Furthermore, the power demand for the rotation of the rotor can also be expressed using the spin ratio and the apparent wind speed. This means that the net power delivered by the rotor can be calculated for each data point once the spin ratio, apparent wind angle, apparent wind speed, ship speed and rotor dimensions are known. It must be noted that the coefficients on which this calculation is based are only valid for Flettner rotors having an aspect ratio (h/D) of 6 and an endplate disc diameter twice the rotor's diameter (Tillig and Ringsberg, 2020). The rotor to be applied complies with these requirements.

The apparent wind speed and angle can be calculated as the wind speed and direction are included in the measured data, as well as the ship speed and course. This means the net power produced by the Flettner rotor can be calculated as a function of the spin ratio with the measured data. In this, the added hull resistance due to application of the Flettner rotor is not yet taken into account. This added resistance originates from the vessel sailing at a small drift angle, a small heeling angle and due to the added resistance from the yaw moment compensation by the rudder. In order to not fully neglect this, but still make for a simple model, a factor on the propulsive power delivered by the Flettner rotor has been applied to account for this. This factor was derived from multiple studies and is conservatively estimated to be a 5% reduction of the propulsive power of the Flettner rotor (Berendschot, 2019; van der Kolk, 2020; van der Kolk et al., 2019; Tillig and Ringsberg, 2020). By applying this factor, it is avoided that the performance of the Flettner rotor is estimated too optimistically. Taking this factor and the power consumption of the Flettner rotor into account, the net propulsive contribution of the Flettner rotor ($P_{net,FR}$) can be calculated for a selected spin ratio of the rotor.

As the spin ratio also influences the power demand of the Flettner rotor, an optimum value for the spin ratio exists. This value is found by optimizing the spin ratio for a maximum value of $P_{net,FR}$. In this optimization, a maximum rotational speed of the Flettner rotor of 180 rpm has been taken into account (Norsepower, 2018). Furthermore, to account for severe wind conditions, a maximum heeling angle of 5 degrees was added as a constraint to this optimization. This angle has been conservatively selected to ensure that all cargoes can be transported and that no changes to the current standards of rigging are to be implemented. The heeling angle can be estimated for each operational data point with the use of stability data from the current P-type and the side force calculated using the formulas provided in the study of Tillig and Ringsberg (2020). Using these constraints, the physical limitations to the application of the Flettner rotor are included in the optimization of the spin ratio.

When the wind conditions do not make for a positive $P_{net,FR}$, the model 'shuts down' the Flettner rotor and takes the added wind resistance due to the Flettner rotor into account. The added wind resistance is estimated using the drag coefficient of a cylinder and follows a standard drag calculation.

The resulting $P_{net,FR}$ is subtracted from $P_{E,new}$ and results in the new effective towing power with the Flettner rotor contribution ($P_{E,FR}$). Now that the model can take the added thrust by the Flettner rotor into account, the methodology used in the model to quantify the effect of sailing at a variable propeller speed can be described.

Variable propeller speed

The fuel consumption reduction for variable propeller speed originates from the ability to vary both the pitch and propeller speed. This means that for each working point of the propeller, the most optimal combination of propeller pitch and speed can be sailed at, which makes for an increase in propulsive efficiency. In the previous performance estimation in section 3, rather blunt assumptions were made with respect to the propulsive efficiency gain. In this model, a more accurate estimation of the performance is favoured since more insight on the actual operating conditions is present using the operational data.

It is known that the gains for variable propeller frequency are highest when the redesign operates in off-design conditions. These can be off-design for several reasons; the speed is much less than the design speed, the propeller load is very low or the encountered conditions cause a highly loaded propeller at lower ship speeds. As it is yet unknown how the new assumptions influence the design point of the propeller, the effective power taking into account the Flettner rotor against ship speeds must be known. From this information, it can be made more clear when the propeller is in off-design conditions and to which extent. Therefore the assumptions with respect to a variable propeller frequency have been made during the actual performance comparison, as the intermediate results need to be known for this. When plotting $P_{E,FR}$ against ship speed for all operational data points, figure 4.2 is obtained. The effect of the engine limitation (and thus slow steaming) is not taken into account in this figure.

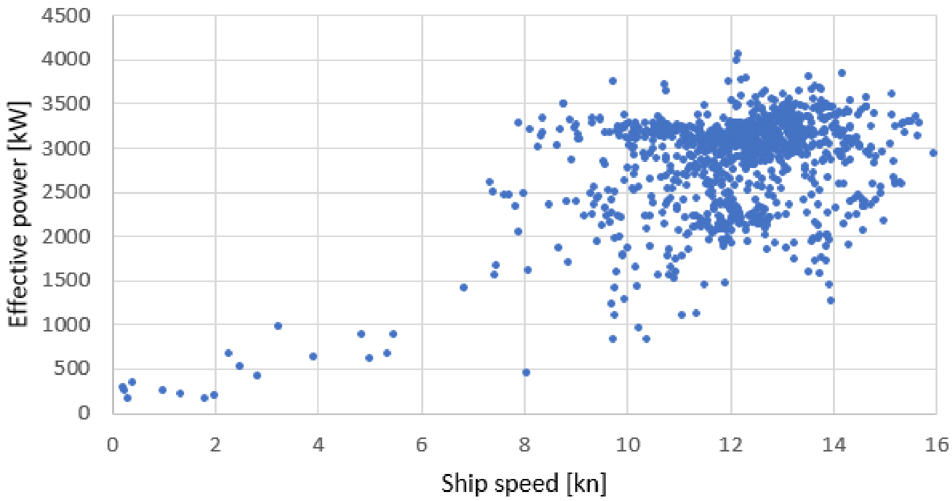

Figure 4.2: Effective power for redesign against ship speed

It is observed from this figure that most operational data can be found between ship speeds of 11.5 and 13.5 kn and associated effective powers between 2700 kW and 3500 kW. These ranges have been analysed and it was found that over 50% of the operational data points while sailing are within these ranges. When speeds lower than 11.5 kn are sailed or when the effective power is lower than 2700 kW, it is assumed that the propeller works in off-design conditions, and an efficiency gain may be present by being able to vary the propeller pitch and speed. The extent of this efficiency gain is assumed to be proportional with the extent of the off-design condition. This translates to the model accounting for a small gain in the propulsive efficiency when speeds just lower than 11.5 kn are sailed and a higher propulsive efficiency increase when even lower speeds are sailed at. The same holds for off-design conditions in terms of effective power; the largest propulsive efficiency gains are applied to the lowest effective powers. This means that the new propulsive efficiency ($\eta_{D,new}$) used to calculate the new engine brake power ($P_{B,new}$) is dependent on the ship speed and effective power. The used values for $\eta_{D,new}$ range from 0.625 to 0.679. As a more accurate estimation of the propulsive efficiency gain due to the ability to sail at a variable propeller frequency can now be made, the engine power required for the redesign can now be calculated.

Engine optimization

The engine optimization needs to make for the lowest overall fuel consumption by properly matching the power need for the redesign to a new engine power. It is assumed that the engine characteristic with respect to the specific fuel consumption follows the same trend as for the currently installed engine, similar to what has been explained in section 3.1.2. This means that in order to produce the required power most efficiently for all operational conditions, the most frequently occurring required brake power range needs to correspond to 85% of the maximum output power of the engine. This is because at this power level, the main engine produces power most efficiently.

As it can be estimated what the required engine brake power is for each operational data point, these results from the studied operational data were used to calculate the required maximum power of the engine accordingly. It was found that engine brake powers between 5500 and 5550 are most frequently occurring. Using these assumptions leads to a new $P_{B,max}$ of 6.5 MW. When discussing the results of the comparison, it will be shown that this indeed makes for the most optimum engine performance.

Finally, using the specific fuel consumption corresponding to the engine load, the fuel consumption rate for the redesign ($\dot{m}_{f,new}$) can be calculated. The values for the specific fuel consumption used range from 180-213 g/kWh.

As the maximum power provided by the engine would now be 3.3 MW lower than with the current P-type, some sailing speeds can now not be met. This means that whenever the estimated $P_{B,new}$ exceeds 6.6 MW, the speed must be lowered to comply with the engine limit. This influences the transport work, as less distance can be covered in that case compared to the current P-type. As it is an important requirement that the redesign does not pose limits on the operability compared to the current design, the speed loss is made up for by increasing the speed in the same voyage where this is possible. This way, the arrival time at a port is not influenced and the total distance sailed in a year remains the same. This will be discussed in section 4.2.2 where the results of the comparison are presented.

Model applied for sailing

An overview of the model used in the comparison is given in figure 4.3. This model has been made in Excel and uses the measured operational data to calculate the new fuel consumption rate.

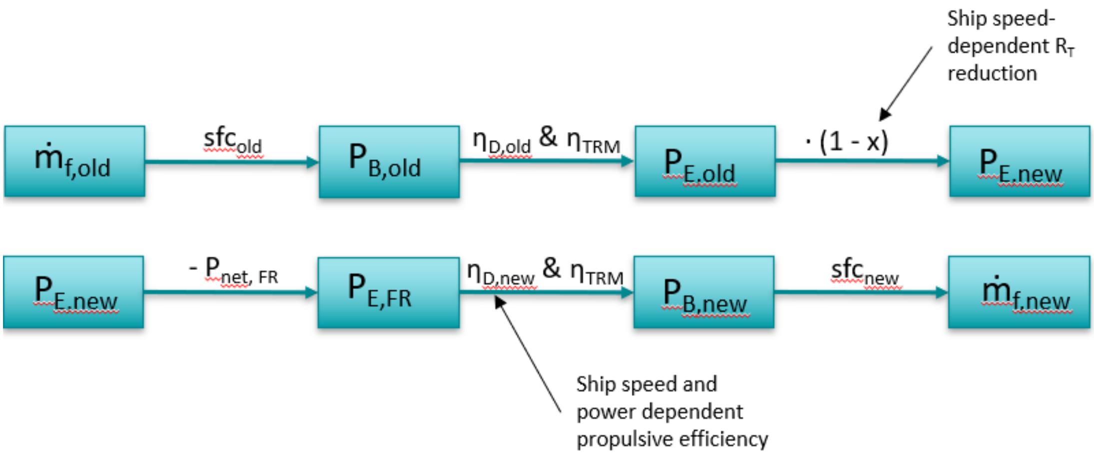

Figure 4.3: Overview of the used model in Excel to compare the current P-type with the chosen concept during sailing

The measured dataset has a data point for every 5 minutes while sailing, this means that the above described model is to be applied to over 50.000 data points for an average year of sailing. This includes the optimisation of the spin ratio of the Flettner rotor to be carried out for all these data points. As this would be highly time consuming, it has been chosen to resize these datapoints to 3-hour averages. This limits the accuracy of the model, however the data resolution is still sufficient to capture the effects of short-term phenomena such as storms.

Cold ironing

For the performance of cold ironing, the same assumptions to estimate the expected performance were made as were discussed in section 3.1.6. This means that for each port visited during the operational period studied, the question was raised whether this port would be able to provide shore-side electricity in 2025. When this is expected, the fuel consumption from the auxiliary generator sets in port is assumed to be only 25% of the original value, meaning that the other 75% of energy consumed is delivered by electricity from shore. This is assumed due to the power fluctuations while loading or unloading, which may require a generator set to be active. In order to account for the situation where the port is able to deliver shore-side electricity, but not at the berths where the redesign loads or unloads the cargo, 1 out of every 4 ports that is expected to provide shore-side electricity is not taken into account.

As a more accurate estimation of the fuel consumption reduction due to the applied technologies can now be made based on operational data, the comparison with the current P-type can now be made.

4.2.2 Results

In this subsection, the results for the comparison of the selected concept with the current P-type will be presented. The comparison has been executed based on a year of operational data of a currently operated P-type. The only two currently operated P-type vessels for which this data is available for the length of a year are the Pietersgracht and the Prinsengracht. Upon inspection of the activity of both vessels during a year, it was concluded that the voyages of the Pietersgracht represent the typical operational profile of a P-type vessel better than the Prinsengracht. This is because the Prinsengracht sailed on a fixed route for the last 6 months in which data was measured, which is less representative of the worldwide operability of these vessels.

The comparison is based on the voyages of the Pietersgracht from 19 august 2019 to 19 august 2020. The main particulars of interest for the comparison are listed in table 4.1. The route sailed in this period is depicted in figure 4.4.

Table 4.1: Important data of Pietersgracht for the inspected operational period

Number of voyages	31
Days sailing	260
Days in port	105
Fuel consumption sailing [t]	5678
Fuel consumption in port [t]	322
Total CO_2 emissions [t]	18743

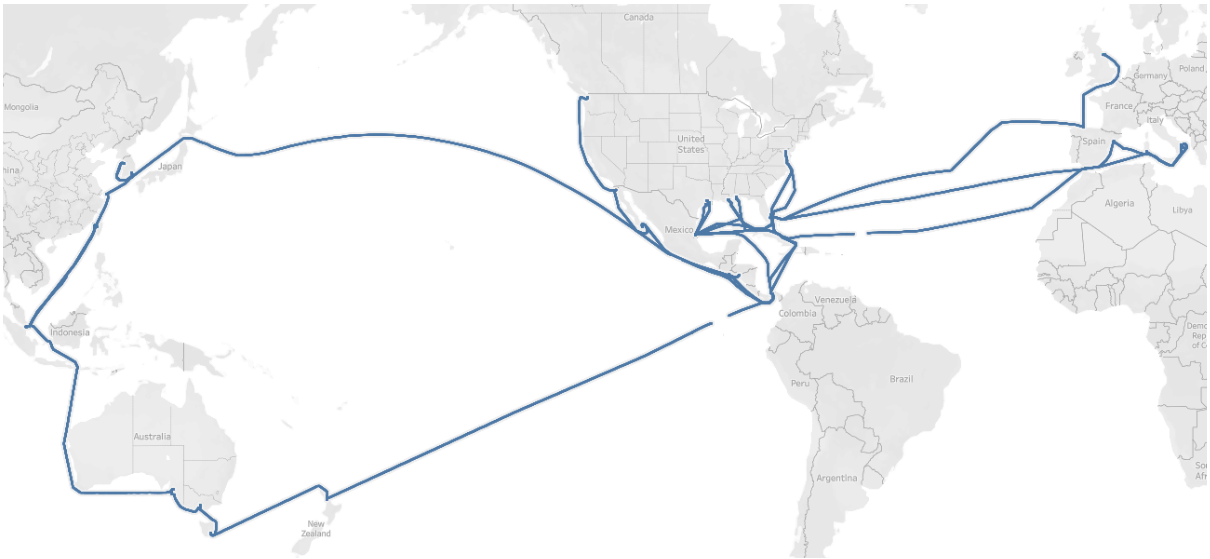

Figure 4.4: Route sailed by Pietersgracht during the inspected operational period

As was stated, the measured data has been averaged in intervals of 3 hours to limit the amount of data points for which the fuel consumption of the redesign is to be calculated. This results in 1840 data points for which the 3-hour average ship speed, wind conditions and fuel consumption rate is known. With these parameters, the fuel consumption of the redesign is calculated for all of these data points.

The resulting fuel consumption while sailing for the redesign is now 4537 ton, a reduction of 20.2%. The minimum fuel consumption reduction on a voyage is 14.9%, and the maximum reduction was calculated to be 31.1%. Each technology has a different contribution to the overall fuel consumption reduction while sailing. The calculation gives insight in the average contributions of the technologies to the overall fuel consumption reduction. The results are presented in the pie chart in figure 4.5. In this, it is observed that the hull redesign and the application of the Flettner rotor have the largest contributions to the fuel consumption reduction. Furthermore, it is observed that for these two technologies, the assumptions done in section 3.1 comply with the results here. This indicates that the year of operational data of the Pietersgracht represents the average values used in section 3.1 quite well.

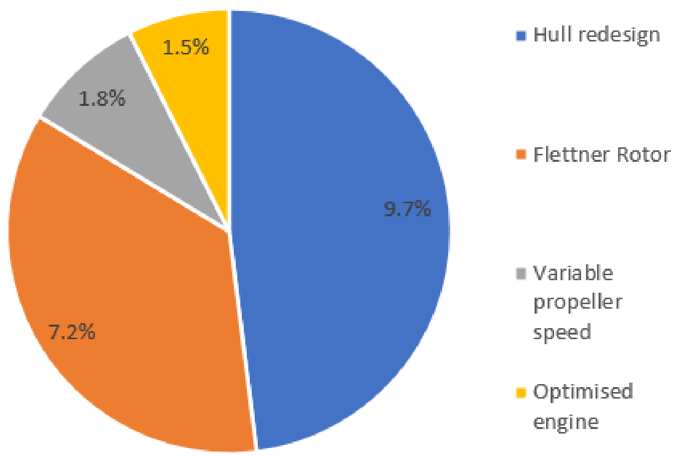

Figure 4.5: Contribution of each technology to the total fuel consumption reduction

Some general remarks on the performance of the different technologies during the observed year of sailing will now be made.

For the Flettner rotor, the performance is investigated for different voyages and for all sailing operational data points. From this, the accuracy of the applied Flettner rotor model is checked. The first noticeable performance of the Flettner rotor is for a voyage along the east coast of the United States, for which a 31.1% reduction of fuel consumption was found. The 3-hour average data for this voyage was inspected and it is due to the Flettner rotor that such a major reduction of fuel consumption occurs. In figure 4.6, this voyage has been set out. The apparent wind speed and angle are on the left vertical axis, and the contribution of $P_{net,\ FR}$ to $P_{E,new}$ is on the left vertical axis. It is observed from this figure, that the Flettner model behaves as is expected. For the whole voyage, the speed was constant so the contribution of $P_{net,\ FR}$ to $P_{E,new}$ is only influenced by $P_{net,\ FR}$. As the apparent wind speed was fairly constant, it can be observed that for an apparent wind angle range between 75° and 105°, the contribution of the Flettner rotor is the largest. This is as expected and explains why for this voyage, a much higher fuel consumption reduction than average was found.

Next to this, the contribution of the Flettner rotor to $P_{E,new}$ is grouped for all 1840 data points, and set out against the apparent wind angle and apparent wind speed. This is depicted in figure 4.7, in which the contribution of $P_{net,\ FR}$ to $P_{E,new}$ is grouped in different colours as seen in the legend. From this figure, the same trend is observed; for apparent wind angles around 90° the highest contributions to the effective power are found for the highest wind speeds. The high contributing data points for apparent wind angles over 120° can be ascribed to the situations where the ship speed is low, and the true wind angle is from behind the vessel. This makes that the apparent wind angle is in this range and due to the low ship speed, a small $P_{net,\ FR}$ can contribute for a large part to $P_{E,new}$, as for low ship speeds, the effective power is low as well. As all results for the

Flettner rotor model can be explained and are in good agreements with the studied literature, this shows correctness of the implementation of the Flettner rotor model.

The optimization of the spin ratio for the highest Flettner rotor contribution had two important constraints; the rpm-limit is not exceeded and the heeling angle due to the Flettner rotor lift and drag should not exceed 5°. The optimization is only limited for a single data point by these constraints, this is the rpm limit. With regard to the heeling angle, the largest heeling angle occurred due to the Flettner rotor is 3.1°.

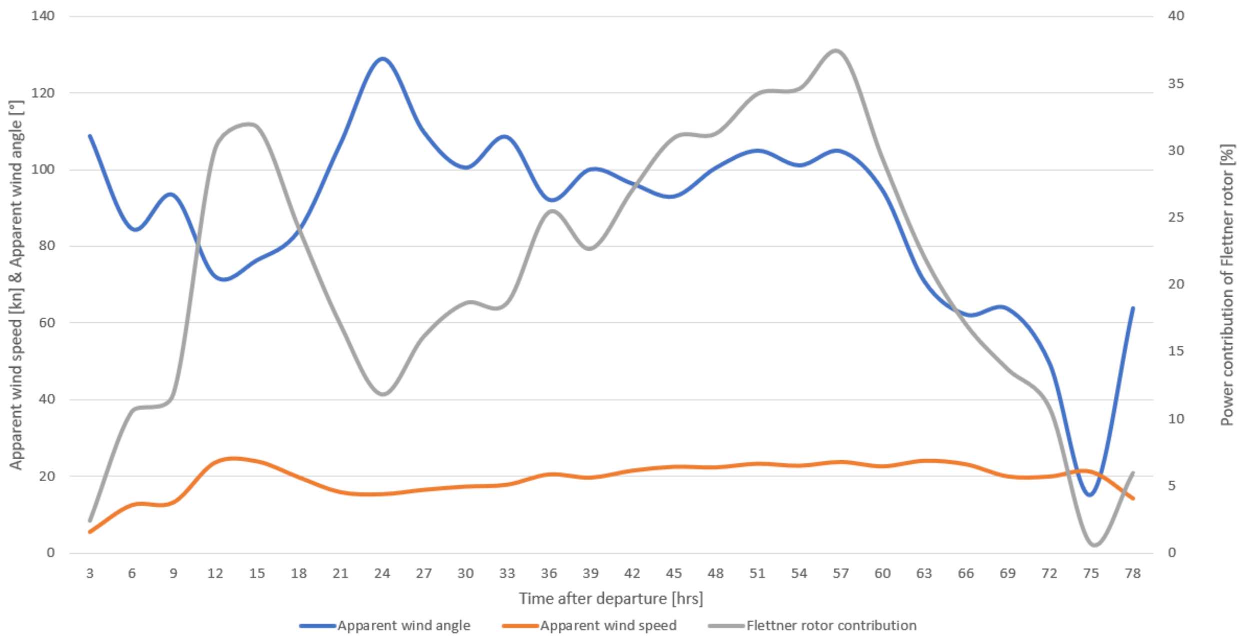

Figure 4.6: Flettner rotor contribution and apparent wind conditions over time for highest contributing voyage

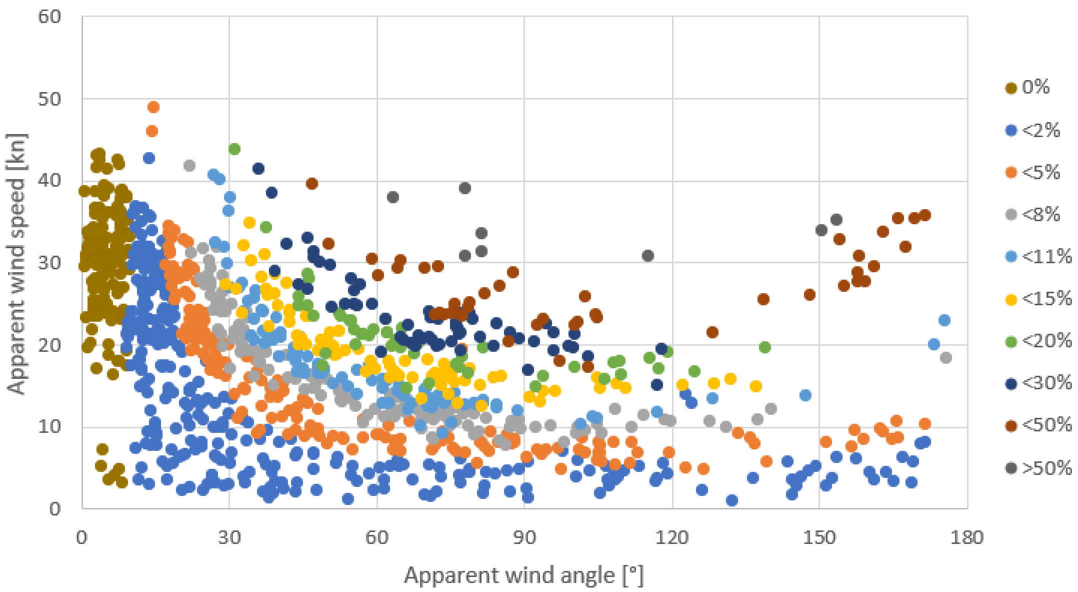

Figure 4.7: Flettner rotor contribution for all data points for different encountered apparent wind conditions

As the Flettner rotor contribution makes for a lowered $P_{E,new}$, the redesign sails more in off-design conditions than the currently operated P-type. This effect is observed in figure 4.8, where P_E for the Pietersgracht and the redesign are plotted against the ship speed. It is observed that the data is more distributed in the graph due to the resistance reduction and Flettner rotor influence. This influences the amount of data points that are classified as off-design.

For the redesign, 52.4% of all data is considered as being off-design. This is either due to a low speed or due to a low effective power. For both these cases, a different working point of the propeller with a different propeller pitch and speed is assumed to positively impact the propulsive efficiency. Taking the time average for all operational data points, a 1.9% increase in propulsive efficiency is applied to the redesign for all operational data points. When only taking into account the off-design data points, an average efficiency increase of 4.0% is applied. This is much less than assumed in section 3.1.5.

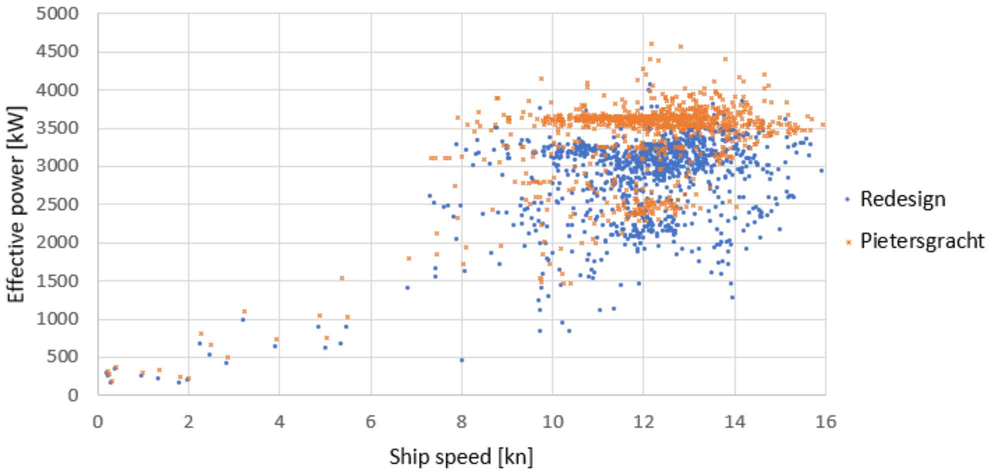

Figure 4.8: Effective power for different ship speeds for the redesign and the Pietersgracht for all sailing data points

The propulsive efficiency increase influences the required engine brake power and makes for a wider distribution of engine loads. This is observed in figure 4.9, where the engine load for the Pietersgracht and the redesign over the studied operational data is shown. In this figure, it is first noted that the engine optimization has been correctly executed with respect to the assumptions done; the most occurring engine loads are between 80% and 90%. When specified further, it was found that 11.5% of all data points were between engine loads of 84% to 86%. Furthermore, when comparing the engine load distribution of the Pietersgracht with the redesign, it is observed that the redesign has a wider distribution of engine loads than the Pietersgracht. This is due to the applied technologies which all make for a reduction of $P_{B,new}$ which varies for each data point. This also explains why the peak in the occurring main engine load of the redesign is lower than that of the Pietersgracht.

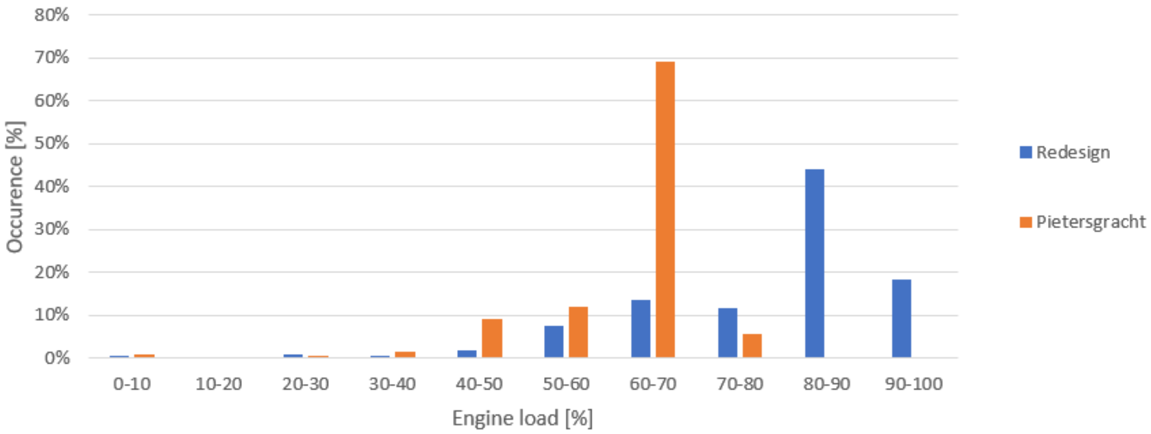

Figure 4.9: Main engine load distribution for Pietersgracht and redesign

Furthermore, it can be noted that the occurrence of engine loads higher than 90% for the redesign is quite large as well. This has to do with the limitation of the engine power at 6.5 MW and due to the reduced speed when the engine limitation has been reached. The speed needed to be reduced for

1.7% of the data points, and this could be compensated by increasing the speed in the same voyage at other data points. The amount of transport work was thus not influenced due to the engine limitations, so the operability of the P-type is not impaired.

Furthermore, upon inspecting the data for which the speed needed to be reduced, it was concluded that the engine limitation was not reached due to an unachievable sailing speed, but due to the encountered environment. This was mainly due to strong headwinds combined with a higher sea state. The average speeds for which the engine limitation was reached is 13.2 kn, and from figure 4.8, it is noted that ship speeds near 16 kn are still reached for the redesign. These speeds can only be reached when either the encountered operational environment is calm, or the Flettner rotor contribution is large.

All in all, from the model which compares a current P-type with the redesign using year's operational data, it is concluded that the redesign can achieve a 20.2% reduction of fuel consumption while sailing. Next to this, it was concluded that the model works as intended and the results are in compliance with the literature study and previously made assumptions with respect to the performance of the emission reduction technologies.

When in port, the application of cold ironing reduces the fuel consumed by the auxiliary generator sets. From the data on the ports called at by the Pietersgracht during the operational period under investigation, it was concluded that 19 out of the 32 ports are expected to deliver shore side-electricity by 2025. In order to account for the port being able to deliver electricity, but not at the berth used by the redesign, this number is reduced to 15 ports. In these 15 ports, 180 ton of MGO is consumed. Following the assumptions done in the previous subsection, the fuel consumption reduction due to cold ironing is 135 ton. The energy equivalent of this fuel is to be delivered by shore-side electricity now with associated specific CO_2 emissions of 475 g/kWh. This results in a reduction of the fuel consumption and carbon emissions in port of 41.8%.

The comparison between the redesign and the Pietersgracht for the whole year of operational data has been executed. The results of this comparison can be found in table 4.2 below, in which all values are in tons. The most important results for the comparison are the total fuel consumption reduction of 21.7% and the total CO_2 emission reduction of 20.6%. The differences of these values with the values presented in table 3.2 can be explained by the more accurate estimation of the performance of the emission reduction technologies and the comparison now being based on actual operational data instead of yearly averages for the whole fleet of P-type vessels.

Table 4.2: Overview of fuel consumption and emissions in tons for the executed comparison between the redesign and the Pietersgracht

	Pietersgracht	Redesign	Reduction	
			ton	%
Fuel consumed sailing	5678	4537	1131	20.2%
Fuel consumed in port	322	188	135	41.8%
Total fuel consumption	6000	4696	1266	21.7%
CO_2 emissions	18743	14879	3865	20.6%

As the emission reduction of the redesign is now known, the influence on the costs is recalculated. This is because the annual costs saved by a reduction of the fuel consumption differs from the estimation in subsection 3.2.5. The new annual fuel cost reduction is 519 k€, based on the results in table 4.2. The CAPEX assumptions were altered as well, for now that the dimensions of the Flettner rotor are known, more detailed information on the price of the rotor could be found. With this, the estimated total CAPEX of the redesign is now 1.96 M€. The NPV calculation and the payback period is influenced by these changes as well. The new results are presented in figure 4.10. It is observed that the NPV of the redesign is now estimated at 4.1 M€ at year 25, and the payback period is just over 5 years. The resulting MAC are -41.4 €/to CO_2 reduced. The sensitivity to a ±30% difference in fuel price is shown as well.

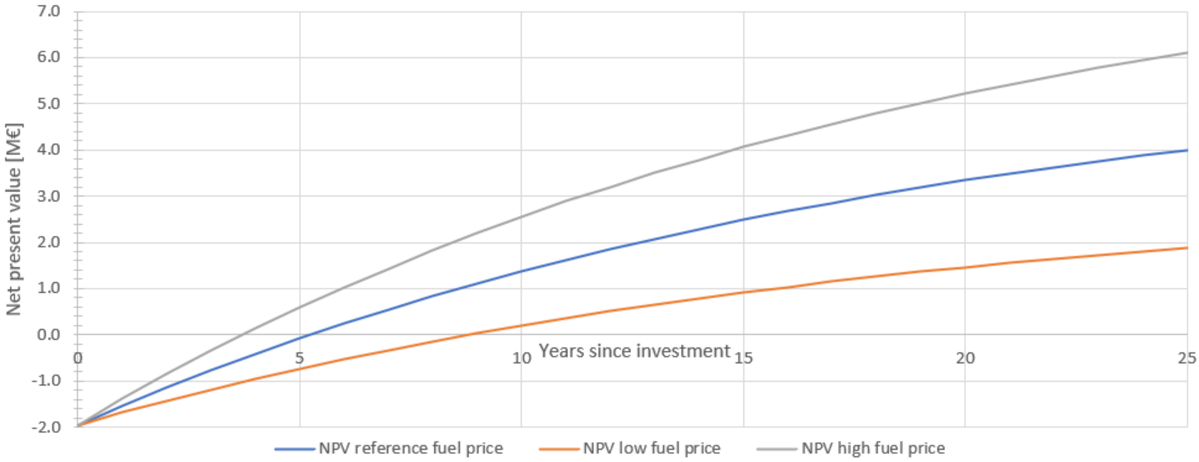

Figure 4.10: NPV over time and sensitivity to fuel price for the redesign

4.3 Additional emission reduction

As the selected concept has been compared against the current P-type, the research can be concluded. But before concluding on and discussing both the redesign and the whole study, some separate remarks will be made on further emission reduction with this concept. This is done since emission reduction was the main goal for the redesign, and the results from the previous paragraph show that the concept does not yet reach the IMO 2030 goals. Recommendations on how to reach these goals will be discussed in this paragraph.

The goals set by IMO for 2030 require the carbon intensity of ships to be reduced with 40% compared to 2008 levels. As there is no reference for the 2008 levels of the P-type (since they were not operational at this time), the 40% reduction is assumed to be compared to the currently operated P-type vessels. The proposed combination of technologies for the redesign enable an emission reduction of 20.6%, as was concluded from the previous paragraph. This means that when this redesign will be operational in 2030, an additional 19.4% reduction in CO_2 emissions is required compared to the current P-type. It is debatable whether regulations are in place at this time to enforce the IMO 2030 goal, however for the scope of this paragraph, it is assumed that these regulations are in place. Furthermore, it is assumed that a carbon tax of € 51 per ton of CO_2 emitted (Parry et al., 2018) is applied in 2030.

With these assumptions, more CO_2 emission reduction is necessary. This could also be profitable when the MAC of additional technologies are less than 51 €/ton CO_2, due to the assumed carbon tax. The combination of technologies that performs best has already been selected, however, the requirement of having a 40% reduction of CO_2 emissions could have influenced the selection of the best performing technologies in section 3. As this is not the case in this study, additional emission reduction is only considered through the use of alternative fuels in this paragraph, not through the use of additional emission reduction technologies listed in section 3.1.

From the literature study executed prior to this research, several different types of alternative fuels have been assessed. The applicability of these alternative fuels to a redesign of the

P-type with a similar operational profile varies greatly; the alternative fuels which have the lowest impact on the redesign in terms of operability and arrangement will be considered in this paragraph. These are for instance drop-in fuels, which have the same properties as conventional fuels and can thus be used in the engine and stored on board without large modifications to the vessel. The difference is that these fuels are produced in such way that the carbon emitted when combusting is offset against the carbon captured from the environment while producing the fuel. These types of fuels are generally biofuels or synthetically produced fuels using renewable energy.

Another promising alternative fuel to reduce CO_2 emissions further for the redesign is LNG. The application of LNG influences the arrangement and operability of the P-type significantly more than drop-in carbon neutral fuels. Recommendations to the application of LNG will be discussed later in this paragraph, after the theoretical application of drop-in alternative fuels has been discussed.

In order to indicate the most important implications to the application of drop-in fuels, it needs to be known how much conventional fuel needs to be replaced with a carbon-neutral alternative. It is known that 19.4% more CO_2 emissions need to be reduced from the comparison with the current P-type on the analysed operational data. This amounts to an additional 3633 ton of CO_2 to be reduced.

The drop-in fuels considered in this section are advanced biofuels and synthetically produced drop-in fuels, as these have the lowest life-cycle GHG emissions. For advanced biofuels, the study of the ICCT (2020) shows that life-cycle GHG emission reductions from 75% to 100% can be expected for several types of biofuels. It is assumed that the CO_2 emission reduction for using an advanced biofuel instead of HFO is 90% over the life-cycle. This amounts to 1296 ton of HFO that is to be replaced with an advanced biofuel with drop-in characteristics. The additional costs associated with these are estimated to be a factor 3.5 higher than HFO per unit of energy, based on several studies on the cost of biofuels (Brown et al., 2020; ICCT, 2020; Balcombe et al., 2019). This results in additional fuel costs of 1.2 M€ per year, equivalent to a MAC of 339 €/ton CO_2. Taking into account the carbon tax, this reduces to 1.05 M€ per year. This still is a very high impact on the operational costs, and it could be concluded that, unless biofuels become considerably cheaper, it is economically more advantageous to just pay the carbon tax.

The other type of drop-in fuels that are considered are synthetically produced drop-in fuels from renewable energy. Contrary to biofuels, synthetically produced fuels can have virtually zero life-cycle GHG emissions (Brynolf et al., 2018; Horvath et al., 2018). This is why it is assumed that only emissions associated with the distribution and transportation of the synthetic fuels are to be accounted for. This results in a reduction of 95% of CO_2 emissions compared to HFO. The costs for these types of drop-in fuels are higher; they are estimated to be a factor 4.5 times higher than HFO (Brynolf et al., 2018). With these assumptions, the additional costs for the use of synthetic drop-in fuels to reach the IMO 2030 goal are 1.63 M€ per year. The MAC for this solution are 450 €/ton CO_2 reduced. Taking into account the carbon tax, the annual additional costs reduce to 1.44 M€.

For both types of drop-in fuels, it can thus be concluded that a significant additional cost can be expected to reach the IMO 2030 goals. Furthermore, the operability of the redesign is affected by the use of drop-in fuels. This is because a large quantity (over 20% of annual consumption) of these fuels need to be bunkered during a year of operation. Furthermore, some types of these drop-in fuels need to be blended with the conventional HFO in order to avoid major modifications to the engine and fuel supply systems. The frequency of bunkering is dependent on the mixing ratio of the drop-in fuel, the storage capacity of these alternative fuels and the availability of these fuels by 2030. These factors pose limits to the vessel's operability as a large amount of these type of fuels need to be combusted during a year of operation and the current availability of these fuels is very limited.

From the literature study on drop-in alternative fuels with low carbon emissions, it became clear that the availability is expected to increase in the coming years and the costs are likely to decline. At this moment, these are the main hurdles to apply these types of solution to reach a GHG emission reduction of 40%. Possibly, in 2025 the above considerations would not be valid anymore. When considering drop-in carbon neutral fuels as a solution to meet the IMO 2030 goals, further research into the expected worldwide availability, the costs and the compatibility with the existing on-board fuel supply and storage system would have to be carried out.

An alternative fuel which currently has a much better availability, and significantly lower fuel costs than drop-in fuels is LNG. Therefore the application of LNG as an alternative fuel is also touched upon in this paragraph. The main benefits and consequences will be discussed in a qualitative manner, and recommendations for further research will be given.

The most important reason to opt for LNG as an alternative fuel is that over the life-cycle, 25% of GHG emission reduction is possible (Gilbert et al., 2018). For this reduction percentage, it is assumed that no methane slip occurs in the engine. Methane slip is the release of unburned methane from LNG to the environment by the exhaust gases. This has a high impact to the climate as methane has a global warming potential 25 times higher than CO_2. Assuming that 25% of GHG emissions can be reduced by using LNG instead of HFO, it can be calculated how much HFO needs to be replaced with LNG for the redesign to reach the IMO 2030 goal. It follows that when all of the HFO consumed during sailing is replaced with LNG, the GHG emission reduction of the redesign is 39.4% compared to the current P-type. This means that next to replacing all HFO by LNG, an additional reduction of 0.6% of the current P-type's GHG emissions might be needed. It is assumed that this is possible by further slow steaming or by blending with bio-LNG.

As was stated, the current availability of LNG is much better than that of the alternative drop-in fuels discussed previously. However, bunkering of LNG is still limited to larger ports and the operability of the redesign is thus influenced as the redesign should solely combust LNG to meet the 2030 goal. To account for serving remote areas where bunkering of LNG is not possible, either the range of the vessel needs to be increased by increasing the LNG capacity on board or more frequent bunkering in larger ports is needed. The latter would mean that more detours are needed during a year of operation. However, it is expected that in the coming years, the availability of LNG increases and it could be concluded that by 2030, worldwide availability of LNG would allow for uninterrupted operability.

Another means to overcome the impaired operability is to install a duel-fuel engine on the redesign, so that conventional fuels can be used in the main engine as well. This decreases the emission reduction and makes for additional fuel capacity on board. Furthermore, the volume for fuel storage is already increased due to the low volumetric energy density of LNG; it is expected that the volume for fuel storage increases with at least a factor 2 (DNV-GL, 2019). The impact on the ship design, range and operability is to be studied further when considering LNG propulsion as an alternative to reach 40% GHG emission reduction.

A major advantage of LNG over drop-in alternative fuels are the fuel costs; LNG has about the same price as HFO per ton, however LNG has a higher energy density. This is why in terms of total fuel costs, LNG offers a cost reduction of around 20%, assuming that the engine efficiency of a gas engine is similar to that of a conventional diesel engine (SEA\LNG, 2019). This means that when applied to the redesign, 342 k€ can be saved in fuel costs annually. The CAPEX of the equipment and storage associated with using LNG are however substantial and can be up to 20% of the newbuilding costs (Wang and Notteboom, 2014). However, a reduction of the CAPEX can also be expected, as LNG as a fuel reduces local emissions like SO_x and PM to an extent where additional equipment to reduce this is not necessary. This means a cost reduction can be expected and this also poses benefits with respect to future regulations on local emissions. The economic performance over the lifetime of the redesign is to be studied more extensively when considering LNG as an alternative to meet the IMO 2030 goals.

When the application of alternative fuels is studied further for the redesign, it is recommended to include the operational range of the redesign when studying the availability of the alternative fuels. As the redesign is more fuel-efficient, the same fuel storage capacity means that the range of the redesign increases. This could mean that the operability would be less impacted by alternative fuels, as the range increase could enable a more efficient bunkering strategy.

All in all, it can be concluded that alternative fuels with a manageable impact on the operability and arrangement of the vessel can be a solution to meet the IMO 2030 goal. Two types of these alternative fuels have been discussed and the most important consequences for the redesign have been pointed out. When one of these alternative fuels are to be considered for application to the redesign, it is now clear which characteristics of these fuels deserve the most priority in the further study. The goal of this research was to find the highest emission reduction while still being feasible in terms of operability and economic performance, whereas a study which had the requirement that the IMO 2030 goal should be met would have been executed differently and may have led to a different combination of technologies, most likely including alternative fuels. This will be discussed to more extent in the next section.

A means of reducing emissions in a way in which no impact on the ship design occurs is by additional slow steaming. From several studies (Faber et al., 2017; Bouman et al., 2017; Lindstad et al., 2015) it was found that slight slow steaming can reduce the emissions by a significant percentage. A reduction of speed of 20% yields an emission reduction of over 20% (Faber et al., 2017). As less fuel is consumed, costs are saved. The operability of the redesign is however affected, less distance being covered during a year of operations. If additional slow steaming is considered an option to meet the IMO 2030 goal, the impact on the transport work is to be studied. From such studies, the decrease in annual profit can be estimated to get better insight in the impact on costs for this measure. Slow steaming can, however, be a short-term solution to reduce emissions significantly.

4.4 Evaluation of redesign

In this last paragraph of this study, the redesign that has been presented throughout this section will be evaluated. First, a short summary of the conclusions that can be drawn from the redesign are given. Secondly, the presented results will be discussed. Finally, recommendations are given for further development of the redesign.

In this section, it was presented how the selected concept compares to the current design. The most important consequences due to the applied technologies have been indicated and a more accurate calculation of the performance of the redesign has been made. Throughout this section, more insight on the practical application of the technologies was gained and with the final performance comparison, the individual performance of the applied technologies became more clear. All in all, a clear overview of the redesign has been presented. This means the final sub-questions of the study can now also be answered:

5. *How does the redesign of the P-type with the chosen combination of GHG emission reduction technologies compare to the original vessel?*

   The redesign has a fuel consumption reduction of 21.7% and a CO_2 emission reduction of 20.6%. The applied technologies to the vessel were all shown to be feasible; meaning that the influence on the ship design, operability and costs were acceptable. The operational profile of the redesign remains mostly unaffected, albeit that the engine optimization makes that certain speeds cannot be attained. Apart from this, the same amount of transport work can be executed in a year of operating and the same routes and ports can be sailed at. The redesign makes for a profitable way of reducing emissions; the investment has a short payback time of 5 years and the NPV at the end of the operational lifetime of the redesign is over 4 M€. Given an investment of nearly 2 M€ this indicates a considerable return on investment. Furthermore, further emission reduction for the redesign has been touched upon and recommendations on how this can be studied most effectively have been given. It can be concluded that, in order to further reduce the emissions to below the IMO 2030 goals, measures exist that have a manageable impact on the arrangement and operability of the redesign.

a. *What are the most significant differences in terms of ship design?*
The most prominent difference is the application of the Flettner rotor and the hull redesign. The Flettner rotor affects the design in such way that the cargo operations using the forward hold are influenced and the visibility from the bridge is limited. Furthermore, it could be that additional ballast capacity is needed or the hull form should be modified to ensure the application of a Flettner rotor. All of the consequences of a Flettner rotor to the ship design are shown not found to be showstoppers for the application of this technology.
The hull redesign could influence the arrangement in especially the bow area. It could also be possible that cargo volume is lost or the main dimensions are to be slightly increased allow an optimized hull redesign. This is to be studied further, but it is expected that this will not limit the operability of the redesign.

b. *What are the most significant differences in terms of operability?*
The redesign is able to attain to the same operational profile as the currently operated P-type vessels. The only difference originates from the engine limitation, which causes a reduction of the sailing speed for 1.7% of the time sailing. It was shown that the effect on transport work can be compensated by increasing the speed where possible. This means the only difference is a different distribution of the operating speeds.
Next to this, the application of a Flettner rotor influences the operability as well; adapted routes may be sailed to achieve as high as possible fuel consumption reduction of the Flettner rotor. This could also influence the sailing time and thus the annual transport work.
No other differences in terms of operability are expected for the redesign compared to the current P-type. This could also be expected, as an important requirement for the redesign was that the applied technologies do not influence the operability. The same routes can still be sailed, and the same ports can still be called at.

c. *How does the redesign perform in terms of costs?*
The applied technologies to the redesign require additional investment costs of nearly 2 M€. The applied technologies result in an annual reduction of the fuel costs of over 500 k€. This makes for a short payback period of 5 years and an expected net present value of the investment of over 4 M€ over the operational lifetime of the vessel. As the marginal abatement costs are -41.4 €/ton CO_2 reduced, profit is made while reducing carbon emissions.

d. *What recommendations with respect to even further emission reduction of the vessel can be made?*
It is recommended that further emission reduction can best be achieved through the use of alternative fuels or slow steaming. Alternative fuels with a manageable impact on ship design and operability are the most feasible. These are for instance the application of LNG or the application of drop-in carbon neutral fuels. Both of these have consequences due to the characteristics or availability of the fuel; the most important consequences have been touched upon and recommendations for further research were given.

> Additional slow steaming can also be an option to reduce the emissions even further, this will however have an negative influence on the annual transport work and thus affect profits from the redesign.

As all relevant conclusions on the redesign have been made and the final sub-questions are answered, the remainder of this paragraph shall focus on discussing the results of the redesign and providing recommendations for further development of the redesign. The conclusions and discussions for the whole study will be presented in the next section.

The results presented in section 4.2 are subject to numerous uncertainties and assumptions which may have led to less reliable results. The most important consequences for uncertainties in the results will shortly be explained.

First, the assumptions made with respect to the resistance reduction due to the hull redesign are cause of uncertainties. This is because they are based on results from literature and not based on an estimation of an actual redesign of the hull. Furthermore, the effect of the sea state on the resistance reduction due to a more slender bow form has not been taken into account. For the scope of this study, a remodelling of the hull form and more accurate predictions on the resistance reduction were not possible and of less significance. When these assumptions involved more operational characteristics and based on an actual hull form, the results would have been more accurate and possibly a higher fuel consumption reduction would be found. Furthermore, the propulsive efficiency of the current P-type ($\eta_{D,old}$) was kept constant for all ship speeds and loading conditions. It is known that this influences the results for the fuel consumption reduction as in practice, this efficiency varies with the operational conditions.

Next to the less detailed estimation of the hull resistance, the way in which the propulsive efficiency gain has been accounted for can be debated. This is because this was based on studies for different ship types and operational profiles. The most important parameters influencing the efficiency gain have been included in the current estimations. Still, the efficiency gain has been estimated based on information provided from the current P-type propeller curve, assuming this would be representative for the redesign. This assumption may have led to inaccuracies in the estimation of the propulsive efficiency gain by enabling a variable propeller speed.

Another limit to the accuracy of the results is that the operational data was averaged to periods of 3 hours. This was done to limit the computing time of the model while still taking the effects of for instance a storm into account. The consequence of time-averaging is that peaks in the operational conditions such as ship speed, wind speed or fuel consumption are not accounted for. This influences the estimated performance of the technologies; the wind speed and direction have a high influence on the performance of the Flettner rotor. This provides less insight in the extremes in operational conditions and might introduce inaccuracies in the results.

Another factor influencing the present results is that these are based on operational data of a current P-type. The P-types are instructed to sail at a fixed fuel consumption and therefore lower their speeds when the operational conditions do not allow for that fuel consumption. For the redesign, the same speeds are assumed to be sailed at. However, due to the expected fuel consumption reduction, a redesign could be operated differently. Due to the higher fuel efficiency, the same annual fuel consumption in a redesign would make for an increased annual transport work. As the IMO 2030 goal is based on carbon efficiency, thus considering the transport work, this means that a possibly even higher reduction percentage can be found by assuming a different operational profile. Furthermore, it is possible that a different operational strategy for the redesign would also make for increased profits. As was also stated in section 4.3, the emission reduction by further slow steaming could also make for a different strategy for the speeds sailed at.

For future research on the redesign presented, the above discussed inaccuracies in the results could be minimized. Several recommendations for future research on the redesign are given in the following.

The most important recommendation to increase the accuracy of the results is to increase the level of detail in the resistance and propulsion calculations. This can be done by performing resistance calculations on the new hull form for various speeds and wave heights. In this way, the fuel consumption for the redesign is calculated more accurately and takes the actual operational conditions better into account. Furthermore, this enables the hull efficiency to be included as a variable in the calculation. When more insight in the specific operational conditions and associated powers is present, the propeller loading variation is also more clear. This enables the calculation of the propulsive efficiency gain to be based on an actual matching of the propeller speed and pitch with the power demand. The actual combinator curves of different controllable pitch propellers and the engine limits could then be used to determine the optimal working point for each operational condition. This would significantly decrease uncertainties in the results for the off-design conditions. Furthermore, the calculated fuel consumption during sailing then would not be based on the operational data of the current P-type, which reduces inaccuracies in the results due to uncertainties in the operational data.

If the above described modifications to the model are implemented in a future study, this would also enable the speed of the redesign to be optimized. It was discussed that given the different fuel efficiency of the redesign, a different speed of the redesign could make for even lower emissions per transport work or make for more profit. For further study on the redesign, it is recommended to study the influence of the ship speed on the carbon intensity, the operational costs and income. It likely follows from this that a different operational profile is favoured for the redesign. This way, the effect of further slow steaming for the redesign can also be quantified.

Next to that, further research into the performance of the Flettner rotor is recommended. The model used in this section was sufficient for the comparison, however it still included conservative assumptions on the added resistance from the Flettner rotor. It is recommended that a more detailed calculation of the effect of the operational conditions on the added hull resistance from the Flettner rotor is executed. Thus, weather routing for the redesign can also be applied as the results for the Flettner rotor’s performance are more reliable. It is expected that the application of weather routing for the redesign increases the performance of the Flettner rotor and makes for even higher CO_2 emission reductions. Having a model which combines a speed optimization with weather routing for the Flettner rotor would provide more insight on the most efficient operational strategy for the redesign.

Finally, it is recommended that the performance of cold ironing is studied further. This is because the current estimation of the performance of cold ironing was based on blunt assumptions on the availability of shore side electricity and on the amount of power that can be delivered. Although cold ironing has a marginal effect on the annual GHG emission reduction, it should be studied in the future as more will then be known on the availability of shore-side electricity for different ports. More insight in whether the power supply from shore would then be sufficient to perform cargo handling operations is also needed. Most fuel is consumed in port when loading or unloading, which means that inaccuracies in the assumptions done during loading and unloading have a large effect on the overall results for cold ironing.

As the evaluation of the redesign has been executed, the research into the best performing combination of GHG emission reduction technologies is concluded. In the following sections, the whole study will be discussed and recommendations on the research will be given.

Conclusions and discussion

In this last section, the study will be concluded and discussed. For the redesign, conclusions have already been given and the results for the redesign have been discussed in section 4.4. The conclusions and discussions given in this section will thus be limited to the methodology of this study. This section will start by answering the main research question, after which additional conclusions will follow and the research is discussed.

The main research question can be answered as all sub-questions of the study have been answered in sections 1 through 4. The main research question is recapitulated:
'Which combination of technologies can best be applied to the redesign of BigLift's P-type to reduce GHG emissions as much as possible within the current industry and operational profile, and how would a concept design with these technologies perform compared to the current design?'

The answer to this question consists of two parts, as the main research question has two parts as well.

The best performing combination of technologies is the combination of hull redesign and optimized engine, a Flettner rotor, a frequency converter and cold ironing. The applicability of these technologies within the current industry and operational profile has been assessed by only constructing combinations of technologies that were proven to be feasible within the intended operational profile and the expected commercial developments by 2025. This means that in the final selection of the best performing combination of technologies, the feasibility and the effect on operability and ship design were not considered as criteria. Instead, the economic and emission reduction performance, as well as the robustness of the combination of technologies were used in this final selection. The selected concept provides a decent emission reduction, at a lower investment risk, and with simpler and more strategic technologies than the other considered concepts. Furthermore, the sensitivity analysis pointed out that this combination of technologies is less affected by factors influencing the expected performance or operational profile. Finally, this combination of technologies was also favoured due to the applied technologies being more simple. It can be concluded that the approach to this study has led to a selected combination of best performing technologies which comply with the prior defined requirements for this study, and thus, it can be stated that the study has been executed successfully.

To answer the second part of the main research question, a comparison of the current P-type with a redesign that makes use of the selected combination of technologies was made. It can be concluded from this comparison that the redesign is estimated to reduce GHG emissions with 20.6% compared to a current P-type vessel. There was no impact on the operability after the redesign; it was shown that the same operations can be executed in a redesign as with current P-type. Furthermore, the impact on the ship design and arrangement was minimal; the application of all the selected technologies were proven not to influence the design in such a way that this would impede the arrangement and operations of the redesign. In particular, the application of a Flettner rotor was shown to affect the stability requirements, but in a such a limited way that no significant changes to the design are needed. The application of the technologies to the redesign will require additional investment costs of nearly 2 M€. As the application of the selected technologies would result in an annual reduction of the fuel costs of over 500 k€, this will result in a short payback period of 5 years and an expected net present value of the investment of over 4 M€ at the end of the operational lifetime (25 years) of the redesign.

The main research question could thus be satisfactorily answered in full. However, several sub goals have been stated as well for this study, which will be concluded on as well:

- *'To select the most appropriate criteria to assess feasibility and to indicate the best performing concept'*

This goal has been met; appropriate criteria have been used throughout the study to assess the feasibility with respect to the technology development and applicability to the operational profile. These criteria were not criteria which could all be quantified for each different alternative, yet, due to the qualitative assessment of the technologies with these criteria, more insight was gained in the feasibility of the individual alternatives. It is expected that this would not be true when only criteria had been applied that are quantifiable and that this would make the assessment unnecessary complex. This is why the criteria used to assess the feasibility of the technologies are deemed appropriate.
For the further selection of the best performing combination of technologies, multiple economic and emission reduction performance indicators were used. These were indicators which allow each concept to be assessed quantitively. This method of assessing was deemed more appropriate as the focus for this assessment was to indicate the best alternative based on quantifiable values for the concepts. The number of performance indicators was limited to create a clear overview on the performance of the concepts and to avoid making the comparison of the concepts too complex.
All in all, it is concluded that the most appropriate criteria have been used in this study as the criteria used fitted the purpose of the assessment in which they were used.

- *'To gain more insight in the benefits of applying a combination of technologies to a redesign'*
This goal is met in section 3, where combinations of technologies were constructed. The benefits of certain combinations have been elaborated; it was found that combining technologies that all have a different origin for GHG emission reduction result in robust concepts with a generally high emission reduction performance. Furthermore, the efficiency improving technologies enable an increase of the range of the vessel for the same fuel capacity. Therefore the impact of a combination of technologies on the ship arrangement and operability would be less, should alternative fuels with a lower energy density be applied in the future.
- *'To provide recommendations for the implementation of the GHG emission reduction technologies on the redesign of the P-type'*
This goal has been met in section 4. Here, the application of the selected technologies has been qualitatively discussed and it was indicated which characteristics of the implementation deserve further study. Next to this, recommendations on the application of alternative fuels are given, to achieve further emission reduction, likely required in the future. It was stated that carbon neutral drop-in fuels and LNG seem to be the most promising alternative fuels as these are expected to have the lowest impact on the ship arrangement and operability, when compared with other alternative fuels.

It is concluded that all goals formulated for this study have been met. The current research method has resulted in an initial exploration of different technologies for reducing GHG emissions, in which technologies having the least influence on the operability and design of the vessel are only considered.

The initial emphasis of this study was more on qualitative comparisons of different (combinations of) technologies, and less on the relative performance of certain technologies or the ranking of different alternatives. This has provided more insight and detailed information on why certain technologies were considered and why others were discarded. It is concluded that this method was most appropriate for the research question relevant for BigLift; their goal was to obtain more insight in how the application of GHG emission reduction technologies could influence the operations of their heavy-lift vessels. If instead, their focus had been to construct a model which can assess the best performing combination of technologies, a different research approach would have been applied and more emphasis would have been given to how different emission reduction technologies could be scored based on different criteria. Most likely, a multi-criteria decision analysis would then have been applied, which would have left less room to study the detailed

application of technologies or to contemplate on the feasibility of these technologies. This is why, for the current research goal and current context of the study, it is concluded that the research method was appropriate.
As the most important conclusions on the research and the research methods have been given, the remainder of this section will consist of a discussion on the study.

The most important point of discussion deals with how the emission reduction potential was measured in this study. As the whole study was set up to be relative to the current P-type and assumed a redesign with the exact same operational profile as the current P-type, the emission reduction has been studied relative to the current P-type vessels. This reduction percentage has been compared with the reduction percentage stated as the IMO goal for 2030; a 40% reduction in carbon intensity from individual ships compared to 2008 levels. The following discussion will be on the comparison of both reduction percentages

No 2008 levels for the carbon intensity are known for the P-type, as these vessels were not yet in operation at that time. As the estimated emission reduction for the redesign uses the operational data of the P-type in 2019 to compare with, this implicitly assumes that the 2019 values are representative for the 2008 values. This is known not to be true, as technological developments have made for more efficient shipping during these 11 years, and the industry has also changed in these years with respect to the speeds that are sailed at. This probably results in an underestimation of the achieved emission reduction percentage, as the carbon intensity would be much higher in 2008 than in 2019. This means that the contents of section 4.3, where it is assumed that, with the expected benefits of the redesign compared to the 2019 data, 19.4% additional GHG emissions need to be reduced to comply with the IMO 2030 goal, are probably not reliable. It is expected that the additional GHG emission reduction to comply with the IMO 2030 goal might be less. Thus, due to a lack of information of the carbon intensity in 2008, and compliance with the IMO 2030 goal not being the main focus of this study, no conclusions on whether the IMO 2030 goals could be met by the redesign can be given in this study.

Next to this, the IMO goal of GHG emission reduction is based on carbon intensity, indicating the mass of GHG emissions per transport work. In this study, the amount of transport work executed annually by the redesign has been assumed to be similar as for the current P-type. This was assumed since the operational profile of the redesign was required to be identical to the operational profile of the current P-type. However, as was stated in section 4.4, it could be that the lowest carbon intensity is found when the operational profile of a redesign is altered. Especially the speeds sailed at have a large influence on the carbon intensity. The current study did not consider the annual transport work to be variable, which means that no insight on whether the resulting combination of best performing technologies in this study indeed make for the lowest carbon intensity and the best compliance with the IMO 2030 goal. This also means that the current results cannot be used in a study which focusses on minimizing the carbon intensity, as for this, the operational profile would also need to be varied and technologies could have been selected which showed better performance fitting that operational profile.

Furthermore, from the operational profile analysis, it became evident that the current P-types could be improved much as these are not operated as was intended during the design process of these vessels. This means that the hull form and main engine were not optimized to the most occurring speeds, making for a less than optimal fuel consumption. Therefore, a redesign of the hull form and an optimization of the engine was included in the redesign, and it was estimated that these make for an emission reduction of 11.2%, over half of the total estimated emission reduction. This means that it must be noted that if the same research method would have been applied to a vessel of similar type which is operated as it was designed for, the results for the emission reduction and economic performance would be less. The hull redesign and engine optimization influence the investment valuation as well, as the reduction of fuel cost from these technologies compensate the payback time of the other technologies applied to the redesign. This means that the transferability of the results of the present study to similar multi-purpose heavy-lift vessels, having a similar operational profile is not certain. It can be concluded that since this study was based on the current P-type, an ‘easy’ GHG emission reduction was found by designing for lower speeds, which does not necessarily have to be true for other ships.

Recommendations

In this section, some general recommendations on future research are given. These follow from the discussion in the previous section and will give an outline of possible further studies on GHG emission reduction for a redesign of the P-type. Recommendations for further research on the selected combination of technologies have already been given in section 4.4.

The most important recommendations for further study on the GHG emission reduction for the P-type are made concerning to the baseline status against which the emission reduction is compared. In section 4.4, recommendations were given on how a model could be constructed that assesses the fuel consumption of the redesign without the current P-type being the basis of this assessment. When such a model is used in a further study, the operational profile of the redesign can also be varied as the speed could also be varied and thus the annual transport work. This way, the comparison of the GHG emission reduction can be based on the carbon intensity of the redesign and when the 2008 levels for similar ships are known, more founded conclusions on whether compliance with the IMO 2030 goal is reached could be provided. It is recommended that in a further study, the operational profile of a redesign is varied in terms of sailing speed, and the influence on the EEDI is studied. It could be concluded from such a study that a different combination of technologies would yield the lowest carbon intensity.

Such a study would also result in a whole different research context and approach. It is recommended that for such a study, the approach includes quantification of the effect of different emission reduction technologies on the annual transport work of the redesign. The method of present study would not be suited for a study which compares the emission reduction not to the current P-type, but based on carbon intensity.

A second important recommendation is made with respect to the strategy used in this study. The currently employed strategy has posed several constraints on the feasibility of GHG emission reduction technologies. Furthermore, the criteria concerning the economic performance also made for a limited construction of combinations of technologies. All in all, the current research context and approach have led to results that are not revolutionary. This was expected since the main constraints resulted in the application of low-impact, efficiency improving GHG emission reduction technologies to be the best solutions.

It is recommended that a similar study would be performed with a less narrow scope, which means that GHG emission reduction technologies which do have a high influence on the ship design and operational profile can be considered. In the present study, the impact of the costs influenced the feasibility of technologies such as fuel cells and batteries, which could make for an even higher emission reduction when applied to a redesign. More insight on the application of technologies having a high impact on the ship design and operations could be gained, if the feasibility criteria in a similar study are less strict or the goal of such a study would be to have a maximum emission reduction. This would lead to a completely different research method and would have definitely led to a different selected combination of technologies. Furthermore, such a study would fill the most important research gap indicated in the literature study; more research needs to be carried out on the application of GHG emission reduction technologies having a high impact on ship design and operability.

Current research context have made for results which are not ground-breaking and a combination of technologies that is not expected to meet the IMO 2030 goals. It does however show that with current constraints from the industry and current commercially available technologies, the IMO goals are not met. This is why it is recommended that further study focusses on how these goals can be met and how this would impact the operability and ship design.

Following the above considerations, a final recommendation for further research is made. It is concluded from this study that within current industry, no combination of technologies exist that is feasible in terms of costs, influence on operability and influence on ship design and able to reach the IMO goals for 2030 and 2050. This means that in the coming years, more research on finding a solution to reduce GHG emissions that is feasible within the current industry is to be carried out. The solutions from these studies, combined with more strict GHG emission regulations would then be adopted by the industry. However, when designing a vessel exactly for this transitional period, this could mean that in order to stay ahead of expected regulations during the lifetime of the vessel, technologies are applied to a design which are not yet commercially attractive or available during the first years of operation. These technologies would be beneficial later in the operational lifetime of the design. A solution could be designing the vessel to be able to accommodate a future refit. This enables the design to operate as efficiently as possible and still be able to reach GHG emission reduction goals that are entering into force during its lifetime. It is therefore recommended that further research is executed which focuses on designing a vessel for this transitional period and taking into account a possible refit during the operational lifetime. This could for instance be focused on the propulsion system, which could be designed in such way that conversion to an alternative fuel can easily be executed.

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Appendix A: Required operational data

A.1 Economies of scale

The principle where the GHG emission reduction comes from for this technology, is that the additional propulsive power does not increase proportionally with the increase of the cargo volume. This leads to a reduced fuel consumption per tonmile cargo transported and thus the GHG emissions are reduced per tonmile cargo transported.

In order to find out whether this principle holds for the P-type, it needs to be known whether additional cargo volume can be filled with the designated cargo type. If this does not seem to be the case, this technology can be excluded from further research as it would make the solution counterproductive in terms of GHG emission reduction performance. If this is not the case, some additional questions with respect to the operations of the P-type should be answered. These include; Can the same ports be called at with larger ship dimensions? Can the same routes be sailed with larger ship dimensions? As can be noted, the questions are mainly used to determine whether the same market can be operated with a ship of increased dimensions. When this holds, an economic analysis will need to be carried out to assess whether the economies of scale principle makes for a competitive design within the designated market, but this will not be performed at this stage.

In terms of the needed data, an analysis of the hold volume utilisation and deck utilisation needs to be carried out, as well as an analysis of the trade routes and ports which limit the vessel's main dimensions.

A.2 Slender hull concept

The physical principle of GHG emission reduction of the slender hull concept is based on a reduction of the wave making resistance by reducing the block-coefficient. This increases the frictional resistance. However, the decrease of the wave making resistance compensates for this, leading to a reduced overall resistance, thus reducing GHG emissions. Especially the added resistance in waves can be reduced significantly by increasing the slenderness of the bow. The reduction of the block coefficient can either be achieved by reducing the cargo volume or by increasing the length of the vessel.

In order to determine whether this GHG emission reduction technology can be applied to a redesign of the P-type, and whether this is effective, the proportion of the wave making resistance with respect to the total resistance needs to be estimated. As this is highly dependent of the ship speed, insight in the operational speed range needs to be acquired from the operational data; what is the distribution of sailing speeds? Furthermore, the impact on the operations when applying this technology needs to be assessed. In order to assess the applicability of both ways of reducing the block coefficient, the hold volume utilization needs to be assessed, as well as whether a length increase limits the ship's ability to operate the same market; Can both ways of reducing the block coefficient be applied? At last, as it is known that this technology is effective for the added resistance in waves, an overview in the encountered wave heights and wave directions is needed; What is the time spent in each sea state and direction?

In terms of the needed data, an analysis of the hold volume utilisation needs to be carried out, as well as an analysis of the trade routes and ports which limit the vessel's length. Furthermore, an analysis of the operational speed range is to be carried out as well as an assessment of the encountered sea states and wave directions.

A.3 Hull coating

The reduction of the frictional resistance of a ship is where the GHG emission reduction originates from when applying special types of hull coating. In order to find out if this holds for a redesign of the P-type, information is needed on the current type of coating used and on the performance of this coating. As the performance is not dependent on the operational profile of the P-type, no information with respect to the operational data is needed.

The specific questions needed to estimate the performance of hull coating are as follows; What type of coating is currently applied to the P-type? What is the influence on the fuel consumption after the application of a new coating?

In order to answer these questions, data on the dry dock maintenance and the applied coating is needed and the fuel consumption before and after a dry dock needs to be available.

A.4 Propeller flow optimization

The reduction of GHG emissions for propeller flow optimization originates from an increased hull and propeller efficiency (van Terwisga, 2013). This in turn is realized by the application of a fixed device which redirects the flow which enters the propeller plane. It is known to be most effective when the original flow into the propeller is not optimal, i.e. having a badly designed stern shape for the propeller operating point. Furthermore, it is known that the propeller flow improving devices are designed for a specific speed, draft and trim of the ship. Large deviations of speed, draft and trim are known to reduce the overall efficiency improvement of the flow optimizing device. Next to this, these devices are mostly used as a retrofit solution, meaning that when taking into account the aft hull shape which optimizes the overall inflow to the propeller during the design process, the GHG emission reduction performance of an additional device may not be worth the investment.

In order to get insight in the applicability and estimated performance of this GHG emission reduction technology, it is thus needed to know what the operational trim and draft range of the current P-type is, what the range in speed is and what kind of propeller is currently used. The specific questions to be answered are: What is the variation in draft, trim and speed? What type of propeller is currently used?

In order to answer these questions, an analysis of the operational speed, draft and trim range is needed, as well as information on the currently used propeller on the P-type.

A.5 Waste-heat recovery

The GHG emission reduction for waste-heat recovery originates from using the exhaust gas waste heat for hot-water generation and additional power generation. Applying this technology depends on whether the recovered energy from the exhaust gases can be used efficiently on board the ship. This means that the questions which need to be answered are; How much power can be extracted from the exhaust gases? How can this amount of power be used efficiently on the ship?

To answer these questions, information on the average fuel consumption of the main engine for different load levels is needed. From this, the amount of heat that can be extracted from the exhaust gases can be estimated. Next to this, the auxiliary power demand and hotel consumption of the current P-type needs to be known in order to answer the second question.

A.6 Cold ironing

For cold ironing, the GHG emission reduction originates from the absence of onboard power production during port calls, as the shore power is used. As has been stated, the emission reduction potential is highly dependent on the port's electricity source; when this is produced mainly from sustainable energy sources, a high emission reduction potential can be expected. Furthermore, the power need during port calls needs to be known in order to estimate the total GHG emission reduction potential as well as the current way this power is produced and the associated GHG emissions. Additionally, it has been stated that it is expected that this technology will only be available in larger ports, so the amount of time spent in larger ports needs to be assessed as well.

The specific questions which need to be answered are thus; What is the power need during port visits? What are the current emissions associated with this? How much time is spent in larger ports? To answer these questions, data on the energy consumption during port calls and the GHG emission factor of this power production are needed. At last, the time spent at which ports needs to be known.

A.7 Solar power

As was stated, the GHG emission reduction relies on the intake of green energy through solar panels. In order to draw conclusions on the applicability of this technology, it needs to be known what deck area can be used for the application of solar panels. Furthermore, it needs to be known whether this power can be effectively used or stored on board of the ship.

The specific questions associated with this are; What is the usable area for solar panels? How can the additional power be used efficiently? To answer this question, data is needed on the deck layout of the current P-type, the cargo deck utilisation and the auxiliary and hotel power demand.

A.8 Flettner rotor

As with solar panels, the physical principle where the GHG emission reduction originates from for wind-assisted ship propulsion is the intake of zero-emission energy. The technology leads to a reduction of the required thrust force and thus main engine fuel consumption. It was found during the literature study that a Flettner rotor is deemed to be the most effective application of wind-assisted ship propulsion. This is mainly due to its high performance while requiring quite a small amount of free deck area. As the performance of the Flettner rotor depends on the apparent wind speed and direction, the question to be answered is 'What is the distribution in apparent wind direction and speed?' Furthermore, it needs to be known what size of Flettner rotor can be placed on which part of the ship. At last, from an operational perspective it needs to be known to what extent voyages can be optimized for the maximum additional thrust generated by the Flettner rotor.

The information needed to answer these questions are data on the apparent wind speed and directions during sailing, data on the deck layout and crane operating radii and information on the current way of voyage planning.

A.9 Hybridization

For hybridization, the GHG emission reduction originates from the fact that the additional batteries enable the engine to always be working on their optimal point in terms of specific fuel oil consumption. The power demand fluctuation is of high influence on the estimated performance, when no large, longer lasting power demand fluctuations are present, the application of batteries on board the ship does not pose any benefits. In order to draw conclusions on the applicability, the performance thus needs to be estimated. The questions associated with the performance estimation are; What is the fluctuation in power demand during sailing and in port? What is the estimated battery capacity needed?

The data needed to conclude on these questions are data on the power plant operational profile and data on the fuel consumption against the engine load (the SFOC-curve or performance graph).

A.10 Fuel cell auxiliary power

For the application of this technology on a redesign of the P-type, it needs to be known whether the auxiliary power demand is suited for the characteristics of a fuel cell system. This depends on the load variability and the needed maximum power. Furthermore, the applicability also depends on the type of fuel that is to be converted by the fuel cell system. In order to draw conclusions on this, the total amount of energy stored for auxiliary and hotel purposes needs to be assessed.

The specific questions to be answered for fuel cell systems are; What is the power demand of the auxiliary power system? What is the variation of auxiliary power? How much energy needs to be stored for auxiliary purposes? The data with which these questions can be answered are data on the auxiliary power and hotel power demand over time and data on the fuel consumption for auxiliary purposes and the fuel capacity for this purpose.

A.11 Slow steaming

The reduction of the average speed results in a disproportionate reduction of the fuel consumption. Although the duration of the voyages increase, the overall fuel consumption reduces due to the nearly quadratic relation between ship speed and fuel consumption. In order to draw conclusions on the applicability of this GHG emission reduction measure, some specific questions need to be answered. These are; What is the current way of depicting the speed of a voyage? Can the same markets be served when sailing at lower average speeds? How much can the speed be reduced? These questions are to be answered in this order, since when it is concluded that the same markets cannot be served when sailing at lower speeds, it does not need to be found out how much the speed can be reduced as the main requirement of the redesign is that the markets to be served are the same as those of the current P-type.

The data needed for this assessment are an analysis of the operational speed range, an analysis of the speed variation for a single voyage, information on the required speed for different voyages and information on minimum speed requirements.

A.12 Voyage optimization

The physical principle where GHG emission reduction originates from for voyage optimization is either to optimize the cargo carried for each voyage or to optimize the voyage based on the added resistance due to the encountered weather or by reducing the operational speed. As the latter has been captured in the previous paragraph, this will not be dealt with for voyage optimization.

In order to draw conclusions on whether voyage optimization could reduce GHG emissions for a redesign of the P-type, it needs to be known how voyages are currently planned in terms of capacity utilisation optimization and weather routing. The specific question associated with this is; What is the current standard of voyage planning for the P-type?

To answer this question, information on the voyage planning is needed, this may not be acquired from operational ship data, but most likely by personal communication with the department responsible for voyage planning.

A.13 Draft-trim optimization

The physical principle where GHG emissions reductions originate from for draft-trim optimization is enabling the vessel to sail at the trim and draft where the total resistance is the lowest for the required displacement. For the best performance of this GHG emission reduction technology, a certain freedom in the draft and trim of the vessel is needed. To estimate whether this freedom would be available for a redesign of the P-type, the operational data of the currently operated P-type needs to be assessed.

The specific questions that are to be answered are; What is the operational trim and draft range? How much flexibility in the draft and trim is present when loaded with cargo? What is the current practice in terms of draft and trim when in ballast? Answering these questions will help give insight in whether it is possible for a redesign to be loaded in such way that the optimum draft and trim can be achieved for most voyages.

The data needed for this assessment are data on the variation in draft and trim, data on the loading conditions and draft & trim philosophy when making loading plans and data on the draft and trim used when sailing empty.

A.14 Condition-based hull and propeller maintenance

The GHG emission reduction for condition-based maintenance originates from a reduced frictional resistance over the ships lifetime. This is because the maintenance is performed based on the condition of the hull and propeller instead of on a regular basis, decreasing the roughness of hull and propeller on a time-average basis.

To be able to conclude on the applicability and expected performance of this measure, the following questions need to be answered; can hull and propeller maintenance be performed during loading and unloading operations? What is the current practice of hull and propeller maintenance? What is the interval in which this maintenance is executed? What is the difference in fuel consumption before and after executing maintenance?

The data which is to be looked into to answer these questions are data on the loading and unloading durations, information on the current practice and interval of hull and propeller maintenance and data on the fuel consumption before and after a dry dock where maintenance has been performed.

A.15 Alternative fuels

In terms of the needed operational data to conclude on the applicability of alternative fuels, the same questions need to be answered for all identified alternative fuels, thus the same data is needed. As the main disadvantage of using alternative fuels is their lower volumetric energy density and specific storage requirements, it needs to be estimated how much of an alternative fuel needs to be stored and whether the range of the current P-type can be reduced without impeding the operability of the ship. The questions associated with this are; What is the current amount of energy stored in bunkers? How much can the sailing range of the redesign be reduced and how does this effect the operability? For this, data on the fuel consumption, bunkering capacity, bunkering interval and amount bunkered is needed. Furthermore, data on the distance and the route sailed between ports is needed in order to conclude on whether the same routes can be sailed with a reduced range.

Another major drawback on using alternative fuels is their limited availability, it has been stated that this is expected to increase in the coming years but this will be mostly limited to larger ports, such as Rotterdam, Singapore and Shanghai. In order to provide a more substantiated conclusion on the availability and impact on operations by using alternative fuels on a redesign of the P-type, it needs to be known how much time is spent at larger ports and what the interval between visit to these ports is.

Appendix B: Performance of concepts

In the following, the created concepts will shortly be presented, and some general remarks on the concepts will be given. To calculate the combined performance of these technologies, the same assumptions as for the assessment of individual technologies in section 3.1 hold. However, due to the combination, several additional assumptions will be elaborated upon as well.

B.1 Concept A: Flettner rotor + Frequency converter

The first combination of technologies is the combination of a Flettner rotor with a frequency converter. The reason for this combination lies within the fact that when a Flettner rotor produces forward thrust, the loading of the propeller blades becomes less. A different working point of the propeller and engine could be beneficial as this result in an increased overall driving efficiency for both the propeller and the main engine. In other terms, when sailing with a Flettner rotor, the engine and propeller work in off-design for a larger percentage of time, which could mean that being able to sail at a different propeller frequency increases the overall efficiency. Nevertheless, the efficiency gain enabled by the frequency converter is still a 3.5% reduction of fuel consumption. The combination of the technologies which make for concept A, result in a total fuel consumption reduction of nearly 1159 ton or 20.8%. The annual CO_2 emission reduction is 3615 ton, making for a reduction percentage of 20.8% as well.

In terms of economic performance, the total CAPEX is limited and equals 1944 k€. Furthermore, the additional OPEX is only 21 k€ per year, due to the maintenance and operation costs of the Flettner rotor and frequency converter. The NPV at year 25 for a reference fuel price and a WACC of 5.4% is 3.8 M€, with an associated payback period of little more than 5 years. This can also be seen in figure B.1. The MAC for concept A are -42.5 €/ton CO_2 reduced.

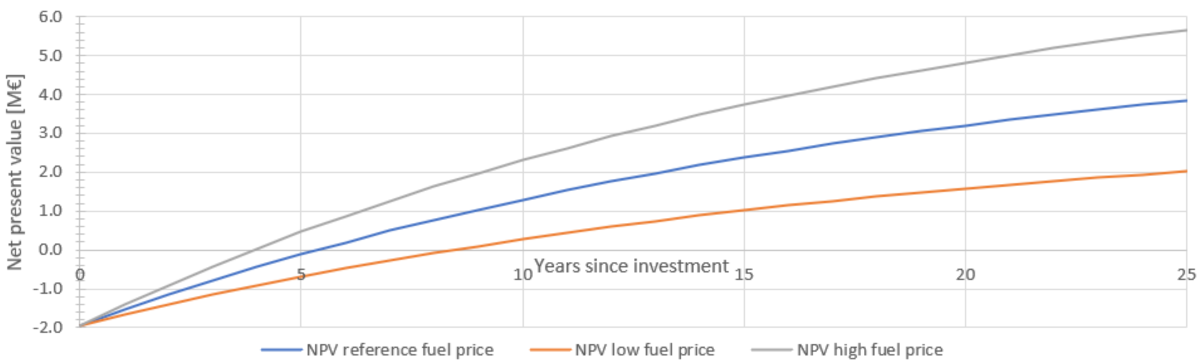

Figure B.1: NPV over time and sensitivity to fuel price for concept A

B.2 Concept B: WHR-system + Hybridisation

Concept B combines the application of a WHR-system and hybridisation. The choice for this combination is that power excesses or shortages from the WHR-system can be covered by the batteries. An assumption for the application of a WHR-system was that it could serve all auxiliary power while sailing, which makes the shaft generator obsolete. This means that the gains by being able to sail at a variable propeller frequency also hold for this concept.

Combining the performance of these technologies results in a fuel consumption reduction of 1207 ton, resulting in a CO_2 emission reduction of 3769 ton and a reduction potential of 21.7%.

For the economic performance of this concept, the CAPEX is much higher, due to the application of batteries. The total CAPEX for the combination of technologies is 5930 k€, which is 3 times more expensive than concept A. This also influences the WACC, due to a larger part of the investment for emission reduction technologies is now to be funded by a loan. The WACC weighted over the total CAPEX results in 3.8%. The OPEX increase is 27 k€ annually.

The NPV over time is depicted in figure B.2, in which it can be seen that the NPV at year

25 is 1153 k€. Furthermore, the payback period is just short of 19 years. The resulting MAC is -12.2 €/ton CO_2.

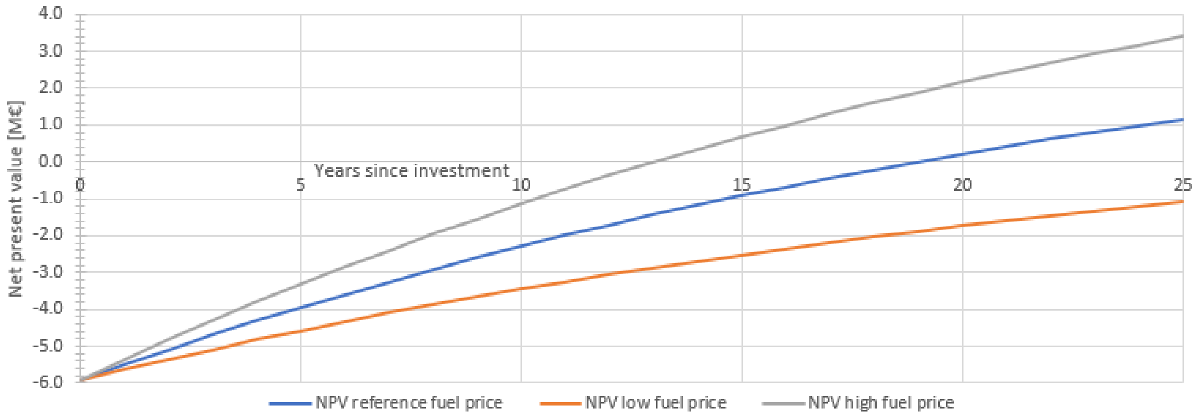

Figure B.2: NPV over time and sensitivity to fuel price for concept B

B.3 Concept C: WHR-system + cold ironing

Another interesting combination of technologies is the combination of a WHR-system with cold ironing, as this decreases the CAPEX of the investment significantly with respect to concept B, while still reducing emissions in port. Again, the gains by being able to sail at a variable propeller frequency are taken into account due to the absence of a shaft generator. The resulting fuel consumption reduction for concept C is 1336 ton, making for an annual reduction percentage of 24.0%. The associated emission reduction is 3915 ton of CO_2 saved, which equals an annual reduction percentage of 22.5%.

The CAPEX associated with this technology is 2654 k€, which results in a WACC of 4.8% associated with the NPV calculation. The influence on OPEX is an additional 92 k€ per year due to electricity and maintenance of the WHR system. The resulting NPV calculation for the combination of technologies is found in figure B.3, where the sensitivity to the fuel price is depicted as well. It can be seen here that the payback time is between 7 and 8 years, and the NPV at year 25 is around 3.7 M€. Furthermore, the MAC associated with concept C is -38.1 €/ton CO_2 reduced.

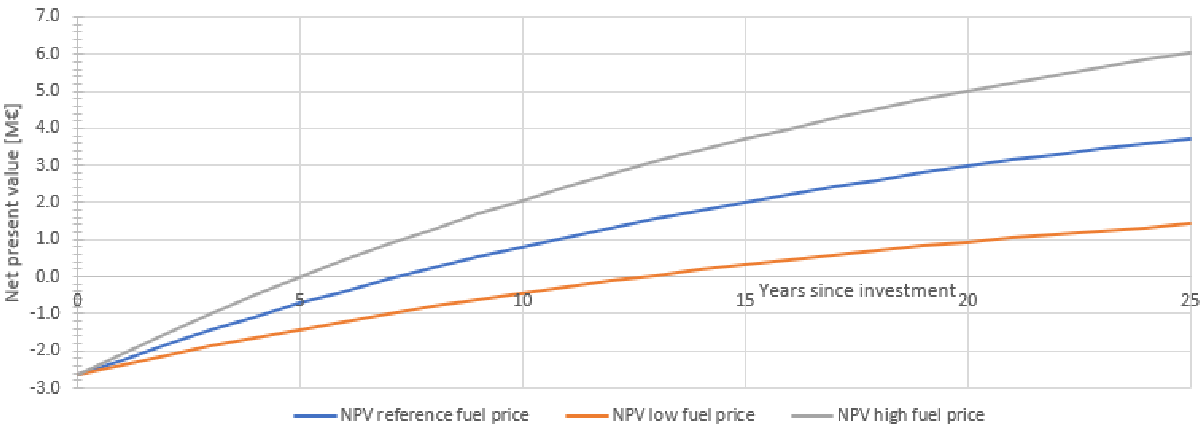

Figure B.3: NPV over time and sensitivity to fuel price for concept C

B.4 Concept D: Fuel cell auxiliary powering + hybridisation

Another combination of concepts is the application of fuel cell auxiliary powering combined with hybridisation. The combination is suitable as the high-temperature fuel cells are generally less suited to follow load variations; applying a battery pack for peak-shaving of the demand is highly applicable for this system. An additional assumption for this concept is that all auxiliary powering is supplied by the auxiliary fuel cell system, this includes the power generation during sailing. The reason for this extended application is that the specific emissions associated with power generation via a fuel cell system are reduced when compared to power generation through a shaft generator and main engine. Furthermore, the benefits of a variable shaft frequency are considered to outweigh the additional costs that continuous power supply by fuel cell system entails. This is accounted for by a doubling of the OPEX for the fuel cell and battery system.

The annual fuel consumption reduction resulting from the combination of these technologies is 1323 ton, which equals a reduction percentage of 23.8%. The associated CO_2 emission reduction is 4132 ton, which also makes for a 23.8% reduction percentage.

The CAPEX of the combination of these technologies is quite large, resulting in an investment of 6.1 M€. The WACC associated with this investment is 3.8%. The OPEX is doubled due to the increased usage of the fuel cell system, resulting in an increased OPEX of 63.4 k€ per year. The NPV over time and the associated sensitivity to fuel price changes of ±30% are found in figure B.4. In this figure, it is seen that due to the large investment and large annual OPEX, the NPV at year 25 is not high; 1162 k€ Furthermore, the payback period using the NPV calculation is between 19 and 20 years. The associated MAC is -11.2 €/ton CO_2.

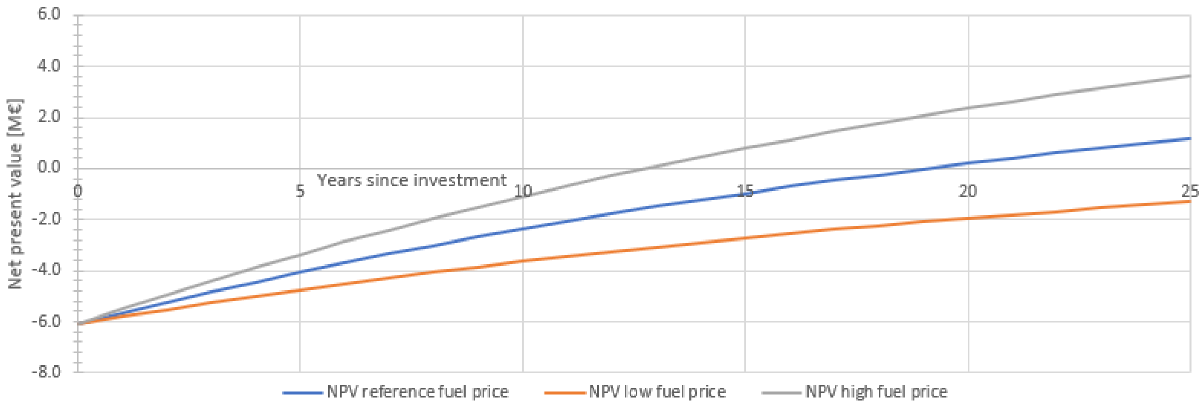

Figure B.4: NPV over time and sensitivity to fuel price for concept D

B.5 Concept E: Flettner rotor + WHR-system

For this concept, only technologies having positive marginal abatement costs are combined. From 3.1.9, it is clear that this is a combination of a Flettner rotor, a frequency converter and a WHR-system. However, as the frequency converter is applied to a shaft generator, and the shaft generator becomes obsolete due to the application of a WHR-system which delivers the auxiliary power demand while sailing, only the Flettner rotor and WHR-system remain. Their combined fuel consumption reduction is 1451 ton per year, which equals an emission reduction of 4528 ton or 26.1%.

In terms of the economic performance, the combined CAPEX of the technologies equals 3604 k€. The combined additional OPEX is 44 k€ per year. The NPV calculation is performed with a WACC of 4.3% and the NPV over time can be found in figure B.5. In this figure, it is observed that the payback period is between 8 and 9 years and the NPV at year 25 is exactly 4.2 M€. The MAC for concept E are -37.1 €/ton CO_2 reduced.

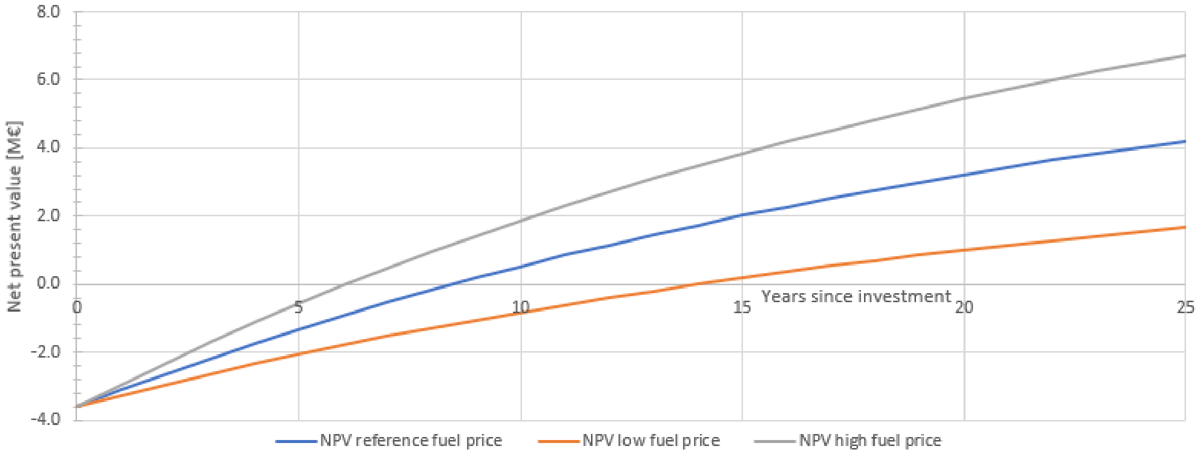

Figure B.5: NPV over time and sensitivity to fuel price for concept E

B.6 Concept F: Flettner rotor + Frequency converter + Cold ironing

Another concept worthwhile of studying is concept A, but with the addition of cold ironing. The choice for this concept is that it is expected that cold ironing will be more broadly developed during the coming years and it gives an additional emission reduction at decent additional costs. Furthermore, as concept A focuses on emission reduction while at sea, the addition of cold ironing focusses on reducing the emissions in port as well.

The resulting fuel consumption reduction is 1327 ton annually, equal to a reduction percentage of 23.9%. The associated emission reduction is 3888 ton or 22.3%. Furthermore, the investment associated with the application of these three technologies is limited; 2394 k€. The additional OPEX is 85.5 k€ per year. The NPV is calculated using a WACC of 5.0% and the sensitivity to the fuel price is given in figure B.6. It is seen in this figure that the payback time is between 6 and 7 years and the NPV at year 25 is 3.9 M€. The MAC for concept F is -40.1 €/ton CO_2.

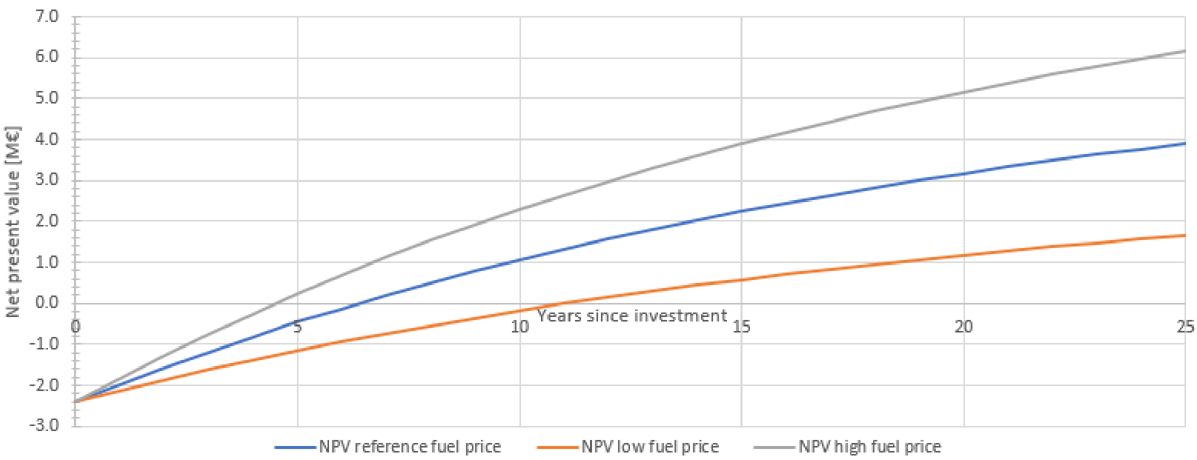

Figure B.6: NPV over time and sensitivity to fuel price for concept F

B.7 Concept G: All compatible technologies

Another combination of technologies which is mainly constructed to show the extreme is by applying all technologies from section 3.1. Again, the frequency converter is not taken into account as the WHR-system makes the shaft generator obsolete. Another technology which is discarded is the application of a fuel cell system for the auxiliary powering, since the use of a WHR-system and cold ironing makes the need for more efficient auxiliary powering during sailing and in port obsolete.

The resulting technologies make for a combined annual fuel consumption reduction of 1694 ton, which amounts to a reduction percentage of 30.5%. The resulting annual CO_2 emission reduction is 5034 ton, which is 29.0%.

The CAPEX associated with the remaining six technologies equals 7998 k€, the highest investment of all concepts. As a large part of this investment is to be financed with a loan, the WACC associated with this is 3.6%. The additional OPEX per year due to the technologies is 110 k€. The NPV over time is given in figure B.7, where it can be seen that the payback period for concept G is just little of 20 years, and the NPV at year 25 for a reference fuel price is 1.3 M€. The MAC associated with this technology is -10.2 €/ton CO_2 reduced.

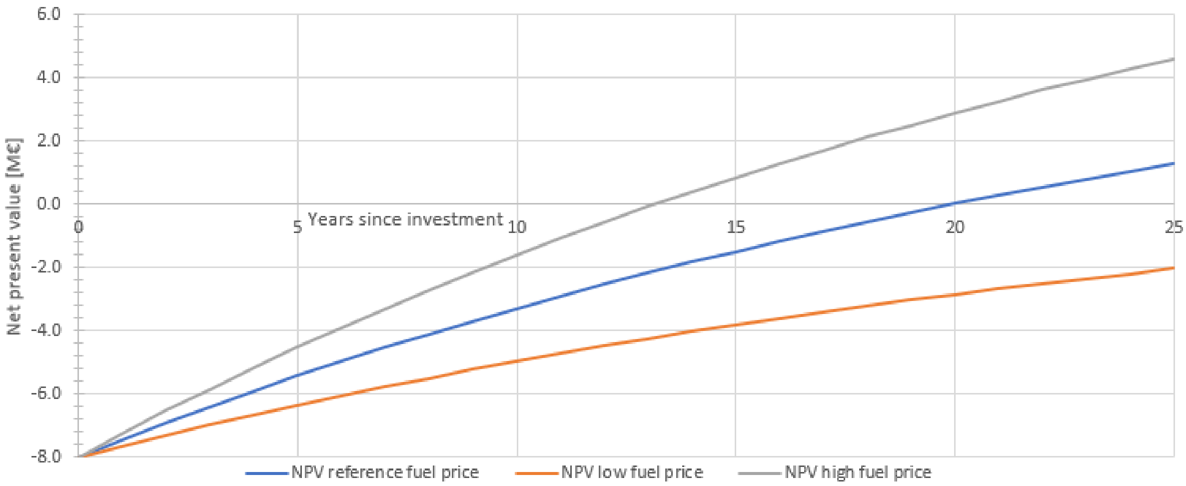

Figure B.7: NPV over time and sensitivity to fuel price

Appendix C: General Arrangement