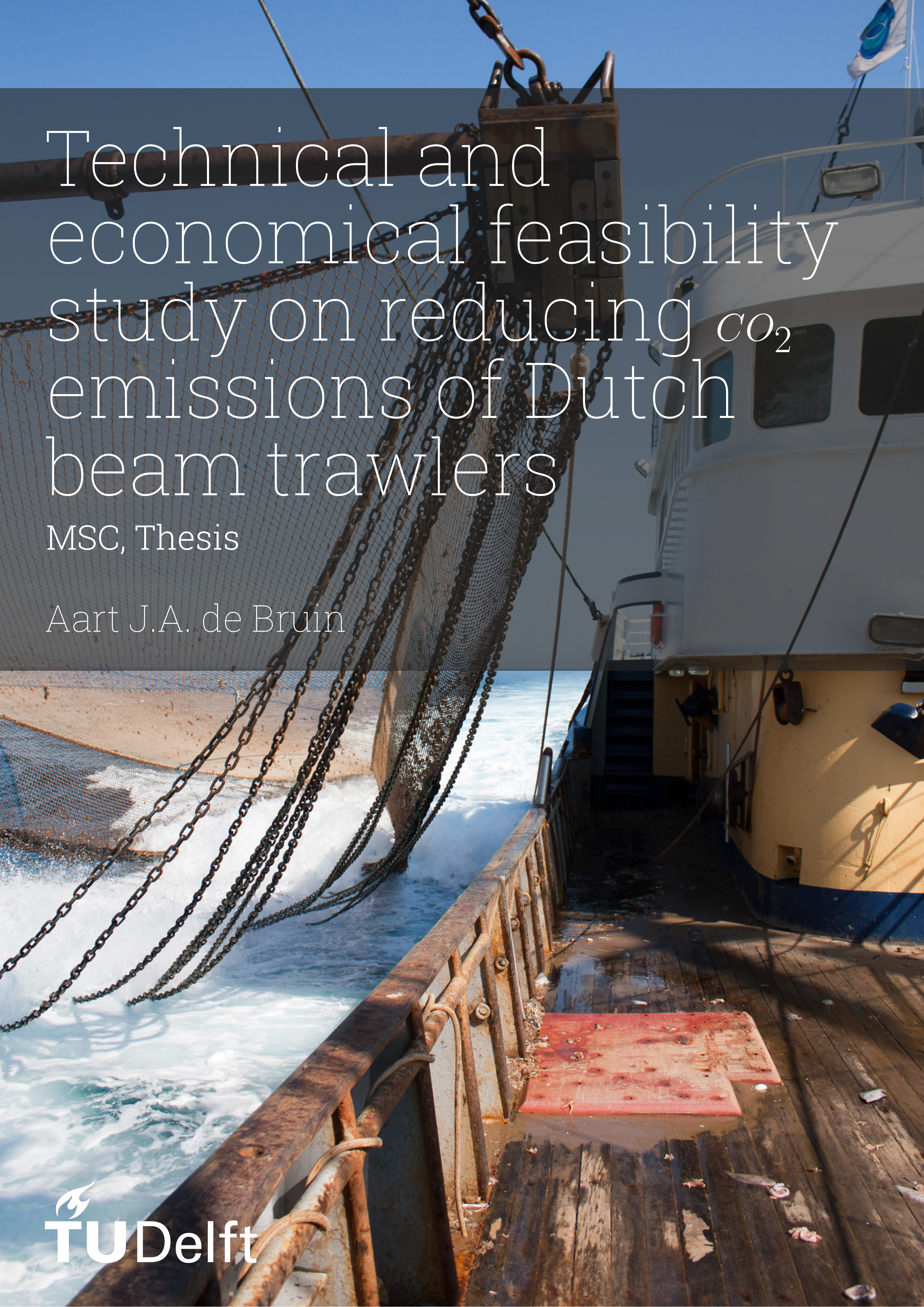

Technical and economical feasibility study on reducing CO_2 emissions of Dutch beam trawlers

MSC, Thesis

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by

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Cover photo: ”UK-1 Albert” dutch beam trawler cleaning the nets[Romkes, 2019]

Abstract

International and local legislation on emission reduction urge the Dutch beam trawler fleet to reduce the use of fossil fuels. In 2015 the United Nations Paris Agreement was signed and as a result IMO and EU set the objective to reduce the GHG or CO_2 emissions of the shipping industry. The Dutch beam trawler has been confronted with many developments within the last decade that reduced the profitability. Two developments that stand out are: (1) Brexit: the Brexit resulted in a significant reduction in available fishing grounds, (2) Ban on pulse fishing: this method of fishing reduced the operational expenses with 30% to 40%, but is banned by the EU. Al a result to these developments in combination with upcoming (inter)national legislation, the Dutch government introduced a plan "Noordzee visie" to help vessel owners to reduce their environmental impact. To continue fishing a Dutch beam trawler therefor has to take measurements to comply with these regulations. It will be inevitable to implement the use of sustainable fuels together with energy saving technologies. Vessel owners want to implement these, but without sacrificing operational effectiveness. Therefor it is required to find how different propulsion configuration which are able to reduce CO_2 will influence the technical and economical performance of a Dutch trawler.

This research consists of two parts: (1) Literature study and (2) Result processing. Within the literature study the current state of a Dutch beam trawler is defined. Secondly potential converters, energy carriers and energy reduction methods are identified which show potential. At last an assessment model is build to find the influence of available propulsion configurations.The technical feasibility is determined by the configuration being able to comply with: operational effectiveness requirements, maximum added draught, maximum added length, and being able to reduce the CO_2 emission with at least 40%. The economical performance of the configurations is assessed by three performance indicators: (1) yearly operational requirements, (2) Capital expenses of configuration and at last (3) Total cost of ownership.

The operational profile of the vessel is divided into two parts: The long cycle is the time from sailing out from port, the fishing and the return into port. The short cycle is the fishing cycle it the repetition of setting, fishing and hauling the nets. Two types of long cycles exist a 100hr and a 160 hour per week. The short cycle on average takes 2.5 hours.
Based on reliability, price and safety aspects multiple converter, energy carriers and energy reduction methods are found for this research. To store the required energy carrier volume including tank arrangement this system examines potential of combining original fuel tank volume together with: net store, fish hold or hull extension.

With the literature study finished the assessment model produces the following outputs.

Technical feasibility: The findings indicate that mono battery configurations are not feasible due to exceeding weight and volume limitations. Fuels like HVO and FAME are technically viable if recognized as zero-emission fuels by the IMO. Hybrid propulsion configurations using MGO-H_2(l) and DF-H_2(l) are feasible for all propeller types due to their higher energy density compared to liquid H_2. Implementing waste heat recovery or regenerative braking systems, or a combination of both, does not solely determine achieving the 40% CO_2 emission reduction target.

See Table 1 for the summary of technical feasible configurations:

Table 1: Technical feasible configurations

			100 hr long cycle	Continuous long cycle
	Fuel	Conf.	Propeller type	Propeller type
MONO	HVO	D-E	Original,1,2,3,4	Original,1,2,3,4
	FAME	D-E	Original,1,2,3,4	Original,1,2,3,4
	DF	D-E	2,4	2,4
	Hydrogen	E	1,2,3,4	-
Hybrid	MGO-H_2	D-E	All	All
	MGO-NMC-Li	D-E	2,4	2,4
	DF-H_2	D-E	All	All
	DF - NMC-Li	D-E	1,2,3,4	2,4

Economical feasibility: Depending on the amount of available financial resources in year 2023, available subsidy and to what extent one is willing to take risks, the following conclusions can be made for different categories of initial capital expenses. Lower capital expenditure options opt for HVO and FAME, due to their MGO similarity, which result in low capital investments. Since the TTW emission of bio fuels is sensitive to regulations the dual fuel methanol configuration with a 4.0m diameter propeller is an option which requires more initial investment, but is less sensitive to regulations and therefor more future ready. With initial investments above €2.0M the combination of 4.0m propeller, together with Orcan WHR and regenerative winch braking, the 100hr cycle performance best for MGO-Hydrogen configuration and the Continuous cycles performance best for a new build beam trawler. Taking into account the remaining value in the TCO a new build beam trawler outperforms all retrofit options, only in the long term 15+ year due to low maintenance and operational expenses.

Preface

This study, titled ”Technical and Economical Feasibility Study on Reducing CO_2 Emissions of Dutch Beam Trawlers,” explores the viability of reducing carbon dioxide emissions in the Dutch beam trawler industry.

This report has been written to fulfill the graduation requirements of MSc in Marine Technology at the Delft University of Technology. I was occupied with researching and writing this thesis from December 2022 till August 2023. It represents a significant milestone in my educational development.

I would like to express my gratitude to my supervisor, A. Kana, for his guidance, support, and expertise throughout the duration of this project. I am grateful for his mentorship and the knowledge he shared. I am also grateful to the entire team at Padmos for creating a supportive and stimulating environment that encouraged me to always continue with the research.

I would also like to extend my appreciation to my parents for their encouragement, understanding, and belief in my abilities. Their support has been a source of inspiration and motivation, propelling me to overcome challenges.

Furthermore, I am grateful for the support and encouragement of my friends. Their presence, and friendship have provided a necessary balance and perspective throughout the demanding academic journey.

The Dutch beam trawler industry has long been an integral part of the Dutch maritime heritage, providing livelihoods and sustenance to countless individuals and communities. However, the sector is currently grappling with the need to adapt and reduce its environmental impact to meet the evolving regulatory frameworks. I sincerely hope this thesis can serve as a small contribution to the preservation of this way of living.

Arnoud de Bruin
Hierden , August 2023

Definitions

Pulse fishing:
Pulse fishing was a Dutch invention that was based on the wish to reduce trawl gear influence on seabed, reduce fuel consumption and reduce the by catch. The fishing gear is flying over the sea bed and with the help of small electricity pulses the flatfish is brought into the net. The traditional beam-trawl fishery for flatfish uses so-called tickler chains to startle fish like common sole and plaice and make them leap into the net. The chains are dragged over the seabed, disturbing the sediment and causing mortality of organisms in the trawl track. In the fishery using the pulse technique, the tickler chains have been replaced by electric pulses to make the flatfish leap into the net.

Beam trawler:
A vessel specially designed to execute fishery with beam trawls, it fishes with a beam trawl on port and starboard side. Beam trawls are heavy duty nets attached to a steel beam that holds the nets open. The belly of the net is made of chains which are dragged along the seabed disturbing the sand and sediment in order to scoop up the target species[4].

Greenhouse gas(GHG) emission:
Greenhouse gas emissions(GHG) emitted gases that trap heat in the atmosphere are called green house gases. The following are categorised as GHG: (1) Carbon dioxide(CO_2) enters the atmosphere through burning fossil fuels, solid waste, trees and other biological materials. (2) Methane (NH_4), is emitted during the production and transport of coal, natural gas and oil. (3) Nitrous oxide (N_2O), is emitted during agricultural, land use, and industrial activities; combustion of fossil fuels and solid waste[12]. In this report GHG is only used to appoint the emission of Carbon dioxide(CO_2)

Thrust deduction factor:
The difference between total thrust of the propeller and the hull resistance R as a fraction of the total propeller thrust is called the thrust deduction factor$t$:

$$t = \frac{K_p * T - R}{k_p * T} \tag{1}$$

The term thrust deduction is chosen because only a part of thr thrust produced by the propeller is used to overcome the pure towing resistance of the ship, the remaining part has to overcome the added resistance.[81]

Wake factor:
An important effect is that the velocity of the water at the propeller location does not equal the ship's speed: the entrained water in the boundary layer around the ship has a certain forward speed. The boundary layer at the ships stern has a considerable thickness and normally the propeller is completely within the region where the water velocity is affected by the hulls presence. As a result the advance velocity v_a of the propeller relative to the water is smaller than the ships speed v_s[81].

Brexit:
The withdrawal of the United Kingdom from the European Union. This event had huge consequences for the area's in which the Dutch fishing was allowed to fish. Dutch fishermen catch almost everything outside of Dutch fishing waters. More than 45 per cent of "Dutch" fish are caught in British waters. In the case of herring, this even amounts to almost 90 per cent.[156]

Landing obligation:
The landing obligation was introduced in 2015 and has been fully in force since January 2019. Rules

related to the landing obligation stipulate that.(1) all catches of species regulated through catch limits (such as mackerel) or minimum size (such as anchovy in the Mediterranean) should be landed and counted against the fishers' quotas (2) undersized fish caught and landed should not be used (sold) for direct human consumption, but for products such as pet food, fish meal, pharmaceuticals, and food supplements(3) producer organisations have a duty to help their members find adequate outlets for undersized catches, without promoting the creation of a market for them(4) EU countries also have the obligation to assist fishers by facilitating the storage of undersized fish and finding possible outlets[4].

Transom area:
Underwater cross sectional transverse area at aft perpendicular.

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Nomenclature

Abbreviations

Abbreviation	Definition
ISA	International Standard Atmosphere
MARPOL	International Convention for the Prevention of Pollution from Ships
IMO	International Maritime Organisation
GT	Gross Tonnage
FPP	Fixed pitch propeller
CPP	Controllable pitch propeller
TRL	Technical readiness level
SFOC	Specific fuel oil consumption
STW	Speed through water
TCO	Total cost of ownership
Nm	Nautical mile, 1852m

Symbols

Symbol	Definition	Unit
V	Velocity	[m/s]
Kn	Vessel speed	[NM/h]
L_pp	Length between perpendicular	[m]
L_{wl}	Length waterline	[m]
B_{mld}	Breadth moulded	[m]
C_B	Block coefficient	[-]
T_{app}	Draught aft perpendicular	[m]
T_{fpp}	Draught forward perpendicular	[m]
$\dot{m}_f$	Fuel flow	[kg/s]
P_O	Open water propeller power	[kW]
P_P	Actually delivered propeller power	[kW]
P_S	Shaft power	[kW]
P_T	The power delivered to propeller moving at velocity v_a	[kW]
P_e	Effective power propeller	[kW]
P_B	Delivered engine brake power	[kW]

1
Introduction

1.1. Background

The fishing industry is recognized as a contributor to pollution and is partly responsible for the greenhouse gas emissions. Therefore, the maritime industry is working towards reducing CO_2, vessel emissions. Within the sector different guidelines have been developed, aimed at reducing the emissions. Two major legislators are the International Maritime Organisation's (IMO), with the 'Greenhouse Gas strategy' [164] and the European union, with the 'Fit for 55' [46]. In 2015 the United Nations Paris Agreement was signed and as a result IMO set the objective to reduce the CO_2 emissions of shipping industry with 40% compared to 2008. The EU has set the reduction of GHG emissions to 55% compared to 1990. The IMO and EU both categorize fishing vessels as a part of the shipping industry. This set of regulations currently have partly similar goals and are applicable to similar sizes of vessels. The EU regulations apply to vessels 5000GT+ similar to IMO regulations which also apply to 5000GT+ vessels. The average Dutch beam trawler Gross tonnage is around 450GT [120], therefore the EU and IMO regulations do not include Dutch beam trawlers for now. Despite this the last serious updates are that IMO will change this, such that fishing vessels with a gross tonnage of 400GT+ [186] will be included and thus apply to Dutch beam trawlers, [164].

IMO regulations will influence the future perspective of the Dutch beam trawler fleet. The Dutch fishing industry has experienced tough years. In the short term, the fleet had to face implementation of the EU landing obligation [4], a ban on pulse fishing(see definitions) [160], increased MGO prices [53] and BREXIT [156]. Due to the EU landing obligation all fish including undersized fish have to be landed on shore. Therefore the fishing quotas(total allowed weight of a specific fish species landed per year) are reached quickly, resulting in decreased earnings [4]. The BREXIT ended the sharing of international fishing quotas and fishing grounds. The total fishing quota of the Dutch fishing fleet was reduced by +/- 25% and the English territorial waters were closed to Dutch fisherman [156]. The current and future development of offshore wind farms within the Dutch territorial waters will put a second serious restriction on the remaining available fishing ground [116]. In the medium term, it is clear that fishers will have to share the North Sea with an increasing number of new users and deal with loss of fishing ground due to development of offshore wind farms and implementation of new nature conservation areas (p.40 [6]). These factors inflicted significant financial damage on the industry, leaving it unable to pursue innovation. As a result, the average age of Dutch beam trawlers is considerably high, with 75% of the 280 active vessels having an average age of 20 years [131]. This old age results in higher operational expenses and relatively high fuel consumption. The beam trawlers are built with 20 year old requirements and equipment. This results in: high maintenance time, high maintenance costs and power plant setups with lower efficiencies, with respect to techniques and theories available today. The old age may result in not meeting future environmental standards or regulations [184].

These developments have led to the Dutch Minister Staghouwer (Agriculture, Nature and Food Quality) to fully commit to scale down the number of fishing beam trawlers and to make the remaining of the beam trawler fleet more sustainable. The Dutch cabinet has reserved €444,- million to stimulate their wish to make the Dutch beam trawler sustainable. A part of the reserved budget €245,- million is meant to innovate [153] the existing fleet. The remaining part of the budget is meant to buy out fishing companies which do not see any future perspective in their company. This perspective can for example, be based on upcoming regulations, no successors in the company or not being financially strong enough to continue fishing. On the first of October 2022 the Dutch government opened the opportunity for fishing companies to sell their fish quota including their vessel to the government [132]. With this remediation the government aims to reduce the total amount of fishing quota in Dutch territorial waters and to create a remaining fleet of fishermen which are willing and able to innovate.

With the buy out and high fuel costs on the horizon studies have been done on reduction of CO_2 emissions by means of alternative energy carriers on new build (beam) trawlers. These where research topics as: feasibility study fishing on natural gas [118], LNG potential energy source [120] and Design Green shrimp trawler [169]. There are mainly three ways to reduce the emitted emission of a vessel: (1) reducing the energy consumption of the vessel, (2) after treatment of the rest product of energy converter or by (3) changing to an alternative fuel. All the mentioned and open source studies are done on new build beam trawlers, these studies discuss one methods to reduce CO_2 and do not combine all three options and aspects together. The application of each study and the missing or use full outcomes are described in Table 1.1.

Table 1.1: Summary of relevant research topics with their (dis-)advantages

Author	Title	Goal	Usefull	limitations
Ir. P. 't Hart [118]	Feasibility on: 'Boomkorvissen op aardgas'	Feasibility of LNG on beam trawler	Information of LNG and the consequences of applications on existing beam trawler	Fuel prices outdated, Available engines and storage tanks characteristics singificantly changed over the years
H. Deelstra [169]	Ontwerp groen (energiezuinige) garnalenkotter	Emission reduction on shrimp trawler	Energy reducing measures exploration	Shrimp trawler, sailing area, new build
Jean-Marc Laurens [107]	Design and retrofit of the propulsion of trawlers to improve their efficiency	Increasing the propulsive efficiency of trawlers	Applications of: ducted and bigger propellers , thrust requirement, propeller efficiencies	Small trawlers, small propellers, different operation profiles,
MDV [120]	Masterplan Duurzame Visserij	Emission reduction twinrig trawler	Energy reducing measures exploration	Twinrig trawler, Diesel-Electric new build
DNV GL [2]	Maritime Forecast to 2050	The future carbon neutral fuel mix options	Information on alternative fuels, energy converters, future developments	Applied: -world wide -to all ship types,

1.2. Involved companies

This thesis is performed in association with Padmos, a family company established in the 1930s. Stellendam is the head quarter of the company with a dry dock with a capacity of 1,200 tons. From Stellendam the company started to build and rebuild multiple types of fishing vessel: beam trawlers, twinriggers, flyshooters, mussel vessels and port tugs. The companies motto is ”We keep you fishing” this represents the thought to prepare fishermen for the future. A future perspective is believed to lie in making the environmental impact of the vessels as small as possible.

1.3. Regulations on maritime emissions

The drivers behind the reduction of the emission of pollutants are national and international regulations. It is expected that a Dutch beam trawler will be subjected to international regulations set by the IMO within coming years. The technical requirements of the vessels are determined by Vissersvaartuigenbesluit 1989(VVB), which is a part of the Schepenwet [192]. The VVB prescribes regulations on redundancy of engines, ship stability, fire fighting and ship communications.
The initial IMO strategy on reduction of CO_2 emissions from ships Resolution MEPC.304(72) [164] is the latest revision concerning emission regulations. These technical frameworks are aimed at implementing a 40% reduction in carbon intensity compared to 2008 across the global shipping fleet by 2030. The next step in the time frame is a 70% reduction in carbon intensity compared to 2008 across the global shipping fleet by 2050. These measures will be implemented through amendments to Annex VI of the 1973 International Convention for the Prevention of Pollution from Ships(MARPOL). This emission cut is compulsory to all purpose vessels 5000GT and above. Although 5000GT is far above the GT of a beam trawler this gross tonnage limit will presumably be changed to 400GT+ [182] [184]. This development which is not implemented yet but is assumed to be implemented causes the beam trawler to be included into the discussed emission cut regulation.

Another large party which develops maritime emission regulations is the EU. The main regulations is 'Fit for 55' [46]. Another type of EU legislation to stimulate the reduction of CO_2 is the implementation of the European Trading System(ETS) by the European commission(EC). To comply with the ETS companies buy CO_2 allowance quota's. The total amount of ETS quota is limited and therefore companies have to decide to emit less CO_2 or pay more for the emitted CO_2 [43]. The emission quota will decrease over the years which means that CO_2 emissions prices will increase [44]. Similar to the ”Fit for 55”, vessels below 5000GT are for now excluded from the ETS [60], [41] .

The fishing industry is mostly excluded from both IMO and EU regulations and will remain exempt. Despite this, rumours spread that within upcoming IMO carbon regulation updates the fishing industry will be included [69]. Due to this great uncertainty, when a policy will be introduced, the vessel owners must determine when and how to act. To comply with the IMO emission regulations is the main requirement the vessel has to meet in this research. This is based on [184], which informs fishing vessel owners to assume IMO regulation will be applicable within a couple of years.

Due to the Dutch government's belief that the implementation of EU and IMO regulations is progressing too slowly, they have devised an additional tax on top of the ETS system. This additional tax is intended to ensure that CO_2 is taxed earlier, this is named the Dutch emission tax, [92] [152]. In Table 1.2 the expected prices from the ETS and the Dutch emission tax system which is an addition to the ETS [28], [52]. The purpose of the Dutch tax system is to provide a sufficiently strong price signal to stimulate long-term investments in low-carbon technologies. The Dutch emission tax system price which is fixed by the Government, while the ETS price depends on the industries supply and demand and therefore is hard to predict.

Table 1.2: EU and Dutch CO_2 emission tax prices, [152], [52], [43], [92]

System/year/€ per tonne	2023	2024	2025	2026	2027	2028	2029	2030
ETS	81	84	84	98	98	98	98	98
Dutch emission tax	5	18	37	50	63	75	91	100

1.4. Societal relevance

The IMO has adopted the ”Greenhouse Gas Strategy” which aims to reduce the CO_2 emission of the maritime industry with 40% in 2030 and with 70% in 2050 both in relevance to 2008. Greenhouse gases trap and hold heat in the earths atmosphere, which results in global warming. The global use of carbon containing fuels has caused an increase in CO_2 in the atmosphere of 320ppm in 1960 till 420ppm in 2020 [110]. If this trend continuous this will have disastrous consequences on the weather, rising sea levels, animal extinctions [76]. Therefore it is relevant to do research in the reduction of greenhouse gasses of the Dutch beam trawler fleet.

The Dutch beam trawler fleet is partly responsible for the weekly supply of fresh wild fish into the Dutch food marked. By complying to the IMO legislation the vessel owners allow them self to continue fishing in the future and supplying the marked with fish. Fish resources play key roles for human food supply and aquatic ecosystems. Fish is among the most traded food commodities, and makes an important contribution to sustainable incomes and employment opportunities [75]. Secondly it is crucial to come to a profitable and sustainable fishery that is in balance with the current available fish stock and available fishing areas. This calls for reorientation and ultimately restructuring of the fleet. That is not just one ecological necessity and a business economic realty, but also a social requirement: people who work in the industry, both on land and at sea urgently need a clear future perspective [188].

1.5. Previous and knowledge gap

During the build up of the literature study multiple studies where found which (partly) treated the main question of this research. Each of these studies come with their own limitations and use full outcomes. In Table 1.1 the most matching studies with their information, limitations and what can be used or why it can not be used are summarized.

The Dutch beam trawler sector is experiencing tough years in which the revenue and profit margins are low. The IMO 2030 regulations requirements will result in more complex vessel and mission equipment, this will result in higher investments and directly or indirectly increase(or decrease) the operational expenses. Looking at emissions and fishing regulations their is a lot of future uncertainty. This uncertainty is driven by future availability fishing grounds and alternative fuel characteristics. Therefor it is reasonable and necessary to model different scenarios to get insight in the influence of propulsion configurations on economical and technical performance.

A research gap is found in the technical and economical feasibility of a 2030 proof Dutch beam trawler. Currently a Dutch beam trawler operates on the edge of being profitable, but it is not yet known and investigated for a 2030 IMO complying Dutch beam trawler.

1.6. Research goal

The goal of this research is to analyze the influence of CO_2 emission reduction methods on their technical feasibility and economical aspects to comply with 2030 IMO regulations of existing beam trawlers. These configurations mainly consist of mono-fuel options, but should also include hybrid configuration proposals. The economical feasibility includes (future) factors such as: hull extension costs, energy carrier prices, maintenance costs, system depreciation and CO_2 emission tax.

1.7. Research Question

To be able to satisfy the research goal the main research question is formulated as:

To what extent is it technically and economically feasible to reduce the CO_2 emissions of Dutch beam trawlers to meet the 2030 IMO emission regulations, while maintaining vessel operational effectiveness?

1.8. Research Sub Questions

The main question is divided into multiple subquestions, from which each subquestion is answered in a separate chapter. At first the Dutch beam trawler has to be investigated. How does the vessel operate, how does the propulsion configuration look a like etc. Therefore in the first subquestion research is done on defining: operational profile, vessel design, relevant regulations and vessel effectiveness. Answering this question will help determining the requirements of new applied systems and set the benchmark from which the research will be based. This sub questions will be answered in chapter 2.

What are the current characteristics of a Dutch beam trawler and what are their requirements?

Secondly, research will be done into the state of the art methods to reduce the emissions of the vessel, which help to identify the main gaps between the required emission reduction and the state-of-the-art. This study will identify the characteristics of different: alternative fuels, energy consumption reduction and exhaust gas treatment. This sub question also looks into which parameters of the energy carriers and systems are important to analyse for this research. This results in the following subquestion with its sub sub questions to clarify the separation within the question. This sub questions will be answered in Chapter 3.

What are the relevant methods to reduce CO_2 *emission on a Dutch beam trawler?*

- What alternative energy carriers are most suitable to be applied on a beam trawler and are available now or in the coming years?
- What energy consumption reduction systems are most suitable to be applied on a beam trawler and are available now or in the coming years?
- What exhaust gas after treatment systems are most suitable to be applied on a beam trawler and are available now or in the coming one to three years?

After determining the possibilities to reduce emissions the feasibility of the configurations has to be determined. To do this, research will be done on building an assessment model which can handle and process the information of sub question 1 and 2. Therefore it must be known what requirements are set for an assessment methodology. It should cover: energy carrier choice, exhaust gas treatment choice, pay back time, energy consumption reduction techniques choice, exhaust gas treatment system choice and their vessel design implications. Therefore multiple possible scenarios which may be used in deciding which strategy needs to be chosen for a 2030 proof beam trawler. This results in the following sub question with its sub sub question to clarify. This sub questions will be answered in Chapter 4.

What are requirements for an assessment model and what parameters should it include to determine the technical and economical feasibility of CO_2 *emission reduction systems?*

- What elements are to be taken into account in the model?
- What requirements are set to future en today uncertainties?
- Which methodologies are capable to process this input and what are there characteristics?

With the model built, the influence of emission reduction methods on the OpEx, Capex and vessel design are known. The model must be able to evaluate the technical configurations across multiple future scenarios, this is treated in Chapter 5.

How will the implementation of a new propulsion configuration influence the, vessel design, and economical performance in different future scenarios?

The second point of attention after the model is build according the outcome of answering sub question 3 it must be tested and checked on its reliability. Therefore the assessment model with its outcomes have to be validated and verified. The goal of this sub question is to determine how the quality and reliability of the model can be checked, Chapter 6.

How can the assessment model for the feasibility of the 2030 proof beam trawler model be verified and validated?

Scope of project

In this brief section, a preliminary explanation is provided regarding the extent to which this research takes certain factors into account.

- Methods to reduce the CO_2 emission including the financial costs and technical consequences are within the scope of the research.

- This research will include the calculation of hybrid options, the available options are based on the 40% CO_2 reduction. This means for example: a 100% hydrogen powered proposal is changed to hydrogen and MGO such that 40% CO_2 reduction is still achieved.
- The scope of this project is the refitting of existing beam trawlers. With the financial help of subsidies it could be possible to apply some of these emission reduction methods. Although it should be kept in mind if it is worth refitting the vessel or buying a new build beam trawler. To determine this the estimated costs and performance of the refitted vessel are referenced to a new build PADMOS beam trawler.
- If it is found not feasible to comply with the 2030 IMO regulations without significant design changes or modifications, then this research will examine changing the operational profile.
- The next step in the IMO carbon strategy which is the 2050 emission reduction is not within the scope of this research.

2

Vessel data

This chapter functions as a starting point of the research by defining the current design, operation and regulations for Dutch beam trawlers. By researching these topics, subquestion 1 will be answered.

”What are the current characteristics of a Dutch beam trawler and what are their requirements?”

Before discussing alternative design options for the vessel it is important to understand how the current vessel is designed and used. For this research a Padmos built beam trawler is chosen as a reference and benchmark vessel. The data of this vessel and her operation is used to determine which data is important to take into account when discussing emission reduction methods and developing an assessment model.

2.1. Vessel specifics

The reference vessel used in this research is a 1987 build beam trawler, Figure 2.1. A summary of the vessel parameters are presented in Table 2.1, all specification can be found in Table A.1. This vessel is used because its operation and propulsion plant is found to be a good representative of an average Dutch beam trawler. The latest study(2021) showed the average age of the 284 active Dutch beam trawlers(including shrimp trawlers) to be 32 years (build 1990), with 75% being older than 20 years. From which the beam trawlers excluding shrimp trawlers have an average total installed diesel power ranging from 1000 to 1450 kW [168]. Therefor by designing the calculation model to fit the case vessel specifications means it can be used for a large variety of Dutch beam trawlers. The vessel is powered by a conventional engine room set up. For this vessel that means the main engine is directly coupled to the propeller by means of a gearbox.

Table 2.1: Ship particulars, case vessel

Lpp	33.75m
Beam	7.5m
Draught	3m
Displacement	500 tons
Block coeff.	0.6
Mechanical data:	
Main engine	1200 kW Stork Werkspoor
Auxiliary DG	335 kW Mitsubishi
Propeller diameter	2.5
Winch	100kW

Figure 2.1: Example beam trawler, for illustration only[Padmos]

The electric board is fed by an auxiliary engine and the hydraulic pump is driven by an auxiliary engine, Figure 2.2. The engines which produce the electrical, hydraulic and thrust are all running on Marine Gas Oil(MGO). The electrical board of a beam trawler has three main consumers which are constant or vary over time:

- **Winch**: This is a winch with six or eight drums on it which can all be operated separately. These drums store steel wires which all have their specific function on the vessel. The winch is mainly responsible for setting, fishing and hauling the fishing nets. This means they winch is only used when hauling and setting the nets. During fishing the winch is blocked by means of a brake to fix the length of the fishing line. The winch is powered electrically or hydraulically, both types of energy is delivered by the diesel powered generator or hydraulic pump. The size and power of the winch depends on the specific fishing gear, but ranches from an installed power of 160kW to 250kW
- **Hotel load**: The systems which represent the hotel load are responsible for: lights, galleys, HVAC, engine room ventilation, engine room pumps, black/grey water pumps and bridge equipment. These machines take care for the continuous welfare of the crew including communication and safety. The hotel load is vessel specific, but is in the order of installed power of 45kW to 150kW.
- **Ice machine and Cooling machine**: These machines make sure that the catch is conserved to optimize the delivered quality of the fish. As soon as the fish is processed on deck the fish is transferred to the fish hold. This hold is cooled to $0°C$ by means of sub cooled brine and ventilators. This system is a so called indirect cooling system. The brine is cooled in the evaporator of a conventional cooling unit. The fish is quickly brought to $0°C$ with the help of flake ice. Sea water is transferred into ice by means of a super cooled rotating roller. The roller is cooled internally by the brine, the brine is also cooled by a conventional cooling unit. A conventional cooling system is defined as, Figure 2.3, it is operating on an a R450 refrigerant. This load is vessel specific, but are in the order of installed power 20kW to 40kW

From these consumers the hotel load and ice/cooling machine are started as soon as the vessel starts operating and are switched off when the vessel arrives in port. These two loads are dependent on the ship's size and crews requirements on living conditions in the accommodation.

For the case vessel the average combined auxiliary load is 63kW, this includes hotel load and Ice/-Cooling machines but excludes required winch power.

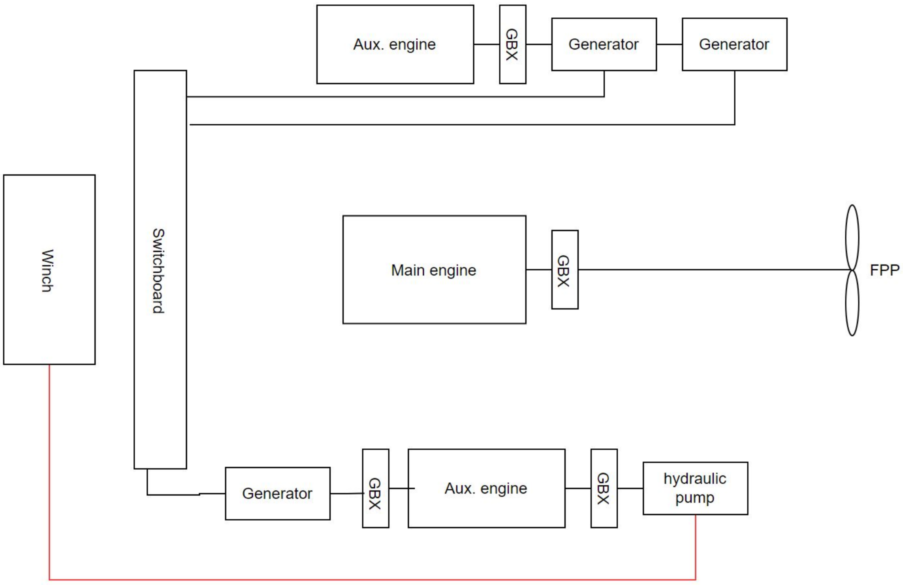

Figure 2.2: Engine room layout case vessel

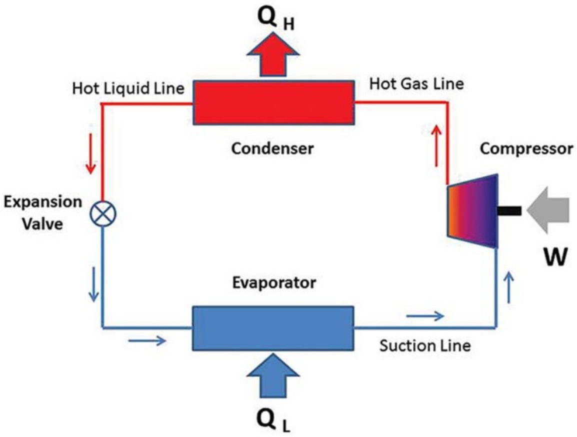

Figure 2.3: Typical base components cooling system

2.2. Operational profile

In this section the particulars of an operational profile of a Dutch beam trawler are examined and defined. The overall operational profile of a beam trawler can be sub divided into a short cycle and a long cycle. This division is made to get a better understanding between different operational profiles. The short cycle, also known as the fishing cycle consists of a repetition of, setting the nets, fishing and hauling the nets. This cycle starts at arrival on the fishing grounds and is repeated until the the decision is made to head to port. The long cycle is the overall fishing trip which consists of sailing to the fishing grounds, fishing(short cycle), sailing back to port from the fishing grounds, Figure 2.5. The different operational profiles and cycles are determined based on information delivered by vessel operators.

Figure 2.4: Operational area Dutch beam trawlers

In general the vessel has two different types of long cycles the 100hr and the 160hr. The beam trawler is mainly operated by two different type of owners, which also use the vessel in two different ways. Therefor a division between the two long cycle is defined and used as a variable in this research. The long cycle has a direct influence on the short cycle, because it will determine how many times the short cycle is repeated. In general the short cycle does not change much between the different type of vessel owners, therefor one short cycle is defined and used. To get an idea of the operational profiles the next two sections elaborate the two different long cycles. The sailing from and to the fishing is the speed which matches with a 9 knots vessel speed. The vessel speed during trawling is always +/- 5 knots, since this has proven to be the ideal speed for the fishing gear that is used [154].

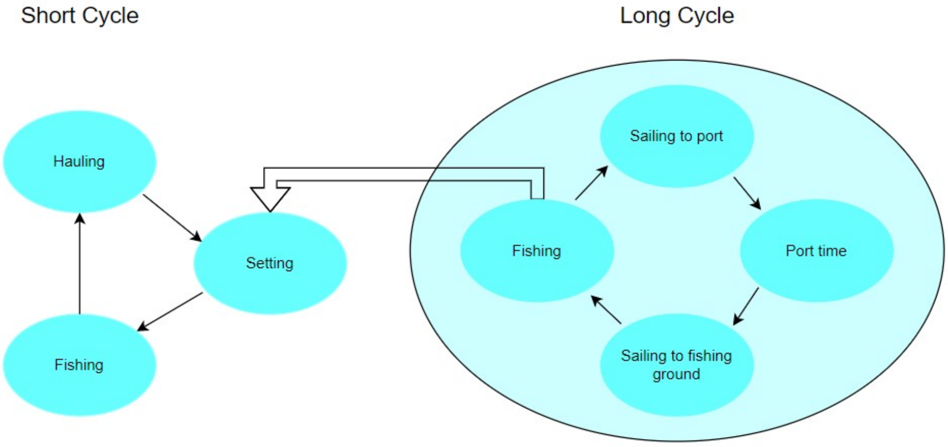

Figure 2.5: Operational profile, short cycle within the long cycle

2.2.1. 100hr Long cycle

This group of owners operate their vessels in such a way that the vessel is in port for the weekends. This is the case either due to their religious belief or because the vessel is operated by one group of crew. Although in a later stage it can be found that the operational days of the vessels have to be changed this is not considered to be an optional suggestion for the crew which are in port due to their religious belief. The operational area of the vessel is in the Dutch economical zone, Figure 2.4, however sometimes also includes United Kingdom waters. If the vessel operates in these areas the departure and arrival port is generally in Harlingen, Vlissingen or Stellendam. This results in an average sailing time from port to fishing grounds of 8 hours. Table 2.2 illustrated a detailed overview of the average 100 hr long profile, which is used in this research.

Table 2.2: 100hr long cycle, operational profile

Day	Start hour	End hour	Operation
Monday	02:00	10:00	Sailing to Fishing grounds
Monday	10:01	23:59	Fishing
Tuesday - Thursday	00:00	21:59	Fishing
Friday	22:00	06:00	Sailing to port

2.2.2. Continuous Long cycle

This operational profile is defined by operating the vessel for almost 7 days a week. The vessel is operated by two groups of crew which have their crew change every Thursday of the week. Mainly this type of operation is based on reducing the average costs of insurance and bank pay off per fishing day. Similar to the 100hr operational profile these vessels also operate from the port Harlingen, Vlissingen, Texel or Stellendam. In general this results in an average sailing time from port to fishing grounds of 8 hours. Table 2.3 illustrates a detailed overview of an average long cycle a continuous operational profile, which is used in this research.

Table 2.3: Continuous long cycle, operational profile

Day	Start hour	End hour	Operation
Thursday	08:00	12:00	Alongside
Thursday	12:01	20:00	Sailing to fishing grounds
Thursday	20:01	23:59	Fishing
Friday-Wednesday	00:00	23:59	Fishing
Thursday	00:01	7:59	Sailing to port

2.2.3. Short cycle

The moment the beam trawler arrives at the fishing grounds the short cycle starts. This cycle is a repetition of setting, fishing, hauling/emptying of the nets. Table 2.4 illustrates a detailed overview of the average short cycle, which is used in this research. The hauling and setting of the nets is a harmony between winch and vessel maneuvering to guarantee the nets remain clear from the propeller.

Table 2.4: Short cycle, also known as fishing cycle

Operation	Time[minutes]	Speed[knots]
Setting	10	2.5
Fishing	150	5
Hauling	10	2.5

.

2.3. Fuel consumption

To determine the amount of fuel used per long cycle, the fuel consumption must be known. The fuel consumption depends on the type of operation the vessel is in. The total fuel consumption depends on the duration of each operation during the long cycle. The fuel consumption also depends on external factors like: sea state, trawl net type, soil type, current, wind speed etc. In Table 2.5, Table 2.6 and Table 2.7, the average fuel consumption of each long cycle is defined. The fuel consumption at each operation is an actual measurement on board including the fuel consumption of the auxiliary engines. This is used as the reference point since this is also the input on how the IMO will calculate the CO_2 emissions of the vessel, as explained in Chapter 3.2.1. The measurement results of the free sailing, bollard pull and fuel consumption are depicted in Figure A.1

Table 2.5: Characteristics 100hr Long cycle

100hr Long cycle	hrs	Percentage	Fuel consumption[l]
Sailing	12	12%	1464
Fishing	76	76%	18228
Hauling/Setting	12	12%	1173
Total	100	100%	20866

Table 2.6: Characteristics Continuous Long cycle

Cont. Long cycle	hrs	Percentage	Fuel consumption[l]
Sailing	12	7%	1464
Fishing	132	80%	31484
Hauling/Setting	20	13%	2027
Total	164	100%	34975

Table 2.7: Fuel consumption per operation

Fuel consumption	[l/hr]
Sailing[9.0kn]	122
Fishing[5kn]	239
Hauling/Setting[3.5kn]	100

2.4. Vessel effectiveness

This section will answer the question ”What makes a good beam trawler?”, this is a part of sub question 1. The answer to this question will be a good representative for most beam trawlers. Although there is a large similarity in operation some performance requirements are vessel owner specific.

The vessel should be able to fish according the desired operation. This means that the vessel is able to tow the desired fishing gear at a certain speed for an amount of hours. The operational time, fishing area and fishing gear also results in a requirement on the minimum amount of full and empty fish boxes to store in the fish hold. The used fishing gear puts requirements on the propulsion and fuel storage, but it also influences the minimum required length of the vessel to store the fishing gear when in transit. Within the next summation the main characteristics on which the performance of a beam trawler is determined.

- **Towing capacity**: The vessel should have enough thrust to be able to fish with a speed overground of 5 knots, no matter which current. The minimum thrust is determined by the specific fishing gear the owner is using. The measured average pulling force in the wires is equal to the minimum required thrust, excluding hull. This normally ranges between 6 to 12 tons depending on fish species.
- **Fish hold**: the size of the fishing hold is influenced by many factors. The landing ports, target species and the OP duration are the most influencing of these factors. The required quantity of

fish boxes is determined by fishing days and target fish species. A fish box has the standard dimensions: 80x45x27cm. Next to a minimum requirement amount of full boxes, there is a minimum on stored empty boxes as well. Since the vessel sometimes lands the fish in the closest port in vicinity there should be enough fish boxes to complete two full fishing trips. This is caused by the high transportation costs for empty fish boxes.

- **Endurance**: The vessel should be able to execute one of the described long cycles, which depends on vessel owner Chapter 2.2.
- **Cooling**: the vessel should have the ability to cool down the fish hold to 0°C. Next to hold cooling, ice flakes are required to decrease the time needed to bring the fish core temperature to 0°C. The cooling and ice machines should be very reliable since the breakdown of this system means destruction of the fish. The brake down of a cooling/ice machine means the end of the fishing week and loss of caught fish.
- **Winch**: A winch with enough drums and steel wire capacity is required for fishing and handling of the fish gear. The winch should have enough brake capacity and the hauling capacity should minimally exceed the weight of the fishing gear including hydrostatic resistance of the water.
- **Working deck**: the length of the working deck should be such that the fishing gear can be stored and sea fastened while in transit. This requirement is already satisfied for an existing vessel, but the desired fishing gear and vessel length are of importance when designing a new vessel.
- **Storage area**: depending on the operator a minimum volume is required to store spare parts for of the fishing gear. This area has an average volume of 24 to 30 m^3

Client specific requirements
Next to the legislation and operational requirements the current vessel owners put additional requirements on the living conditions and safety of the crew. This results in for example: requirements on maximum vessel motions(anti rolling tanks), noise levels, maintenance low machines and internet connections. Although these requirements could be very specific they do not result in significant changes in design or operation and are therefor not in the scope of this research.

2.5. Vessel legislation requirements

The beam trawler is designed and built based on different types of requirements: (1) operational requirements, (2) personal preference of the vessel owner on how to use the vessel and (3) the requirement set by Dutch and international legislation. Within this chapter the most important and influencing vessel requirements are discussed and elaborated.

Technical
Two types of technical legislation apply to a Dutch beam trawler: IMO and vissersvaartuigenbesluit 1989(VvB). The IMO sets international regulations for the safety of fishing vessels. These regulations set rules for construction and equipment of fishing vessels. The regulations are defined in Annex 25 of the Torremolinos Protocol of 1993 [87]. These legislation puts a standard on noise, safety, construction, power distribution, redundancy, water integrity, fire integrity etc. Technical requirements are also set by IMO through Safety of Life at Sea(SOLAS), these prescribe specific regulations regarding safety features, procedures, systems etc. The VvB applies to fishing vessels of 24m<L<45m. The VvB prescribes safety regulations which apply to new and excisting fishing vessels, which are build to be used commercially to catch fish or other sources from the seas. These safety regulations relate to:

- Construction
- Watertight integrity
- Stability(seaworthiness)
- Machine- and Electrical installations
- Protect, detect, and fire fighting
- Safety crew
- Rescue equipment and facilities
- Emergency procedures and radio communication

Environmental
The regulations concerning emissions of the vessel are described in chapter 1.3. Beside the emission legislation a second group of environmental legislation is set by the EU and Dutch government. The Dutch fishing management is regulated by the Visserijwet and the Visserijbesluit[191] [192]. This legislation has a direct influence on the economical and technical performance and requirements of the vessel. The Visserijwet prescribes legislation for:

- Fishing areas
- Fishing Quota
- Fishing net set up and sizes
- Inspections
- Fishing outside territorial waters

The EU legislation is represented by the Common fisheries policy(CFP) [42]. The Common Fisheries Policy (CFP) is the mechanism and set of rules through which European fishing fleets and fish stocks are managed. It began in 1970 and was most recently reformed in 2014. The CFP applies to all EU member states, but only 22 of the EU27 are coastal states. It gives all European fishing fleets equal access to EU waters to create fair competition. It aims to ensure that European fishing is sustainable, balancing the desire to maximise catches with conserving fish stocks. CFP has four main policy areas:

- Fisheries management – ensuring the long-term viability of fish stocks like cod, tuna, and prawns in EU waters
- International policy and co-operation – working with non-EU countries and international organisations to manage shared fisheries, including Norway, Iceland, Morocco and Cabo Verde.
- Market and trade policy – creating fair competition in the market and setting standards on seafood products sold within the EU to protect consumers, such as requirements for clear product labels.
- Funding – money to support fishermen transitioning to more sustainable fishing and assist coastal communities in diversifying their economies. The UK has chosen to spend €19.3m of its EU funding on improving sustainability in the sector during 2014–20.

Another type of legislation which is related to environment is the International Convention for the prevention of Pollution from Ships(MARPOL). It is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes.

2.6. Chapter conclusion

In conclusion of this chapter subquestion 1 is investigated and answered:

"What are the current characteristics of a Dutch beam trawler and what are their requirements?"

The average age of a Dutch beam trawler is +/- 20 years, this old age is caused by the small profits and uncertain future perspectives within the last and coming decades. The vessels average characteristics ranging: L_{pp}:35-42m, $B_{moulded}$:6-9m, T_{mid}:3-4.5m, D_{prop}:2-3m, $Prop_{speed} : 200 - 300rpm$ and an installed P_b:1000-2000kW. The future perspective showed a concerning amount of offshore wind turbine parks at sea, BREXIT and the ban on emission friendly pulse fishing etc.

The propulsive and auxiliary power required to operate the vessel is generated by diesel engines. This means that the propeller is driven by an internal combustion 4-stroke engine fueled by MGO. The auxiliary systems are powered by a minimum of two internal combustion engines from which both can produce electricity and additionally one is equipped with a hydraulic pump. The main energy consumers onboard are the ice & cooling machines and the winches. It is found that the state of the art for beam trawlers limits itself to optimized propeller and diesel engine configurations but does not go any further.

The eventful years will be followed up by strict future Dutch and European legislation. The IMO, Dutch government and EU accepted legislation putting limits or reduction programs on the production of CO_2

emissions. In short these IMO technical frameworks are aimed at implementing a 40% reduction in carbon intensity compared to 2008 across the global shipping fleet by 2030. To stimulate these implementation of CO_2 emission reduction the EU and Dutch government introduced and tax system to penalize the emission per tone CO_2.

The vessel operation is divided into an average long cycle and short cycle, from which the short is an average of the whole fleet but the long cycle changes depending on vessel owner. The short cycle is the fishing cycle, which consists of fishing, hauling and setting of the nets. The Long cycle is the cycle from port to fishing grounds and back in port. Due to religious belief or company policies the long cycle varies between vessels.

At last research is done on the technical requirements of a Dutch beam trawler. The technical requirements consist of two parts: (1) Dutch(VvB) and IMO(SOLAS) legislation on how the vessel should be build, (2) Operational requirements to be able to operate the vessel as a beam trawler. From which the second are the most influential on the vessel design of the current MGO fueled vessels. The operational requirements consist of: minimum thrust force at 5 knots, minimum fish hold volume, minimum fishing endurance, minimum storage volume, minimum winch power, and a minimum capacity cooling machines.

Economically the margin between costs and revenue are small. The latest development concerning the buy out of fishing licenses and future regulations make it very hard to predict how the coming years are going to look a like. Due to the Dutch governments subsidy on vessel retrofitting, vessel owners are willing and openly looking at possibilities to reduce their CO_2 emission. The two main drivers which are influenced by the operators and designers to increase the profitability of the vessel are amount of catch-ed fish and fuel consumption. From which the last is of most concern within this research. The retrofitting of beam trawlers require large capital investment and it will influence vessel design and Opex. Another uncertainty in this retrofitting is that the conditions for receiving subsidy are not yet fully developed.

3

Emission reduction exploration

To achieve the goals set out by the IMO which could come into force for the Dutch fishing sector, steps have to be taken. To make a technically feasible outcome more likely, this chapter researches ways to optimize the reduction of CO_2 emission on beam trawlers. This chapter attempts to answer the subquestion:

"What are the relevant methods to reduce CO_2 emission on a dutch beam trawler?"

The identified methods to reduce the emission of CO_2 are categorized as: (1) energy converter together with alternative fuel carriers, (2)energy consumption reduction methods and by (3) exhaust gas after treatment. Due to the urgency of the problem and the available subsidy in the coming year this research looks at methods which have a high level of technical readiness. The intention of this decision is to make this research more practically usable in the near future, since this is required due to the nature of the problem. After Chapter 3.1 and Chapter 3.2 a selection is made in: energy carrier, fuel (re)former's and energy converters combinations.

3.1. Energy converters

The vast majority of marine propulsion and auxiliary plants onboard ocean-going vessels are diesel fueled internal combustion engines(ICE's). Although these engines have proven to be reliable, future propulsion setups show to deviate from the use of ICE's only. Therefor it is expected that diesel engines will be replaced in a foreseeable period of time. The developments of future emission inventories is a challenge, driven by requirements for global model studies of the effects of the emissions on climate. The research, studies and experiments executed on the development of new energy converters resulted in a significant grow on technical readiness level(TRL) of a system [10]. Due to these developments different alternatives for the ICE energy converter are discussed within this paragraph. Second from ICE, fuel cells will be discussed since these show great potential. Although FC's are new, their high efficiencies and ability to operate without CO_2 emissions has already led to the application of FC's on vessels. The latest converter treated is the electric motor, the application of this converter is a direct result when energy converters are used which produce electrical power instead of mechanical power.

3.1.1. Internal combustion engine

ICE's are highly developed, and they have a wide range of power application, a wide range of rotational speed application and operate with efficiencies ranging between 35% to 55% [162]. The internal combustion engine is a relatively simple engine, its history showed to be highly reliable and easy to maintain. A disadvantage of the diesel engine is the low power density and the high specific emissions. Another characteristic of the engine is the operational area(toque-speed characteristics) in relation to efficiency. Since all beam trawlers already use diesel powered ICE's, all relevant other data will be available per ship to use as a benchmark. ICE's need to be developed to operate on alternative fuels, the major engine manufacturers believe this is possible soon. Therefore internal combustion engine could remain a dominant energy converter in the coming 20 to 30 years [61].

Three types of solutions exist to reduce the CO_2 of an ICE: (1) by refitting the engines so it can run in combination with an alternative fuel, (2) new build engine running only on alternative fuel and (3) new build engine running on dual fuel(diesel in combination with alternative fuel). The retro fitting of engines of older age is only found reasonable with methanol fuels and for drop in fuels [119]. Therefor many engine manufacturers have built their engines to be ”retrofit ready” in the last decade. These engines enable future modular retrofits with a limited cost. Since the average age of the trawler engines is high (Section 1.1) the engines are not retrofit ready. This means that there is no opportunity to operate the engine on another fuel [195] [145] [197]. Although this would be a good short term solution to make it possible to comply with regulations the demand for retrofit packages towards methanol engines is currently too small. Hence, only new DF and new retrofit ready diesel engines are considered in this thesis.

The main challenge of methanol fuel in an existing diesel engine is that the diesel engine is a compression ignition engine. However methanol is a spark ignition fuel, due to the high octane number. New engines use diesel pilot fuel to ignite the methanol, this concept is known as the dual fuel engine [57] [77]. 100% fuelled Methanol engines are available(MAN, MTU, Wartsila) and are used but still require time to fully develop [189] [125]. Engines running on Ammonia are expected to be ready to use in 2024 [187]. Another option is the hydrogen fueled ICE, these engines require serious development from manufacturers, some forecast and claim to be ready to install hydrogen engines in 2030 [117] [45] or 2025 [64].

3.1.2. Fuel cells

Fuel cells are electrochemical devices which convert fuel directly into electricity without any combustion. The fuel cells operate on pure hydrogen, this hydrogen is (re)-formed from ethanol, methanol, ammonia or pure hydrogen. Some fuel cells have the ability to reform fuel like ammonia or methanol to hydrogen on the anode side of the fuel cell. This internal reforming can pose problems. These problems cause lower reliability, for this reason it is common to execute the reforming of the fuel before it enters the fuel cell(p.347 [181]). To complete the transformation from fuel to energy the fuel reforming is also treated in Chapter 3.1.3. Fuel cells rely on two electrochemical half reactions to split hydrogen and thereby generating electrical energy. As seen in the equations (3.1 & 3.2) the fuel cell does not produce any harmful emissions, only pure H_2O.

$$H_2 \rightarrow 2H^+ + 2e^- \tag{3.1}$$

$$O_2 + 4H^+ + 4e^- \rightarrow H_2O \tag{3.2}$$

The fuel cell has no rotational parts which increases the reliability and reduces the maintenance costs in the longer term. Another advantage of a fuel cell is the noise-free operation [181] [149]. The theoretical process of a fuel cell is the reversed process of the electrolysis [166]. A fuel cell is built up by a cathode and anode separated by an electrolyte, the composition of the electrolyte determines the working principle of the fuel cell. The fuel cells are divided into two categories: low temperature and high temperature, the separation temperature is defined at respectively 200 °C (chapter 5.6 [109]). A study that compared different fuel cells shows that the efficiency declines with an increasing working temperature [190]. The most notable technologies for fuel cell types are: alkaline fuel cells (AFC), polymer electrolyte membrane fuel cell(PEMFC), high temperature PEMFC(HTPEMFC), Phosphoric Acid Fuel Cell(PAFC), solid oxide fuel cells(SOFC) and molten Carbonate Fuel Cell(MCFC) [22] [26] [177].

From these the high temperature PEMFC is already excluded due to the fact that HT fuel cells have a longer startup time compared to LT fuel cells. Also the ability to cope with rapid power demands is a dis-advantage, where a LT PEMC can change its load from 0% to 100% in 10 seconds a HT PEMC needs around 15 minutes, which is seen as a large disadvantage when hauling the nets and setting the nets. A lack in power in these stages where power demand is changing frequently can cause fishing gear getting stuck in the propeller. Therefor hybridization with larger batteries is necessary to give the same performance as LT fuel cells. A higher quantity of stacks is necessary to reach the same power output or same efficiency as for hydrogen low temperature PEM. This causes higher stack costs, higher stack volume, and stack weight compared to the low temperature PEM fuel cell [90], [181], [177]. Due to the dis-advantage of HT FC's they are not discussed any further. The HT fuel cells with their working principle, advantage and dis-advantages are treated in Appendix B.

Polymer electrolyte membrane fuel cells

Of all commercially available fuel cell types and categories the PEM Fuel cell is able to achieve the highest output per weight or volume [127], has the heighets electric efficiency and is most reliable. The four biggest marine manufacturers that fabricate PEM fuel cells are: Nedstack, PowerCellution, Ballard Power and Cummins. Other companies which supply good quality and reliable PEMFC are available but their application is limited to road transport [12] [47], [79].

PEMFC uses a solid sheet of electrolyte that is bound on both sides to sheets of catalysed porous electrodes. This type of FC has two working principles, HT(High Temperature) and LT(Low Temperature). The usual polymer membranes operate at near ambient temperatures(LT), this enables the PEMFC to start up quickly. The absence of corrosive and hazardous fluids makes it able to function in any orientation. Developments have brought current densities up to 1 A/cm^2, while reducing the used amount of platinum. Both the specific power and area-specific power density of the LT PEMFC are higher than for any other type of fuel cell [55] [181]. However, the electrolyte, electrode and bipolar plate are degrading causing the expected lifetime not to exceed 40.000 hours.

The working principle of PEMFC is as following: Hydrogen fuel is processed at the anode where electrons are separated from protons on the surface of a platinum-based catalyst. The protons pass through the membrane to the cathode side of the cell while the electrons travel in an external circuit, generating the electrical output of the cell(Equation 3.4). On the cathode side, another precious metal electrode combines the protons and electrons with oxygen to produce water, which is expelled as the only waste product (Equation 3.5), [193].

$$Anode: 2H_2 -> 4H^+ + 4e^- \tag{3.3}$$

$$Cathode: O_2 + 4H^+ + 4e^- -> 2H_2O \tag{3.4}$$

$$Overall: 2H_2 + O_2 -> 2H_2O \tag{3.5}$$

3.1.3. Fuel (re)forming

The fuel cells anode requires pure hydrogen, this is easily accomplished when the stored fuel is hydrogen. With the exception from hydrogen each fuel has to be reformed into pure hydrogen to feed the fuel cell. There are three developed and reliable methods to reform the fuel: (1)auto thermal reforming(ATR), (2)portial oxidation(PO) and (3)steam reforming, of which the latest is most efficient [181]. ATR is mostly used to form hydrogen from methane, the reforming uses the reaction of methane with oxygen and carbon dioxide or steam to form syngas(hydrogen gas with carbon dioxide gas) [115]. However, it requires a supply of pure oxygen, for which an air separation unit(ASU) is needed; this hinders the adoption of ATR in industrial applications because of high capital and high operational costs [146]. Partial Oxidation a.k.a. gasification, is the chemical reaction when a hydrocarbon feedstock and a sub-stochiometric of pure oxygen are reacted together.

Steam reforming is a technique to produce syngas with the help of the reaction of hydrocarbons with water. This endothermic reaction this consumes energy from the surrounding. This technique is a well developed and proven in the hydrogen production. The process is performed at 700-1000°C, and a 3-5bar pressure, together with a catalyst to produce hydrogen, carbon monoxide, and a small amount of carbon dioxide. In the ”water-gas shift reaction” steam and carbon monoxide react together with a catalyst to produce carbon dioxide and more hydrogen. The final process ”pressure-swing adsorption” carbon dioxide are removed from the gas stream, leaving essentially only hydrogen [8]. Steam reforming is suitable for multiple fuels: ethanol, propane, methanol [66]. For the reforming of methanol, ammonia a reforming efficiency of 80% can be reached [147].

3.1.4. Electrical machines

Electrical machines will play an important role in the future application of marine propulsion systems. The application of Fuel cells in combination with energy saving devices means the propulsion system has to be electrical. Electrical machines therefor play a big roll in the generation of electricity and in the the conversion from electrical energy into mechanical power. An electrical machine is converting mechanical energy into electric energy or electric energy into mechanical energy. The conversion efficiency of electric machines depends somewhat on the size of the machine, but is generally high: 92% to 96%. The lost energy is converted into heat, in case of part load the efficiency is lower [100]. Since electric motors are over dimension-ed for safety reasons, the motors are usually used in the 75-100% of rated power.

In general induction machines are used as electrical machines. These are the workhorses of the industry and are very reliable and relatively cheap, the only disadvantage is the wear and tear of slip ring and brushes. The second dominant electric machine is the Permanent Magnetic motor, this motor has the highest power density and highest efficiency up to 98% [142]. In general two systems dominate the marked for these motors namely: (1) frequency controlled AC motors and (2) SCR controlled DC motors. In general SCR DC motor systems have an higher efficiency at higher power applications [102].

3.1.5. Outcome Energy converter review

After the review on the available and future energy converters the following conclusions are drawn based on Table 3.1. The internal combustion engine is and will remain a much applied method to convert chemical energy into mechanical energy. The MGO and dual fuel ICE will be further used in this research due to their cost, reliability and ability to reduce CO_2.

Within the Fuel cell review it is found that the LT PEMFC shows most potential, the system is reliable, high energy density, quicker response to load variation and simple system compared to high temperature fuel cell with similar efficiencies which require complex and expensive equipment to accomplish this. Steam reforming will be used if required by the fuel and fuel cell combination since is has the highest TRL, despite this it will have a significant contribution to the overall systems volume, weight and costs. The only dis-advantage of the PM motor are the demagnetizing of the machine and the high capital costs of the machine. Due to the lack of available margins in available volume and weight in combination with the high efficiency it is chosen to use the PM motor in this research. The efficiencies, power and volumetric densities of the used energy converters and reformers are summarized in Figure 3.1 and Table 4.1.

Table 3.1: Energy converter review [3], [90], [179]

Converter		TRL marine application	Advantage	Dis-advantage
ICE	MGO	High	- Reliable - Cheap	- Low efficiency - Low power density
	Dual Fuel	Medium	- CO_2 reduction -	- No retrofit package - MGO still required
	Hydrogen	Low	- No CO_2 emission	- Low efficiency -Not reliable -Expensive
Fuel Cell	PEMFC	Medium	- High electrical efficiency - Reliable - High power density	- Many stacks for larger powers
	PAFC	Low	- High overall efficiency with heat recovery -Reliable	- Complex - Acid -Energy density
	SOFC	Medium	- High overall efficiency with heat recovery -Internal fuel reforming	- Complex - Expensive -Cooling required
	MCFC	Low	- Less fuel quality requirements - High - Internal fuel reforming	- Large power application -Complex -Expensive
EM	PM	High	- High efficiency - High power density	- Expensive
	Induction	High	- Reliable - Cheap	- Wear slipring - Low efficiency part load
Steam reforming		Medium	- High efficiency	- Complex - Large volumes/weight -Expensive

3.2. Alternative energy carrier

In this section the most promising and applicable energy carriers to reduce CO_2 emission on a beam trawlers are discussed. There potential is assessed by researching the technical, environmental, economical, and social aspects. The primary CO_2 emission reducing energy carriers that are identified by the industry are chosen, see list below. Some energy carriers automatically come with their own specific energy converter, for example Iron powder. The feasibility of an energy carrier is mainly determined on the parameters: ability to reduce CO_2, readiness to be applied(in combination with converter) and social perspective.

- MGO
- Hydrogen
- Methanol
- Ammonia
- Batteries
- HVO
- FAME
- Iron powder
- Sodium borohydride

These energy carriers were chosen on the development they have gone through in the last years which resulted in a growing interest for their application in the marine industry. Therefor some relatively new fuels are discussed to find out their potential as well. Each fuel paragraph starts with a general introduction of the fuel, secondly the most relevant safety aspects are treated. Since the regulations in chapter 1.3 refer to the on board emitted gasses, the energy carriers are judged on their ability to reduce the TTW(tank to wake) CO_2 emissions. After all, the responsibility for the well-to-tank emissions is allocated to the fuel producers, thirdly well to tank(WTT) is a study on its own and therefor not in the scope of this thesis. The following fuels are not discussed: (1) nuclear due to high costs and not ready to apply on small vessels [85], (2) LPG, CO_2 emission reduction to low compared to risks and impact of methane slip [165].

3.2.1. MGO and CO_2(Benchmark)

At the moment all Dutch beam trawlers are operating on MGO fuel, with the fuel specifics and the known fuel consumption in each operational profile the emission of CO_2 can be calculated. In Table 3.2 an overview of the fuel specifics which are the starting point to the calculation of the CO_2 per operational profile [161]. ISO's definition for MGO is a general purpose marine distillate that must be free from traces of residual fuel. The IMO does not calculate the CO_2 per specific ship, but uses multiple factors the determine the effectiveness of the vessel 1.3. Since these do not apply to a beam trawler the IMO GloMeep calculation sheet [93] should be used. This method uses a global average operation profile and fishing ship type to determine its contribution to CO_2 emission. This will not be a good representative to use as a benchmark since a beam trawlers operation and dimensions differ to much from an average IMO defined fishing vessel operation. Therefor the actual fuel consumption together with the emission factor Table 3.3 are used [88]. Within this research the emission of CO_2 by the vessel it self is taken into account.

Table 3.2: ISO 8217 Fuel specifications [161]

Fuel	Marine Gas Oil
Density	860 kg/m3 at $15°C$
LHV	43.2 MJ/kg
Boiling point	150-380 $°C$
Flash point	>60 $°C$
Viscosity	2-6 mm2/s

Table 3.3: Conversion factor IMO [88]

Type of fuel	reference	Carbon Content	CF(t-CO2/t-Fuel)
1. Diesel/Gas Oil	ISO 8217 Grades DMX throught DMC	0.875	3.206
2. Light Fuel Oil(LFO)	ISO 8217 Grades RMA through RMD	0.86	3.151
3. Heavy Fuel OIL(HFO)	ISO 8217 Grades RME through RMK	0.85	3.114
4. Liquefied Petroleum Gas(LPG)	Propane Butane	0.819 0.827	3.000 3.030
5. Liquefied Natural Gas(LNG)		0.75	2.750

This gives the following total emissions per cycle Table 3.4 & Table 3.5

Table 3.4: Emission 100hr long cycle

100hr Long cycle	hrs	percentage	emission[ton]
Sailing	12	12%	4694
Fishing	76	76%	58440
Haluling/setting	12	12%	3762
Total	100	100%	66895

Table 3.5: Emission 160hr long cycle

164hr Long cycle	hrs	percentage	emission[ton]
Sailing	12	7%	4694
Fishing	132	80%	100939
Haluling/setting	20	13%	6497
Total	160	100%	112129

3.2.2. Hydrogen

Hydrogen(H_2) is commonly produced by converting natural gas or coal into hydrogen gas and CO_2, this is a process which requires a lot of energy. H_2 can be stored as a super cooled liquid or in a compressed condition meaning it can not be stored efficiently at atmospheric conditions. Hydrogen has a heating value three times higher as MGO. The hydrogen price has dropped over the last years since the costs of steam reforming has decreased significantly [2] [198]. Regulations will influence the speed of application by H_2 production industries and the hydrogen consumption industries. Next to price, hydrogen storage is an important parameter which will determine the feasibility for application.

The compressed storage of hydrogen has the advantage that it does not need an expensive and complex management system to handle the stored and consumed hydrogen, since the hydrogen is at ambient temperature. This also means that the hydrogen has no losses when there is no consumption. The tanks are divided into categories I to IV. These are tanks capable to handle 200-700 bar, the tank type identifies the construction material, tank shape and inside tank material(steel, carbon etc.) [2].

The super cooled liquefied storage tank stores hydrogen at a temperature of -253$°C$. Therefor thermal losses are a concern which are partly tackled by making the tanks cylindrical to reduce the exposed area[183]. Due to the heating of the cooled hydrogen, the tank pressure increases. To reduce this pressure increase, the hydrogen is released into the fuel converter or into the atmosphere. There are many manufacturers[1] [89][91] which become/are specialists in booth type of hydrogen storage.

Safety and Regulations aspects

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[1] Lincoln, Quantum, Luxfer, MAN Cryo, Linde

The ignition of hydrogen is easy, and the conditions of ignitions is very low. These characteristics cause the storage and use of hydrogen to be ruled by strict regulations. These regulations concern: detection, alarms, ignition control, ventilation, leak control, safety distances and hazardous zones. Safety control systems require investment and little space, in contradiction the ventilation, hazardous zones and structural tank enclosure could be problematic. There are no direct regulations for the storage of hydrogen as a fuel, only recommendation's for hydrogen as a cargo [136]. The regulations that apply are written in "International Code of Safety for Ships using Gases or other Low-flash point Fuels(IGF)" [134]. Regulation 6.11.1 prescribes fuel containment requiring full or partial secondary barriers which shall be inerted with a dry inert gas and kept inert with make-up gas provided by a gas generation system(p.64 [134]). As the regulations do not provide specific tank spacing and clearances, the research does not incorporate the use of IGF (International Code of Safety for Ships using Gases or other Low-flashpoint Fuels). This omission is primarily due to the fact that the IGF is intended for storage rather than fuel-related purposes.

3.2.3. Methanol

Methanol in the chemistry known as methyl alcohol, is the simplest alcohol in the alcohol group. The fuel is seen and described as one of the most potential fuels to de-carbonize the shipping industry. At ambient temperature and with an atmospheric pressure the Methanol is in a colorless liquid phase. The fluid is soluble in water, biodegradable and smells like alcohol [143][198]. Methanol is a toxic fluid which will have serious polluting and health consequences when released. Due to the liquid phase at atmospheric pressure and ambient temperature the fuel can be stored in conventional ship tanks. This means that methanol can be stored in every tank shape. Since methanol is a widely available and traded product, the infrastructure for the chemical industry is already available locally and globally [63],[14]. Methanol is produced from different types of feedstock, at the moment natural gas is the most dominant feedstock for the production in the industry. Methanol is not carbon free its carbon weight ratio content 37.5%, therefor it has the highest hydrogen-to-carbon ratio of any liquid fuel(p.4 [143]).

Safety and Regulations aspects

Due to the existing infrastructure and use of methanol in the industry the regulations are fully developed. The IMO is the leading party, represented by the SOLAS amendments which prescribes resolution MSC.391 in the IGF code [135]. There are three rules which could have significant influence the potential on the implementation of methanol. These concern: hazardous areas, cofferdam around fuel tanks and fuel tank under water line. Three hazardous zones are defined: 0,1 & 2. These zones concern the area around the fuel tank, fuel preparation areas and the ventilation outlet/inlet of the ventilation pipes. The area with a 6 meter radius of the ventilation outlet, 3 meter radius a fuel outlet/inlet. When operating on methanol, additional requirements for the tanks are in place. As methanol is a low flash-point and toxic fuel, protective cofferdams around the tanks are necessary which need to be large enough for inspection with openings of 600x600 mm (Lloyd's Register, 2021). Cofferdams are not necessary around surfaces bound by shell plating below the lowest possible waterline, other fuel tanks containing methanol, or methanol fuel preparation spaces.. Lastly Methanol tanks are not allowed to be adjacent to the side shell above the lowest draught line [180] [143].

3.2.4. Fatty acid methyl ester (FAME)

Fatty acid methyl ester, is a nontoxic biodegradable bio diesel that can be produced from a wide array of vegetable oil and fats. It is produced from plant based oils, animal fats and waste oil by transesterification. In this process multiple oils(triglyceride) are transformed into methyl esters and glycerol. This reaction requires a methyl or ethyl alcohol. FAME is the most commonly used type of bio-diesel, in the industry it is known under ISO 8217:2017. The fuel characteristics are almost similar to MGO. Differences are: the lubrication properties of FAME are better, this results in a slightly higher engine efficiency. The FAME has a higher viscosity than MGO, which is caused by the high molar mass. The disadvantage of FAME is the storage, the fuel has the urge to deteriorate in a matter of months, also the growth of bacteria(bug growth) is a concern. Although these problems can be slowed down or stopped by addition of chemicals. The most severe problem is corrosion, this is most critical for bio diesel in higher concentration (B80-B100). Some types of hoses and gaskets could degrade, leading to loss of integrity and interaction with some metallic material such as copper, brass, lead, tin, zinc, etc. The fuel show an increased formation of deposits in tank [82]. FAME can be a blend in or it can be used without blending, 100% FAME is called B100. The EU is the biggest producer of FAME globally. The production of FAME produces a well to tank emission of 0.42 $kgCO_2/kgFAME$. Due to the vegetable basis of the fuel, the tank to wake CO_2 emissions are almost equal to zero. As mentioned earlier, the combustion will still produce CO_2 but the biological nature and source of the fuel makes that the IMO defines the TTW as equal to zero to stimulate the application of the fuel in the maritime sector [164]

Safety and Regulations aspects
Regulations concerning the storage and safety of FAME are prescribed in: MARPOL Annex VI Regulation 18 and MARPOL Annex VI Regulation 3. Besides the mentioned problems, FAME can be used as a drop in fuel meaning the same storage regulations count as for MGO.

3.2.5. Ammonia

Ammonia is a energy carrier frequently mentioned to have the potential to meet the emission reduction regulations in the maritime sector. Ammonia is a colourless fuel which is in gas form at atmospheric conditions. The fuel becomes liquid at a temperature of -33$°C$ with a pressure of 1013 $mbar$, the fuel becomes liquid at 10 bar pressure [83]. Therefor the storage of the fuel is done in cooled or pressurized tanks. Ammonia chemically known as NH_3 it does not contain any carbon, resulting in zero carbon emissions by the fuel converter. The ammonia is produced using grey or green energy which has its influence on the WTT pollution, currently grey natural gas is used via the Haber-Bosch process [25].

Ammonia is transferred into mechanical energy by a combustion engine or a fuel cell. Due to zero emission potential of the fuel a step wise implementation could be considered. Therefor switching to 100% ammonia as a maritime fuel and ammonia diesel combination could be beneficial as an intermediate step. Ammonia virtually eliminates SO_x, the NO_x emission depends on the chosen energy converter but is said to be equal to an ICE on MGO[83]. The choice of storing ammonia as a fuel is likely to be in a pressurized tank type C at ambient temperature(p.18[83]). The storage in a refrigerated tank requires such an arrangement to be reliable, resulting in many back-up systems. This makes pressurized tanks more simple and reliable in use [83],[187], without much difference in energy storage density.

Safety and Regulations aspects
Ammonia is: toxic, corrosive, soluble and flammable, therefor many safety and regulation aspects apply when using it as a fuel. The fuel has a low flash point, therefor it falls under the IGF code [170]. A low concentration of ammonia gas can not be smelled or sensed by human. The high solubility of the ammonia gas causes the danger of absorption by body liquids which leads to skin burns. The IMO prescribes the installation of detectors and water spray(water absorbs ammonia) installation to reduce the consequences of ammonia release. There are technical regulations concerning ventilation and ventilation stops when a leakage is detected. The pressurized tanks require a minimum clearance from the hull to reduce the risk of tank damage after collision or grounding. The tank must be protected from mechanical damage and the fuel transfer system must be double walled [165]. The spillage of ammonia in the water will cause a serious threat to aquatic organisms, it will kill most in proximity since lethal value are easily exceeded. Another important aspect in the use of ammonia is the social perspective. In general ammonia is related to danger by the crew and people since it is toxic. Therefor perspective of ammonia as a fuel needs to change before it is accepted and used as an alternative energy carrier [111], the impact of social perception is even more important for a vessel working in the fresh food industry.

3.2.6. Batteries

Due to the increased power densities, lower costs and the longer lifetime of batteries there has been a growing interest in batteries for marine application. Although the development are positive, the energy density is still relatively low +/- 1 MJ/kg and 2 MJ/dm^3, [74] [103]. Batteries are available in all shapes, sizes and working principles. As with the other alternative fuels, the volumetric energy density and gravimetric energy density are the most essential aspects of the battery. Batteries have the potential to be zero emission. The battery study is limited to the Li-ion type batteries [74] since, these have the highest gravimetric and volumetric energy densities at the moment. The LCO(Lithium-Cobalt) batteries where not chosen due to unstable operation at increasing cell sizes and high capital costs. The application of batteries in the maritime industry is said to be promising for vessel with a 2 to 3 day endurance or range [158]. Next to weight and volume energy density the batteries performance is depending on: charging time, discharging time and delta state of charge(DSOC). DSOC is the percentage of the total battery capacity that is utilized during discharge. The charging time of the battery is categorized in C-rate, which is measured in h^{-1}, a 1C battery charges in 30 minutes. A lower battery density normally means a charging class of 4C and higher. A higher DSOC means a lower life time also an short discharging time results in a lower lifetime.

Safety and Regulations aspects
The safety aspects and failures which require additional attention are: internal cell failure, internal or external short circuit, over(di)charge and over temperature. These failures could develop in the following events: gas development, fire risk, explosion and most importantly a thermal runaway. A thermal runaway is an increase of temperature of $20°C/min$. The internal increase of pressure and temperature could lead to the melting of the separator which will cause an internal short circuit. This will again result in the evaporation of the battery fluids which causes pressure increase in the cell(p33 [74]). This fumes could cause explosion when ignited by an external source. The exothermic reaction of a run away propagates to other cells quickly and is very difficult to stop. Therefor batteries have to be stored in a closed environment which is properly ventilated [73]. To prevent the consequences of a thermal runaway in a cell, a dedicated foam installation has to be installed. This system continuously monitors the temperature of each cell, and can inject foam in large and fast quantities [68]. These well developed systems make batteries a promising and safe application.

3.2.7. Hydro treated Vegetable Oil(HVO)

HVO is a biofuel which is produced by a chemical reaction between bio mass lipids(fatlike substance) and H_2 which creates a stable bio-fuel. HVO is said to be beneficial over FAME in the long term[73], due to its used feedstock. The DNV has characterized HVO as a promising alternative fuel [72], since HVO can be used as a drop-in fuel. Since the fuel is made from biomass, the emission strongly depend on the biomass or feedstock which is used for the production. In general there is a reduction of NO_x and SO_x but the CO_2 emission is variably but could reach more than 60%, depending on used feedstock. In contradiction to FAME, HVO has low lubrication properties which require chemical additions to the engines lubrication oil.

The social perspective of the fuel is low, articles and research have been written on the negative impact of bio-fuels, including the effect of bio-fuels on food prices and land use(land grab by) [72]. Due to used feedstock the production will never reach a height that the complete maritime sector can be supplied [51]. Major drawback lies in the use of Palm oil feedstock, procurement can however be specified for supplies without any Palm Oil. The EU Renewable Energy Directive (RED ii) aims to ban all palm oil in biofuels in stages by 2030. As a result, manufacturers are ramping up their non-palm oil sources [67]. Traditional oil refineries have been converted to HVO production and this has led to the increase of more than 40% capacity in the last five years. Due to the fact that this fuel is a mix of vegetable oils with hydrogen it requires energy and so produces CO_2 for production. The combustion will still produce CO_2, but the biological nature and source of the fuel makes it that the IMO defines the TTW as equal to zero.

Safety and Regulations aspects
Due to the fact that HVO has a similar chemical structure as MGO fuel there are no safety issues, extra regulations or extra crew qualifications for the application compared to MGO.

3.2.8. Iron powder

Iron powder as a fuel has shown promising possibilities in marine application [105]. Similar to some other metals, iron releases heat when it is burned. The grain size of the iron powder are similar to the thickness of a hair [167]. The powder is solid at atmospheric pressure and temperature. The combustion forms products which are also solid at atmospheric conditions. The heat released during combustion is recovered and turned into mechanical power by means of a steam turbine [17]. The reaction product which is rust, has to be stored onboard. The combustion product can be reformed into iron powder onshore. Although further research is needed it can be said that the combustion of iron powder has little to zero CO_2, SO_x and NO_x emission. The potential of iron powder is partly based on its high energy density, which is higher than some conventional fuels, although the specific energy is low. Another advantage is that the iron powder can be stored in atmospheric (conventional)tanks. Tanks shaped as silos are used, this means a lower storage efficiency compared to conventional MGO tanks. The second point of concern is the technical readiness level of the boiler which transforms the iron powder into steam. This boiler type is not yet applied in the industry, only in research setups [36]. The filtering of the exhaust gas product to recover the oxide particles is well developed but not applied in the maritime industry as well. The exhaust gas product(rust), requires 1.6 more volume as consumed iron powder, this results in large required storage volumes for fuel and exhaust product.

Safety and Regulations aspects
There are no direct IMO regulations concerning storage and use of iron powder. Only the IMDG-code(International Maritime Dangerous Goods) written by IMO defines regulations on the transportation of iron powder as a cargo. This code prescribes actions for: firefighting, first aid, accidental release but also includes the storage and handling measurements. Although these regulations are not specific and only concern general topics like dry storage, ventilation and temperature. There are no regulations concerning, tank positions, tank strength, hazardous area etc. The lack of regulations is caused by the low technical application in the maritime sector.

3.2.9. Sodium borohydride

Hydrogen can be used and stored in its pure form H_2, but storing hydrogen in its pure form requires large and strong tanks. Sodium Borohydride($NaBH_4$) is able to bond hydrogen, and it is found potential for maritime application [128]. An advantage of $NaBH_4$ is that it is stored in atmospheric conditions, this makes $NaBH_4$ easier and safer to store compared to H_2. $NaBH_4$ is a white solid which is stored on board in a liquid solution/blend with a base($NaOH$). By hydrolysis reaction with pure water(distilled water) it produces hydrogen. This reaction is very slow naturally but the reaction speed can be increased by the use of acid as an activator. The released heat during hydrolysis can also be used to heat up the reactor, which again will increase the speed of reaction. Next to hydrogen this reaction also produces $NaBO_2$ sodium metaborate, this could be regenerated into $NaBH_4$. To produce 1 kg of hydrogen(H_2), 4.7 kg of $NaBH_4$ is required.

Storing $NaBH_4$ in its pure form gives the highest energy density, but gives challenges for the fuel supply system and the hydrogen production reaction. The storage of fuel blends 30, 50 or higher are liquid and therefor have an easier fuel supply system. The most promising storage systems for marine applications are Volume-exchange tank [106]. The VET consists of three flexible separate tanks in one compartment. One for the Fuel, one for the exhaust product and one for the activator(H_2O or Acid) [101], this tackles the problem of large volumes of produced exhaust product. The exhaust product product can be reduced by filtering out the H_2O from the $NaBH_2$ by means of reversed osmosis(RO) on board [128]. Although the energy carrier show potential, the TRL is currently low, [128].

Safety and Regulations aspects
Hydrogen production by means of sodium borohydride is a new principle in the maritime sector, therefor no direct regulations exist. Transport regulations for $NaBH_4$ are defined by the international chemical safety cards(ICSC) under the code 1426 and 3320. The solution is categorized as corrosive. The generation of hydrogen depends on the ratio of the reaction between fuel, acid and stabilizer. The acid used to increase the reaction speed is another point of concern. The acid used in the reaction is hydrochloric acid(HCL), this liquid solutions consists of 30 wt.% HCL. This results in the classification to be a dangerous liquid, this means contact with eye, skin inhalation and ingestion needs to be avoided. The tank surface has to be coated with a material which resits the acid solution and tank must be ventilated with a scrubber fan [137]. The spilling of the acid due to leakages or human error should be prevented since the acid will destroy the ships steel hull, the acid it self is non flammable and non explosive.

3.2.10. LNG

Liquefied natural gas which majorly consists of methane which has the chemical equation of CH_4. This gas is the cleanest of the fossil fuels. LNG is also relatively safe since it is lighter than air, therefor it can not create a flammable gas carpet. The combustion of LNG produces relatively much water, also it is easy to filter out contamination's in the fuel. The gas becomes liquid at -163° around atmospheric pressure. Similar tanks must be used as in Section 3.2.2, which means large volume losses due to the tank shape. Together with the volumetric energy density this means that to store the same amount of energy two times the MGO tank volume is required. Due to the lower carbon content of LNG compared to MGO the fuel has the potential to reduce the CO_2 emission with 15% to 20% when used in a combustion engines [49]. A large disadvantage is the release of CH_4 into the atmosphere if leaked or not ignited in the engine. This gas is referred to as methane slip, which has a 34 times higher contribution to ozone depletion as CO_2. The large advantage of LNG is the potential to reduce the NO_x with 75% and the SO_x practically with 100%.

3.2.11. Outcome Energy carrier review

First of all the drop in fuels HVO and FAME are researched further. The higher fuel prices in combination with potential storage problems do not tackle the advantage of their similarity MGO and the reduction in TTW emissions.

Hydrogen has the advantage to be zero emission in TTW. The volume required to store the liquidized fluid could be a potential problem. But the direct use of hydrogen in high efficiency fuel cell systems promises to be very beneficial.

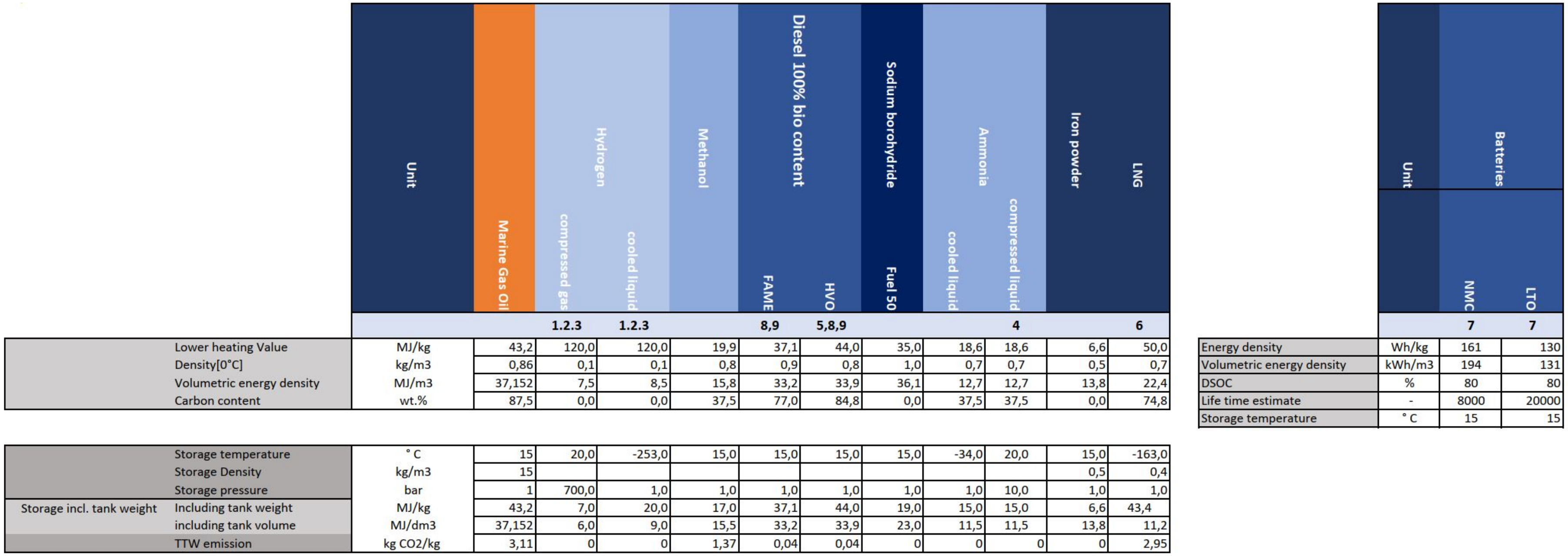
Methanol is partly categorized as a drop in fuel, the only dis-advantage can be found in the required 600mm cofferdam around the fuel tank. The high TRL in combination with the fuel being partly drop the fuel is further researched.

Iron powder and Sodium borohydride: although these fuels could definitely be the future energy carriers, the application in the coming years does not seem feasible. The converters, auxiliary systems including the storage systems require more research since systems still have to prove to be reliable enough for marine application.

Ammonia application has showed potential due to its potential in storage, volumetric energy density and technical majority in energy converting. The dis-advantages is ammonia having a high toxicity and a negative social reputation. A beam trawler has a relative high number of crew for its vessel size, this will impose problems with working area's and hazardous area's. Also the social perspective of ammonia together with a food supply chain, therefor ammonia is not investigated any further.

Battery potential is depending on: volume/weight energy density, DSOC, DoD, charging and average power delivery of power pack. Due to the operational profile there is potential to use batteries in combination with another energy converter. For this research the NMC lithium type battery is further investigated on its application.

Figure 3.1 illustrates a summary on the advantages and dis-advantages of the researched energy carriers.



		Unit		Hydrogen		Methanol	Diesel 100% bio content		Sodium borohydride	Ammonia		Iron powder	LNG
			Marine Gas Oil	compressed gas	cooled liquid		FAME	HVO	Fuel 50	cooled liquid	compressed liquid		
				1.2.3	1.2.3		8,9	5,8,9			4		6
	Lower heating Value	MJ/kg	43,2	120,0	120,0	19,9	37,1	44,0	35,0	18,6	18,6	6,6	50,0
	Density[0°C]	kg/m3	0,86	0,1	0,1	0,8	0,9	0,8	1,0	0,7	0,7	0,5	0,7
	Volumetric energy density	MJ/m3	37,152	7,5	8,5	15,8	33,2	33,9	36,1	12,7	12,7	13,8	22,4
	Carbon content	wt.%	87,5	0,0	0,0	37,5	77,0	84,8	0,0	37,5	37,5	0,0	74,8
	Storage temperature	° C	15	20,0	-253,0	15,0	15,0	15,0	15,0	-34,0	20,0	15,0	-163,0
	Storage Density	kg/m3	15									0,5	0,4
	Storage pressure	bar	1	700,0	1,0	1,0	1,0	1,0	1,0	1,0	10,0	1,0	1,0
Storage incl. tank weight	Including tank weight	MJ/kg	43,2	7,0	20,0	17,0	37,1	44,0	19,0	15,0	15,0	6,6	43,4
	including tank volume	MJ/dm3	37,152	6,0	9,0	15,5	33,2	33,9	23,0	11,5	11,5	13,8	11,2
	TTW emission	kg CO2/kg	3,11	0	0	1,37	0,04	0,04	0	0	0	0	2,95

	Unit	Batteries	
		NMC	LTO
		7	7
Energy density	Wh/kg	161	130
Volumetric energy density	kWh/m3	194	131
DSOC	%	80	80
Life time estimate	-	8000	20000
Storage temperature	° C	15	15

Figure 3.1: Energy carriers characteristic summary, [83] [77] [101] [105], [3]

3.3. Reducing energy consumption

Methods that reduce the fuel consumption will also reduce the CO_2 emission if carbon is present in the used fuel. This section focuses on discussing the most promising methods that have the potential to be retrofitted on board beam trawlers. (1) The potential of propeller optimisation is researched, since the current propulsive efficiency is low and previous company projects show good results in reducing fuel consumption. (2) wind energy is chosen to be treated since the development of new products in this marked is so high and the operational area looks favourable for application. (3) heat recovery systems are treated since beam trawlers do not yet work with these systems, while new and efficient systems are developed over the last years for smaller propulsion systems.

3.3.1. Propeller design

Within the beam trawler fleet a large variation of propeller setups is applied. In general a reversible gearbox is used together with a CPP or FPP, and in most cases, a nozzle(or duct) has also been applied for decades. With the reversible gearbox it is possible to clear nets when they got stuck in the propeller. The used propellers are divided in two groups, fixed pitch propeller(FPP) and CPP(controllable pitch propeller). The pitch of a FPP is fixed, since the blades are rigidly attached to the hub. The amount of thrust developed by a propeller is controlled by the rotational speed speed of the propeller. FPP ships require a reversible engine or a reversible gearbox to be able to sail astern. The advantage of a FPP is that it is cheaper, has a higher efficiency and lower operational costs.

CPP consists of a hub with the blades mounted on separately, so that they can rotate, thus changing their thrust. The blade angle is controlled by hydraulic pressure which flows though a hollow propeller shaft to a hydraulic power pack. Changing the pitch angle results in changing the propellers angle of attack, thus changing the thrust without adjusting the rotational speed. CPP are applied on ships with multiple dominating operational conditions, the engine can always be set in a optimum operational point increasing its efficiency. Propellers driven by electric motors can run at much broader ranches with power ranges from 50% to 100% their efficiency remaining near the peak of optimum efficiency. The CPP requires a large hub, a hollow shaft and a control system and a restricts the propeller blade design since they have to pass each other when reversing. Therefor the CPP is expensive and has slightly lower efficiency than a FPP. To increase the technical and financial feasibility of complying with 2030 IMO regulation a FPP is used in this research (p.180 [81]).

The propeller, either a fixed or a controllable pitch propeller may be placed in a duct. A duct is a ring surrounding the propeller with a cross section that has a wing like profile. The duct can offer additional propeller protection, but most important it contributes to the thrust generated by the propeller Figure 3.2. The duct profile contributes to the thrust by shaping its cross section in such an away that the flow is accelerated through the duct. Therefor the thrust can be increased without changing the propeller diameter. Ducts are specifically efficient below 12 knots, making them very favourable and applied in large number in newer beam trawlers (Figure 3.3). To increase the technical and economical feasibility of complying with 2030 IMO regulation a duct is chosen to be applied in this research(p.181 [81]).

Figure 3.2: Controlable pitch propeller in a duct/nozzle [26]

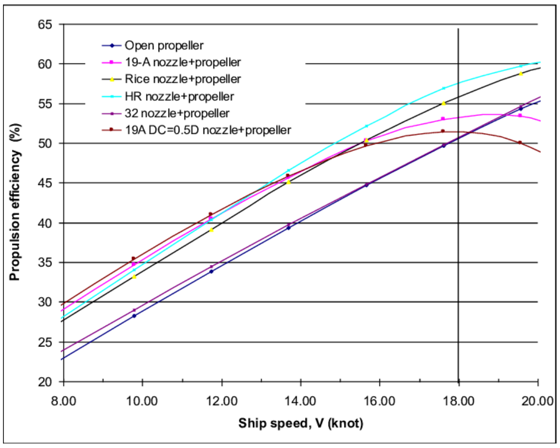


Figure 3.3: Propeller performance with and without nozzle [35]

The optimization of the propeller can be approached on two ways: (1) optimizing propeller diameter or (2) optimizing propeller rotational speed. By increasing the propeller diameter and decreasing the propeller rotations per minute a significant required brake power reduction can be achieved. The higher efficiency is caused by the reduction of blade loading. This is achieved by accelerating more water mass, with a lower velocity difference between ship speed and wake Figure 3.4. The lower speed difference and the lower rotational speed of the propeller result in less rotational and kinetic losses on propeller and wake[19].

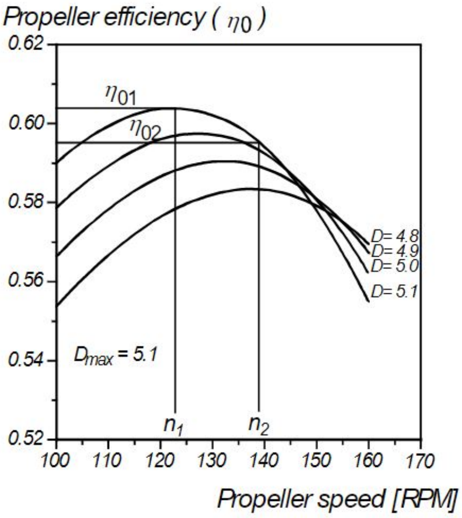
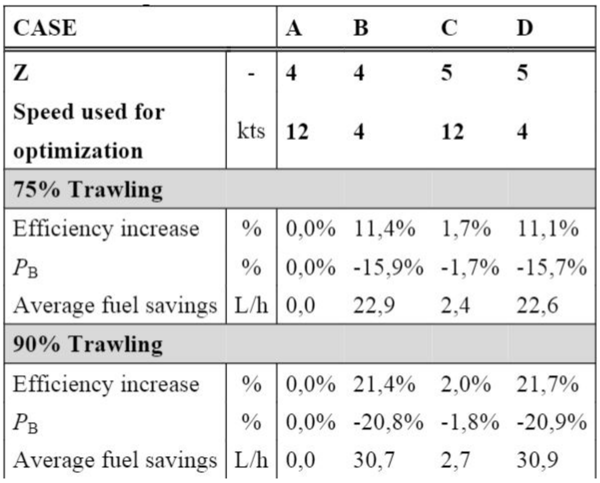


Figure 3.4: Performance of increasing propeller diameter [78]

As explained in Section 2.2 beam trawlers have two advanced speeds and therefor two design point have to be considered for the conception of the propulsive system. If the design is optimized for one condition the other one will not have an optimized efficiency. If the propeller is designed for free sailing, it performs worse in trawling conditions, and vice versa for the propulsive system. A study done on propeller optimisation for free sailing or trawling with different operational profiles, concludes which operation should be optimized [107]. It can be observed in Figure 3.5, the highest average fuel saving is obtained when the propeller is optimized for trawling(4-5 knots). To increase the technical and economical feasibility of the design, trawling is the operation to optimize the propulsive system for[40].



CASE		**A**	**B**	**C**	**D**
Z	-	**4**	**4**	**5**	**5**
Speed used for optimization	kts	**12**	**4**	**12**	**4**
75% Trawling					
Efficiency increase	%	0,0%	11,4%	1,7%	11,1%
P_B	%	0,0%	-15,9%	-1,7%	-15,7%
Average fuel savings	L/h	0,0	22,9	2,4	22,6
90% Trawling					
Efficiency increase	%	0,0%	21,4%	2,0%	21,7%
P_B	%	0,0%	-20,8%	-1,8%	-20,9%
Average fuel savings	L/h	0,0	30,7	2,7	30,9

Figure 3.5: Propeller diameter optimisation for fishing vessel [107]

The engine of a beam trawler is always connected to the propeller shaft by means of a gearbox since it is a medium or high speed engine. Therefor the propeller speed can be matched to the prime mover, such that the optimum speed and the corresponding pitch ratio has to be determined. The second method determines the largest possible diameter which matches the torque and rotational profile of the engine. In this research the diameter of the propeller will be chosen as large as possible to provide lowest blade loading and highest efficiency. The maximum propeller diameter including the duct is limited by the hull design.

The potential optimisation of the propeller is done according the method described below. (1) the required shaft power of the vessel is determined by calculating hull resistance. (2) The required P_d is determined with propeller characteristics and PropCalc [98]. These values are then compared with the benchmark in Chapter 3.2.1, an example of the case vessels bollard pull, trawling and free sailing is given in Appendix A. (3) The last step is to come up with a propeller which can deliver the same thrust with a lower required propeller shaft power P_d. Therefor comparisons are made with multiple Wageningen Nozzle propellers and Wageningen 19A ducted propellers. In this research it is assumed that the engine or electric motor can deliver full power at all rotational speeds.

3.3.2. Winch

A hydraulically or electrically powered winch is used to haul and set the nets. With the setting of the fishing gear the winch is paying out cable while braking to keep the cable on tension. The brake transforms the mechanical braking force into friction which is again reformed to heat. Two methods are identified to reduce the required energy to haul and set the fishing gear.

1. Changing the operation in which the nets are set and hauled such that minimum fishing line tension is achieved while maintaining control of the nets. Thereby reducing the required propeller and/or winch power. This requires change in operation such that a point is found in which safe operation, no fish loss and reduced required winch and engine power are satisfied. At the moment an average beam trawler sails at a speed of 3.5 knots when setting nets and with 3.5 knots when hauling. A certain speed is required to be able to steer the vessel. To achieve this speed a certain amount of propulsion power is required. The increased vessel speed increases the required winch power during hauling and increases the braking power when setting. By reducing the relative speed between ship and fishing gear the possibility appears that fish swims out of the nets. With these requirements an optimized hauling and setting speed can be determined to reduce the engines brake power during these operations and thereby reducing CO_2 emissions.
2. Maintaining the operation and thereby recover energy by means of regenerative winch braking is another option. This is based on research and application of regenerative breaking in cars and cranes. Regenerative braking is an energy recovery method that converts kinetic energy into a form of electricity which can be directly stored or consumed. The holding capacity of the winch brake to safely control the motion of the fishing gear is replaced by a generator which controls the rotational speed of the winch. The holding capacity of the winch is controlled by sending a varying current(A) to the winch motor which now operates as a generator. An induction motor can be rebuild to be used as a generator. Therefor capacitors have to be added to the generator. The capacitor will supply reactive power which will raise the output voltage on the generator. Capacitor value installed is various because it is based on increasing voltages in the generator. For maximum output a control device Induction Generator Control(IGC) in the form of an active frond end drive is required. The use of an induction motor as a generator has been applied widely in Micro Hydro Power even though it has shortcoming in terms of efficiency and voltage regulation [7]. Despite the required retrofit costs and required energy to make regenerative braking possible the high repetition of setting gear makes it worth investigating.

To determine the feasibility of regenerative winch braking the operational profile, fishing gear and winch characteristics should be known. The weight of the fishing gear and winch type varies per beam trawler, but the fishing gear, hauling and setting is similar in general. The reference calculation is built up with the following data (Table 3.6).

Table 3.6: Regenerative winch braking, calculation data (p.471 [100])

Fishing gear weight	4	t
Fishing line tension	4	t
Pay-out length fishing line	340	m
Pay out speed	1	m/s
Drum diameter inner	0.4	m
Drum diameter outer	0.8	m
Setting repetition 100hr cycle	35	-
Setting repetition 144hr cycle	50	-
Winch mechanical efficiency	0.99	-
Winch core loss efficiency	0.98	-
Generator p.f.	0.8	-
Converted power per short cycle	P_{con}	$T_{ind} * \omega_r$

3.3.3. Wind Energy

Two methods are discussed to use the energy available in wind: (1)transferring wind energy into electrical energy or (2) using the wind energy to create thrust. In the sections below a selection of three systems are researched that show potential and are ready to be applied in the maritime industry. In the complete Dutch beam trawler fleet there is no vessel using wind energy as a method to reduce the vessel energy consumption, there is also no known open source research done on it.

Wind turbine

A wind turbine transfers kinetic energy of wind into mechanical energy which is again transferred in electrical energy. Each turbine comes with its own shape, efficiencies and dimensions. Every wind turbine carries a power rating. This is the maximum power it will produce for every moment the turbine operates at its rated wind speed. The amount of energy a wind turbine can be expected to produce in a given year depends upon the power curve, wind speed and capacity factor of the area. The actual energy produced divided by the energy the turbine could produce if it always ran full time is called the capacity factor [70]. Next to the generated electrical power the wind turbine contributes to the total vessel resistance as well, the resistances can be divided into two parts, tower resistance and blade resistance Figure 3.6.

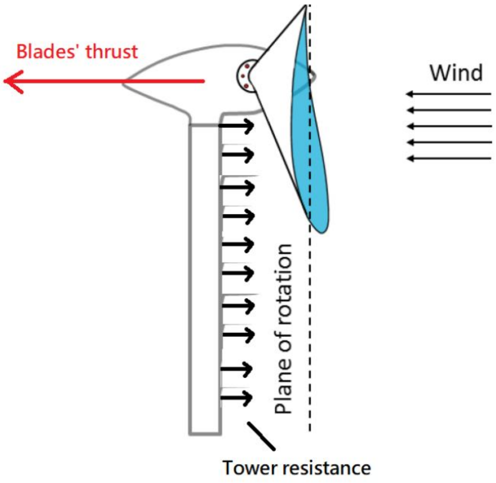


Figure 3.6: Wind turbine principles resistance and thrust [172]

Econowind Ventifoil

An Econowind Ventifoil transforms wind energy into thrust which is used as an addition or replacement to the thrust delivered by the propeller. The wind direction is transferred by an aluminium vertical sail which has a wing profile Figure 3.7. With the help of an electrical powered fan a part of the air flow on the low pressure side is transferred into vertical direction to increase the pressure difference over the wing. This principle is known as boundary-layer-suction, which increases the efficiency for wind energy to thrust. In heavy and/or unfavourable wind conditions the VentiFoil's can not operate due to much wind force and incoming green water. The smallest size of Ventifoil which is available has the following characteristics: 10m high, 1,10m thick. The fan is powered by 15 kW electric motors.

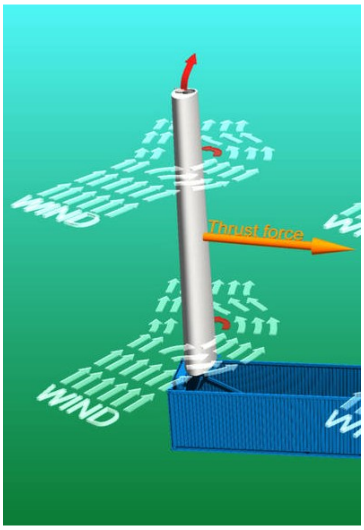


Figure 3.7: Econowind, wind assisted propulsion [F. Veldhuis employee Econowind]

Flettner rotor

A Flettner rotor transforms wind energy into thrust which is used as an addition or replacement to the thrust delivered by the propeller. The "cylindrical sail" gains propulsive power with the Magnus effect as an electric motor turns/spins the cylinder, which is a rotor vertically installed on the deck. This type has drawn increasing attention lately. It works on the same principle as a baseball pitcher throwing a curveball when the ball curves because of its rotation. When wind meets the spinning Rotor Sail, the air flow accelerates on one side of the Rotor Sail and decelerates on the opposite side of the Rotor Sail. The change in the speed of air flow results in a pressure difference, which creates a lift force that is perpendicular to the wind flow direction. The same principle applies to all rotating spheres and cylinders[113]. The use of two end disks ensures very favourable flow conditions around the rotor. The rotors acts additive to the propeller and with increasing sailing performance the main engine power is to be reduced efficiently. Although this concept is well proven and shows thrusts equivalents of 200kW(22 m/s) for a 24 meter high Flettner the efficient exponential drops when decreasing the height. This results in a minimum height supplied by the marked of 18 or 21 meters, with weights ranging from 34 ton to 36 tons.

3.3.4. Solar power

Due to the development of efficient, thin and flexible solar panels over the last years this report contains a small study into the potential of solar power application. When the sun projects at a solar panel the photons hit the thin layer of silicon on the top of a solar panel, these protons knock of the electron from the silicon atoms. The charge created here produces an electric current, which is captured by wiring in the solar panels. Monocrystalline silicon cells are most efficient and most used for maritime application [175]. Batteries are used to store the produced energy of the solar panels. When designing the system the first limitation is the available space appropriate for accommodating. The solar panels resource strongly depends on the latitude of operation and the climatic conditions. As mentioned earlier the climatic conditions can be rough on the North sea and the 55° Latitude result in lower solar panel potential. Secondly the available area for the panels is very minimum. The forecastle and aft deck of the ship are the only position, although this part face rough weather conditions and are partially shadowed. The price of 3000 $/kW is another factor which substantiate the drawback of solar panels for beam trawler application [129].

3.3.5. Exhaust heat recovery

The energy converters produce a certain flow of exhaust gas product, which contains energy. An average of 25% to 40% off the input energy is lost in exhaust gas, for an MGO fueled ICE. Given the importance of increasing energy conversion efficiency for reducing both the fuel consumption and CO_2 gas emissions of converters, scientists and engineers have done lots of successful research aimed to improve converters efficiencies (Ch. 7 [81]). However, in all the energy saving technologies studied, exhaust heat recovery (EHR) is considered to be one of the most effective means and it has become a research hot spot recently [126] [15] [139]. The conversion of thermal energy is generally done using one of the following principles:

- A steam Rankine cycle is the most efficient concept to recover energy from exhaust gases. A steam Rankine cycle converts thermal energy for direct use with an estimated efficiency of 8-28% in the temperature range in question (250-530 °C) and is therefore most suitable to recover energy from the exhaust gas.
- Organic Rankine cycle is the most efficient concept for direct use. ORC has the highest efficiency (7-20%) for low-medium temperature heat (70-280 °C) and is therefore most suitable to recover heat from the cooling water(p.13-19 [80]).
- The Stirling engine is the most efficient concept to convert stored energy into electricity.

Since MGO and all other studied alternative fuels do not contain sulphur, there is no requirement on minimum exhaust gas temperature. When sulphur is percent in fuel and the exhaust gas temperature is cooled to much +/- 200°C-300°C sulphuric acid is formed by condensation of H_2SO_4 which will damage all metal parts in the exhaust gas system. Two systems which are suitable for cooling water energy recovery and exhaust gas energy recovery are examined on their ability to be applied namely: ORCAN(organic rankine cycle) and Steam rankine cycle(SRC):

ORCAN:
The Orcan Efficiency Pack derives its name from the Organic Rankine Cycle (ORC) principle upon which it is based. Suitable for waste heat from exhaust gases, jacket cooling water, steam and thermal oil. The system works with the refrigerant liquid R245 which evaporates at 15°C at atmospheric pressure. Inside the efficiency PACK an Organic Rankine Cycle (ORC) is used to transform thermal heat into electrical power. The ORC is a closed steam (vapor) cycle in which an organic working fluid (hydrocarbon) is used. Figure 3.8 shows a simplified model of the ORC system.

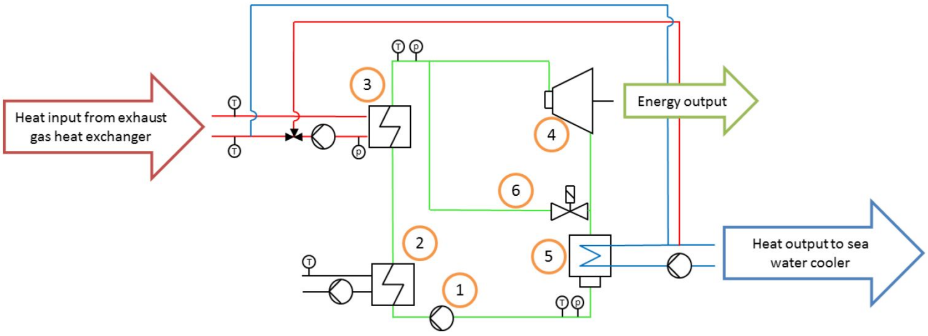


Figure 3.8: Orcan efficiency pack cycle, [Berger Maritiem]

In the ORC system (efficiency PACK) a feed pump (1) transfers the liquid working fluid into a pre-heater (2) in which the fluid is heated below boiling temperature. The pre-heater is usually heated by an engine's jacket cooling water (HT cooling water). After the pre-heater the fluid is evaporated and superheated in the evaporator (3). The evaporator is heated by a pressurized hot water loop. The superheated steam then drives the expansion machine (4). The expansion machine is connected to a generator to produce electricity. In the condenser (5) the steam at low pressure is finally liquefied again to close the steam cycle. Orcan Efficiency packs showed a potential to recover 6% to 7% of the installed engine power. Depending on the operational hours this could result in significant reduction of CO_2 emissions and a short systems payback period. the system comes with an average costs of 250 $\frac{€}{kW}$, with a weight of approximately 36 $\frac{kg}{kW}$ [65].

Steam Rankine Cycle:
With higher exhaust gas temperatures the steam Rankine cycle will exceed the ORC in efficiency. The STR system works according Figure 3.9.

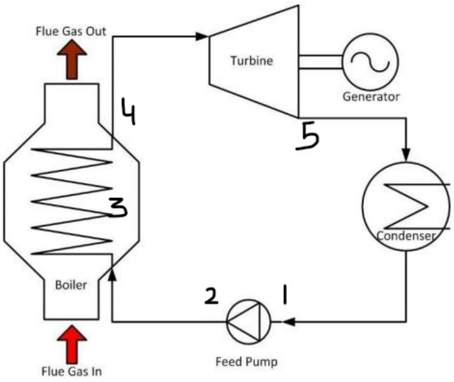


Figure 3.9: Steam Rankine, Cycle steps, [159]

The overall process involves a liquid which is heated and condensed repeatedly. There are four processes happening. At first an isentropic pressure increase takes place (1-2). The working fluid, now at high pressure, is heated with the external heat and is evaporated (2-3). working fluid, which now is a gas, is superheated (3-4) to reduce condensation as the gas expands through the expansion device in an isentropic expansion and generates mechanical work (4-5). The wet vapor runs through the condenser where it once again becomes a liquid (5-1), this cycle is as mentioned repeated. If heat source temperature reaches 350 °C, efficiencies are very similar to the ORC. For temperatures above 350 °C, the thermal efficiency of the ORC will exceed the system using an organic fluid. SRC has the ability to reduce the MGO consumption with 9% (p.15, p.32 [80]), the system costs are approximately $\frac{€}{kW}$ at ABB.

3.3.6. Outcome Energy reduction review

Based on the research in this section, a summary is visualized in Table Table 3.7. The potential to optimize propeller dimensions is found promising, although it comes with significant capital investment. This is caused by the fact that many beam trawlers still operate with relatively small diameter propellers with high rotational speeds, resulting in low open water efficiencies.

Secondly, the optimization of winch operations, together with the availability of regenerative braking, was examined. The potential of the two opposes each other, but they could both significantly improve the required winch power. The reduction of sailing speed while setting and hauling does not come with any investment costs and is therefore easy to achieve. Regenerative braking requires an upgrade of the winch or a completely new winch, thus requiring an investment. It is concluded that it is worth looking into the application of these methods and systems.

Wind and solar power are promising, but they have also shown some disadvantages. In general, there is a lack of available free area to install the systems, and if the area is available, the position with respect to incoming green water is very unfavorable. The wind systems are of such size and weight that they would have a negative influence on stability; therefore, their application is not investigated any further.

Exhaust heat recovery is found to be promising in its application on beam trawlers. Depending on the propulsion setup, the recovered energy could be significant, and the generated electricity can be charged into batteries or fed to an electric motor. The installation of this system will require an electricity distribution system for storage or direct use. The only disadvantage of exhaust gas energy is found in the high system costs and the reduction of efficiency with load variation. It is concluded that it is worth further exploring the application of the OCRAN and SRC systems.

Table 3.7: Summary, energy consumption reduction methods [7] [113] [129] [159] [65]

		TRL marine application	Advantage	dis-advantage
Propeller	D_{prop} increase	High	-High eff. increase	- New GBX costs - Prop.+Duct costs
Winch	OP	High	- No costs - Easy applicable	- Potential neg. influence on OP
	RB	High	- easy to apply - Reliable	- Only with EM - New winch or upgrade
Wind	Turbine	Medium	- Custom dimensioning - Reliable - Robust	- Weight addition - Required area - Stability
	Econo	High	- Thrust deduction - Reliable	- Large - Required area - Stability
	Flettner	High	- Thrust deduction - Reliable	- Large - Required area - Stability
Solar		Medium	- Reliable	- required area - costs vs output
EHR	ORCAN	High	- Easy applicable - Reliable	- Expensive - Volume/weight required
	SRC	High	- High efficiency	- Complex - Expensive - Low efficiency, with small P_B

3.4. Exhaust product treatment

The last method to reduce the emission of CO_2 is the so called end of pipe solution or secondary methods. Only technologies that are feasible for a marine application are discussed. This means that for example three-way catalysts are not treated since the oxygen concentration from the propulsion setup exhaust product is way to high to let the three-way catalyst work optimally. There are many treatment systems on the marked which aim to reduce NO_x or SO_x(coal industry), these also have a secondary effect to lower the CO or CO_2 by small portions. Although each contribution to the reduction of CO_2 is welcome these systems are not treated. Both type of carbon capture system discussed in this chapter are of the aqueous type. This means that the exhaust gas is washed with water or seawater with a chemical solvent to react and attach the carbon to the washing fluid. The main advantage of PCCC(Post Combustion CO_2 capture) over other processes is that it can be retrofitted to existing plants without significant modifications in a short duration of time [99].

3.4.1. MEA Scrubber

Studies have shown that the absorption technology in carbon capture technology best fits maritime application and is most mature [30]. A capture system which works according this principle is the aqueous monoethanolamine(MEA) scrubber, this system has a high potential and proven systems to reduce CO_2 [11]. It primarily consists of an absorber, a heat exchanger and a stripper Figure 3.10. The CO_2 in flue gas (Flue Gas) enters to the bottom of the absorber and the MEA solvent (Cold Lean MEA) enters to the top of the absorber. The MEA solvent selectively absorbs the CO_2 via exothermic reaction. The CO_2 is captured at top of the stripper and CO_2 lean solvent (Hot Lean MEA) drains the bottom of the stripper(the secondary exhaust product). The cold lean solvent (Cold Lean MEA) is recycled and enters to the top of the absorber" [95].

Note that CO_2 emissions also occur during the CO_2 capture process as this process requires energy. Specifically, CO_2 capture processes use steam to run the stripper and electricity to run compressors in the compression and liquefaction sections. A study showed that to capture 1244 kg/h of CO_2, there is a CO_2 release of 418 kg/h; this is equivalent to 33.6% [112]. MEA scrubbing is an expensive option, US$40 to 70/ton of CO_2 removed [37]. In addition, the system has a slow absorption rate and a small solvent capacity [9].

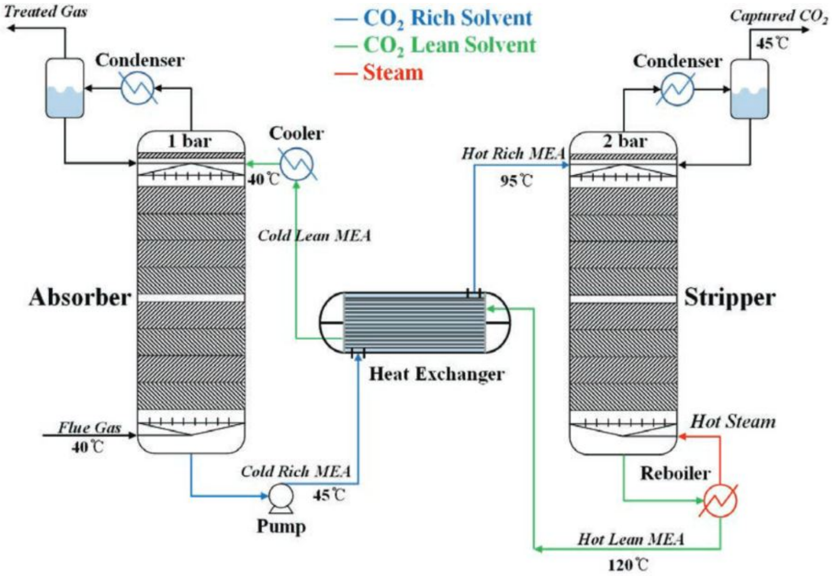


Figure 3.10: MEA scrubbing, process and component overview [96]

3.4.2. NH_3 Scrubber

An approach that may provide another route of reducing CO_2 emissions from power plants is separation by an ammonia reagent. CO_2 capture by aqueous ammonia is paid more and more attention for its advantages of high efficiency, low investment and convenient operation. Once the CO_2 is captured,

the ammonia-based solution is regenerated to release CO_2 and ammonia. The ammonia is recovered and send back to the scrubbing process, and the CO_2 is in a form that is ready for geological storage. Ammonia is not consumed in the scrubbing process, and no separate by-product is created. CO_2 released is compressed for sequestration while the ammonium carbonate solution is returned to the scrubber for re use.
The solvent, “rich” in CO_2 is then thermally regenerated in a stripper. The stripper column is a packed column, too with a re-boiler to heat the solvent to ca. 120°C. The vapour stream from the stripper is condensed to recover water vapour and other volatile components, while the product CO_2 stream can be sent for compression or further use [99] Figure 3.11. Although the Scrubbing is a promising system it is an expensive, heavy and complicated system which is normally applied on large power plant configurations.

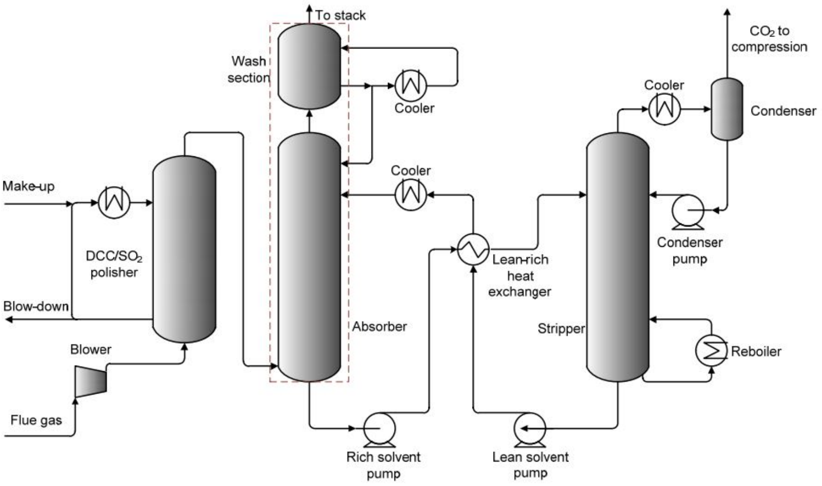


Figure 3.11: NH_3 scrubbing, process and component overview [138]

3.4.3. Outcome exhaust product treatment review

Although the emission reduction percentages sound very promising these capture systems are not taken into account in this research. This decision is based on the following reasons. (1) First of all the significant investment. It is found that the removal of CO_2 in small Flues gas flows requires a large system which is expensive and heavy [196]. (2) Secondly the optimal efficiency is achieved with high flue gasses(Gas fueled engines) from large engines, this is in contradiction with the relatively small engines in dutch beam trawlers which is limited to 2MW. At last these systems are only applied in the maritime sector for large vessels, systems for small engine ratings are researched and are not mature enough to be applied in the industry for the coming 2-3 years.

3.5. Conclusion

In conclusion of this chapter, a summary is give which answers the subquestion:

”What are the relevant methods to reduce CO_2 emission on a dutch beam trawler?”

The research concludes several key findings on energy converters for marine applications. The internal combustion engine (ICE) remains a widely used method for converting chemical energy into mechanical energy. MGO and dual fuel ICE are favored in this research due to their cost-effectiveness, reliability, and ability to reduce CO_2 emissions.

Among fuel cells, LT PEMFC (Low-Temperature Proton Exchange Membrane Fuel Cell) shows the most potential due to its reliability, high energy density, quick response to load variation, and simplified system compared to high-temperature fuel cells. Permanent magnet (PM) motors are chosen due to their high efficiency, despite the demagnetization issue and higher capital costs. The study includes further research in application of Orcan and SRC systems to recover the exhaust gas energy from the converters.

While hydrogen offers zero emissions, storage volume is a potential concern. Methanol, categorized as a drop-in fuel, requires a 600mm cofferdam around the fuel tank. Iron powder and sodium borohydride are considered future energy carriers but require more research for marine application. Ammonia shows promise in energy storage and density, but its high toxicity and negative social reputation pose challenges. Battery potential depends on various factors from which energy density and specific costs are driving. Due to the rapidly improving performance of batteries, NMC lithium batteries are further investigated for application.

The research also explores optimizing propeller dimensions, winch operations, and regenerative braking to enhance vessel performance. Wind and solar power face challenges related to available space and unfavorable positioning. Exhaust heat recovery shows promise in beam trawlers but has high system costs and reduced efficiency with load variation.

Capture systems for CO_2 reduction are not considered in this research due to significant investment costs and their suitability for large vessels rather than smaller Dutch beam trawlers.

4

Assessment model

In Chapter 1.5, a research gap is identified. To address this gap, it is deemed necessary to model various scenarios in order to gain insights into the impact of propulsion configurations on technical and economic performance. Due to emission and fishing regulations, there is a lot of future uncertainty. This uncertainty is driven by the future availability of fishing grounds and alternative energy carriers regulations. Despite many useful studies related to this topic, no studies were found that specifically addressed the defined problem. To address this research gap, subquestion 3 is defined. This chapter explains and describes the model used to answer subquestion 3.

> *"What are requirements for an assessment model and what parameters should it include to determine the technical and economical feasibility of CO_2 emission reduction systems?"*

The model should be able to determine the technical and economic influences of CO_2 reduction methods on board Dutch beam trawlers. The proposed model is developed with the purpose of making the research work easily applicable to different beam trawlers. The model input is derived from the research conducted in the previous chapters. The model should function as a support tool to facilitate well-founded decisions when assessing retrofit possibilities. The options proposed in the model are all based on retrofitting existing models. At a later stage, the retrofitting options will also be referenced to a Padmos new build beam trawler.

The application of CO_2 reduction methods will result in potential iterations in ship design. This is due to the lower energy densities of the energy carriers compared to conventional ones. The safety requirements for alternative energy carrier storage will also result in additional required volume. To accommodate the extra required volume the vessel can be extended in length without changing the layout. The required volume can also be gained by (partly) using the fish hold. If required, extra volume is gained in lengthening since this is most favourable looking at added volume versus capital expenses [54], for existing vessels.

Vessel effectiveness in model architecture:
Within this research, in Chapter 2.4, multiple operational effectiveness requirements were defined. These requirements are all incorporated into the model as either variable input parameters or fixed parameters:

1. **Endurance** is represented by a variable input for fishing and transit hours.
2. **Towing capacity** is incorporated as an average fixed relation between vessel speed and fishing gear dimensions.
3. **Fish hold** is included as a variable input, representing the total volume of the original fish hold.
4. **Cooling** is incorporated as a fixed continuous required electrical power to ensure cooling and ice production.

5. **Working deck** requirements are not taken into account, as there is no vessel configuration that reduces the working area. These requirements are only relevant for new builds or when fuel tanks are positioned on deck.
6. **Storage volume** is considered by taking into account the volume of the net store available. This variable is used to assess the effectiveness of utilizing this volume for energy carrier storage.

The top to bottom model is introduced in Figure 4.1. All calculation steps are indicated by green numbered boxes. The model is divided into three sections: (1) literature study, (2) technical feasibility and, (3) economical feasibility. The model starts at the top (blue), where a combination of emission reduction configurations is proposed. Different combinations of propulsion setups and emission reducing methods are tested on their technical feasibility (yellow), secondly their influence on economical performance is tested (red). Firstly, the mono-fuel configurations are tested, secondly the combination of two different energy carriers (hybrid) is tested according the same calculations sequence.

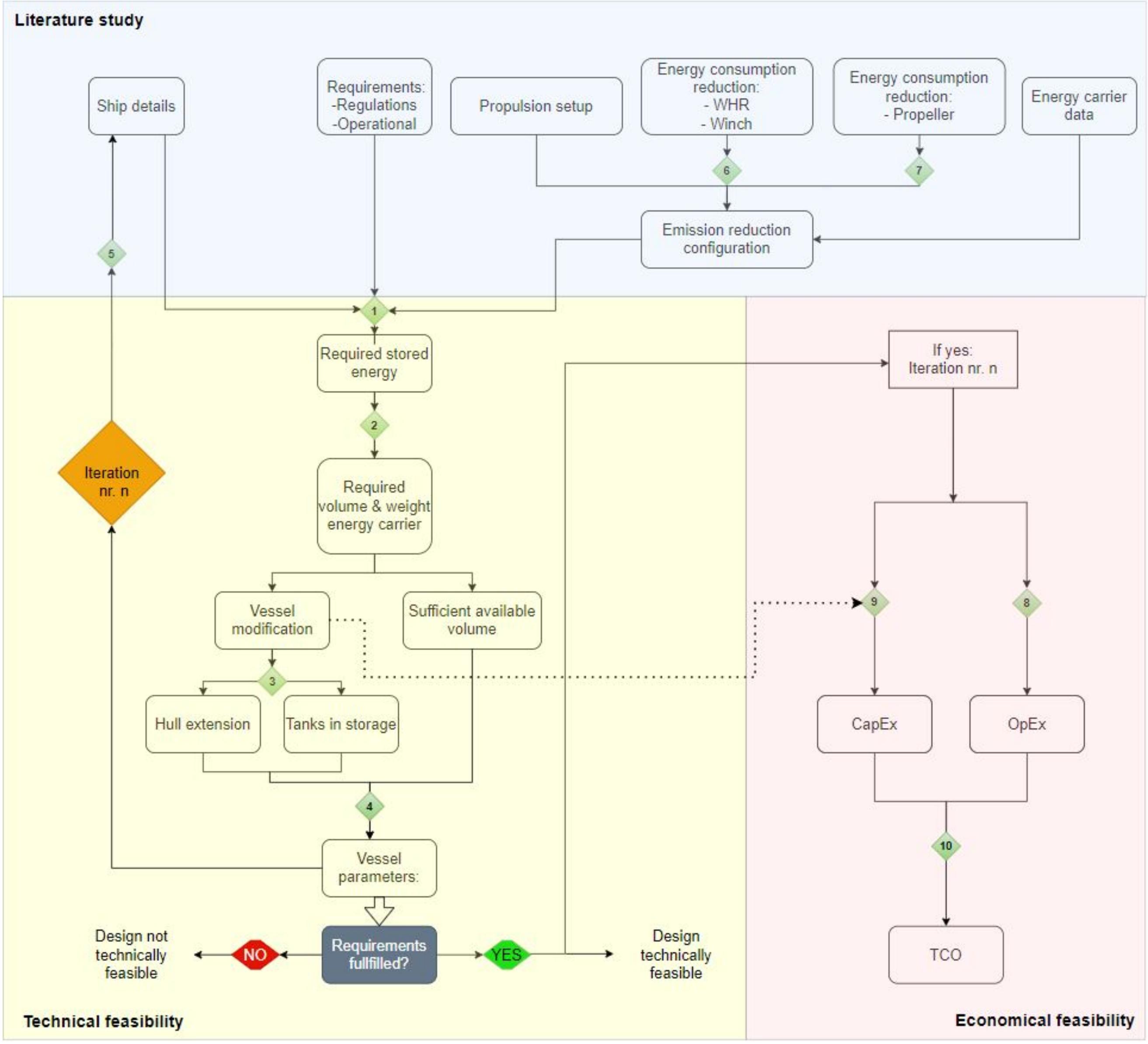


Figure 4.1: Assessment model overview

4.1. Technical feasibility

Within this section each specific calculation and decision within the model is described, to determine the technical feasibility of each propulsion configuration. The CO_2 emission reduction of the configurations is presented as a percentage compared to original vessel CO_2 when it was built, this is done since the IMO introduces their regulations with an % with respect to 2008.

The Energy Efficiency Existing Ship (EEXI) indicator is not suitable for this study due to the complexity of correction factors for beam trawlers, exclusion of non-conventional propulsion systems, and reliance on cargo transport distance, [59]. Similarly, the Energy Efficiency Design Index (EEDI) is not chosen because it is designed for new build vessels, [38]. The Carbon Intensity Indicator (CII) is also not selected as it measures emission per transport work, [58] [59]. Therefore, a different method is preferred for its simplicity and applicability to existing vessels. Due to the characteristics of these indicators and the lack of appropriate factors for this type of fishing vessels, these methods are not used in the calculations.

Tank-to-wake(TTW), this research utilizes TTW emissions for several reasons. While gathering data for Well-to-Wake (WTW) emissions, which cover the entire fuel life cycle, proves complex, TTW emissions, focusing solely on ship operation emissions, are more accessible and easier to interpret. TTW emissions are preferred due to their direct relevance to in-use ship operations, ease of monitoring, and practicality for regulatory compliance. They enable a simplified assessment of a ship's environmental performance, facilitating straightforward comparisons between ships and routes. It's worth noting that Well-to-Tank (WTT) emissions, which require additional data and forecasting, fall outside the scope of this thesis.

The emission reduction percentage is expressed as a percentage reduced with respect to the original amount. Thus amount is the consumed fuel per cycle calculated in Table 2.7 multiplied by the emission factor of MGO stated in Table 3.3, which results in Table 3.4 and Table 3.5. The emission for the other researched energy carriers is stated in Figure 3.1.

1. Required stored energy

The total required energy stored onboard is calculated using input from: ship detail, operational and regulation requirements and propulsion configuration setup. The following parameters must be known to calculate the total required stored energy for a long cycle:

- Energy consumption
    - $P_{fishing}$, energy requirement fishing (kW)
    - $P_{transit}$, energy requirement transit (kW)
    - $P_{auxiliary}$, energy requirement auxiliary (kW)
- Operational profile
    - $T_{fishing}$, fishing hours (hrs)
    - $T_{transit}$, transit hours (hrs)
    - $T_{auxiliary}$, auxiliary hours (hrs)
- Propulsion configuration
    - η_{conv}, converter efficiency (-)
    - η_{reform}, reformer efficiency(-)
    - $\eta_{TRM} = \eta_{shafting} * \eta_{gearbox}$, transmission efficiency (-)
- E_{req}, Required energy ($GJ/trip$)

The required P_D and auxiliary power per operation are determined in, Section 4.1. Depending on the propulsion configuration the proper transmission and converter efficiencies will be taken into account. The required power for fishing, trawling and auxiliary is kept separate in all calculations, this to simplify the implication of hybrid applications on a later stage. The separate calculations will also give a better understanding on the energy consumption per operation. This results in the following equations:

$$E_{req} = (E_{fishing} + E_{transit} + E_{aux}) \tag{4.1}$$

$$E_{fishing} = (T_{fishing} * P_{fishing}) * \frac{1}{\eta_{conv} * \eta_{reform} * \eta_{TRM}} \tag{4.2}$$

$$E_{transit} = (T_{transit} * P_{transit}) * \frac{1}{\eta_{conv} * \eta_{reform} * \eta_{TRM}} \tag{4.3}$$

$$E_{aux} = (T_{aux} * P_{aux}) * \frac{1}{\eta_{conv} * \eta_{reform} * \eta_{TRM}} \tag{4.4}$$

In Section 3.2 and 3.3, the reformer and converter efficiencies are defined for the different energy carriers and propulsion configurations. The efficiency of reformer and converter are assumed to be constant. Although this is a rough assumption it will not further complicate the technical solutions. Next to frequency converters, AFE and generator losses, no further electronic distribution losses are taken into account.

Table 4.1: Converter characteristics, [179] [102] [15] [61] [190] [119] [179]

Converter	Energy carrier	η	kW/kg	Comments
ICE	Diesel	48	71	
ICE	Diesel-methanol	50	65	95% methanol, 5 % diesel
Electromotor	electricity	96	5	PM
SOFC	hydrogen	60	119	
LT PEMFC	hydrogen	60	400	
GBX	-	99	5(CW) 9(CW-CCW)	
Shafting	-	99	-	
Generator	-	88	-	mechanical ->electrical
Active front end(AFE)	-	96	n/a	Switchboard ->EM propeller

The energy reduction or production as a result of the application of WHR, regenerative winch breaking or change in hauling/setting procedure are incorporated in the consumed auxiliary power, these will be discussed in calculation step 7.

2. Required volume & weight energy carrier

Using the required energy per operational profile, together with the volumetric energy density including tank, an estimate can be made on the required storage volume, see equation 4.5. With the gravimetric energy density and the required energy per long cycle the total required energy carrier weight can be estimated as well, equation 4.6.

$$V_{req} = \frac{E_{req}}{\rho_{volume}} \tag{4.5}$$

$$W_{req} = \frac{E_{req}}{\rho_{weight}} \tag{4.6}$$

Where:

- V_{req}, required volume to store energy (m^3)
- W_{req}, required weight to store energy ($tons$)
- ρ_{volume}, volumetric energy density (GJ/m^3)
- ρ_{weight}, gravimetric energy density (GJ/kg)

The data necessary for these calculations is provided in Section 3.2. The calculations assume that the required energy carrier is stored in a single tank, with the exception of methanol, which has specific tank requirements. Methanol is assumed to be stored in two large tanks, as shown in Figure F.1. The hydrogen storage ratio in terms of energy per volume (GJ/dm^3) is determined based on [97], as depicted in Figure 3.1.

3. Vessel modification

Due to lower energy carrier densities, it is assumed that the available original bunker volume may not be sufficient for some propulsion configurations. To create additional storage volume, two options are investigated in this research.(1) Option explores the possibilities of utilizing other available storage volumes to store the energy carrier. (2) Option involves extending the vessel's hull to accommodate the required energy carrier volume. Figure F.1 illustrates the two proposed options for energy carrier storage. The combination of using the fish hold and net store is not examined, as it would result in the inability to store necessary spare materials.

Storage volume

Two storage areas are identified which could be (partly) used to store energy carrier, these are the netstore and the fish hold, see Figure 4.2.

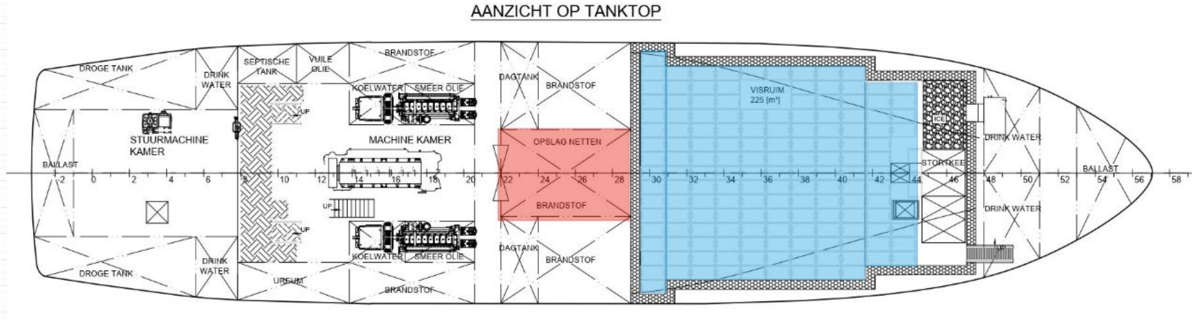


Figure 4.2: Example, additional available storage volume [Padmos image], Shaded red: netstore, shaded blue: fish hold

The use of these storage volumes will come with operational and technical consequences. For example partly using the fish hold will result in a reduction in the ability to store full fish boxes. The required extra volume is calculated by subtracting required volume from Section 4.1, minus the available volume in original storage tanks. The product of this sum, is the volume which is lost in the original net store or fish hold. With equations Equation 4.7 and Equation 4.8 the weight and energy of the energy carrier which is stored in net store or fish hold can be calculated.

$$E_{added} = V_{add} * \rho_{volume} \tag{4.7}$$

$$W_{added} = \frac{E_{added}}{\rho_{weight}} \tag{4.8}$$

$$V_{addedstoragevolume} = L_{extension} * A_{midsection} * 0.85 \tag{4.9}$$

0.85 represents an approximated 85% of this mid section area is allocated for new storage tanks, leaving the remaining space for additional piping, hallways, and other purposes. The author acknowledges that the specific percentage could vary, as an accurate value was not found in the literature. Thus, the author recognizes the need to experiment with different percentages later to assess their impact on the research findings.

Vessel extension

To gain additional volume for energy carrier it is identified not to be possible or favourable to position tanks on other positions. The main reasons for this decision are: (1)increase tank dimensions on top, deck area is lost. (2)increase tank dimensions towards bottom, not possible due to presence of tank top and or hull. (3) position tank behind wheelhouse not favourable due to high point of gravity, safety since accommodation is located below and potential identified hazardous area around tanks. (4) tank on top of bow not allowed due to requirements on horizontal field of vision [164].

Vessel extension could be a good alternative to prevent changes in operational profile and vessel arrangement. The vessel is extended at midship due to section since this results in the highest additional volume per extended meter and in general due to no systems being present here the costs are lowest as well. This is the result of the vessel having the largest moulded beam and highest mid section coefficient here. Adding length, weight and volume in the hull will result in additional hull resistance. Extra hull resistance results in more required stored energy to operate the same operational profile, to take this effect into account this calculation step is included in an iteration loop. The hull resistance is determined using ship details and a resistance prediction model which is explained in Chapter 4.1. The extension length is determined according equation 4.10.

$$L_{extension} = \frac{\frac{E_{required} - E_{stored}}{\rho_{volume}}}{D_{midship} * B_{midship} * C_{midship}} \tag{4.10}$$

After calculating the added volume with equation: 4.10, the additional steel weight should be known to estimate the capital costs of extension. Since the vessel dimensions and original weights are known, the extension weight is estimated manually. Based on the provided midship dimensions and steel structures shown in Figure 4.4, it is possible to estimate the weight of the extension.

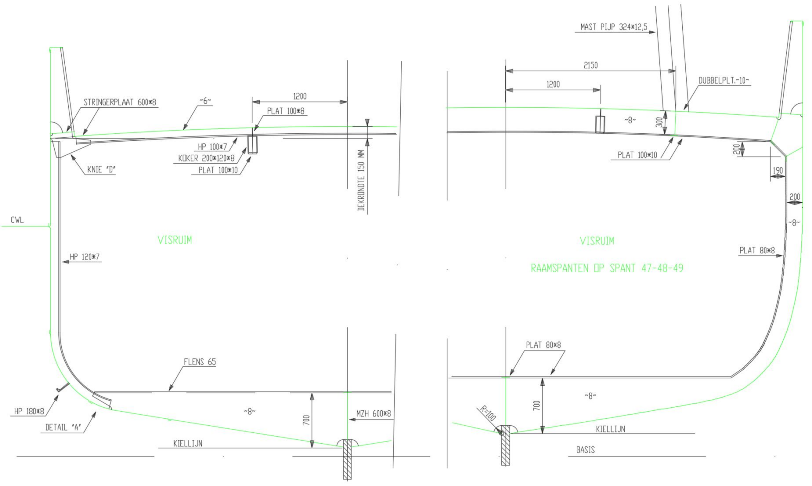


Figure 4.3: Example, beam trawler mid section used for weight and volume calculation[Padmos image]

The area and volume of a typical frame and web frame are calculated, together with an average steel density and frame spacing this results in a weight per meter extension, see Table 4.2. For these calculations shipbuilding steel grade A is used.

Table 4.2: Weight of midship framing

Area	m^2	$\eta_{steel}(\frac{kg}{m^3})$	Weight(kg)
Webframe	9,16	7850	575
Typical frame	4,83	7850	305
Total	n/a	7850	4800/m

5. Hull resistance

Considering the vessel particulars, it is possible to estimate the speed-resistance curve. However, due to limited information regarding the hull, various estimation methods were explored.
The only input which is available is: engine data, energy carrier consumption in different operations and bollard pull tests. As a reference vessel a new build beam trawler is used from which all data is available. The company does not own any license to use commercial prediction programs. This results in the available resistance prediction with empirical methods to be limited to:

- Hollenbach, for displacement vessels[20]

- Holtrop & Mennen, for displacement vessels[121]
- Van Oortmerssen, for smaller displacement vessels[133]
- Britisch Columbia, for smaller displacement vessels with a low L/B ratio[32]

For the validation of different hull resistance predictions a DELFTship license is granted for a week. One of the prediction methods used in DELFTship is Hollenbach. The Hollenbach model requirements on parameters are met for a beam trawlers and the model description matches with a beam trawler. Secondly Van Oortmerssen is checked on its parameter requirements and found complying for a beam trawler. Although the van Oortmerssen (p.15 [194]) makes use of data points and vessel specific parameters which are determined by different ships series, these series are not available to public. The British Colombia was found not to be open source, so it can not be used. The Holtrop & Mennen is referenced to the power speed curve executed by MARIN on a similar Padmos beam trawler. It is found that Holtrop & Mennen approaches the actual hull resistance best, the methods parameter requirement are satisfied(Table 4.3) and will therefor be used. The variation between reference and Holtrop & Mennen: Fishing +0.1kN, Transit +0.6kN. Due to the operational profile and the ratio's between hull and fishing gear resistance this method is found to be suitable.

The input parameters are determined with the 3D hull scans in CAD or line planes from the specific vessel if available. The equation's and parameters used are defined and explained in [122].

Table 4.3: Holtrop & Mennen ratio requirements [122]

Ratio's	Method requirement	Dutch beam trawler
L/B	[3.9, 14.9]	4.5
B/T	[2.1, 4.0]	2.59
LCB%	[-5,5]	-2.5
Intrance angle	[1, 90]	35
bulb above keel line	[0, 0.6T_{fpp}]	0.3T_{fpp}
Fn	[0.06, 0.77]	0.3 - 0.7
Cp	[0.55, 0.85]	0.83

Vessel weight and volume

The new emission reduction configuration come with their own specific weight and volume requirements. The weight of each propulsion setup is estimated using kg/kW ratios from, Table 4.1 given by studies or by manufacturers, equation 4.11. This estimation will be used to check if the vessel weight increases or decreases. The change in vessel weight will result in a reduction or increase of draught and thus displacement. The new characteristics will again be used as an input to re-calculate the hull resistance. The draught increase or decrease is determined using the water plane area and the sea waters density, equation 4.11. In this calculation the weight and volume of electrical distribution is not taken into account. The vessel extension option which explained and elaborated in Equation 4.1 will influence the underwater volume, waterplane area and wetted surface area, it is assumed that the weight in water of section including energy carrier is zero.

$$\Delta T = A_{waterplane} * (\Delta_{new} - \Delta_{old}) * \rho_{SW} \tag{4.11}$$

- ΔT, draught change w.r.t T original(m)
- Δ_{new}, new vessel displacement(t)
- Δ_{old}, original vessel displacement(t)
- ρ_{SW}, seawater density(kg/m^3)

With the new draught the parameters required for the hull resistance are determined in CAD.

6.1 WHR

Depending on propulsion configuration, a certain amount of exhaust gas and cooling water is produced. The recovered energy is converted into electric energy which can be used to charge batteries or to feed the electric board. Although the application of waste heat sounds straight forward there are a couple of hidden requirements which have to be met. First of all there is a lower limit on the temperature and flow of exhaust gas and cooling water, to operate properly. Secondly the ship should have a single general exhaust channel in which the heat exchanger can operate. Due to the efficiency of different power converters and configurations the waste heat available varies. Therefor this calculation only uses the fishing hours as usable operational hours. Secondly the WHR is not applied to mono fuel NMC-Li battery configurations and hybrid configurations with NMC-Li as a second energy carrier.

The energy input in combination with the converters efficiency will be used to estimate the available waste heat. Multiplying this energy flow by the heat recovery systems efficiency will result in the amount of electricity which can theoretically be retrieved, equation 4.12. The used percentages and efficiencies of energy converters and heat recovery systems are mentioned in Chapter 3.1 & section 3.3.

$$E_{recovered} = \dot{m}_f * h_l * \eta_{conv} * \eta_{recovery} \tag{4.12}$$

Using:

- h_l, lower heating value, $(\frac{MJ}{kg})$
- $\dot{m}_f$, energy carrier consumption, $(\frac{kg}{h})$
- $E_{recovered}$, recovered electrical energy, (kWh)

6.2 Energy consumption reduction winch

This calculation step is divided into two parts: (1) regenerative braking, (2) change operation hauling/setting. For the gear resistance in water and on the seafloor two researches of Wageningen University & Research are used, [151], [150]. To be able to compare the results of the calculations a benchmark operation is defined in Table 4.4:

Table 4.4: Benchmark hauling & setting fishing gear

STW ship[kn]		Winch[m/min]		Weight[t]	Gear resistance[kN]				
Hauling	Setting	Hauling	Setting	Gear in air	1 kn	2 kn	3 kn	4 kn	5 kn
3.5	3.5	100	120	7.5	5	7	10	16	30

Regenerative braking

As described in Chapter 3.3.2 energy is lost during setting of the gear. With the application of regenerative braking a certain amount of energy can be recovered. The recovered energy is calculated according the following data and equations: payout speed/minute, payout wire tension, payout length, winch dimensions, fishing gear resistance and vessel speed. For the application of making an electric motor to operate as a generator it has to be fitted with an active front end(Chapter 3.3.2), this system has an efficiency of 95% including mechanical losses [7].

$$P_{recover} = 2\pi * n_{winch} * Q * Time * \eta_{system} \tag{4.13}$$

$$Q_{winch} = 2 * \frac{T_{wire}}{2} * r_{drum} \tag{4.14}$$

$$n_{winch} = \frac{Payoutspeed}{2\pi * r * 60} \tag{4.15}$$

Using:

- n_{winch}, winch rotational speed, (s^-1)
- r_{drum}, drum radius, (m)
- Payout speed, (m/min)
- T_{wire}, wire tension, (N)
- Q_{winch}, torque around winch axe, (Nm)

Change operation

By changing the operation for setting and hauling of the nets, energy can be saved. In this step the propulsion power is brought to a minimum while adjusting the hauling and setting speed such that safe operation is maintained, due to propulsion efficiency being lowest w.r.t. electric motor, Chapter 4.1. The potential saving is determined referencing the benchmark to the new operation. The new operation requires a minimum ship speed of 1.5 STW, and a positive or negative speed 0.5 knots difference between vessel and fishing gear of depending on hauling or setting. The two values which are referenced are the required winch power and the propulsion power. The required or lost winch power is calculated according equations: 4.13, 4.14 & 4.15. The required propulsion power is the sum of vessel speed and $\Delta\ speed$ between hull and fishing gear, which is approximated with the help of hull's resistance curve and an estimation on beam trawl fishing gear resistance with the help of mentioned sources(Chapter 4.1) and measurement(p.28-33 [23]). After calculations the following table can be completed:

Table 4.5: Potential energy saving by optimizing winch operations

	Hauling			Setting		
	Winch P[W]	Propulsion P[kW]	Time[minutes]	Winch P[W]	Propulsion P[kW]	Time[minutes]
Reference						
New						
Difference						

The potential of this option is completely depending on the skipper of the vessel. Therefor this energy saving option can not be applied in general, since some skippers are already aware of this method/way of operating. But since this study looks into energy saving with reference to 2008, it is calculated and applied on all the proposed configurations with exception of the original base case.

7. Propulsion power

After determining the hull resistance of the vessel the propulsion power has to be determined, to be able to calculate the energy consumption of the vessel per operation. The calculation step between hull resistance and required propeller power is executed according (p.64 [81]). Due to the lack of available specific information on hull and propeller, some specific assumptions or characteristics have to be made or determined. The data which is available is the current fuel consumption, vessel speed and fishing gear resistance. This data is used to determine the characteristics of the current propeller which is used as the benchmark.

The following efficiencies and characteristics have to be known to come to the propulsive efficiency and propeller power:

$$\eta_H = \frac{1-t}{1-w} \tag{4.16}$$

$$\eta_O = \frac{P_o}{P_p} \tag{4.17}$$

$$\eta_R = \frac{P_p}{P_s} \tag{4.18}$$

With the input off the propeller designer, the scope of this research and a study outcome [18] the hull efficiency(η_H) is assumed to be constant:

$$\eta_H = \frac{1-0.21}{1-0.25} = 1.053 \tag{4.19}$$

This does not mean that t and w do not change but it is assumed that they change such that the hull efficiency remains constant. Despite this being a rough assumption and highly dependent on the specific ship and propeller combination, it is still assumed so because there is no further information available for each ship at this stage of checking different feasibility's. According to the information which was available [104] [33] the efficiency has chosen to be 1,053.

Secondly, the relative rotative efficiency η_R is also assumed to be constant [34].

$$\eta_R = \frac{P_p}{P_s} = 1.07 \tag{4.20}$$

The last changing and important, is the open water efficiency (η_O). With the known fuel consumption, auxiliary power, hull resistance, trawl gear resistance and the stated efficiencies above the open water efficiency can be estimated. By using the actual brake power, P_B (Appendix A), less varying parameters are introduced and thus less sensitivity to errors is build in, Table 4.7.

$$P_E = R * v_s \tag{4.21}$$

- P_E, effective towing power, (kW)
- R, hull and fishing gear resistance per operation, (kN)
- v_s, ship speed, (m/s)

Table 4.6: Case vessel hull resistance, for fishing and transit

Operation/resistance	v_s(m/s)	Hull(kN)	Fishing gear(kN)
Fishing	2,58	5,5	65,0
Transit	4,63	20,0	0

Table 4.7: Theoretical open water efficiency original propeller η_O

Operation	P_B	P_D	P_E	η_{GBX}	η_S	η_R	η_H	η_O
Fishing	890	871	182	0,99	0,99	1,07	1,053	0,19
Transit	420	411	93	0,99	0,99	1,07	1,053	0,21

To reduce the required brake power the open water efficiency of the propeller has to be increased. This is done by increase of propeller diameter, Chapter 3.3.1. With the known fishing conditions and the determined propeller characteristics, different propeller diameters are investigated. The new proposed propellers are determined using PropCalc or propeller data sheet. A side note on this statement is that these calculation programs do not include matching with the installed propulsion setup. This can results in the engine not being able to supply the requested torque on a certain propeller speed. Since this study will look into the application of different propulsion setups and energy converters, for simplicity it is assumed that the matching of K_q will not pose any problem in this study. This assumption also tends to be realistic since: latest development in sustainability subsidy requirements proved to request a DC switchboard and an electric propulsion setup, therefor an EM will be used. For the increase of open water efficiency this study looks at two different types of propellers, Table 4.8.

Table 4.8: Proposed new propellers, Wageningen ducted series

	Propeller type 1, 3	Propeller type 2, 4
Type	Ka 19A	Ka 19A
Diameter	3,4 & 4	3,4 & 4,0
Ducted	nozzle 19A	nozzle 19A
Blades	4	5
Disc area ratio	0,6	0,6

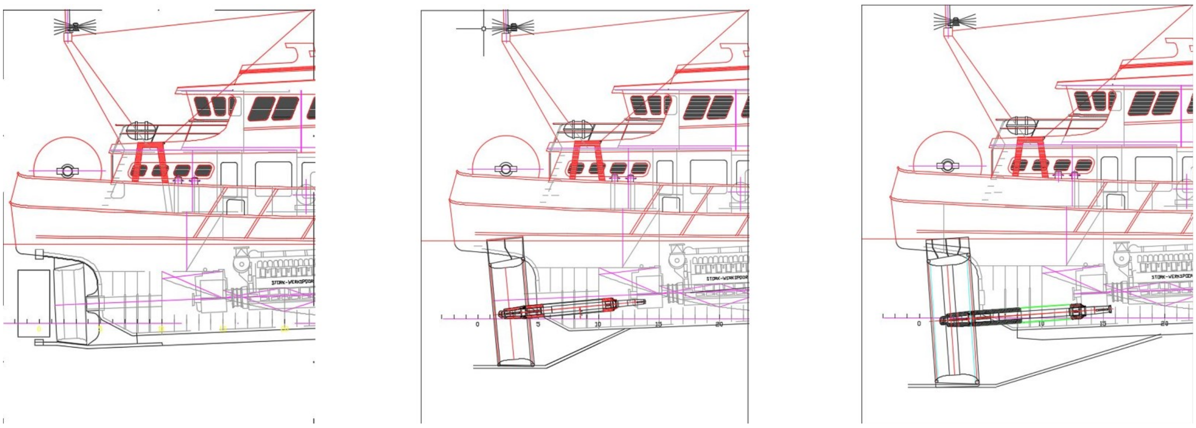


Figure 4.4: Visualization propeller diameter increase
Original[left], 3.4m[mid] and 4.0m[right] diameter propeller[Padmos image]

With the introduction of new propellers, the new required delivered shaft power can be determined. With the new required shaft power the new brake power can be determined. This P_D is the input for calculation Step 1.

Requirements full filled?

Once the necessary energy carrier volume has been determined, the new emission reduction configuration of the ship is evaluated to ensure it meets the operational and regulatory requirements outlined. An essential requirement is comparing the available energy carrier storage volume with the required volume. If the available volume falls short, this study suggests methods for creating additional storage capacity. Once these calculations are made, the new hull parameters are determined for each propulsion configuration. The combination of hull adjustments, along with the added weight and volume of the propulsion configuration, serves as input for the iterative process. These iterations aim to enhance the accuracy of the actual new hull resistance and propulsion power.

Secondly the configuration is checked on 2 other requirements namely:

- Maximum added average draught: **0.3m**
  The impact of added draft on vessel-specific values is influenced by functional and regulatory limitations. Stability, maneuverability, structural integrity, and seakeeping are among the characteristics affected by increased draft. Additionally, minimum stability and freeboard requirements must be fulfilled. The extent to which added draft affects these values can vary depending on the vessel's unique characteristics, purpose, and operational conditions. Although it is beyond the scope of the project, a value of 0.3m is assumed as a reasonable and acceptable measure.
- Maximum added extension: **3.0m**
  The extension length may be subject to restrictions due to functional or regulatory limitations arising from the combination of GT (gross tonnage) and required crew certificates. Moreover, the extension length will have implications for stability, maneuverability, structural integrity, and seakeeping. Consequently, the impact of the extension length on these values may vary depending on the vessel's characteristics, purpose, and operational context. While this falls outside the project's scope, a value of 3.0m is assumed as a suitable and acceptable measure.

If the propulsion configuration does not meet the requirements it is deemed technically infeasible. If the configurations meets the requirements the next step is to assess their economical performance. Using the known consumed energy carrier, energy carrier prices, propulsion configuration prices the OpEx and CapEx are estimated, (see Step 9, 9 and 10). If the configuration does not meet requirements the configurations is found not technical feasible.

4.2. Economical feasibility

Within this section the economical feasibility of an emission reduction configuration is determined. In the sub-section below a explanation on how the economical feasibility parameters are calculated and defined. The three metrics on which the performance of the ship are going to be judged are (1) operational expenses(Opex), (2) capital expenses(Capex), and (3) Total cost of ownership(TCO). These metrics are about to find the costs of the new vessels with respect to meeting emissions requirements.

8. Operational Expenses

To determine the economical feasibility of emission reduction systems the OpEx of the emission reducing configuration must be known. It represents the expected yearly costs of operating a propulsion configurations. In this calculation the energy carrier specifics, operational profile and energy consumption are combined to determine the costs per cycle. Although the application of new propulsion configurations will come with different: life times, overhauling intervals, consumables,licenses of engineers and maintenance costs this research will only use consumed energy carrier prices, emission taxes(Chapter 1.3) and maintenance costs to estimate the OpEx (see equation 4.22). This decision is made based on the defined economical performance of the vessel in Chapter 2.5.

$$OpEx = Energy\ Carrier + CO_2\ emission\ taxes + Maintenance \tag{4.22}$$

Using:

- $Energy\ Carrier$, required amount of energy carrier per year multiplied by price
- CO_2 emission taxes, CO_2 emission per year multiplied by tax price
- Maintenance, the yearly costs required to keep propulsion configuration and ship in good and reliable condition.

Maintenance costs

To obtain the most accurate estimate of the expected costs per propulsion configuration, the annual maintenance costs need to be determined. These costs will always be an approximation as they depend on various variables such as operational hours, whether the work is performed in-house or by a subcontractor, etc. Additionally, predicting breakdowns is challenging. However, through the expertise of Padmos and insights from case studies, an attempt has been made to determine an annual cost estimate for ship maintenance.

Internal combustion engine

Due to the similarity in working principle of the engines and the fact that this research only considers new engines, the operational expenses of all internal combustion engines are closely aligned with each other. Resulting from conversation with Padmos employees and [29] a yearly maintenance costs for propulsion only is determined. These values are used for booth type of long cycles.

- ICE MGO, ...
- ICE HVO, ICE FAME, ...
- ICE DF, ...

LT PEMFC

It is assumed that the majority of the propulsion system-related maintenance costs originate from the limited lifetime of the costly fuel cell system. The lifetime of PEM fuel cells is said to be 10,000 to 40,000 hours, after which a refurbishment is needed. In a study optimizing the design of LT PEMFC powered ferry, the lifetime for PEM fuel cells was said to be 10.000 to 40.000 hours [144], this study uses 20.000 hours life time. According the two types of long cycles and the proposed hybrid configuration the required amount of refurbishments is calculated:

- Mono fuel
  - 100hr, 4 refurbishments, 15 year lifetime
  - Continuous, 6 refurbishments, 15 year lifetime
- Hybrid
  - 100hr, 2 refurbishments, 15 year lifetime
  - Continuous, 3 refurbishments, 15 year lifetime

The operating hours of the fuel cell in the hybrid configuration are based on the assumption that initially, all power is supplied by the internal combustion engines (ICEs), and subsequently, the fuel cell (FC) provides the remaining power to meet the operational requirements. This means that the operational hours of the fuel cell is depending on the ratio of energy carrier supply, and thus always lower than the operational hours of the long cycle. The fuel cell refurbishment cost was set to € 1000/kW, similar to the assumption of the SF-BREEZE optimization study (p. 25 [144]).

NMC-Li battery
Most of the maintenance costs associated with propulsion systems are believed to stem from the limited lifespan of the expensive battery system. Additionally, the maintenance costs of electric motors are considered negligible [176]. Xalt Energy has indicated that NMC-Li batteries, operated at a depth of discharge (DSOC) of 80%, can be expected to last for more than 10,000 cycles at a charge/discharge rate of 1C [174]. However, the actual cycle life varies between the two different long cycles, due to available charge time. For the 100-hour cycle, a charging time of 48 hours is available, while the charging time for the Continuous cycle is limited by the operational profile to 12 hours. Despite this difference the depth of charge and cycles do not exceed expected cycle life time. Consequently, a battery system operational lifespan of 15 years is assumed for both the 100-hour long cycle and the Continuous cycle. This means that the operational expenses of the battery system are accounted for as part of the capital expenses for the year 2023, with an additional of €$25000/year$ to take into account inspections, replacement of faulty cells or modules and HVAC systems [174].

Vessel maintenance
Next to propulsion configuration maintenance costs an cost item for all other auxiliary vessel maintenance is estimated. Two variations are made here, maintenance for an existing average beam trawler and a new build vessel. To avoid going into too much detail due to the sensitivity of this data coming from the company, an average beam trawler is expected to have an annual cost item of ..., while a new build is anticipated to have a cost item of ... euros

9. Capital Expenses

With the propulsion configurations that meet the requirements, an estimation can be made on the system prices and vessel retrofitting prices. The propulsion configuration system prices can be estimated using average $\frac{€}{kW}$ fractions. The retrofitting prices of the vessel are difficult to estimate, since they are vessel specific. Steel prices and labour prices are fixed but the required amount of hours and steel are difficult to estimate. The capital costs of retrofitting are significant and therefor must be included in the economical feasibility. The companies history in vessel retrofitting is used to estimate working hours for the different retrofitting options. The added weight of the extension section is already known, see Chapter 4.1. With an average price on steel welding, cutting and pre-forming costs this results in the costs to make the section. For example: a recent hull extension required ... hours to cut the hull in two and another ... hours to join the section again.

The CapEx is built up as the sum of propulsion configurations costs, propeller, winch modifications, WHR and vessel extension costs, equation 4.23.

$$CapEx = Propulsion\ configuration + Energy\ saving\ devices + Hull\ extension \tag{4.23}$$

Vessel depreciation

Due to the aging of beam trawler, there is a difference in the depreciation of the existing average beam trawler, the new propulsion configuration, and the depreciation of a new build beam trawler. The following depreciation periods and factors are used:

- Existing hull retrofitted vessel, life cycle 15 years, current average beam trawler price decreases with $\frac{1}{15}$ per year
- New build beam trawler, lifetime 20 years, initial investments decreases $\frac{1}{20}$ per year
- ICE, life cycle 20 years, initial investments decreases $\frac{1}{20}$ per year
- LT PEMFC, the depreciation is taken into account by average refurbishment costs per year
- NMC-Li, life cycle 15 years, initial investments decreases $\frac{1}{15}$ per year

10. TCO

One widely used approach is the analysis of the total cost of ownership (TCO), equation 4.24. TCO takes into account not only the upfront investment costs but also the operational and maintenance expenses over the system's lifetime. By considering the entire lifecycle of the system, TCO offers a more accurate representation of the actual economic impact of the new configuration [94]. A new propulsion configuration may require significant investment upfront, but its long-term cost implications are equally crucial. TCO analysis helps in identifying potential cost savings over the operational lifespan of the system. For instance, a propulsion configuration with higher fuel efficiency and lower maintenance requirements may result in substantial cost reductions over time, offsetting the initial investment. TCO analysis allows for a fair comparison of different propulsion configurations [171]. By calculating and comparing the total costs associated with each option, decision-makers can identify the most economically viable solution. This approach ensures that the evaluation process considers not only the initial investment but also the ongoing operational expenses, providing a more comprehensive and accurate assessment.

$$TCO_{yearly} = CapEx + Opex \tag{4.24}$$

- TCO_{yearly}, the yearly total cost of ownership[€/year]
- $Capex$, the capital expenditures[€]
- $Opex$, the operational expenditures[€/year]

In the context of the new propulsion configuration, the vessel's expected lifetime is considered to be 15 operational years. Consequently, the residual value of the investment, or the remaining value of the system after its useful life, is expected to be negligible or zero. This expectation arises from factors such as technological obsolescence, wear and tear, and the introduction of newer, more efficient propulsion technologies over time. Given the vessel's expected lifetime of 15 operational years, the TCO analysis typically focuses on this relatively short time horizon. Since the remaining value of the investment is negligible or zero by the end of this period, including it in the TCO analysis would not significantly impact the overall economic assessment. Only at a later stage when a new build vessel is included into the configurations, a remaining value will be included since this vessels lifetime is more than 15 years, 4.25. The remaining value is determined according, equation 4.2.

$$TCO_{yearly} = CapEx + Opex - Remaning\ value \tag{4.25}$$

4.3. Conclusion

The answer to sub question:

> *"What are requirements for an assessment model and what parameters should it include to determine the technical and economical feasibility of CO_2 emission reduction systems?"*

To make sure the vessel can continue fishing, the following effectiveness requirements are included into the model: Endurance, Towing capacity, Fish hold, Cooling, Working deck and Storage volume. The technical feasibility is determined using input from: onboard power measurements, construction/technical documentation, operational profile and input from the literature study. With the known hull dimensions the resistance is determined using Holtrop & Mennen, together with the fishing gear resistance the P_d is determined. The P_d, together with configuration efficiency, OP and energy carrier characteristics results in an amount of required mass and volume of energy carrier. With the known hull dimensions different options are proposed to store this amount.

The economical feasibility is determined using input from the literature study and the in house knowledge of Padmos. The capital investment to retrofit the vessel is the sum of, energy converter, gearboxes,DC Switchboard ,tank storage, energy recovery system(s) and extension costs. These system costs are all determined ratios determined in the literature study. The operational expenses are the costs of energy carrier and emission tax per long cycle.

The overall economical performance of a propulsion configuration is determined with the TCO. TCO takes into account not only the upfront investment costs but also the operational and maintenance expenses over the system's lifetime. By considering the entire lifecycle of the system, TCO offers a more accurate representation of the actual economic impact of the new configuration.

With the application of the described steps above, the technical and economical feasibility of a 2030 IMO proof Dutch beam trawler can be determined.

5

Results

This chapter presents the results of the assessment model, for different configurations applied to the case beam trawler, sailing with an 100hr and Continuous Long cycle. In the economic evaluation, it is assumed that the retrofitted case vessel will have an remaining operational lifespan of 15 years. The effects of the measures aimed at reducing CO_2 emissions are initially examined individually, and the outcomes of these analyses are presented in Section 5.1. Within Section 5.2, 5.3 & 5.4 discusses the influence of different (future)scenarios. Lastly the overall conclusion of the case study on the vessel is described in Section 5.5. The scenario's represent an alternation from used input parameters to find there influence on certain outputs. The input parameters treated are: Scenario 1, energy carrier price and Scenario 2, carbon emission tax. These are also known as Exogenous uncertainties, uncertainties that cannot be controlled by a company.

The subsidy which will be available after the buy out, section 1.1, is assumed to be granted to vessels investing in Diesel Electric configurations, [123]. To increase the economical feasibility of this thesis, the proposed propulsion configurations are therefore D-E, with exemption of the reference D-D configuration.

The last scenario aims to find the most effective method to make the beam trawler comply with IMO 2030 CO_2 emission regulations. By treating all these topics this chapter will answer the main question:

> *"How will the implementation of a new propulsion configuration influence the, vessel design, and economical performance in different future scenarios?"*

In Section 5.1, the technical feasibility of the propulsion configurations is determined, secondly it visualizes the economical performance of the configurations.

5.1. General results

Chapter 2 provides a description of the baseline input parameters for the study. This encompasses both mono fuels and hybrid configurations, as well as energy carrier prices for both the year 2022 and proposed future features. The required volume, weight, extension and cost of each configuration are calculated. In this section, the results are broken down and presented to the reader in reference with the original propulsion configuration with the same operational requirements. Due to the amount of proposed emission reducing configurations and therefore model outputs, some results are illustrated and visualized as trends to keep matters clear.

The results start by illustrating the available energy carriers in combination with their energy converter Table 5.1, secondly it introduces the overall efficiency for booth original and new propulsion configurations.

Table 5.1: Propulsion configurations with overall efficiencies

Converter	**Fuel**	**Configuration**	**Tank to Propeller shaft**	**Tank to SWBD**
ICE(original)	MGO	D-D(original)	0.47	0.46
ICE	MGO	D-E	0.45	0.48
ICE	HVO	D-E	0.43	0.46
ICE	FAME	D-E	0.45	0.48
ICE	DF	E	0.45	0.48
PEMFC	Hydrogen	E	0.61	0.65
Battery	NMC-Lithium	E	0.95	0.98

Together with the overall efficiencies, the operational profiles and all energy consumers the total required stored energy can be estimated, Table C.1. For the hybrid configurations a combination of these efficiencies is used, according the correct proportions.
The hybrid propulsion configurations are a combination of the energy carriers listed in Table 5.2. The calculations are designed to store the maximum amount of the main energy carrier on board, considering a 40% reduction in CO_2 emissions. The remaining required energy is stored as the secondary energy carrier. These hybrid combinations of energy carriers are chosen based on the assumption that they are the most economically feasible. The combination of Hydrogen and NMC-Li for example will result in significant capital investments, and complex combination of systems. HVO and FAME already achieve 40% CO_2 and are therefor not used in the hybrid configurations.

Table 5.2: Hybrid configurations considered in this research

Main energy carrier	Sec. energy carrier	Configuration
MGO	Hydrogen(l)	D-E
MGO	NMC-Li	D-E
Methanol	Hydrogen(l)	D-E
Methanol	NMC-Li	D-E

The required stored energy onboard for hybrid configuration to full fill the operational requirements are visualized in Table C.2.

The required energy to meet the operational requirements is now transferred into a required stored energy carrier volume for both mono and hybrid configurations, the outcome is presented in Table 5.3 and Table 5.4. The required volumes mentioned here are including storage tank.

What can be concluded from these tables is that for both long cycles, the mono or hybrid configurations with hydrogen, methanol and batteries require more volume than available. The propeller types which represent increasing diameters clearly show that they have a significant influence on decreasing required stored energy and therefore volume. Due to the similar characteristics the bio and synthetic diesels show small deviations compared to required MGO volume.

Table 5.3: Required storage volume[m^3] for mono fuels configurations, red: more volume than available

			100hr long cycle					Continuous long cycle				
			Propeller					Propeller				
Converter	Fuel	Configuration	Original	Type 1	Type 2	Type 3	Type 4	Original	Type 1	Type 2	Type 3	Type 4
ICE	MGO	D-D	22	18	15	18	15	36	29	25	29	25
ICE	MGO	D-E	23	19	16	19	16	38	30	26	30	26
ICE	HVO	D-E	25	21	18	21	18	42	33	28	33	28
ICE	FAME	D-E	25	20	17	20	17	41	33	28	33	28
ICE	DF	D-E	73	59	50	59	50	121	96	81	96	81
PEMFC	Hydrogen	E	117	93	79	93	79	191	151	128	151	128
Battery	NMC-lithium	E	232	188	161	188	161	380	305	259	305	259

Secondly the sum of total required energy carrier storage volume for hybrid configurations in visualized in Table 5.4.

Table 5.4: Required storage volume[m^3] hybrid configurations, red: more volume than available

			100hr long cycle					Continuous long cycle				
			Propeller					Propeller				
Main energy carrier	Sec. energy carrier	Configuration	Original	Type 1	Type 2	Type 3	Type 4	Original	Type 1	Type 2	Type 3	Type 4
MGO	Hydrogen(l)	D-E	63	41	27	41	27	103	65	42	65	42
MGO	NMC-Li	D-E	99	61	37	61	37	163	97	58	97	58
Methanol	Hydrogen(l)	D-E	89	66	54	66	54	145	107	88	107	88
Methanol	NMC-Li	D-E	114	75	54	75	54	186	120	88	120	88

Multiple options are proposed to store the volumes mentioned in Table 5.3, and Table 5.4. Table 5.5, Table 5.6 and Table 5.7, illustrate the required extension length only using the existing storage tank volume, the green columns illustrate the reduction in extension length if the netstore is used to store energy carrier. The cells are marked red, if the extension length exceeds maximum as stated in Section 5.1.1.

Table 5.5: Hull extension[m] for 100hr long cycle, green: hull extension reduction if netstore used, red:extension exceeding maximum

			100hr long cycle									
			Propeller									
Converter	Fuel	Conf.	Original	-	1	-	2	-	3	-	4	-
ICE	MGO	D-D	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
ICE	MGO	D-E	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
ICE	HVO	D-E	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
ICE	FAME	D-E	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
ICE	DF	D-E	1,0	-0,5	0,4	-0,4	0,1	-0,1	0,4	-0,4	0,1	-0,1
PEMFC	Hydrogen	E	3,1	-0,6	2,1	-0,5	1,6	-0,6	2,1	-0,5	1,6	-0,6
Battery	NMC-Lithium	E	7,4	-0,6	5,6	-0,5	4,5	-0,5	5,6	-0,5	4,5	-0,5

Table 5.6: Hull extension[m] for Continuous long cycle, green: hull extension reduction if netstore used, red:extension exceeding maximum

			Continuous long cycle									
			Propeller									
Converter	Fuel	Conf.	Original	-	1	-	2	-	3	-	4	-
ICE	MGO	D-D	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
ICE	MGO	D-E	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
ICE	HVO	D-E	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
ICE	FAME	D-E	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
ICE	DF	D-E	2,9	-0,5	1,9	-0,5	1,3	-0,5	1,9	-0,5	1,3	-0,5
PEMFC	Hydrogen	E	6,0	-0,5	4,4	-0,5	3,5	-0,5	4,4	-0,5	3,5	-0,5
Battery	NMC-Lithium	E	13,3	-0,6	10,3	-0,6	8,4	-0,5	10,3	-0,6	8,4	-0,5

Similar tables are visualized for the hybrid propulsion configuration, Table 5.7.

Table 5.7: Hull extension[m] hybrid configurations, green: hull extension reduction if netstore used, red:extension exceeding maximum

			100hr long cycle										Continuous long cycle									
			Propeller										Propeller									
Main energy carrier	Sec. energy carrier	Configuration	Original	-	Type 1	-	Type 2	-	Type 3	-	Type 4	-	Original	-	Type 1	-	Type 2	-	Type 3	-	Type 4	-
MGO	Hydrogen(l)	D-E	0,9	-0,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2,5	-0,5	1,0	-0,5	0,1	-0,1	1,0	-0,5	0,1	-0,1
MGO	NMC-Li	D-E	2,0	-0,4	0,5	-0,5	0,0	0,0	0,5	-0,5	0,0	0,0	4,6	-0,5	1,9	-0,5	0,4	-0,4	1,9	-0,4	0,4	-0,4
Methanol	Hydrogen(l)	D-E	1,2	-0,5	0,3	-0,3	0,0	0,0	0,3	-0,3	0,0	0,0	3,00	-0,5	1,40	-0,4	0,70	-0,5	1,40	-0,4	0,70	-0,5
Methanol	NMC-Li	D-E	2,2	-0,5	0,6	-0,5	0,0	0,0	0,6	-0,5	0,0	0,0	4,60	-0,5	2,00	-0,5	0,40	-0,4	2,00	-0,5	0,40	-0,4

The following trends can be observed in the three tables above. The application of mono battery configurations exceeds the maximum extension length for both long cycles. For the 100-hour long cycle, the use of Net store can prevent the need for a hull extension. Regarding the use of Net store in general, the maximum extension reduction is 0.6m for all cycles and configurations. The incorporation of energy carrier storage in Net store does not lead to configurations transitioning from being technically infeasible to feasible for the 100-hour cycle. However, for the continuous long cycle hydrogen mono hydrogen, the utilization of Net store does not result in technical feasible configurations.

Table 5.8 and Table 5.9, illustrate the reduction in capacity to carry full fish boxes if it is decided to store the energy carrier in the original storage tanks plus fish hold. Due to the dimensions of the fish boxes (lxbxh:800x250x270mm) the influence of also using the netstore for fuel storage has little to no influence. This is mainly caused by the rounding of to whole fish boxes, this is done since the 800mm is positioned in the ships longitudinal direction. To better interpret these tables, the original design can store +/- 1200 full fish boxes.

Table 5.8: Reduction in full fish box storage capacity if fuel stored in available tanks plus Fish Hold, mono-fuels

			100hr long cycle					Continuous long cycle				
			Propeller					Propeller				
Converter	Fuel	Configuration	Original	Type 1	Type 2	Type 3	Type 4	Original	Type 1	Type 2	Type 3	Type 4
ICE	MGO	D-D	0	0	0	0	0	0	0	0	0	0
ICE	MGO	D-E	0	0	0	0	0	0	0	0	0	0
ICE	HVO	D-E	0	0	0	0	0	0	0	0	0	0
ICE	FAME	D-E	0	0	0	0	0	0	0	0	0	0
ICE	DF	D-E	360	180	180	180	180	720	540	360	540	360
PEMFC	Hydrogen	E	720	540	360	540	360	1440	1080	900	1080	900
Battery	NMC-lithium	E	1800	1260	1080	1260	1080	3060	2340	1980	2340	1980

The same table is made for hybrid propulsion configurations, Table 5.9

Table 5.9: Reduction in full fish box storage capacity if fuel stored in available tanks plus Fish Hold, hybrid

			100hr long cycle					Continuous long cycle				
			Propeller					Propeller				
Main energy carrier	Sec. energy carrier	Configuration	Original	Type 1	Type 2	Type 3	Type 4	Original	Type 1	Type 2	Type 3	Type 4
MGO	Hydrogen(l)	D-E	360	0	0	0	0	720	360	180	360	180
MGO	NMC-Li	D-E	540	180	0	180	0	1080	540	180	540	180
Methanol	Hydrogen(l)	D-E	360	180	0	180	0	720	360	180	360	180
Methanol	NMC-Li	D-E	540	180	0	180	0	1080	540	180	540	180

The two tables above tell that the storage of fuel in fish hold results in significant reduction of full fish boxes. Especially the long cycle mono fuels and hybrid configuration illustrate that most of storage area will disappear. Together with the fact that in general the Continuous cycle requires 1.5 to 2.0 more fish storage capacity(w.r.t. 100hr), this tends to result in not meeting effectiveness requirements.

A representation for the available storage options is provided in Appendix E.

Within the last technical tables the extra added weight and Draught per configuration for booth Long cycles are referenced with the original configuration, Table 5.10. The propulsion configuration weight consists of energy converter, energy carrier and WHR system. It is assumed that the weight is distributed evenly over the vessel, which results in an equal submersion of the hull. These tables illustrate that using NMC-Li as an energy carrier/converter is not logical and impossible to carry. The weight of the hull extension is not taken into account as it is assumed the weight is equal to the created additional buoyancy.

Table 5.10: Weight deviation[ton] compared to original(grey), mono fuel. red: deviation exceeding maximum

			100 hr long cycle					Continuous long cycle				
			Propeller					Propeller				
Converter	Fuel	Conf.	Original	1	2	3	4	Original	1	2	3	4
ICE	MGO	D-D	31	-6	-10	-6	-10	43	-9	-14	-9	-14
ICE	MGO	D-E	3	-4	-8	-4	-8	3	-6	-12	-6	-12
ICE	HVO	D-E	3	-4	-8	-4	-8	4	-6	-11	-6	-11
ICE	FAME	D-E	6	-2	-6	-2	-6	8	-2	-8	-2	-8
ICE	DF	D-E	24	13	7	13	7	39	22	12	22	12
PEMFC	Hydrogen	E	4	-4	-8	-4	-8	11	-1	-7	-1	-7
Battery	NMC-lithium	E	436	347	292	347	292	719	568	477	568	476

Using a hybrid propulsion configuration results in an additional energy converter, due to the operational profile this converter must be able to produce the required power in booth transit and fishing condition. Table 5.11, illustrates the total weight deviation compared to the original propulsion configuration including energy carrier weight.

Table 5.11: Weight deviation[ton] compared to original(Table 5.10), hybrid. red: deviation exceeding maximum

			100hr long cycle					Continuous long cycle				
			Propeller					Propeller				
Main energy carrier	Sec. energy carrier	Configuration	Original	Type 1	Type 2	Type 3	Type 4	Original	Type 1	Type 2	Type 3	Type 4
MGO	Hydrogen(l)	D-E	10	0	-5	0	-5	13	-1	-8	0	-8
MGO	NMC-Li	D-E	168	86	38	87	38	273	138	58	138	58
Methanol	Hydrogen(l)	D-E	23	13	8	13	8	35	21	14	21	14
Methanol	NMC-Li	D-E	129	48	7	48	7	211	77	-4	77	-4

In Figure C.2, the influence on weight and draught when the two types of WHR and regenerative braking are applied are visualized.

If the weight deviation is positive this will result in an added draught and thus displacement, wetted surface and transom area. The added draught is dependent on water plane area and seawater density, The maximum added weight is limited since it will reduce the free board and their for decreases seaworthiness of the vessel. Within this thesis a maximum additional hull submersion of 0.3 meter is used, 5.1.1. What can be seen is that w.r.t. the 250 m^2 waterplane area only the mono battery configuration will exceed this maximum.

At last the CO_2 reduction percentage is calculated and referenced to the original amount of CO_2 emission per long cycle, Table 5.12. Secondly Figure C.3 illustrates the influence of WHR systems and regenerative braking on CO_2 reduction. Since the mono fuels are using the same emission factor for booth 100hr and continuous long cycle the CO_2 emission reduction are equal. As mentioned before the hybrid fueled configuration are based on achieving 40% CO_2 reduction, therefore their emission reduction is not visualized, since they all achieve 40%. For the WHR systems the battery is not taken into account since these do not have enough heat flow in the exhaust.

Table 5.12: CO_2 emission reduction, green: configurations technical feasible

			Propeller				
Converter	Fuel	Conf.	Original	1	2	3	4
ICE	MGO	D-D	0%	19%	31%	19%	31%
ICE	MGO	D-E	-4%	16%	28%	16%	28%
ICE	HVO	D-E	90%	92%	93%	92%	93%
ICE	FAME	D-E	93%	94%	95%	94%	95%
ICE	DF	D-E	16%	32%	42%	32%	42%
PEMFC	Hydrogen	E	100%	100%	100%	100%	100%
Battery	NMC-lithium	E	100%	100%	100%	100%	100%

5.1.1. Technical feasibility

With the outcome of 5.1, the following conclusions can be written about the technical feasibility of a IMO 2030 proof Dutch beam trawler. The technical feasibility is determined by:

- achieving 40% CO_2 emission reduction
- Maximum added average draught 0.3m
- Maximum extension length 3m

Both long cycles

Not one of the mono battery configuration is feasible due to exceeding maximum added draught and extension length. Due to the similarity to Marine Gas Oil, the fuels HVO and FAME are technically feasibly. This applies only as long as the IMO considers the emission factor of FAME and HVO fuels as zero emission fuels. The hybrid propulsion configuration MGO-H_2(l) and DF-H_2(l) are technically feasible for all propeller types including the original propeller. This is mainly caused by the ”relatively” high energy density of Methanol and MGO compared to liquid H_2.

What also can be concluded is that not in one situation the WHR or regenerative braking or a combination of the systems makes the difference between meeting or not meeting the 40% CO_2 emission reduction, see Table 5.12. This does not directly mean that it is also not worth it to install, but it will always contribute to additional complexity, volume and weight of the overall machinery configuration.

100hr long cycle

Methanol configuration only achieves 40% CO_2 emission reduction if combined with application of propeller type 2(4.0D). Due to carbon still being present in methanol and in the pilot fuel, the bigger diameter propeller is required to reduce the energy consumption of the cycle. For the application of a mono-fuel hydrogen configuration the propeller also has to be upgraded to type 1 and type 2, to prevent exceeding maximum extension. The hybrid configuration MGO-NMC-Li is feasibly for all propellers, this is mainly caused to MGO having a high energy density, therefore only a small amount of energy from batteries is required. The hybrid configuration DF-NMC-Li is feasibly is only feasibly with propeller type 2, this is caused by the low energy density of the batteries and the lower energy density of methanol in reference to MGO.

Continuous long cycle

Although the DF configuration requires hull extension or storage in fish hold, the combination with a type 2 propeller will result in a feasibly configuration. H_2(l) as a mono fuel is not technically feasible for any propeller type due to exceeding extension length, or amount of lost volume in fish hold. The technical feasibly hybrid configurations are similar to the 100hr long cycle with the exception of DF-NMC-Li. Due to additional required volume of methanol w.r.t. MGO. The additional required energy of batteries is of such scale that this hybrid configuration is only feasible together with a type two propeller.

The unfeasible configurations will be excluded from the scenarios which follow in the upcoming sections. Table 7.1, summarizes the technical feasibly propulsion configurations. Figure F.2, roughly illustrates the propulsion configuration concepts.

Table 5.13: Technical feasible configurations, red: reference configuration case vessel

	Fuel	Conf.	100 hr long cycle Propeller type	Continuous long cycle Propeller type
MONO	MGO(reference)	D-D	Original	Original
	HVO	D-E	Original,1,2,3,4	Original,1,2,3,4
	FAME	D-E	Original,1,2,3,4	Original,1,2,3,4
	DF	D-E	2,4	2,4
	Hydrogen	E	1,2,3,4	-
Hybrid	MGO-H_2	D-E	All	All
	MGO-NMC-Li	D-E	2,4	2,4
	DF-H_2	D-E	All	All
	DF - NMC-Li	D-E	1,2,3,4	2,4

5.1.2. Economical feasibility

With the technical feasible configurations summarized in section 5.1.1, Table 7.1, their economical performance w.r.t. original propulsion configuration can be found. Since propeller type 3 and type 4 show similar performance on technical(energy reduction and weight) and economical aspect(Capex), they are excluded to keep the results clear. It is chosen to visualize the Operational expenses, TCO and the effectiveness ratio. The Cost effectiveness ratio is the ratio of Capex divided by achieved % of CO_2 emission reduction.

Figure 5.1 and Figure 5.2 illustrate the operational and total cost of ownership of the 100hr long cycle. Table 5.14 and Table 5.15, show the capital expenses for the two different methods of energy carrier storage for booth long cycles. At last in Figure 5.3 and Figure 5.4 the Continuous long cycle operational expenses and TCO.

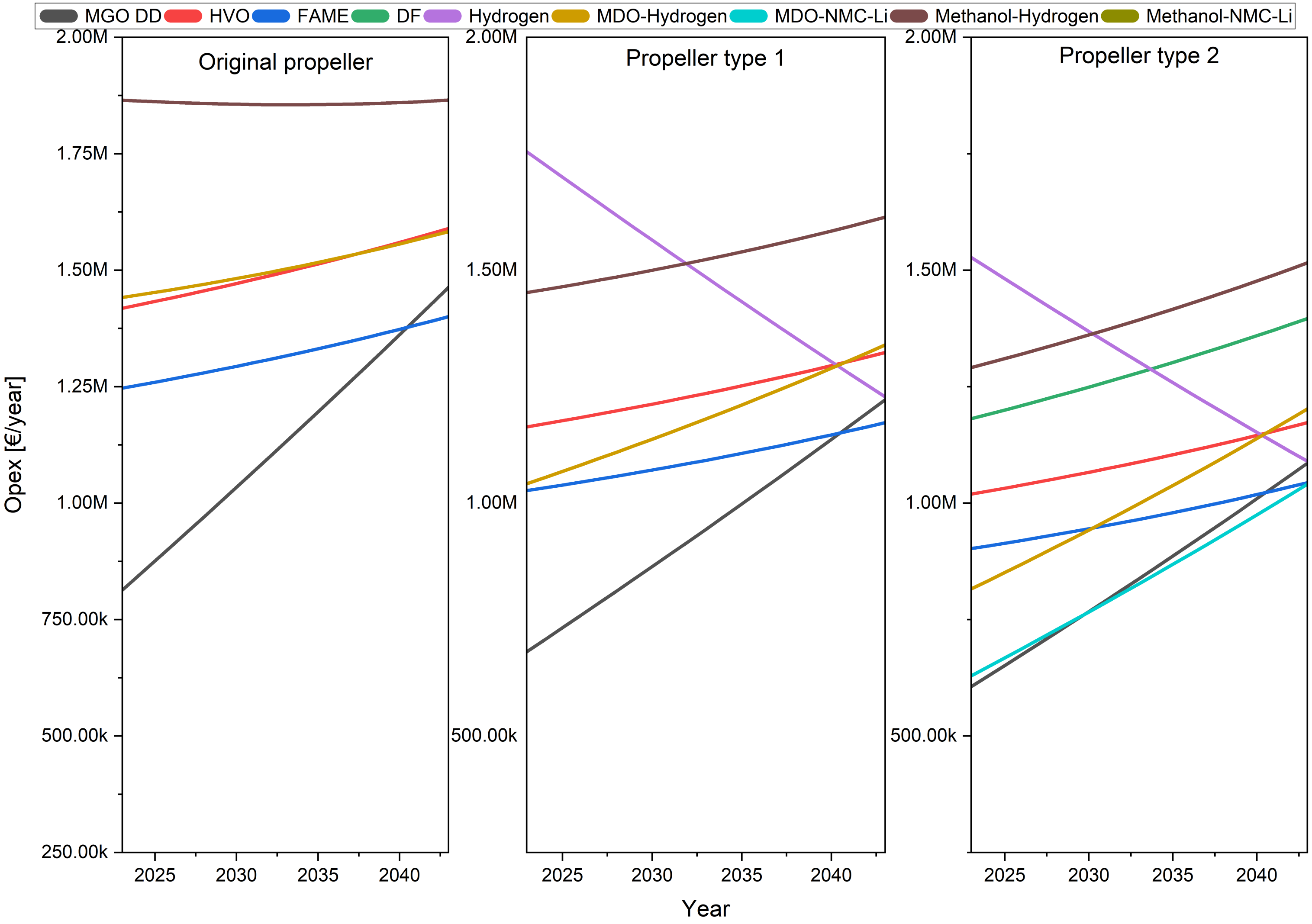


Figure 5.1: Operational expenses technical feasible configurations, 100hr long cycle

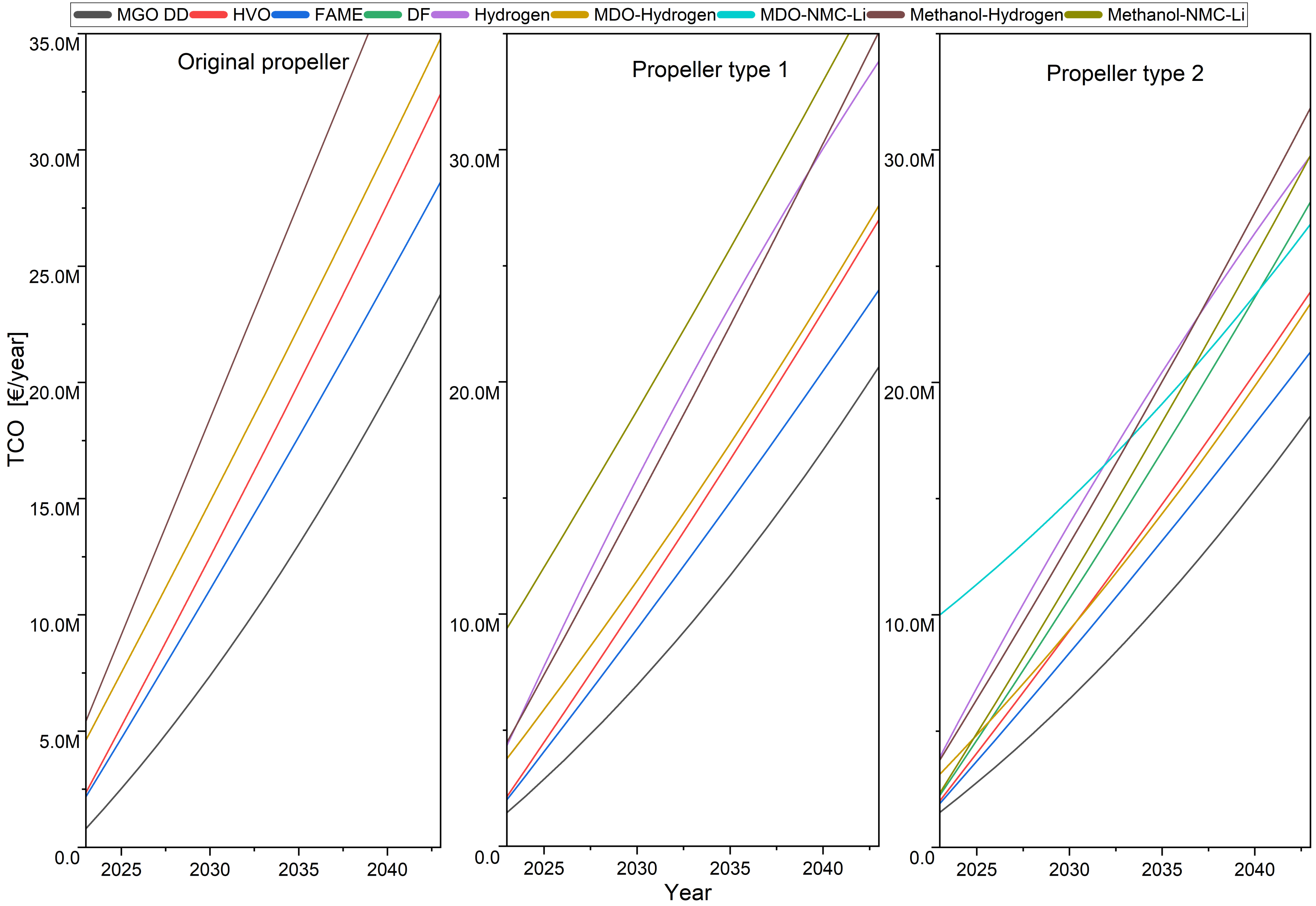


Figure 5.2: TCO, technical feasible configurations, 100hr long cycle

Table 5.14: Capital expenses, additional volume gained by extension of the hull if required

				100hr long cycle					Continuous long cycle				
				Propeller					Propeller				
	Converter	Fuel	Configuration	Original	Type 1	Type 2	Type 3	Type 4	Original	Type 1	Type 2	Type 3	Type 4
MONO	ICE	MGO	D-D	€ 512.600	€ 779.693	€ 908.190	€ 789.828	€ 918.190	€ 512.600	€ 779.693	€ 908.190	€ 789.828	€ 918.190
	ICE	HVO	D-E	€ 942.195	€ 991.095	€ 994.427	€ 1.001.312	€ 1.004.427	€ 942.195	€ 991.095	€ 994.427	€ 1.001.312	€ 1.004.427
	ICE	FAME	D-E	€ 942.195	€ 991.095	€ 994.427	€ 1.001.312	€ 1.004.427	€ 942.195	€ 991.095	€ 994.427	€ 1.001.312	€ 1.004.427
	ICE	DF	D-E	€ 1.210.837	€ 1.230.747	€ 1.216.980	€ 1.241.001	€ 1.226.979	€ 1.102.213	€ 1.116.619	€ 1.099.851	€ 1.126.882	€ 1.109.844
	PEMFC	Hydrogen	E	€ 3.069.847	€ 2.666.616	€ 2.385.448	€ 2.677.343	€ 2.395.422	€ 2.950.808	€ 2.560.962	€ 2.308.178	€ 2.571.745	€ 2.318.119
E. recovery	ORCAN			€ 275.000	€ 214.428	€ 178.750	€ 214.500	€ 178.750	€ 275.000	€ 214.428	€ 178.750	€ 214.500	€ 178.750
	SRC			€ 935.000	€ 729.054	€ 607.750	€ 729.300	€ 607.750	€ 935.000	€ 729.054	€ 607.750	€ 729.300	€ 607.750
	Regen. braking			€ 15.000	€ 15.000	€ 15.000	€ 15.000	€ 15.000	€ 15.000	€ 15.000	€ 15.000	€ 15.000	€ 15.000
	Prim. carrier	Sec. carrier	-										
Hybrid	MGO	H_2	D-E	€ 3.183.499	€ 2.734.193	€ 2.337.218	€ 2.611.811	€ 2.347.417	€ 3.279.499	€ 2.782.193	€ 2.337.218	€ 2.744.811	€ 2.347.417
	MGO	NMC-li	D-E	€ 35.643.032	€ 18.940.309	€ 9.373.790	€ 18.967.109	€ 9.389.427	€ 57.727.435	€ 29.490.183	€ 13.570.172	€ 29.528.573	€ 13.583.036
	DF	H_2	D-E	€ 3.569.823	€ 3.025.790	€ 2.470.117	€ 3.036.450	€ 2.480.329	€ 3.738.165	€ 3.140.391	€ 2.799.770	€ 3.151.059	€ 2.809.980
	DF	NMC-Li	D-E	€ 25.427.840	€ 8.071.857	€ 1.047.934	€ 8.098.700	€ 1.084.999	€ 41.908.210	€ 11.826.057	€ 1.404.588	€ 11.869.609	€ 1.414.649

Table 5.15: Capital expenses, additional volume gained by storage in fish hold if required

				100hr long cycle					Continuous long cycle				
				Propeller					Propeller				
	Converter	Fuel	Configuration	Original	Type 1	Type 2	Type 3	Type 4	Original	Type 1	Type 2	Type 3	Type 4
Mono	ICE	MGO	D-D	€ 512.600	€ 779.693	€ 908.190	€ 789.828	€ 918.190	€ 512.600	€ 779.693	€ 908.190	€ 789.828	€ 918.190
	ICE	HVO	D-E	€ 942.195	€ 991.095	€ 994.427	€ 1.001.312	€ 1.004.427	€ 942.195	€ 991.095	€ 994.427	€ 1.001.312	€ 1.004.427
	ICE	FAME	D-E	€ 942.195	€ 991.095	€ 994.427	€ 1.001.312	€ 1.004.427	€ 942.195	€ 991.095	€ 994.427	€ 1.001.312	€ 1.004.427
	ICE	DF	D-E	€ 1.077.837	€ 1.097.747	€ 1.083.980	€ 1.108.001	€ 1.093.979	€ 1.102.213	€ 1.116.619	€ 1.099.851	€ 1.126.882	€ 1.109.844
	PEMFC	Hydrogen	E	€ 2.792.847	€ 2.437.616	€ 2.204.448	€ 2.448.343	€ 2.214.422	€ 2.950.808	€ 2.560.962	€ 2.308.178	€ 2.571.745	€ 2.318.119
	Prim. carrier	Sec. carrier	-										
Hybrid	MGO	H_2	D-E	€ 3.050.499	€ 2.734.193	€ 2.337.218	€ 2.611.811	€ 2.347.417	€ 3.050.499	€ 2.649.193	€ 2.337.218	€ 2.611.811	€ 2.347.417
	MGO	NMC-Li	D-E	€ 35.462.032	€ 18.807.309	€ 9.373.790	€ 18.834.109	€ 9.389.427	€ 57.402.435	€ 29.309.183	€ 13.437.172	€ 29.437.573	€ 13.450.036
	DF	H_2	D-E	€ 3.388.823	€ 2.892.790	€ 2.470.117	€ 2.903.450	€ 2.480.329	€ 3.509.165	€ 2.959.391	€ 2.666.770	€ 2.970.059	€ 2.676.980
	DF	NMC-Li	D-E	€ 25.198.840	€ 7.938.857	€ 1.074.934	€ 7.965.700	€ 1.084.999	€ 41.583.210	€ 11.645.057	€ 1.271.588	€ 11.688.609	€ 1.218.649

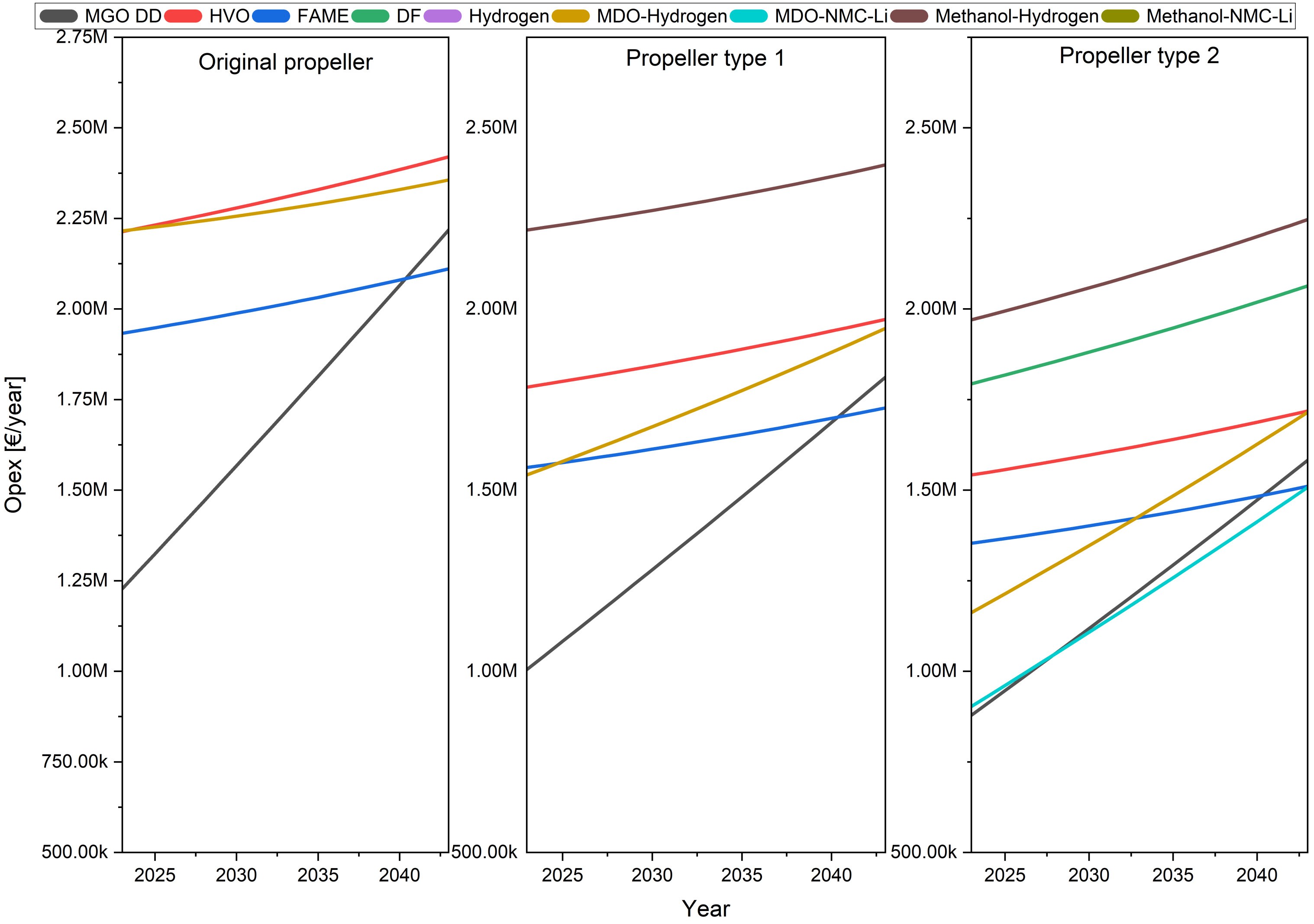


Figure 5.3: Operational expenses technical feasible configurations, Continuous long cycle

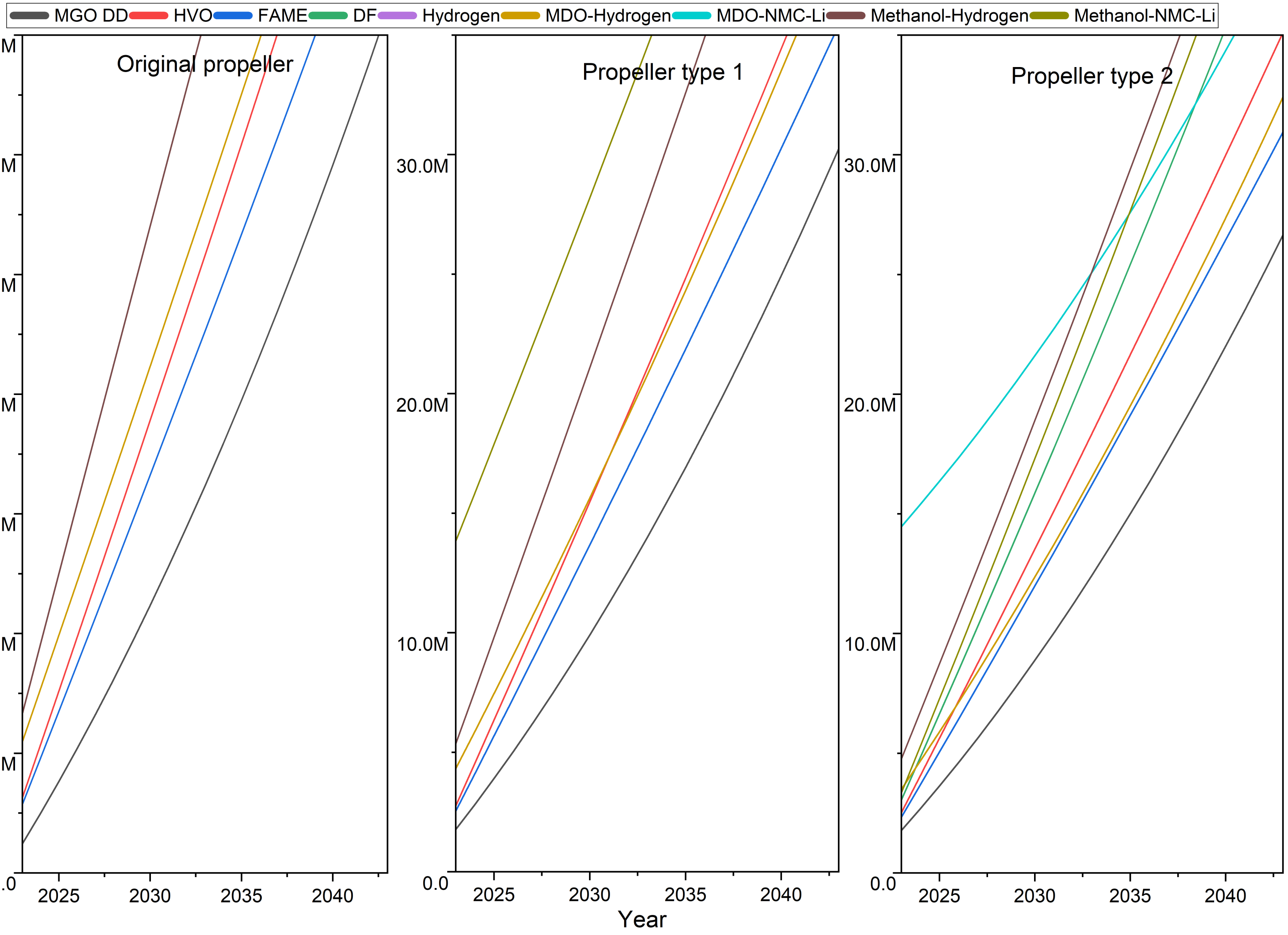


Figure 5.4: TCO, technical feasible configurations for Continuous long cycle

Other financial performance indicators will be discussed in Section 5.4, to prevent discussing and presenting double information. Within the sections 5.2 and 5.3 the figures will be analyzed.

5.2. Scenario 1, High fuel price

The energy carrier price has a large impact on the daily operational costs of the vessel. Energy carrier prices fluctuate over long or short periods of time, since they are influenced by many world wide factors. Furthermore, the prices of renewable energy carriers are expected to decrease, whereas the price developments of LSMGO and HVO/FAME are expected to increase. The current prices of energy carriers are stated in Chapter 3.2. The prices indicated here are the current and forecasted energy carrier price used within this research. However, the price development over the years is still unknown, and therefore 2050 projection are based on a lot of uncertainty. Since short-term price are depend on fluctuations caused by supply, demand, regulations, etc, it is decided to ignore fluctuations. However, long-term price changes will be incorporated. Since there is no knowledge of the future, a simple linear price (in)decrease is assumed from the 2023 price to the 2050 projection. It is decided that complicated projections on energy price per year or exponential (in)decrease is not beneficial because this only adds uncertainty to the model and does not per definition give a better result. The prices expressed in €$/GJ$ can therefor vary when comparing the World Energy Outlook (WEO 2022, [1]) and International Energy Agency (IEA 2019, [86]) reports. These variations occur because different agencies or companies specialize in specific energy carriers or have demonstrated reliability in the past, influencing the price sources. To anticipate, the projection for 2050 is increased and decreased with 30% to find the influence of the price of the energy carrier on the economic feasibility.

A relatively large 30% uncertainty is chosen based on price developments in the last decades. The enormous volatility that energy prices have shown due to Covid-19 and the Ukraine war [130] [13]. These events show that predictions are often wrong, and a (large) uncertainty must be taken into account for the projected price in 2050.

In Table 5.16 the start and forecasted energy carrier prices, and in Figure 5.5 incl. 30% uncertainties in upper and lower bound.

Table 5.16: Energy carrier price current and future, $[\frac{€}{GJ}]$

	Fuel costs 2022	**Fuel costs 2050**	**Source**
MGO	17	17	[88]
HVO	31	31	[72]
FAME	28	28	[82]
Methanol	39	27	[143]
Hydrogen	70	33	[86], [2]
Electricity	27	10	[71]

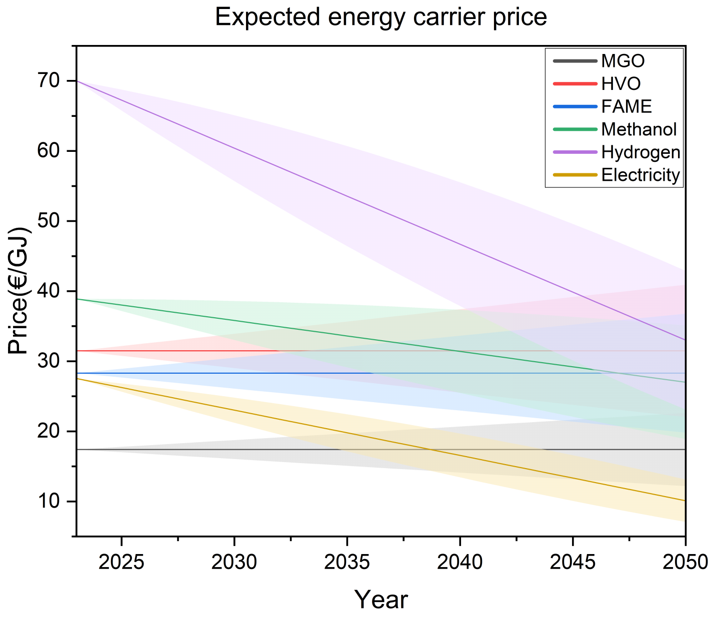


Figure 5.5: Energy carrier price, including uncertainty upper and lower bound

For the high fuel price scenario, the upper bound of 30% is used. This will affect booth the yearly OpEx and TCO. To find the influence of high fuel prices, the OpEx and TCO for the coming 20 years are illustrated Figure D.2 without the application of any WHR system or regenerative system. As can be seen in the technical feasibility, the influence of increasing propeller diameter is significant. Therefore, the influence of proposed 3.4m and 4.0m diameter propellers is visualized for all technically feasible configurations. The influence of high fuel prices on the Continuous long cycle can be seen in Appendix C.

Considering high fuel price scenarios provides a more robust risk assessment. While a high fuel price scenario helps assess the potential impact of cost increases and market volatility. It helps identify the potential risks associated with relying on the case of low(forecasted) fuel prices and assess the sustainability of the project in the long term [39]. Figure D.1, the motivation on why a high energy carrier price is assumed to be more realistic than a low energy carrier price, with reference to forecasted [163]. So in summary, for this scenario a 30% high limit is taken into account for energy carrier price, but in all other scenario's the price is used as forecasted in Table 5.16.

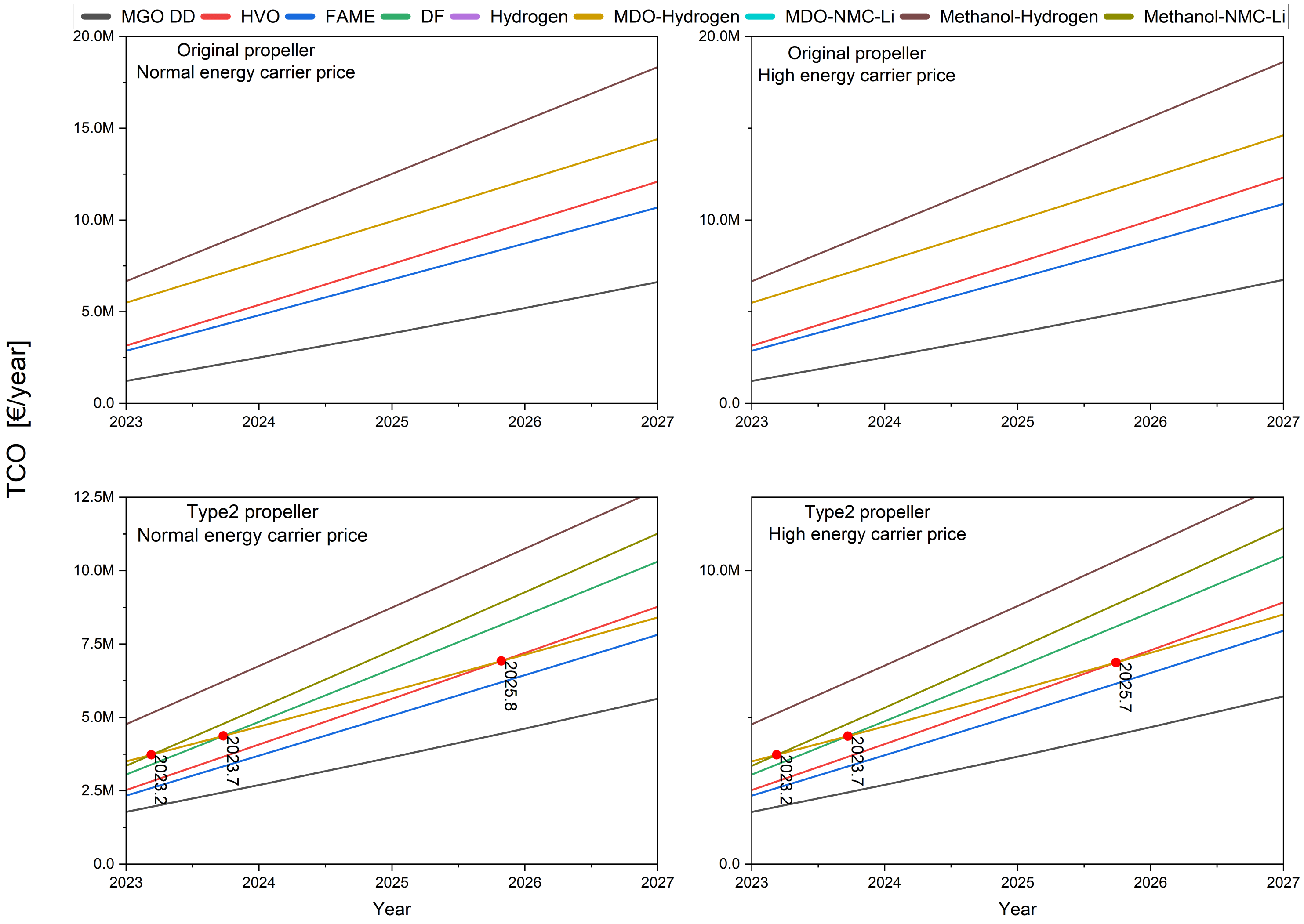


Figure 5.6: TCO, predicted energy carrier prices and the high energy carrier case

The graphs in Figure 5.6 show that despite the increasing fuel prices, there are no changes in the order of cheapest to most expensive options. The intersections of TCO (Total Cost of Ownership) also remain unchanged, contrary to expectations and the reason for conducting this scenario. This is due to all prices increasing collectively by a fixed percentage, up to a maximum of 30% above original. It is also evident that the more expensive energy carriers are more sensitive to price increases at a given percentage.

The influence on payback time for the high fuel price scenario for Orcan, SRC or Regenerative system application on yearly operational costs and TCO are examined in Figure D.3 and Figure D.4. The original propeller is illustrated since the Orcan and SRC will have the greatest potential to be economical feasible due to the highest produced and required energy. If the systems are not economically favourable here, they will definitely not be for propeller type 1, type 2, etc.

At last Table 5.17 and Table 5.18 illustrate the influence on operational expenses when referenced to the normal predicted energy carrier prices as in Table 5.16.

Table 5.17: Increase operational expenses with respect to normal energy carrier price, for original propeller

			100hr			Continuous		
			2033	2038	2043	2033	2038	2043
Mono	ICE	MGO DD	106%	108%	110%	107%	109%	110%
	ICE	HVO	109%	114%	118%	110%	114%	119%
	ICE	FAME	109%	113%	117%	110%	114%	119%
	ICE	DF	108%	111%	113%	109%	112%	114%
	PEMFC	Hydrogen	110%	114%	118%	110%	115%	120%
Hybrid	MDO	Hydrogen(l)	108%	110%	112%	108%	111%	114%
	MDO	NMC-lithium	106%	108%	110%	107%	109%	111%
	Methanol	Hydrogen	108%	112%	114%	109%	112%	115%
	Methanol	NMC-lithium	108%	111%	113%	108%	112%	114%

Table 5.18: Increase operational expenses with respect to normal energy carrier price, for type 2 propeller

			100hr			Continuous		
			2033	2038	2043	2033	2038	2043
Mono	ICE	MGO DD	106%	108%	109%	106%	108%	110%
	ICE	HVO	109%	113%	116%	109%	114%	118%
	ICE	FAME	108%	112%	116%	109%	114%	117%
	ICE	DF	108%	110%	112%	108%	111%	113%
	PEMFC	Hydrogen	109%	113%	117%	110%	114%	118%
Hybrid	MDO	Hydrogen(l)	106%	108%	109%	107%	109%	111%
	MDO	NMC-lithium	106%	107%	109%	106%	108%	110%
	Methanol	Hydrogen	108%	110%	112%	108%	111%	113%
	Methanol	NMC-lithium	108%	110%	112%	108%	111%	113%

These tables demonstrate that the application of energy reduction methods results in operational costs being less sensitive to price increases in energy carriers. This is partly because the amount of consumed energy carrier decreases, thus reducing operational costs. Secondly, it can be observed that despite a 30% increase, these factors remain lower, partially due to the maintenance factor and carbon tax remaining unchanged, which proves to be significant in certain configurations.

Next to the illustration above more detailed additional results of influence on high energy carrier price on economical performance are represented in Appendix D in Figure D.5, Figure D.6, and Figure D.7.

These illustrate the influence on overall operational expenses and total cost of ownership. Secondly the payback period for the two types of waste heat recovery are visualized.

Conclusion

The graphs indicate that despite rising fuel prices, the order of cheapest to most expensive options remains unchanged. The intersections of TCO also do not change, which was unexpected given the scenario being examined. This lack of change can be attributed to the collective increase in prices by a fixed percentage, with a maximum of 30%. Moreover, it is clear that higher-priced energy carriers are more susceptible to price increases at a given percentage. The tables demonstrate that implementing energy reduction methods reduces the sensitivity of operational costs to price increases in energy carriers. This reduction is achieved through a decrease in the amount of consumed energy carriers, leading to lower operational costs. Additionally, even with a 30% increase, these factors remain lower, mainly because the maintenance factor remains unchanged, proving to be significant in specific configurations.

Zooming in on TCO figures it can be seen that the intersections between propulsion configurations hardly changes for booth. This is logical since higher investment costs generally result in an operational expenses reduction. Therefore high fuel prices will result in shorter pay back periods. This is observed for both 100hr and Continuous long cycle. As Section 5.1, 5.1 also illustrates is that the mono configurations fueled on hydrogen and NMC-Li are a factor 2 higher in 2023 but due to forecasted prices are almost equal to Diesel(bio and synthetic) when approaching 2038. This trend is more intensified in this scenario, mainly caused by the fractional increase used in this method.

5.3. Scenario 2, High CO_2 emission tax

It is assumed that the fishing fleet will be included in the Dutch emission tax system, since the sail under Dutch legislation and flag. The exact details of the inclusion of shipping is as of yet unknown, but it can nonetheless be expected that a CO_2 tax for shipping will be implemented in the near future, Section 1.3. The rate of this tax is the subject of many discussions but is considered out of scope for this study. However, it is interesting to find the influence of CO_2 price to the new drive-train options compared to the current system on board the ship. Similar to section 5.2, only the technical feasible configurations will be analyzed on their influence on Opex and TCO. To keep things clear the same graphs and tables as in section 5.2 will be used. The influence of high emission tax prices on the Continuous long cycle can be seen in Appendix C.

Implementing the maritime sector into the Dutch emission tax system is still uncertain and also depends on the development of regulations from the EU. Another uncertainty is the number of free allowances allocated for the maritime sector. This scenario will use the predicted CO_2 emission prices Figure 3.10 with an uncertainty of 50%, Figure 5.7 as determined in [148] [16]. In this scenario, the vessel owner will be charged with the costs for the entire amount of its CO_2 emissions. So in summary, for this scenario a 50% high limit is taken into account for the emission tax, but in all other scenario's the price is used as forecasted in Table 5.19.

Table 5.19: Calculation based on legislative proposal "Wetvoorstel CO_2-heffing industrie", Art. 71p [16]

Statutory price trajectory of carbon levy in 2021

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Levy rate(in EUR per tonne CO_2)	30	40.56	51.12	61.68	68.12	76.42	83.21	89.72	94.20	103.92

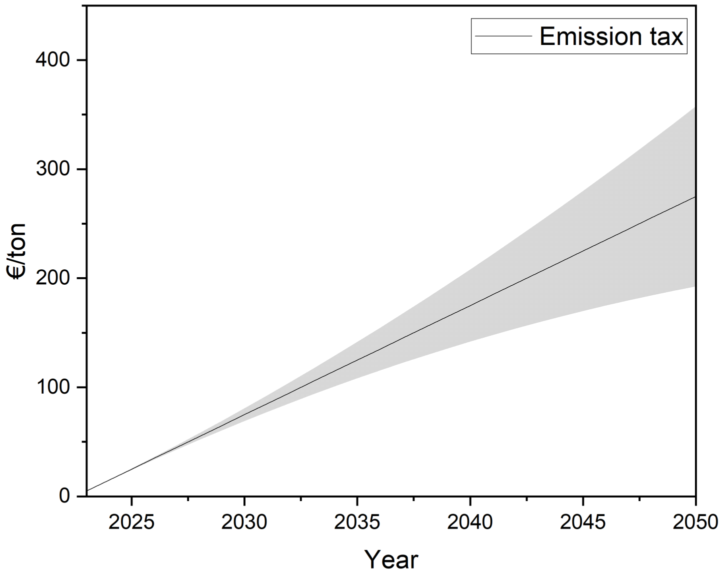


Figure 5.7: Dutch CO_2 emission tax including 30% uncertainty

For the high emission tax price scenario, the upper bound of 50% is used. This will affect booth the yearly OpEx and TCO. To find the influence of high fuel prices, the OpEx and TCO for the coming 20 years are illustrated Figure E.1 without the application of any WHR system or regenerative system. As can be seen in the technical feasibility, the influence of increasing propeller diameter is significant. Therefore, the influence of proposed 3.4m and 4.0m diameter propellers is visualized for all technically feasible configurations. Secondly Figure E.2 and Figure E.3 illustrate the influence of high tax prices on achievable reduction in operation expenses and payback time for booth types of waste heat recovery systems.

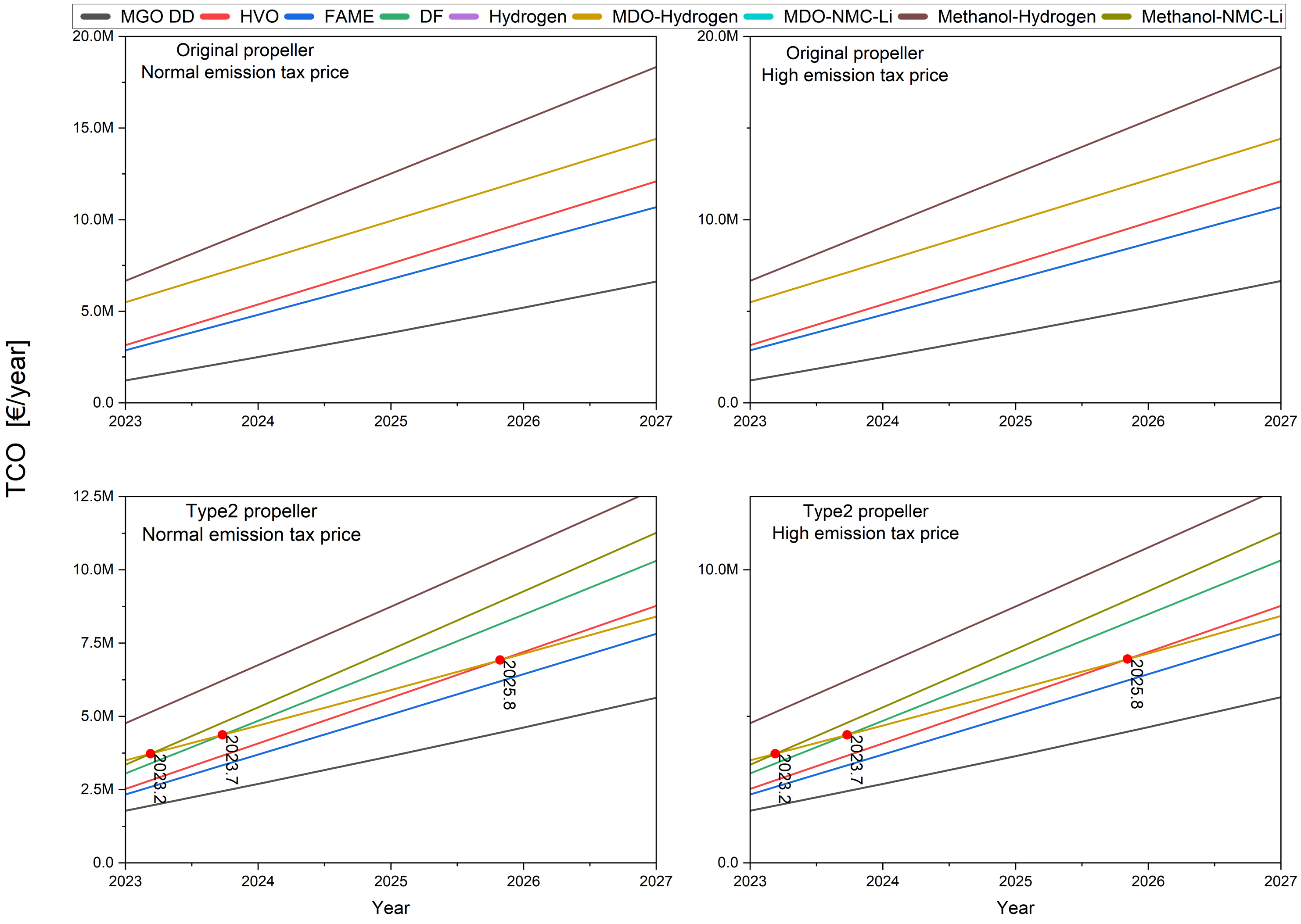


Figure 5.8: Total cost of ownership for predicted energy carrier prices and the high emission tax case

Table 5.20: Increase operational expenses with respect to normal emission tax price, for original propeller

			100hr			Continuous		
			2033	2038	2043	2033	2038	2043
Mono	ICE	MGO DD	105%	109%	114%	105%	110%	115%
	ICE	HVO	100%	101%	101%	100%	101%	101%
	ICE	FAME	100%	101%	101%	100%	101%	101%
	ICE	DF	102%	105%	109%	103%	106%	110%
	PEMFC	Hydrogen	100%	100%	100%	100%	100%	100%
Hybrid	MDO	Hydrogen(l)	102%	105%	108%	102%	105%	109%
	MDO	NMC-lithium	103%	107%	111%	104%	107%	112%
	Methanol	Hydrogen	102%	104%	107%	102%	104%	107%
	Methanol	NMC-lithium	102%	105%	108%	102%	105%	109%

Table 5.21: Increase operational expenses with respect to normal emission tax price, for propeller type 2

			100hr			Continuous		
			2033	2038	2043	2033	2038	2043
Mono	ICE	MGO DD	104%	108%	113%	105%	109%	114%
	ICE	HVO	100%	101%	101%	100%	101%	101%
	ICE	FAME	100%	101%	101%	100%	101%	101%
	ICE	DF	102%	105%	108%	103%	105%	109%
	PEMFC	Hydrogen	100%	100%	100%	100%	100%	100%
Hybrid	MDO	Hydrogen(l)	103%	106%	110%	104%	107%	112%
	MDO	NMC-lithium	104%	107%	112%	104%	108%	113%
	Methanol	Hydrogen	102%	105%	108%	102%	105%	109%
	Methanol	NMC-lithium	102%	105%	108%	102%	105%	109%

What is clearly visible is that despite a high uncertainty of 50%, the influence compared to the general results is smaller. It can also be observed that configurations with high CO2 reduction are even less sensitive, which is caused by the almost absence of emissions. Despite that, this table still shows that a second advantage of reducing emission is that it makes you less sensitive to the uncertain development of tax systems on emissions.

Next to the illustration above more detailed additional results on influence on economical performance by high emission tax is represented in Appendix E in Figure E.4, Figure E.5, and Figure E.6. These illustrate the influence on overall operational expenses and total cost of ownership. Secondly the payback period for the two types of waste heat recovery are demonstrated.

Conclusion

In general it can be seen that the influence of high energy carrier price(Section 5.3) on operational expenses is much larger than high CO_2 emission tax. therefore Opex and TCO of the hybrid configurations is significantly higher, this is caused by the hybrid configurations being based on 40% CO_2 emissions. The remaining 60% of CO_2 emission is therefore still penalized.

In general it can be seen, than again the high tax price has a positive influence on the payback time of WHR systems applied on MGO and Methanol configurations since these still produce much CO_2 compared to the other fuels. This also means that the influence of CO_2 emission tax on: HVO, FAME, Hydrogen and NMC-Li mono fuel configurations is minimal.

Despite all trends described here, the TCO figures does not show much variation. Again this is mainly caused by the fact of operational expenses being less sensitive to emission tax than for energy carrier price. Compared to Section 5.1, the TCO's still follow up low to high on the same sequence.

5.4. Scenario 3, 40% CO_2 emission reduction

The scenario's above have shown the sensitivity to energy carrier price and carbon tax price on operational expenses and TCO. The last scenario will find the best method to achieve an 40% CO_2 emission reduction, this section will therefore answer the main question of this thesis. Although the output of the assessment model is very clear, the decision on different configurations still requires personal interpretation and personal preference.

For example, deciding to store fuel in the fish hold results in a reduction of stored full fish boxes. Some operators will not experience any limitations in that regard, while others may decide that they cannot reduce this amount by 100 boxes. The financial influence on where to store the energy carrier will guide this decision, although the personal preference or operation of the vessel will be the determining factor. The leading decision may be influenced by factors such as maximum hull length, maximum GT for sailing licenses or classification society, although these are not considered in this thesis. Also the cheapest overall configuration for a 15-year payback period is not always feasible, as the lowest TCO in 15 years may require a significant capital investment in year 2023.

Within this section predicted energy carrier prices and Dutch carbon taxes are used without any deviation factors, Table 1.2 and Table 5.16. The TCO of all technical feasible configuration with the different options for energy carrier storage will be referenced to each other and to the original diesel direct configuration to find best estimated methods to answer the main question.

This scenario also includes the operational expenses and total cost of ownership of a new build Padmos beam trawler Figure 5.9. The new build price is estimated on ... with a MDO energy consumption of ....J for a 100hr long cycle and ....J for the Continuous cycle. Referenced to the case vessel a new build Padmos beam trawler reduces the CO_2 emission with more than ...% using similar fishing gear. Hence, it is technically feasibly to buy a new build trawler to comply with IMO 2030 CO_2 emission regulation. Due to confidentiality not more information and specifications of a new build trawler are given.

Figure 5.9: Z-483 Jasmine, a 2020 Padmos new-build beam trawler

Based on the figures in Section 5.1, it can already be concluded that the application of larger diameter propellers is very promising since they also reduce the requirement to extend the vessel. Hence, the application of a large diameter propeller is a very cost effective measurement to reduce CO_2 emissions and operational costs. Based on the performance of other emission reducing methods in section 5.1 and Appendix C the following can be concluded:

- Waste heat recovery ORCAN outperforms SRC
- Hybrid configurations with NMC-Li shows significant capital investments but pays of in reducing operational expenses

- If the vessel is already D-E the regenerative option pays of
- HVO and FAME show low capital investment but are outperformed in the long run, due to the high operational expenses caused by energy carrier price not forecasted to decrease.
- Large diameter propeller pays off, especially for the hybrid configurations

Based on these developments it is assumed that using a larger diameter propeller is highly cost-effective regardless of the chosen energy carrier it is decided to further analyse the configuration with the type 2 and type 4 propeller applied. Figure 5.10 demonstrates the economic performance of the 100-hour and Continuous long cycle, combined with either a type 2 or type 4 propeller, for all technical feasible propulsion configurations. The type 2 and type 4 the same technically and economically performance, section 5.1 and are therefore referred to as one and the same in the following sections.

Figure 5.11 represents the total cost of owner ship, minus the remaining value of the ship including its propulsion configuration, equation 4.25 explains, with the remaining value calculation elaboration in Equation 4.2

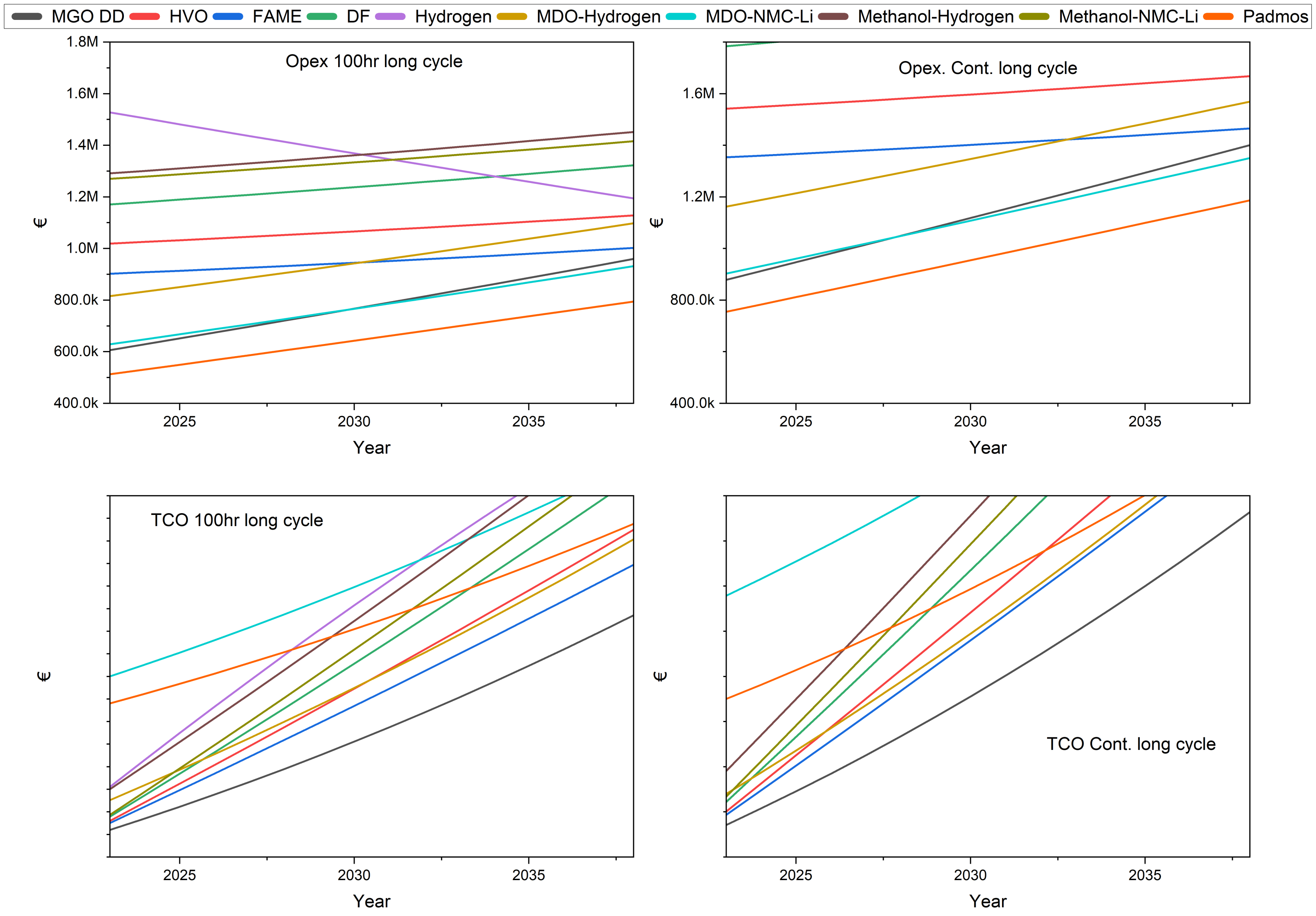


Figure 5.10: Opex and TCO, for type 2 propeller, 100hr and continuous long cycles, including new build vessel. The MGO DD is the reference to original costs

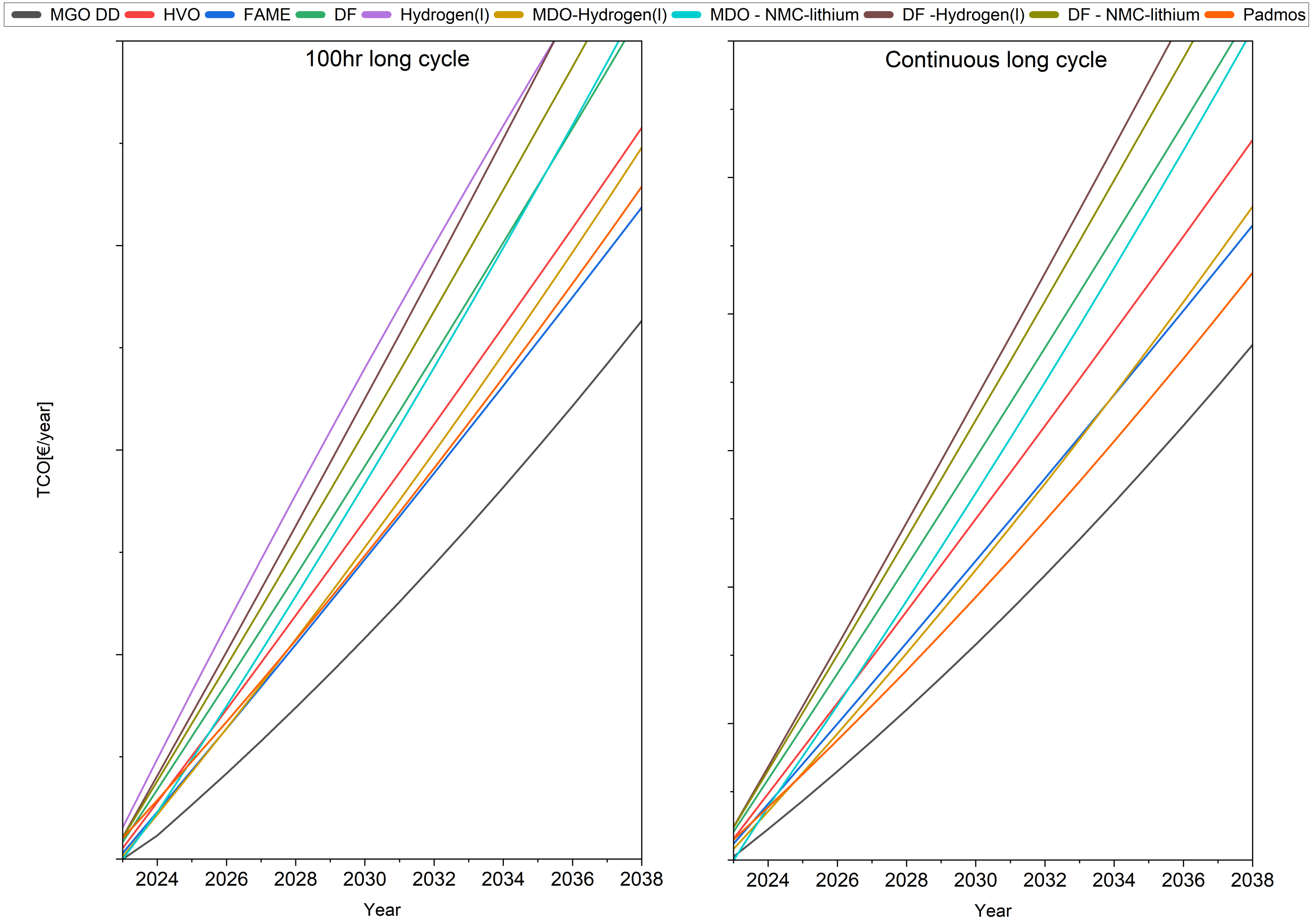


Figure 5.11: $TCO - remainingvalue$, for type 2 propeller including new build vessel. The MGO DD is the reference to original costs

A couple of trends can clearly be spotted for the long term 15 year projection, Figure 5.10: The new build vessel surpasses all retrofit configurations in operational expenses performance, primarily due to two factors. Firstly, the maintenance costs of the hull, including auxiliary systems, are significantly lower compared to retrofit configurations due to the age of the hull and systems. Secondly, fuel costs are low because MGO is relatively inexpensive, and the energy consumption is minimized due to the hull being optimized for a 4.0 meter diameter propeller. In contrast, the DF hybrid configurations yield poorer results compared to the MDO hybrid configurations, for operational expenses. This is directly attributed to methanol being a more expensive fuel than MGO, and the carbon emission tax not compensating for the equal amount of emissions generated by both fuels. The TCO for hybrid configurations favors the DF battery over the MDO-battery because methanol has a lower carbon content. Consequently, this results in reduced capital investment requirements for batteries, which are known to be costly. Although the HVO and FAME show promising numbers, they still exhibit a significant operational increase compared to the original configuration. However, over the long term, this difference diminishes as the emission tax rises. The Total Cost of Ownership (TCO) analysis for the 100-hour long cycle indicates that while the new build vessel has low operational costs, its performance is somewhat hindered by a high TCO resulting from substantial capital expenses in 2023. Despite higher operational expenses, the HVO and FAME demonstrate promising TCO lines due to being drop-in fuels, which require lower capital expenses. The MDO-Hydrogen, despite having higher capital expenses compared to fuels like MGO, HVO, FAME, or DF, shows good results owing to the decreasing forecasted hydrogen prices.

Based on Figure 5.11 a short description on what can be concluded when including the remaining value of ship and propulsion configuration into the TCO: in contraction to Figure 5.10 the high capital expenses in year 2023 are roughly included for in these figures. The hybrid MDO-NMC Li option shows promising values looking at operational expenses despite its high capital expenses in 2023, this is again assumed to be caused by the low forecasted electricity. What should be taken into account is that the battery life time is calculated to be 15 years for booth long cycles, based on the amount and type of charges and dis-charges. Therefor if, for any reason, there is a desire to proceed with the vessel, it would require a significant capital investment for the battery configurations. This is not the case for the other options. The options for mono hydrogen can be concluded to be technically or economical not feasible using the forecasted parameters from Table 5.16. The drop in fuels HVO and FAME actually show to be a very good option, but as mentioned their TTW factor is very sensitive to interpretation of IMO regulations, and thus could result in not being technically feasibly in 2030 when regulations change. To eliminate this uncertainty, an alternative option could be chosen, such as methanol. The main drawback of this option is the currently predicted higher energy carrier prices, which consequently increase the TCO.

An overview on the cost effectiveness of different systems and their ability to reduce CO_2 emission with reference to an 100hr long cycle, Table 5.22. This table represents the investment per option divided by the percentage[%] of CO_2 emission reduction as explained in the introduction of chapter 4.

Table 5.22: Cost effectiveness CO_2 reduction options, for 100hr long cycle, hybrid options ratio for technical feasible configuration

		$\frac{€}{\%}$	Max %
Propeller	Prop 1	€ 14 229	16%
	Prop 2	€ 12 006	28%
	Prop 3	€ 14 848	16%
	Prop 4	€ 12 359	28%
Energy recovery	Orcan	€ 97 216	3%
	SRC	€ 286 148	3%
	Regen	€ 70 368	0.21%
	Winch opt.	€ 2	0.50%
Mono fuel	HVO	€ 10 510	90%
	FAME	€ 10 142	93%
	DF	€ 88 905	14%
	Hydrogen	€ 30 698	100%
Hybrid fuel	MGO-H_2	€ 79 587	40%
	MGO-NMC-li	€ 335 929	40%
	Methanol-H_2	€ 89 246	40%
	Methanol-NMC-li	€ 291 126	40%

Increasing the propeller diameter is an effective way, as expected and mentioned earlier, to reduce energy consumption and thus carbon dioxide emissions. However, as mentioned earlier, the maximum CO_2 reduction achieved is not sufficient to comply with the IMO 2030 regulations. Despite methanol being considered a partly drop-in fuel, its relatively low percentage of CO_2 reduction results in a less favorable ratio compared to the drop-in fuels HVO and FAME. Hydrogen performs well, partly due to achieving a 100% reduction, which compensates for its high capital expenses and contributes to its overall good score. The hybrid configuration ratios are also high, this is mainly caused by two factors. Firstly, it is considered that both converters must be able to provide the required power for trawling, which results in high initial system costs. Secondly, the emission reduction is exactly brought to 40% by adjusting the energy carrier ratio to allow the use of the cheapest fuel.

As visualized in Appendix F, the energy carrier can be stored on different locations. The available volume is influenced by vessel and operational specifications. These are variations in for example: fishing area, fish species, processing method, landing method, spare material, etc. Al these factors influence the decision on where it is practical and possible to store fuel. Table G.1 visualizes the influence of certain decisions, the tables purpose is to find the consequences of certain decisions. The calculations in Table G.1 are based on Table 5.5, Table 5.6 and Table 5.7.

Although the influence of extension on operational expenses is small, Figure 5.12 shows the relation between: additional operational expenses per long cycle, extension costs(Capex) and the reduction in fish boxes if storage in fish hold. In which hull extension is defined as the added length. The x-axis steps are made to fit a fish box which is stored longitudinal in the fish hold. In reality the extension of the hull is done by frame to frame distance, to guarantee structural integrity.

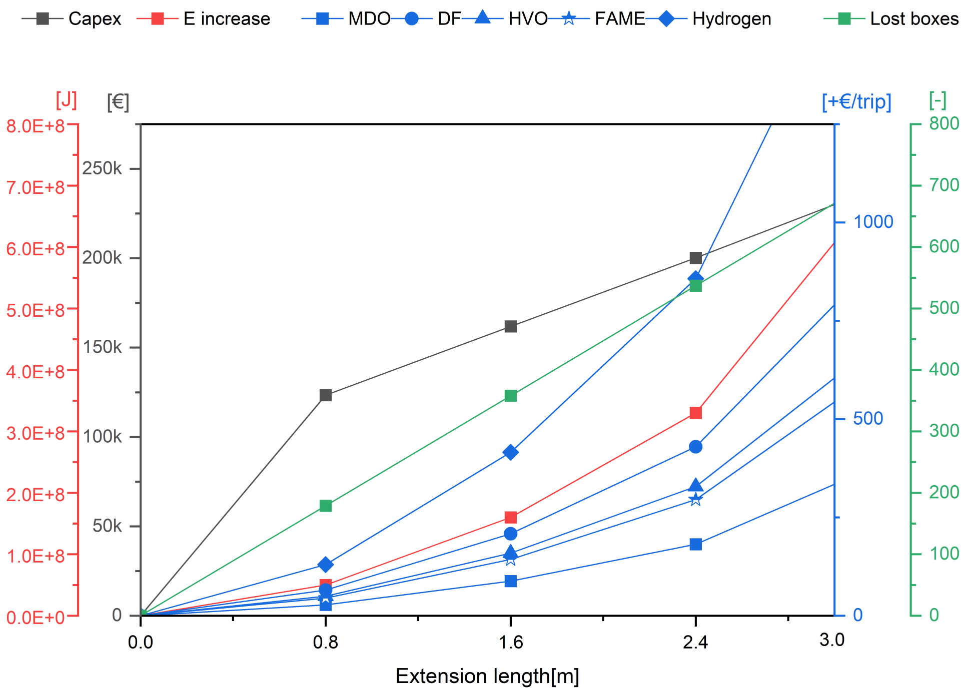


Figure 5.12: Relation between: vessel extension, storage in Fish hold, capital expenses and Opex increase for the 100hr long cycle

Based on Figure 5.12, and Figure F.1, the following can be concluded regarding the different methods of energy carrier storage. First of all, for practical considerations, it is not advised to use both the netstore and fish hold to store the energy carrier since this will result in not being able to store spare nets. If only the netstore is used, a special section of storage area could easily be created in the fish hold if absolutely necessary. The costs to extend the vessel are very small compared to the costs for propulsion configurations (Table 5.14). Figure 5.12 shows that baseline costs of extension are especially important since these ”hardly” change between an 0.8m or 1.6m extension. This trend means that when deciding to extend the vessel, the extension length is not that important when looking at costs. This also reinforces why you wouldn’t want to use a netstore if you extend since the costs to prevent giving up such a practical volume are very low. These trends also concluded why it is not economically advised for the combination of hull extension and storage in fish hold. This leaves two options to store the energy carrier: (1) original tanks + hull extension or (2) original tanks + fish hold.

The practical influence of using the fish hold is the reduction of storage volume for fish boxes. The practical influence of hull extension is a potential increase in operational costs due to increased hull resistance or having to comply with additional regulations and tax,port,insurance, and license requirements. Both influences were visualized in Figure 5.12. Especially operational costs of hydrogen and methanol show to be sensitive to hull extension, due to high energy carrier prices.

Figure 5.12 also shows that the increase of operational costs in reference to the original (Section 5.1) is small, namely €23,913 + €400 for a 2.4-meter hull extension with an 100-hour long cycle, HVO. Only in the absence of financial resources would the choice be made to store the energy carrier in the fish hold. However, if an owner is convinced to have an excessively spacious fish hold and only a small additional volume is needed for energy carrier storage, then the fish hold is adviced to be used.

5.5. Conclusion

In this chapter, a comprehensive assessment model has been utilized to evaluate diverse technical configurations of energy carriers, energy converters, and energy reduction methods. The outcomes en-

compass analyses conducted on various emission reduction techniques for the case vessel mentioned in Table A.1, which operates under both Continuous and 100-hour operational profiles. After linking the technical feasibly outcomes with the economical costs and influences the most cost-effective options when sailing (partly) on alternative energy carriers together with other emission reduction methods were determined.
This chapter has answered subquestion 5:

”How will the implementation of a new propulsion configuration influence the operational effectiveness, vessel design and economical performance in different future scenarios?”

Technical feasibility

Both long cycles:
None of the mono battery configurations are feasible due to exceeding the maximum added draught and extension length. However, fuels such as HVO and FAME are technically feasible as long as they are considered zero emission fuels by the IMO. The hybrid propulsion configurations MGO-H_2(l) and DF-H_2(l) are technically feasible for all propeller types, including the original propeller, due to the relatively higher energy density of Methanol and MGO compared to liquid H_2. Table 7.1, summarizes the technical feasible configurations.

It can also be concluded that the implementation of WHR or regenerative braking systems, or a combination of both, does not determine whether the 40% CO_2 emission reduction target is met or not. However, installing these systems will contribute to additional complexity, volume, and weight of the overall machinery configuration.

100hr long cycle:
Dual fuel configuration only achieves the 40% CO_2 emission reduction target when combined with propeller type 2(4.0D) to reduce energy consumption. Mono-fuel hydrogen configuration requires propeller upgrades to prevent exceeding the maximum extension. The hybrid configuration MGO-NMC-Li is feasible for all propellers due to the high energy density of MGO, requiring only a small amount of energy from batteries. The hybrid configuration DF-NMC-Li is only feasible with propeller type 2 due to the low energy density of the batteries and methanol.

Continuous long cycle:
The DF configuration, when combined with a type 2 propeller, results in a feasible configuration, although hull extension or storage in the fish hold may be required. Mono fuel H_2(l) is not technically feasible for any propeller type due to exceeding the extension length or losing volume in the fish hold. The technically feasible hybrid configurations are similar to the 100hr long cycle, except for DF-NMC-Li, which requires additional volume due to methanol requirements. The energy scale of batteries is such that this hybrid configuration is only feasible with a type two propeller.

Economical feasibility

Depending on the amount of available financial resources in year 2023, available subsidy and to what extent one is willing to take risks, the following conclusions can be made for different categories of initial capital expenses:

€0-€2.0M
The cheapest option to meet the 2030 regulations is the switch to bio-diesels HVO and FAME. Because these options are fully drop-in, there is no need for significant investments in system and vessel conversion, which applies to both types of long cycles. However, a major drawback of this strategy is the sensitivity to future regulations. This is partly due to the fact that the low CO_2 emissions for these fuels are entirely determined by regulations and the limited availability of raw materials. As a result, it is possible that within a short period, this option will no longer ensure IMO compliance.
A second option that can be recommended for any type of fuel and long cycles is to increase the propeller nozzle diameter. section 5.4 has demonstrated in multiple ways that with a relatively small

investment, operational costs can be significantly reduced. This also results in these systems having a low payback period. Although the Orcan WHR is estimated to have a payback period of 8-9 years (100-hour cycle) and 5 years (Continuous cycle), the investment of approximately €250k is still significant and does not determine compliance with the IMO regulations. Although in the long run the Orcan will result in a reduction of TCO compared to not applying it.

For booth long cycles an option which requires more initial investments although less sensitive to regulations and can therefor be cheaper in the long run is the conversion to methanol dual fuel configuration, this applies for the configurations with 4.0m diameter propeller. The methanol option requires a lower investment, but has an higher operational costs. The MDO-battery option is not seen as a potential option for now due to the high initial investment. If battery costs reduce it could be a serious option thanks to the low predicted operational costs mainly caused by low forecasted electricity prices. The MDO-Hydrogen is also not an option, due to the CapEx exceeding €2.0M.

€2.0M+
In addition to the retrofit options, this option also includes the possibility of building a new ship. Once again, it is recommended to use a larger propeller for all configurations. Looking at Figure 5.10 and Figure 5.11, it can be observed that in the long term, both types of long cycles show that the hybrid MDO-hydrogen and the new build options deliver the best results in terms of Total Cost of Ownership. For both options, it is again noted that they will be less sensitive to future prices of alternative fuels or the impact of (inter)national regulations on tax emissions.
In the assessment between the retrofit option to MDO-hydrogen and the newbuild, it should be considered that after the assumed 15-year lifetime, the retrofit option will have virtually no remaining value, and the hull of the ship will be technically written off due to its age. This is not the case for the newbuild option, which still holds significant remaining value and is technically capable of many more years of service, provided it is well-maintained.
As calculated with this model, no attempt has been made to calculate the labor hours required for installing the new propulsion configuration. However, the mentioned newbuild price does include the total cost of materials and labor. As a result, the lines for retrofit and new build may give a distorted picture.

Therefore, despite the ease of saying it and the possibility of achieving it financially, committing the company to a large debt for many years, a newbuild ship is considered a better option when considering costs and lifespan.

Energy carrier storage
Due to practical considerations, it is not advised to use both the netstore and fish hold to store the energy carrier. The costs to extend the vessel are very small compared to the costs for new propulsion configurations (see Table 5.14). This trend means that if one decides to extend the vessel, the extension length is not that important when looking at costs. This also reinforces why you wouldn't want to use a netstore if you extend, since the costs to prevent giving up such a practical volume are very low. The practical influence of using the fish hold is the reduction of storage volume for fish boxes. The practical influence of hull extension is a potential increase in operational costs due to increased hull resistance. The increase in operational costs, in reference to the original configuration (Section 5.1), is very small.
Only in the absence of financial resources would the choice be made to store the energy carrier in the fish hold. However, if an owner is convinced to have an excessively spacious fish hold and only a small additional volume is needed for energy carrier storage, then the fish hold can also be used.

6

Verification and Validation

This last chapter treats and answers the last subquestion of this research:

”How can the assessment model for the feasibility of the 2030 proof beam trawler model be verified and validated?”

6.1. Model verification

A number of steps and calculations were explained and presented in section 4.1 and 4.2, where the assessment model was explained. There is a significant chance on typing and actually building the model, so model verification is required. This section is dedicated to ensuring the reader that the presented model is implemented correctly. Table 6.1 shows the tested cases and results. This is done by entering diverse parameters which are known to lead to specific outcomes. First, the current state scenario, meaning sailing on MGO, is tested. After running the scenarios it will be checked whether the given values correspond with the expected outcomes. All expected outcomes, as presented in Table 6.1, matched the actual outcomes and the model performed as expected, and is, therefore, successfully verified.

Table 6.1: Verification cases applied to assessment model, [84]

Test case	Result	Expected?
Input case vessel parameters, MGO fueled	Fuel cons, 22m3	Yes
Input case vessel parameters, check DE configuration	Energy cons. increase by 7%	Yes
Input case vessel parameters, Hydrogen fueled	Consumed hydrogen volume 3x that of MGO	Yes
Input case vessel parameters, Propeller diameter 2.5m	The P_d shows an average 22% P_d reduction with a 3.4m propeller	Yes
Change gravimetric energy density NMC batetry by 25% of original	Added converter weight *4, draught increase more than 1.5m, design not feasible	Yes
Increase of MGO long cycle by 1 fishing day	Required energy increased by +/- 25%	Yes
Reduce available tank storage by 50% of original, case vessel parameters	DF hull extension from 0.1m to 1.0m	Yes
Hull extension of 4m	The hull resistance shows very small change, both transit and fishing.	Yes
Increase MGO Fuel cell price by 125% from original	Operational costs long cycle increase with 125%	Yes

6.2. Model validation

To increase the credibility of the results the model must be validated as well. The method used to validate the behaviour of the model is explained and discussed in this section. Till today no beam trawlers exist which are fueled by the proposed alternative energy carrier and converter. Therefor the predictions of the proposed configurations cannot be compared to existing ships. To be able to validate the assessment model the ”Validation square” is used [140], visualized in Figure 6.1. The main goal of the validation method is to: ”Validate design research in general”. For a research design method, the

’logical empiricist validation’ is not easily applicable. Therefor, the choice is made to go with a ’Relativist validation’, this method is defined by six steps:

1. Prove the validity of each individual component in the model
2. Prove that the information flow is consistent between components
3. Prove that example problems are representative for actual use of the model
4. Prove that the results of the example problems are useful and serve the purpose of the model
5. Prove that the method in the model is useful for achieving the purpose of the model
6. Accepting that the usefulness of the model also applies beyond the example problems

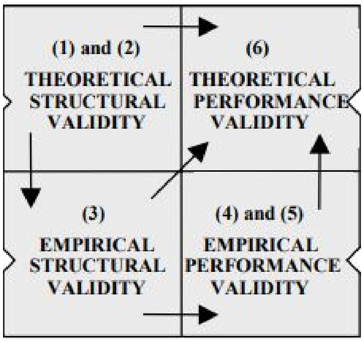


Figure 6.1: Validation square [140]

6.2.1. Theoretical Structural Validity

In this section the validity of the individual components of the assessment model are discussed. Secondly the consistency of the information flow to and from different components. The results of the individual components of the model are valid and each component of the assessment model is based on well found examples within the maritime sector of other relevant literature. By doing this the steps of the validation square are executed, Figure 6.1. In general each calculation step within the model can be validated individually, but some input parameters contain uncertainties. Therefor it is checked if the components of the assessment model are consistently connected with each other.

Construct Validity

In Chapter 4, the assessment model with its calculation steps was introduced and explained. Some calculation steps were already validated with the help of literature while other calculation steps were a logical calculation step. The calculation steps with the arguments are briefly repeated and explained here, to prove their appropriateness. This has to be proved since the model will not be entirely accurate, but will function as a solid indicator. The Relativist validation approves the involvement of objective and subjective within in the model without there being one single correct answer.

Step 1, Required energy

This step uses many outputs from other steps together with many emission reduction parameters studies. The outcome of each calculation of required (electric) power will be validated in the specific calculation step. With the help of a study on energy consumption [5], it is found that the propulsion, winch, cooling and hotel load represent 99% of the total consumed power, and therefor only these are taken into account. The OP and vessel parameters are all found by Wageningen University & research studies and information from customers.

Step 2, Required volume & weight
The output of calculation step 1 in combination with, propulsion configuration overall efficiency, volumetric and gravimetric energy densities of the energy carriers result in the total consumed and required storage volumes and weights. Therefor the outcome of this calculation is mainly influenced by the energy carrier characteristics determined in 3.2 and Step 1 input. 3.2 data is based on universal studies or company information which are referenced with each other, therefor this calculation step is found to be valid. With the help of system suppliers and full scale pilot projects an average efficiencies were determined for the propulsion configurations. Since the system will be purchased within the coming 0 to 2 years, good and reliable system efficiencies can be used.
Although well founded studies are used, some uncertainty can not be avoided. For example the required storage volume of methanol or liquid hydrogen. The stowage factor of cryogenic hydrogen is depending on the size and quantity of tanks since these are shaped cylindrical. The stowage factor of methanol is depended on the hull Depth and percentage of the tank being below or above the waterline due to safety regulations, see 3.2.3. In general the volumetric energy densities are based on application in one tank. Since energy carrier application on a beam trawler will be stored in multiple tanks due to available positions and IGF code. To partly account for this a case study is done on an existing beam trawler, with three tanks for methanol and cryogenic hydrogen and data from 3.2 and [108].

Step 3, Vessel modification
The required energy carrier storage volume is referenced with the available storage volume. If the available volume is less than required the vessel must be adjusted. This calculation step determines how much volume of the fish hold volume is occupied or how much the vessel must be extended if the fish hold is not used. The vessel is extended at mid ship section since this results in the highest additional volume per extended meter. This is the result of the vessel having the largest moulded beam and highest mid section coefficient here. Also it ensures that the extended section aligns well with the existing hull, minimizing any abrupt changes in shape or contour and therefor reducing capital costs. Extending the length at this location helps distribute the added stresses and loads more evenly, minimizing the risk of structural weaknesses or excessive bending moments, [31].

The two options/calculations are both based on the case study vessel. Therefor these calculation steps mainly consists of logical interpretation of effective gained storage volume in fish hold or by extension determined with help of technical drawings. The outcome of these calculations are therefor found to be reliable and to be validated.

Step 4, Vessel parameters
This calculation step calculates the overall added weight and volume to determine new ship parameters as a result of the application of a new propulsion configuration. This is done with: energy carrier, required propulsion powers, kW/kg ratio and modifications weight & volumes. The gravimetric power densities of converters are based on studies and actual supplied converters and are therefor found accurate enough for preliminary ship design.
The added water plane area, wetted hull area, displacement and draught is calculated based on hydrostatic ship stability equations, [50] together with ship drawings.

Step 5, Hull and Gear resistance
The resistance estimate is based on the method of Holtrop and Mennen [122]. In Chapter 4, the different hull resistance methods were referenced with each other. With the known Speed-Resistance curve of dutch beam trawler, the Holtrop and Mennen showed smallest deviation from actual. The method is well established for academic and commercial use and it is therefor assumed that the results are accurate enough for preliminary ship design. The fishing gear resistance is estimated using two different studies([21], [24]) which proposed Speed-resistance equation's based on many practical measurements.

Step 6, WHR
The feasibility to recover energy from the exhaust product of different energy carriers is based on a view system characteristics. The two different WHR systems efficiencies are determined by the system supplier, Chapter 3.2. The recovered energy is depending converter efficiency, exhaust temperature & flow,

and the amount of hours the system can operate in. The systems only operate during fishing hours since this operation produces a constant large flow of waste energy. The systems are only applied to ICE and FC propulsion configuration due to minimum required temperature and flow requirements of the system [126] [15], [139]. The heat recovery efficiency of the systems is based on case studies according manufacturers, and are therefor found reliable.

Step 7, Propulsive power

The propulsive power for transit and trawling are determined by on board measurements, this is used for the reference/benchmark. From the previous step the required effective propulsive thrust for fishing and transit are known. For this step the thrust and wake deduction factors where assumed to be constant. With the chosen propellers, and the available data, the only unknown factor is the required P_d. This is determined with the help of PropCalc. This program uses the propeller diameter and required thrust to determine the P_d. By referencing the original ships propeller to a similar propeller in Propcalc similar required powers are found. PropCalc is a well known and frequently used program for booth professional and academic markets. The program is relatively old and are still widly used today, this shows the validity of the program.

Step 8, OpEx

This calculation is depending on energy carrier prices and CO_2 emission tax prices. The short term price estimations are relatively reliable, in contra dictionary to long term energy carrier price predictions. With the help of [86], [148] &[16], the best estimates are used, although as mentioned future price forecast's are very sensitive.

Step 9, CapEx

This calculation consists of system costs purchase price, material costs and labour. The long term estimation of energy converter prices is difficult and shows great variation depending on multiple world wide drivers. Since the capital expenses are made in year 0, future many uncertainties are excluded. Therefor the €$/kW$ ratios, material costs and labour costs estimated and determined in Chapter 3 are used and found to be reliable.

Step 10, NPV

This calculation uses the input of Step 8 and Step 9 together with a determined interest rate to determine the NPV. This means that the only new parameter introduced here is the average interest rate. Although the interest rate shows great short term variations, the long term interest periods approach good estimations [48]. Therefor this parameter is included into the sensitivity analysis.

6.2.2. Accepting method consistency

As could be seen in Figure 4.1 the calculation steps and information flow is visualized. The elaboration in Chapter 4 and the section above describes the input and output of each calculation. Here it is demonstrated that for each calculation step there is an adequate input available and required. Secondly this also showed that the output of the calculation steps is based on the previous steps output. The output of the calculation is again used as an input for the next calculation with the help of other fixed determined parameters from Chapter 3. The information assumed to be readily available are all coming from the literature study part of the assessment model. Because the components only import information that is generated from previous components in the design loop, the information flow is considered to be consistent.

6.2.3. Example Problems

Within this step the second quarter of the validation is performed, this to build confidence in the assessment model. The square has been used to validate a design method, namely the Hierarchical Product Platform Realisation Method(HPPRM) This is done by executing the following steps:

- Document that the example problem is similar to other problems that have been used on these methods;
- Document that the example problem represents the actual problem for which the method is intended

- Document that the data associated with the example problems can support a conclusion

Acceptance of the example problems used in the method is done in stages. Due to the research goal the assessment model already aims at a specific type of vessel. With the help of [5] and average type of beam trawler is found and used in this study. The construct regarding vessel dimensions, operational profile, propulsion configurations are all build with this vessel in mind. This has resulted in each calculation step being tailored around the specified vessel operational requirements. The calculations of weight, volume and emissions of propulsion configurations are viable for any structure with these particular configurations. The operational and functional vessel requirement from the example vessel problem results in output data that can be used to construct and formulate an conclusion.

6.2.4. Usefulness for representative example problems

Within 2, 1 the specific example problem of this thesis is introduced. The problem is based on a combination of international regulations for a specific type of ship. The assessment model is build based on these two known factors. The hull resistance, gear resistance, available storage volume's and operational profiles are all based on the reference vessel which is assumed to be a good representative for a Dutch beam trawler. The problem presented in this research can be regarded to as a ”real world problem”. By optimising the assessment model and performing different scenarios, an actual new proposed design method is proposed, see Chapter 5. Therefor it is found that first two requirements of the HPPRM are met.

6.2.5. Usefulness linked to applying method

To link the usefulness of the example model of ”OD-6” with the assessment method, each construct within the assessment model is run individually. By running the individual steps, and comparing those to the results as a whole it can be determined if the method is the reason for these results. Only knowing the vessel parameters of a beam trawler, we have accurate data but no way this will lead to determining the feasibility which results in the method not being met. The same can be concluded looking at the technical feasibility part and economical feasibility part when running them individually. What is crucial for these constructs is that they require input form the vessel information construct, to come up with their own use full information. This statement is even more applicable for the economical feasibility, since this is again dependent on the outcome of technical feasibility together with vessel information. Therefor the technical feasibility provides results that relate to goal of the method, but fully dependent on input from vessel information. Therefor it can be concluded that this method is not as refined as other existing methods or design spirals but definitely show comparisons. From these comparisons, the usefulness of the applied assessment model can be linked to the usefulness of the results obtained from the base line and scenarios.

6.2.6. Accepting usefulness beyond example problems

Theoretical performance validity is the last step in the validation square. It is the expansion of the empirical performance validity, which was meant to show the usefulness for some limited instances (case study problem). This last step is to accept the usefulness of the methods beyond the example problem. In other words, to claim generality of both the research methods as well as the constructs used. This research aimed to show the feasibility for the application of new propulsion configuration to make a Dutch beam trawler comply with 2030 IMO emission regulations.

A case study was used as a ”average beam trawler” to generate all the results, generality for Dutch beam trawlers always was the goal of this research. The use of a base ship to be used as a case study should not have the effect of limiting the research to that case. But by focusing on the Dutch beam trawler vessels and running different operational profiles and fishing gear, a more general conclusion and recommendations can be reached. This complies with the Pederson validation square which explains:

”The purpose of going through the Validation Square is to present ‘circumstantial’ evidence to facilitate a leap of faith, i.e., to produce belief in a general usefulness of the method with respect to an articulated purpose.” [141]. This refers to the ”External validity” of the research [124], or the validity of using the applied methods outside of this case study. The conclusion in section 6.1 presents the verification that the constructed assessment model, can be applied to the base ship model.

6.3. Conclusion

In summary the answer on the sub question is given in this section:

> *"How can the assessment model for the feasibility of the 2030 proof beam trawler model be verified and validated?"*

In conclusion, the presented assessment model has undergone verification and validation processes to ensure its correctness and reliability. The verification process involved testing the model with diverse parameters known to lead to specific outcomes. All expected outcomes matched the actual outcomes, indicating that the model performed as expected and was successfully verified.

The validation process used a relativist validation method, which consists of six steps. The first step involved proving the validity of each individual component in the model, which was achieved by validating the calculation steps with relevant literature and logical reasoning. The second step focused on ensuring consistent information flow between components, and it was confirmed that the output of each calculation step served as input for the subsequent steps.

Construct validity was established by explaining and justifying each calculation step in the assessment model. The appropriateness of the calculation steps was proven through literature references, studies, and logical interpretation. While uncertainties existed in some input parameters, efforts were made to ensure the components of the assessment model were consistently connected with each other.

The example problems used in the assessment model were found to be similar to other problems used in the design method. The example problem represented the actual problem for which the model was intended, and the associated data supported meaningful conclusions. The assessment model was tailored around a specific type of vessel, and the example problem was based on a well-defined beam trawler, which allowed for reliable and representative results.

The usefulness of the assessment model was demonstrated through its application to the example problem. By running the individual components and comparing the results to the overall results, it was confirmed that the model contributed to the obtained outcomes. The technical feasibility and economic feasibility constructs relied on input from the vessel information construct, indicating the interconnectedness of the components and the usefulness of the assessment model in providing relevant information.

In conclusion, the assessment model showed theoretical structural validity, consistency in information flow, and usefulness in generating reliable results for the given example problem. While further validation with real-world data and comparisons to existing ships are not possible due to the absence of vessels fueled by the proposed energy carrier, the steps taken in verification and validation instill confidence in the correctness and reliability of the assessment model.

7
Conclusion

In order to address climate change and meet the targets outlined in the Paris Agreement, it is imperative for the maritime industry to undergo transformation. However, due to numerous variables, uncertainties, dependencies, and specific requirements, there will be diverse optimal solutions for various vessel types and market segments. There currently is limited (public) research focusing on zero or emission reduction on Dutch beam trawlers. Consequently, the following research question has been formulated for this study:

To what extent is it technically and economically feasible to reduce the CO_2 emissions of Dutch beam trawlers to meet the 2030 IMO emission regulations, while maintaining vessel operational effectiveness?

The main research question of this research is solved by answering the seven subquestions that will be answered subsequently.

1. *What are the current characteristics of a dutch beam trawler and what are their future requirements?*

The average age of a Dutch beam trawler is +/- 20 years, this old age is caused by the small profits and uncertain future perspectives within the last and coming decades. The vessels average characteristics ranging: L_{pp}:35-42m, $B_{moulded}$:6-9m, T_{mid}:3-4.5m, D_{prop}:2-3m, $Prop_{speed} : 200 - 300rpm$ and an installed P_b:1000-2000kW.

The propulsive and auxiliary power required to operate the vessel is generated by diesel engines. The auxiliary systems are powered by a minimum of two internal combustion engines from which both can produce electricity and additionally one is equipped with a hydraulic pump. The main energy consumers onboard are the ice & cooling machines and, safety & communication and the winch. It is found that the state of the art for beam trawlers limits itself to optimized propeller and diesel engine configurations but does not go any further.

The eventful years will be followed up by strict future Dutch, European legislation and IMO. The IMO, Dutch government and EU accepted legislation putting limits or reduction programs on the production of CO_2 emissions. In short these IMO technical frameworks are aimed at implementing a 40% reduction in carbon intensity compared to 2008 across the global shipping fleet by 2030. To stimulate these implementation of CO_2 emission reduction the EU and Dutch government introduced a tax system to penalize the emission per emitted tone of CO_2.

The vessel operation is divided into an average long cycle and short cycle, from which the short is equal on the whole fleet but the long cycle changes depending on vessel owner. The short cycle is the fishing cycle, which consists of fishing, hauling and setting of the nets. The Long cycle refers to the round trip from port to fishing grounds and back to port. A 100-hour long cycle is currently utilized, while a continuous 160-hour long cycle has been determined as a suitable average and is therefore implemented.

2. *What are the relevant methods to reduce CO_2 emission on a Dutch beam trawler?*

Based on Table 3.1 it is concluded that, the internal combustion engine is and will remain a much applied method to convert chemical energy into mechanical energy. The MGO and dual fuel ICE will be further used in this research due to their low cost and high reliability. It is found that the LT PEMFC shows most potential due to:, the system reliability, high energy density, quick response to load variation and simple system compared to high temperature fuel cell with similar efficiencies. Permanent magnet (PM) motors are selected for their high efficiency, despite the demagnetization issue and higher initial costs. Given the limited available volume and weight constraints, coupled with the high efficiency requirements, the decision is made to utilize the PM motor in this research. The efficiencies, power and volumetric densities of the used energy converters and reformers are summarized in Figure 3.1 and Table 4.1.

The drop in fuels HVO and FAME are found to be promising. The higher fuel prices in combination with potential storage problems do not tackle the advantage of their similarity MGO and the significant reduction in TTW emissions. Hydrogen has the advantage to be zero emission in TTW. The volume required to store the liquidized fluid could be a potential problem. But the direct use of hydrogen in high efficiency fuel cell systems promises to be very beneficial. Methanol is partly categorized as a drop in fuel, the only dis-advantage can be found in the required 600mm cofferdam around the fuel tank and lower energy density w.r.t. MGO. The high TRL in combination with the fuel being partly drop in the fuel is further researched. Iron powder and Sodium borohydride: although these fuels could definitely be the future energy carriers, the application in the coming years does not seem feasible. Since the converters, auxiliary systems including the storage systems which come with these energy carriers require more research. Ammonia application has showed potential due to its potential in storage, volumetric energy density and technical majority in energy converting. The dis-advantages is ammonia having a high toxicity and a negative social reputation and is therefor not found suitable to apply in the short term. Battery potential is depending on: volume/weight energy density, DSOC, DoD, charging and average power delivery of power pack. Due to the operational profile there is potential to use batteries in combination with another energy converter. For this research the NMC lithium type battery is further investigated on its application. Figure 3.1 illustrates a summary on the advantages and dis-advantages of the researched energy carriers.

Based on the research in this section a summary is visualized in Table 3.7. The potency to optimize the propeller dimensions are found promising, the investment is relatively low w.r.t alternative converter prices. This is caused by the fact that many beam trawler still operate with relatively small diameter propellers with high rotational speeds which result in lower efficiencies. Secondly the optimisation of winch operations together with the availability of regenerative braking were examined. The reduction of sailing speed while setting and hauling does not come with any investment costs and is therefor easy to achieve. Regenerative braking requires an upgrade of the winch or a completely new winch and thus requires an investment. Due to zero capital costs the winch optimized operation is always applied. The potential of regenerative braking is also found worth applying, due to low capital investment if board net is already DC. Wind and solar power are promising due to there ”Free” energy reduction but they also show dis-advantages. In general there is a lack of available free area to install the systems and if the area is available the position with respect to incoming green water is very unfavorable. The wind systems are of such size and weight that it would have negative influence on stability, therefor their application is not investigated any further. The exhaust waste heat recovery(Orcan & SRC) is found to be promising in its application on beam trawlers. Depending on the propulsion setup the recovered energy could be significant, the generated electricity can be charged into batteries or fed to an electric motor. The only disadvantage of exhaust gas energy is found in the high system costs and the reduction of efficiency with load variation. Although the emission reduction percentages of emission capture systems sound very encouraging these capture systems are not taken into account in this research. Due to to volume and weight of the systems. Also they are not fully mature for the application on small engine powers and the high capital costs w.r.t. reduction in CO_2 emission is very low.

3. *What are requirements for an assessment model and what parameters should it include to determine the technical and economical feasibility of CO_2 emission reduction systems?*

To make sure the vessel can continue fishing, the following effectiveness requirements are included into the model: Endurance, Towing capacity, Fish hold, Cooling, Working deck and Storage volume. The technical feasibility is determined using input from: onboard power measurements, construction/technical documentation, operational profile and input from the literature study. With the known hull dimensions the resistance is determined using Holtrop & Mennen [122], together with the fishing gear resistance([151] [150]) the P_d is determined. The P_d, together with configuration efficiency, OP and energy carrier characteristics Figure 3.1 results in an amount of required mass and volume of energy carrier. With the known hull dimensions different options are proposed to store this amount.

The economical feasibility is determined using input from the literature study and the in house knowledge of Padmos. The capital investment to retrofit the vessel is the sum of, energy converter, gearboxes,DC Switchboard ,tank storage, energy recovery system(s) and extension costs. These system costs are all determined ratios determined in the literature study. The operational expenses are the costs of energy carrier and emission tax per long cycle.

The overall economical performance of a propulsion configuration is determined with the NPV. Considering the long-term interest rates in the euro area, the study uses an average rate of 1.3% as the discount rate. The NPV calculation allows investors to assess the present value of future cash flows and determine the viability of the investment. The NPV does not show to be very sensitive to CO_2 emission tax, not even the high carbon content fuels. The high fuel price scenario has a notable influence on NPV. These lines maintain the same order, but they shift proportionally upward, and the payback periods for alternative fuels also increase.

4. *How will the implementation of a new propulsion configuration influence the operational effectiveness, vessel design and economical performance in different future scenarios?*

Technical feasibility

With the outcome of 5.1, the following conclusions in Table 7.1 can be stated on the technical feasibility of a IMO 2030 proof Dutch beam trawler. Table 7.1, summarizes the technical feasibly propulsion configurations. The feasibility is determined by the configuration meeting all effectiveness requirements, being able to execute the long cycle, being able to reduce 40% CO_2 emission reduction and not exceeding maximum added weight or length.

Table 7.1: Technical feasible configurations, red: reference configuration case vessel

			100 hr long cycle	Continuous long cycle
	Fuel	Conf.	Propeller type	Propeller type
MONO	MGO(reference)	D-D	Original	Original
	HVO	D-E	Original,1,2,3,4	Original,1,2,3,4
	FAME	D-E	Original,1,2,3,4	Original,1,2,3,4
	DF	D-E	2,4	2,4
	Hydrogen	E	1,2,3,4	-
Hybrid	MGO-H2	D-E	All	All
	MGO-NMC-Li	D-E	2,4	2,4
	DF-H2	D-E	All	All
	DF - NMC-Li	D-E	1,2,3,4	2,4

Economical feasibility

Depending on the amount of available financial resources in year 2023, available subsidy and to what extent one is willing to take risks, the following conclusions can be made for different categories of initial capital expenses:

€0-€2.0M

The cheapest option to meet the 2030 regulations is the switch to bio-diesels HVO and FAME. Because these options are fully drop-in, there is no need for significant investments in system and vessel conversion, which applies to both types of long cycles. However, a major drawback of this strategy is the sensitivity to future regulations. This is partly due to the fact that the low CO_2 emissions for these fuels are entirely determined by regulations and the limited availability of raw materials. As a result, it is possible that within a short period, this option will no longer ensure IMO compliance.

A second option that can be recommended for any type of fuel and long cycles is to increase the propeller nozzle diameter. section 5.4 has demonstrated in multiple ways that with a relatively small investment, operational costs can be significantly reduced. This also results in these systems having a low payback period. Although the Orcan WHR is estimated to have a payback period of 8-9 years (100-hour cycle) and 5 years (Continuous cycle), the investment of approximately €250k is still significant and does not determine compliance with the IMO regulations. Although in the long run the Orcan will result in a reduction of TCO compared to not applying it.

For booth long cycles an option which requires more initial investments although less sensitive to regulations and can therefor be cheaper in the long run is the conversion to methanol dual fuel configuration, this applies for the configurations with 4.0m diameter propeller. The methanol option requires a lower investment, but has an higher operational costs. The MDO-battery option is not seen as a potential option for now due to the high initial investment. If battery costs reduce it could be a serious option thanks to the low predicted operational costs mainly caused by low forecasted electricity prices. The MDO-Hydrogen is also not an option, due to the CapEx exceeding €2.0M.

€2.0M+

In addition to the retrofit options, this option also includes the possibility of building a new ship. Once again, it is recommended to use a larger propeller for all configurations. Looking at Figure 5.10 and Figure 5.11, it can be observed that in the long term, both types of long cycles show that the hybrid MDO-hydrogen and the new build options deliver the best results in terms of Total Cost of Ownership. For both options, it is again noted that they will be less sensitive to future prices of alternative fuels or the impact of (inter)national regulations on tax emissions.

In the assessment between the retrofit option to MDO-hydrogen and the newbuild, it should be considered that after the assumed 15-year lifetime, the retrofit option will have virtually no remaining value, and the hull of the ship will be technically written off due to its age. This is not the case for the newbuild option, which still holds significant remaining value and is technically capable of many more years of service, provided it is well-maintained.

As calculated with this model, no attempt has been made to calculate the labor hours required for installing the new propulsion configuration. However, the mentioned newbuild price does include the total cost of materials and labor. As a result, the lines for retrofit and new build may give a distorted picture.

Therefore, despite the ease of saying it and the possibility of achieving it financially, committing the company to a large debt for many years, a newbuild ship is considered a better option when considering costs and lifespan.

Energy carrier storage

Due to practical considerations, it is not advised to use both the netstore and fish hold to store the energy carrier. The costs to extend the vessel are very small compared to the costs for new propulsion configurations (see Table 5.14). This trend means that if one decides to extend the vessel, the extension length is not that important when looking at costs. This also reinforces why you wouldn't want to use a netstore if you extend, since the costs to prevent giving up such a practical volume are very low.

The practical influence of using the fish hold is the reduction of storage volume for fish boxes. The practical influence of hull extension is a potential increase in operational costs due to increased hull resistance. The increase in operational costs, in reference to the original configuration (Section 5.1), is very small.

Only in the absence of financial resources would the choice be made to store the energy carrier in the fish hold. However, if an owner is convinced to have an excessively spacious fish hold and only a small additional volume is needed for energy carrier storage, then the fish hold can also be used. For the case vessel it is found that if required additional storage volume remains below 20m^3, which is equal to a loss in storage capacity op approximately 200 fish boxes, is found to be acceptable.

5. *How can the assessment model for the feasibility of the 2030 proof beam trawler model be verified and validated?*

The presented assessment model has undergone verification and validation processes to ensure its correctness and reliability. The verification process involved testing the model with diverse parameters known to lead to specific outcomes. All expected outcomes matched the actual outcomes, indicating that the model performed as expected and was successfully verified. The validation process used a relativist validation method, which consists of six steps. The first step involved proving the validity of each individual component in the model, which was achieved by validating the calculation steps with relevant literature and logical reasoning. The second step focused on ensuring consistent information flow between components, and it was confirmed that the output of each calculation step served as input for the subsequent steps. Construct validity was established by explaining and justifying each calculation step in the assessment model. The appropriateness of the calculation steps was proven through literature references, studies, and logical interpretation. While uncertainties existed in some input parameters, efforts were made to ensure the components of the assessment model were consistently connected with each other. In conclusion, the assessment model showed theoretical structural validity, consistency in information flow, and usefulness in generating reliable results for the given example problem. While further validation with real-world data and comparisons to existing ships are not possible due to the absence of vessels fueled by the proposed energy carrier, the steps taken in verification and validation instill confidence in the correctness and reliability of the assessment model.

8

Discussion

Throughout this thesis, several assumptions and simplifications have been employed to reach the presented conclusions. It is important to acknowledge that some of these assumptions may not hold true in different scenarios, potentially leading to inaccuracies in the results. In this discussion, these points will be revisited, emphasizing the influence of these assumptions on the validity and applicability of the results in real-world contexts.

The final conclusion of this thesis heavily relies on these design choices and may not provide a complete representation of the overall picture. Although efforts were made to incorporate all relevant factors as much as possible, it is important to acknowledge the limitations in time and resources associated with a master's thesis. This restricted the ability to create detailed designs for all energy carriers and configurations. Apart from this crucial aspect related to the design strategy, there are other methodological points that warrant discussion. Despite the numerous assumptions made, the list below will primarily focus on the points that have had a significant impact on the conclusion of this thesis.

Technical

- It is assumed that beam trawlers fish with the same fishing gear all year long. Actually, this is not the case. Some vessels change their fishing techniques depending on the availability of fish species during different seasons. This results in different operational profiles and towing forces. Consequently, the optimized configuration that is favorable for one fishing method may not be as advantageous for another fishing technique.

- The model only considers CO_2 emissions, but other emissions, such as NO_x, SO_x, and particulate matter are also important to consider in the decision.

- During fishing, the resistance of the fishing gear accounts for approximately 90-95% of the total resistance of the vessel and gear. Research is already being conducted to reduce this resistance, and with pulse fishing, a method was found to lower resistance by approximately 50%. However, this technique is currently banned by the EU. Despite this, further exploration is needed to find an alternative method that can achieve similar results as this technique.

- The energy consumption reduction due to the application of larger diameter propeller uses hull and rotative efficiency to be constant. Although it was found to be sufficient for this research, these assumption could case uncertainty. To achieve more accurate results, it is advisable to consider a range of possible efficiencies or incorporate additional factors that can influence propeller efficiency in the analysis. This may involve conducting further research, using empirical data, or employing computational fluid dynamics (CFD) simulations to account for the varying efficiency of the propeller under different operating conditions.

- The energy densities used, including tanks for certain energy carriers, depend on the number of tanks used. In this thesis, an average value is employed, although this approach can introduce uncertainties due to the variable nature of tank quantities.

- Presently, the model assumes that alternative energy carriers HVO, FAME and hydrogen have (almost) no well-to-wake emissions. However, this assumption is not accurate, and it is necessary to conduct further research to incorporate well-to-tank emissions into the model.

- The model does not include the assessment of stability after different energy carriers and converters are proposed. Switching to alternative energy sources may involve modifying the vessel's (added)weight distribution. This can result in the ship no longer meeting the stability requirements set by the Dutch inspection authorities.

- The required fuel volume is based precisely on the number of hours per operational profile. This quantity does not take into account any reserves or margins. In reality, there should always be a certain amount of reserve fuel, especially in the case of rough seas conditions or heavy loads. Taking this into account could result in different results in feasibility.

- It is assumed that the overall efficiency of the propulsion configuration is constant, this could cause inaccuracy in particular conditions. This is caused by the fact that the efficiency of a propulsion system can vary based on several factors, including vessel speed, loading conditions, sea state, and environmental conditions.

- Since the IGF is not fully developed for the fuel storage of methanol and hydrogen on small-sized vessels, this study only considers tank position and cofferdams in accordance with the IGF if available. Venting, construction and safety systems are not taken into account, which may result in inaccuracies in the estimated added volume or weight.
- Despite the fact that the Dutch beam trawl fleet has similar vessels, it would be beneficial to conduct various case studies using different ships to examine if the results differ significantly from each other.
- The limitations on added draught and extension as mentioned in Section 5.1, could be further investigated as they are determined by vessel specific regulations and parameters.

Economical
While it is not possible to validate the price of the alternative energy carrier for 2050, the model relies on the most reliable current information and estimates available. Consequently, it is anticipated that these assumptions hold validity.

- The prevailing market trend indicates a growing interest in methanol dual fuel configurations. This trend has the potential to lower the price of methanol while potentially driving up the prices of other alternative energy carriers. It is recommended to investigate the power and influence of this trend.

- The quantity and price of caught fish, both presently and in the future, are not being considered in this analysis. These factors depend on numerous variable parameters that are outside the scope of this thesis. However, in order to gain a clearer understanding of the profitability of both current and potential propulsion configurations, it may be beneficial to incorporate this factor into the assessment model.

- The operational expenses do not include maintenance costs; therefore, the conclusion is not fully comprehensive. The different propulsion configurations exhibit completely distinct requirements for maintenance and refurbishment. This results in a significant variety of annual maintenance costs per configuration, which in turn could lead to changes in the most promising propulsion configurations.

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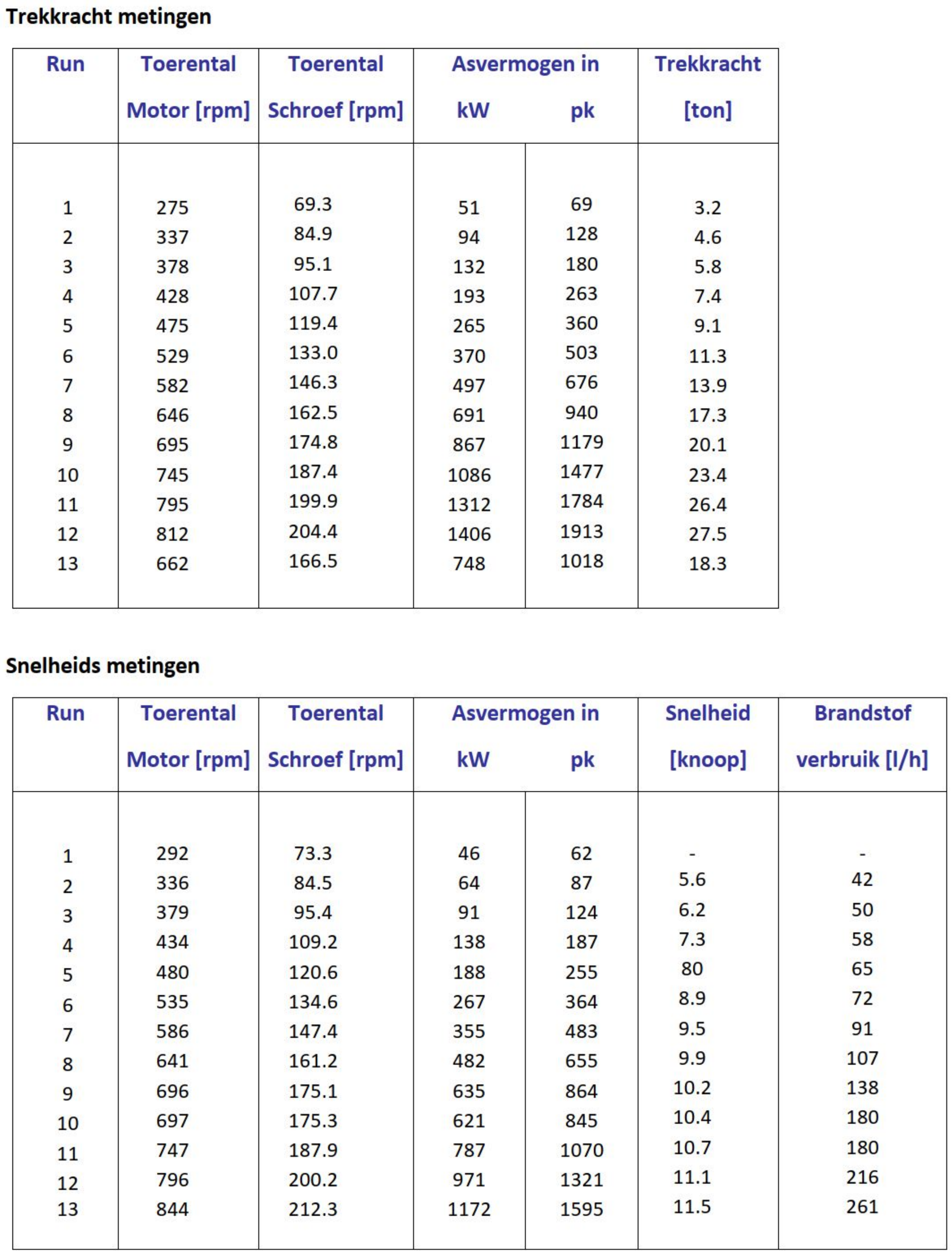
A

Vessel particulars

Table A.1: Specifications case vessel

Vessel	Case vessel
L_{pp}	34.0 m
L_{wl}	29.2 m
B_{mld}	7.5 m
Draft	3.9 m
T_{app}	3.0 m
T_{fpp}	2.8 m
Displacement[t]	230 t
Block coeff.	0.6 $-$
Midship section coeff.	0.8 $-$
Transom area	1.8 m^2
Netstore volume	4.5 m^3
Fish hold volume	150 m^3
Fuel bunkers	47 m^3
Mechanical data:	
Main engine	1200 kW
Propeller GBX ratio	1:5.8
Propeller blades	5 $-$
Propeller diameter	2.5 m
Propeller shaft draught	4 m
Auxiliary DG	175 kW
Hydraulic DG	175 kW
Winch power	125 hp



Trekkracht metingen

Run	Toerental	Toerental	Asvermogen in		Trekkracht
	Motor [rpm]	Schroef [rpm]	kW	pk	[ton]
1	275	69.3	51	69	3.2
2	337	84.9	94	128	4.6
3	378	95.1	132	180	5.8
4	428	107.7	193	263	7.4
5	475	119.4	265	360	9.1
6	529	133.0	370	503	11.3
7	582	146.3	497	676	13.9
8	646	162.5	691	940	17.3
9	695	174.8	867	1179	20.1
10	745	187.4	1086	1477	23.4
11	795	199.9	1312	1784	26.4
12	812	204.4	1406	1913	27.5
13	662	166.5	748	1018	18.3

Snelheids metingen

Run	Toerental	Toerental	Asvermogen in		Snelheid	Brandstof
	Motor [rpm]	Schroef [rpm]	kW	pk	[knoop]	verbruik [l/h]
1	292	73.3	46	62	-	-
2	336	84.5	64	87	5.6	42
3	379	95.4	91	124	6.2	50
4	434	109.2	138	187	7.3	58
5	480	120.6	188	255	80	65
6	535	134.6	267	364	8.9	72
7	586	147.4	355	483	9.5	91
8	641	161.2	482	655	9.9	107
9	696	175.1	635	864	10.2	138
10	697	175.3	621	845	10.4	180
11	747	187.9	787	1070	10.7	180
12	796	200.2	971	1321	11.1	216
13	844	212.3	1172	1595	11.5	261

Figure A.1: Example vessel measurements [Padmos]

B

Considered fuel cells

Phosphoric Acid Fuel Cell

This FC is categorized as a High-Temperature Fuel cell, meaning operation temperatures above 200 °C [55]. Electrochemical reactions are quicker and therefor losses in electrokinetic effects lower, resulting in higher electrical efficiencies. Higher operational temperatures result in overall efficiency decreasing, chapter 3.1.2. Since exhaust gases are of such high temperatures the production of energy is feasible and thereby the overall efficiency can be increased.

Due to installation in multiple sectors the PAFC has proved its performance and behaviour are well understood. It is the oldest type of working fuel cell that was commercially sold. The PAFC is equivalent to the proton exchange membrane fuel cell, but is has phosphoric acid as the electrolyte. The fuel cell consists of an anode and a cathode made of a finely dispersed platinum catalyst on carbon and a silicon carbide structure that holds the phosphoric acid electrolyte [173]. The operation of the cell is less sensitive for carbon dioxide pollution in the air inlet. A disadvantage of the PAFC is that when compared to other fuel cells of similar weight and volume, it produces less power[62]. Since the electrodes are composed of platinum particles which is placed on a porous, this increases the cost of this kind of FC, consequently around €3000 per kW[27]. The Efficiency reaches up to 45% with a utilization factor of 85% for the fuel and a 50%-70% for the air[114]. The PAFC currently has an 1600 to 3100 A/M^-2 with an lifetime expectancy of around 5 years(40000 hrs)[155].

Solid oxide fuel cells

Similar to phosphoric acid fuel cell the SOFC is also categorized as a High Temperature fuel cell. The SOFC operates at temperatures in the range of 600 till 1000 °C, this also means that the fuel cell can operate without the help of an expensive catalyst[157] to reform the fuel if not hydrogen. This results in fuels like LNG and methanol to be fed directly in to the FC. This also applies to ammonia which is thermally cracked on the Anode[56]. Another advantage is that the fuel may contain small contamination's. Although the TRL for direct use of LNG, ammonia and methanol is very low. A disadvantage of the SOFC is that the overall installation requires multiple external parts and these require additional investment and reduce the reliability.

The high temperature operation also require fuel to be heated and exhaust system to be cooled[56]. The electrical efficiency of the SOFC is not high due to the high temperature exhaust product. To make a SOFC interesting a waste heat recovery system is fitted on the SOFC exhaust. This system typically exists of a steam turbine which transforms kinetic energy into mechanical energy which is later transferred into electrical energy by a generator[195]. The efficiency is around 60% for the electrical part and up to 85% together with waste heat recovery[178].

Molton Carbonate Fuel Cell

The molton carbonate fuel cell is the most complex of modern fuel cells. The electrolyte material is a lithium and potassium carbonates which are both in solid phase at 20 °C, the cell operates at 650°C. As already noted, the high temperature inside the fuel cell means that reforming can easily be carried out internally using a simple nickel catalyst rather than a more complex catalyst that might be required at lower temperature. Due to the complexity of the system the fuel cell is only seen as an option for larger power applications(>100kW). The electrolyte conducts carbonate ions and these mediate the cell reaction. Carbon dioxide is produced at the anode of the cell while it is consumed at the cathode. Due to the high temperature process the exhaust steam can be recovered and transferred into electrical energy. The fuel cell has an electrical efficnecy of 65% and can reach an overall efficiency with waste heat recovery of 85% [144]. Another advantage of the fuel cell can be achieved by combining it with an internal combustion engine which produces CO_2. This due to the fact that the cathode of the FC consumes CO_2. On this way the FC acts as a CO_2 filter. This also means that if there is no CO_2 in the fuel, an external source has to supply CO_2 to the FC [185].

C

Technical feasibility, additional model results

Table C.1: Required energy[GJ] mono fuels, orange cells indicate higher required energy, grey: original

			100hr long cycle					Continuous long cycle				
			Propeller					Propeller				
Converter	Fuel	Configuration	Original	Type 1	Type 2	Type 3	Type 4	Original	Type 1	Type 2	Type 3	Type 4
ICE	MGO	D-D	800	648	554	648	554	1307	1049	892	1050	892
ICE	MGO	D-E	830	672	574	672	574	1357	1089	925	1089	925
ICE	HVO	D-E	865	700	598	700	598	1414	1134	964	1135	964
ICE	FAME	D-E	830	672	574	672	574	1357	1089	925	1089	925
ICE	Methanol	D-E	831	672	574	672	574	1367	1089	925	1089	925
PEMFC	Hyrdogen(l)	E	625	496	424	496	424	1019	804	683	804	683
Battery	NMC-Li	E	395	319	273	320	273	645	518	440	518	440

Table C.2: Required stored energy[GJ], hybrid configurations, orange cells indicate higher required energy

			100hr long cycle					Continuous long cycle				
			Propeller					Propeller				
Main energy carrier	Sec. energy carrier	Configuration	Original	Type 1	Type 2	Type 3	Type 4	Original	Type 1	Type 2	Type 3	Type 4
MGO	Hydrogen(l)	D-E	748	628	555	628	556	1224	1020	898	1020	898
MGO	NMC-Li	D-E	654	576	529	576	529	1069	937	858	937	858
Methanol	Hydrogen(l)	D-E	778	658	594	658	594	1273	1069	970	1069	970
Methanol	NMC-Li	D-E	713	635	588	635	588	1166	1034	955	1034	955

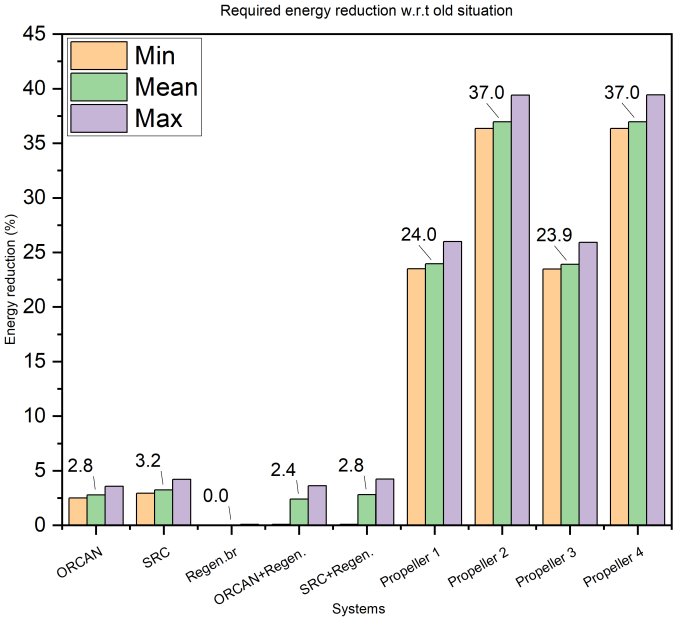


Figure C.1: Reduction required stored energy

Figure C.1 illustrates the reduction of required stored energy onboard a beam trawler for the proposed energy consumption reduction methods. For booth 100hr and continuous long cycle. The percentage mentioned is with respect to the original configuration mentioned in Table C.1.

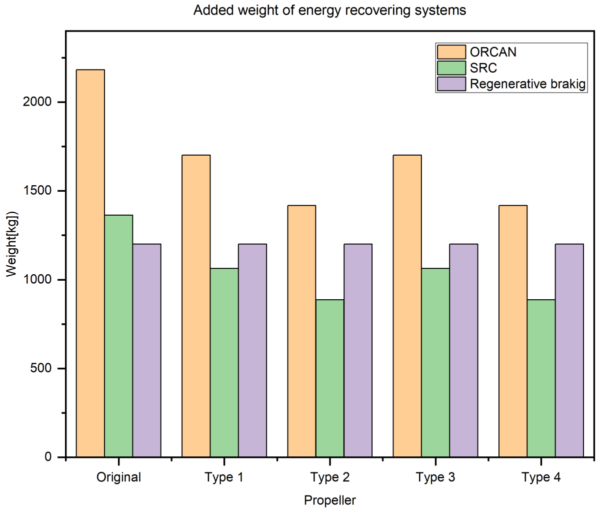


Figure C.2: Average added weight[kg] Orcan, SRC and Regenerative braking

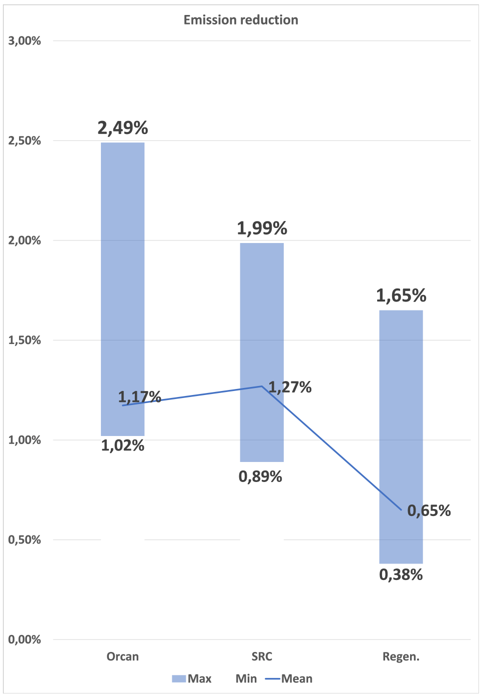


Figure C.3: Average CO_2 emission reduction[%] Orcan, SRC and Regenerative braking

In which the maximum is achieved with original propeller setup and the minimum with the type 2 and 4 propellers.

First of all it can clearly be seen in Figure C.2 and Figure C.3 that the application of SRC and Orcan result in significant reduction of operational expenses. Although the SRC results in the slightly higher energy recovery and therefore energy requirement reduction. This is counteracted in the total costs of ownership, due to the high capital investment of the SRC system. Despite the high fuel price scenario, the pay back period exceeds 20 years, this is not economically feasible. The Orcan shows pay back periods between 5 and 18 years, and is therefore found economically feasible if investment budget allows.

D

Scenario 1, additional results

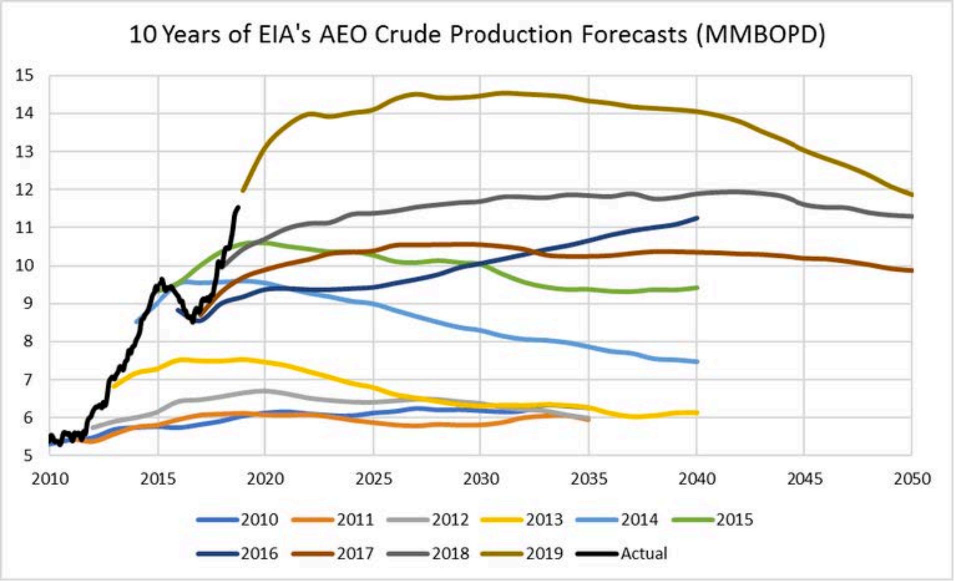


Figure D.1: Forecasted crude oil prices by EIA’s AEO versus actual prices, [163]

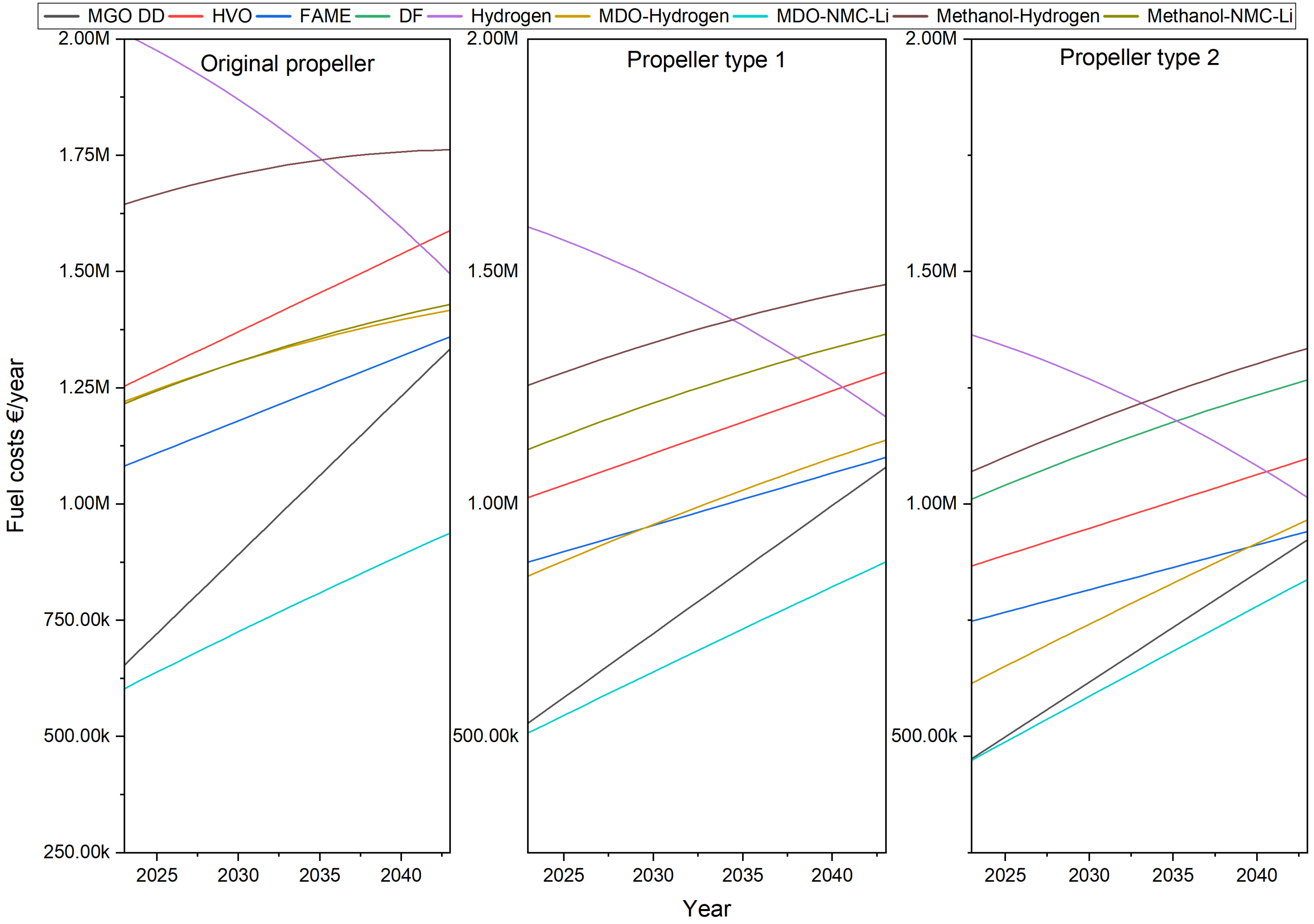


Figure D.2: Operational expenses, 100hr long cycle, High fuel price

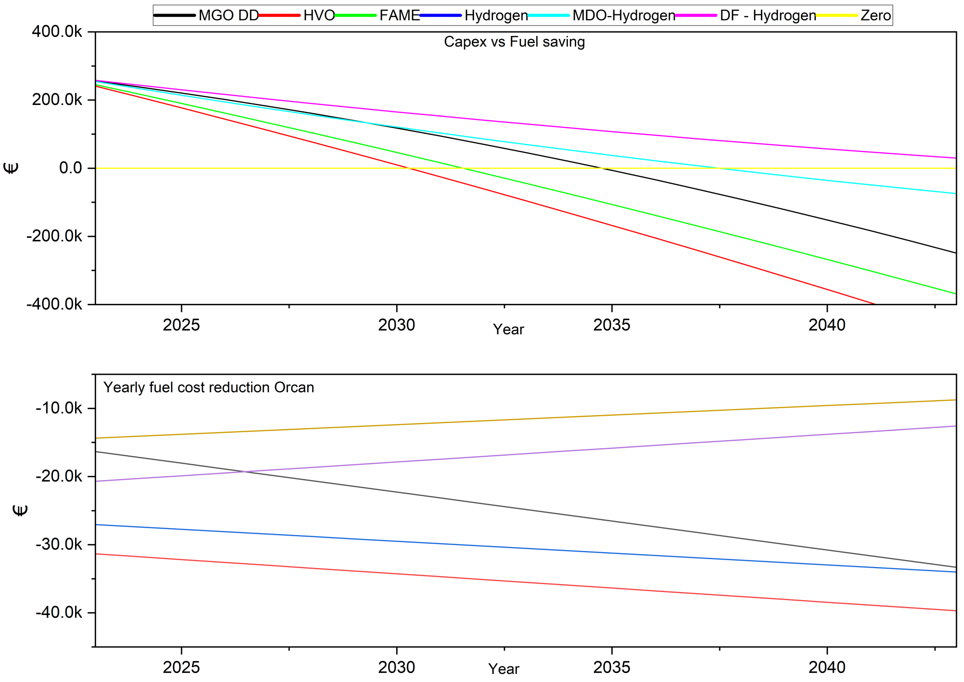


Figure D.3: High fuel price influence on ORCAN, 100hr long cycle

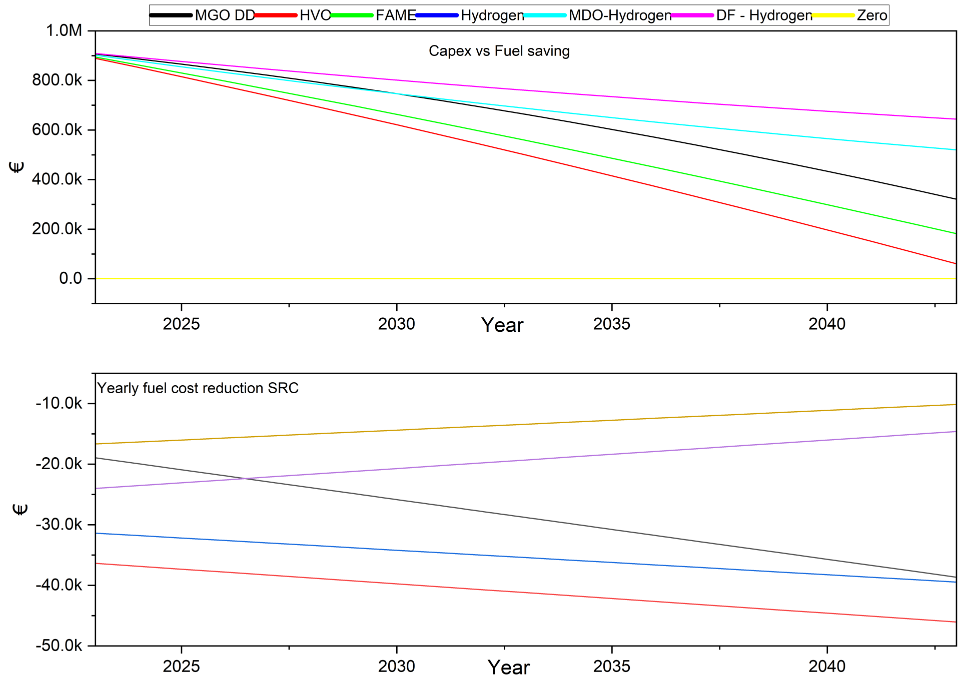


Figure D.4: High fuel price influence on SRC, 100hr long cycle

Scenario 1, High fuel price for Continuous long cycle

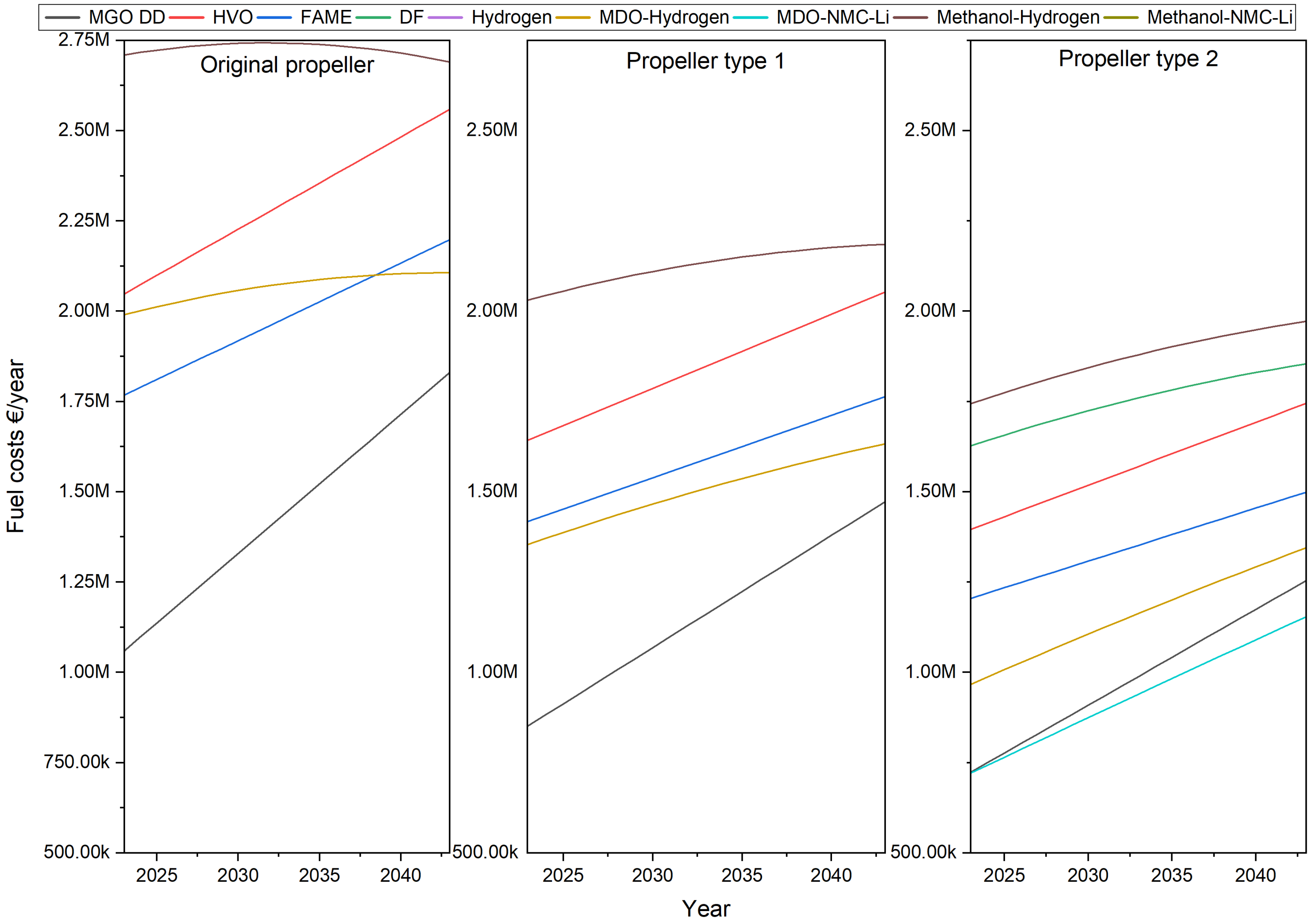


Figure D.5: Operational expenses, Continuous long cycle, High fuel price

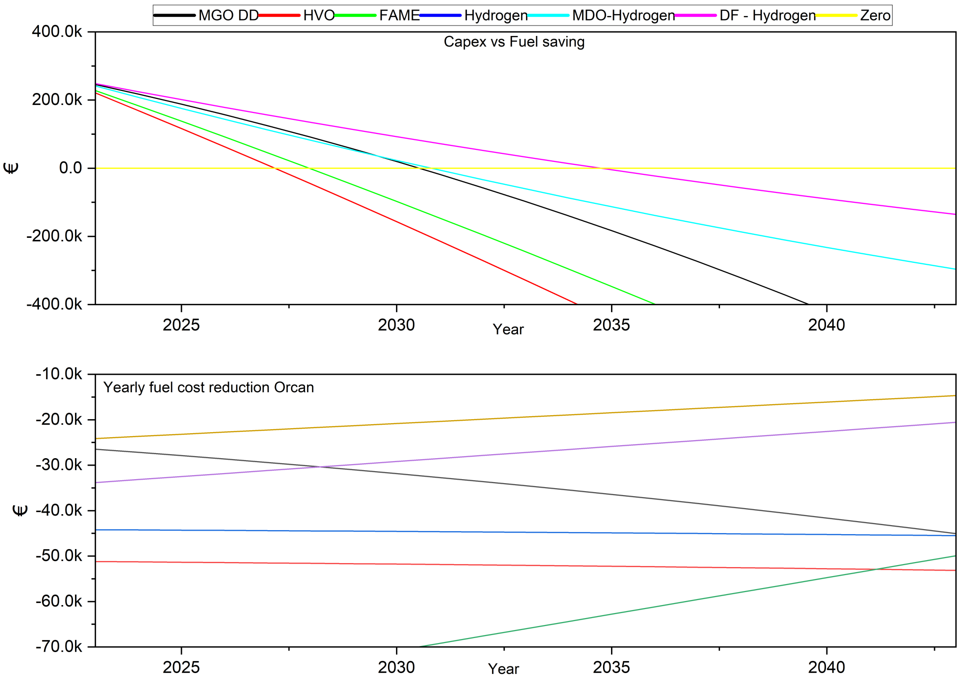


Figure D.6: High fuel price influence on ORCAN, Continuous long cycle

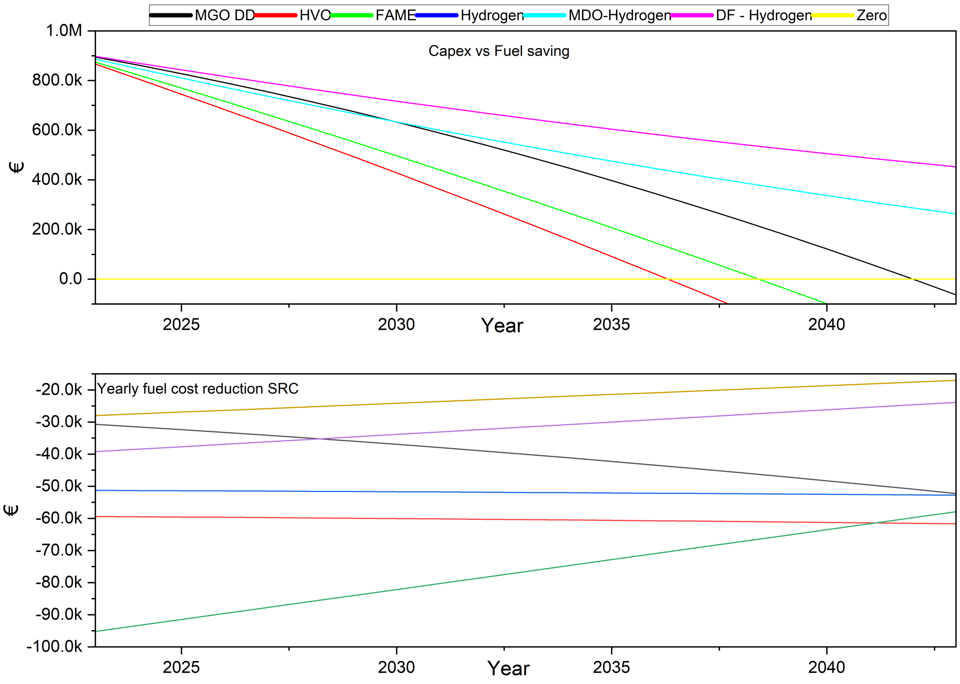


Figure D.7: High fuel price influence on SRC, Continuous long cycle

E

Scenario 2, additional results

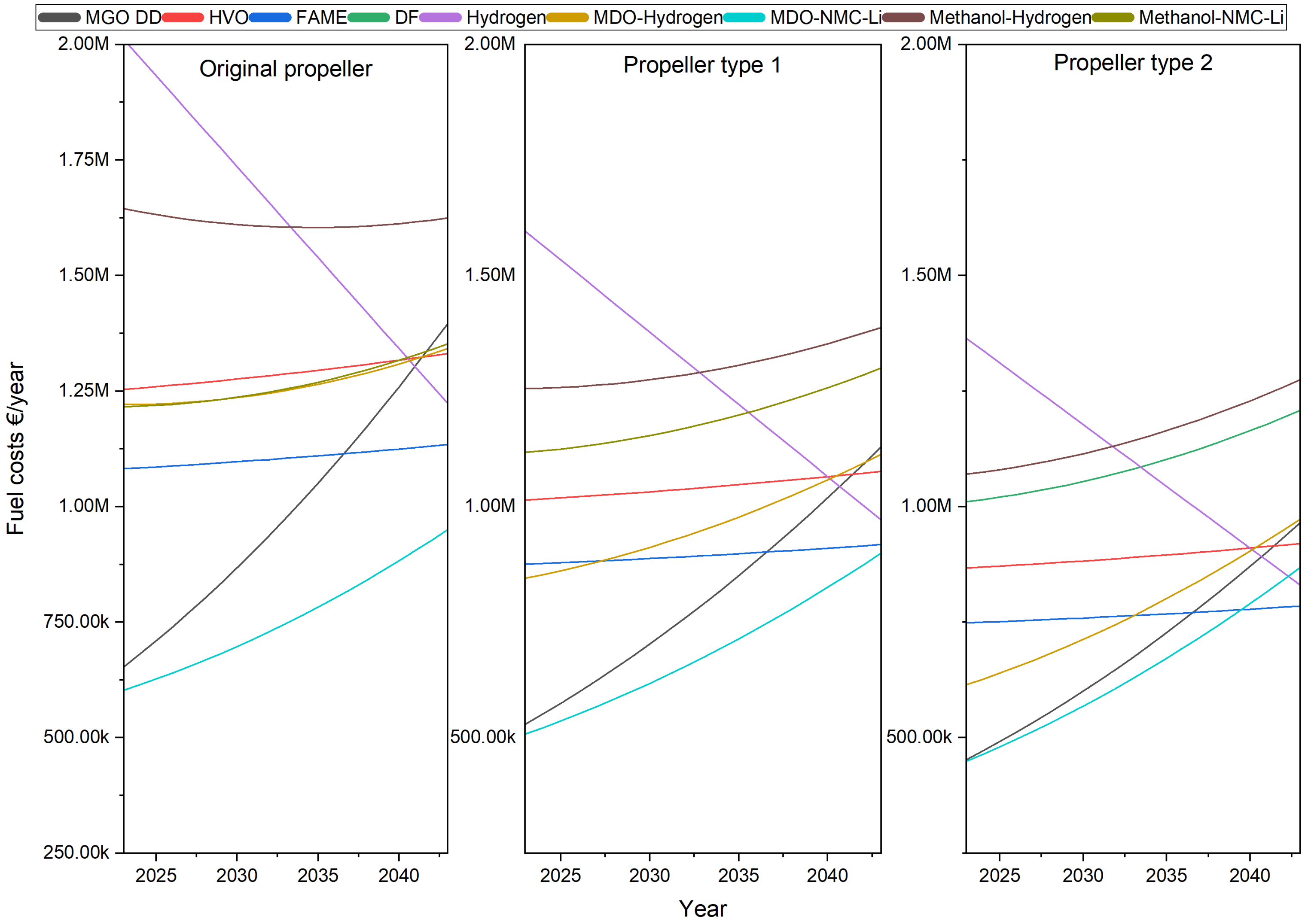


Figure E.1: Operational expenses, 100hr long cycle, high tax price

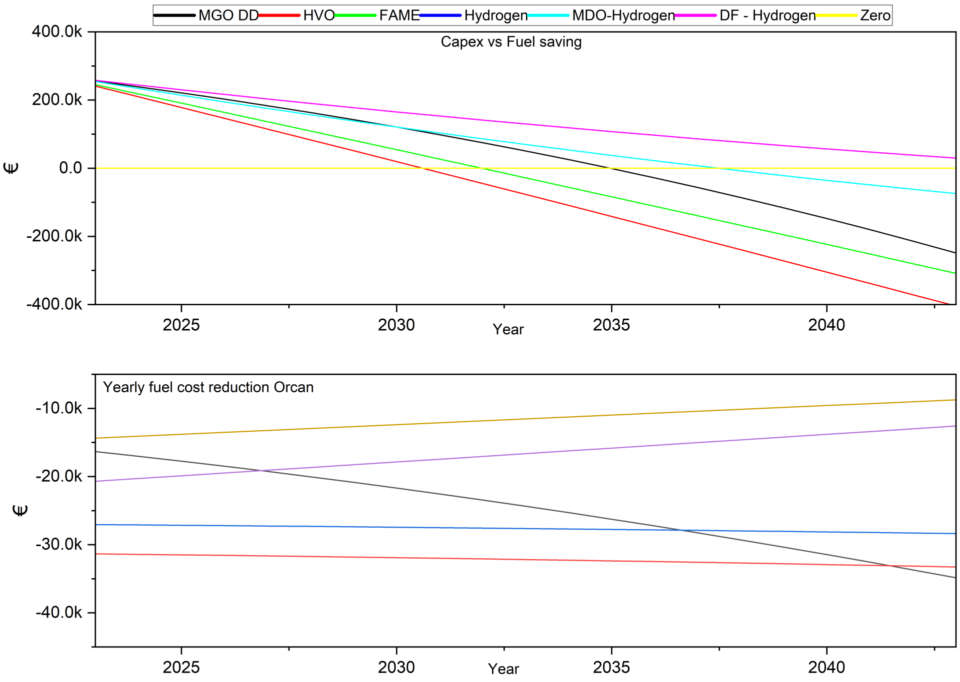


Figure E.2: High tax price influence on ORCAN, 100hr long cycle

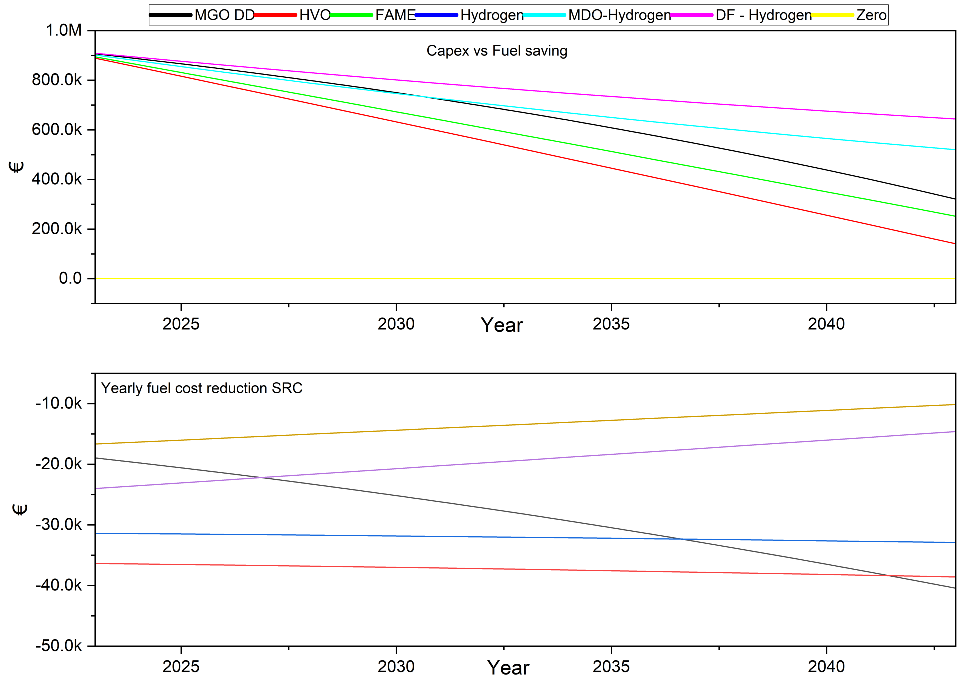


Figure E.3: High tax price influence on SRC, 100hr long cycle

Scenario 2, High tax price for Continuous long cycle

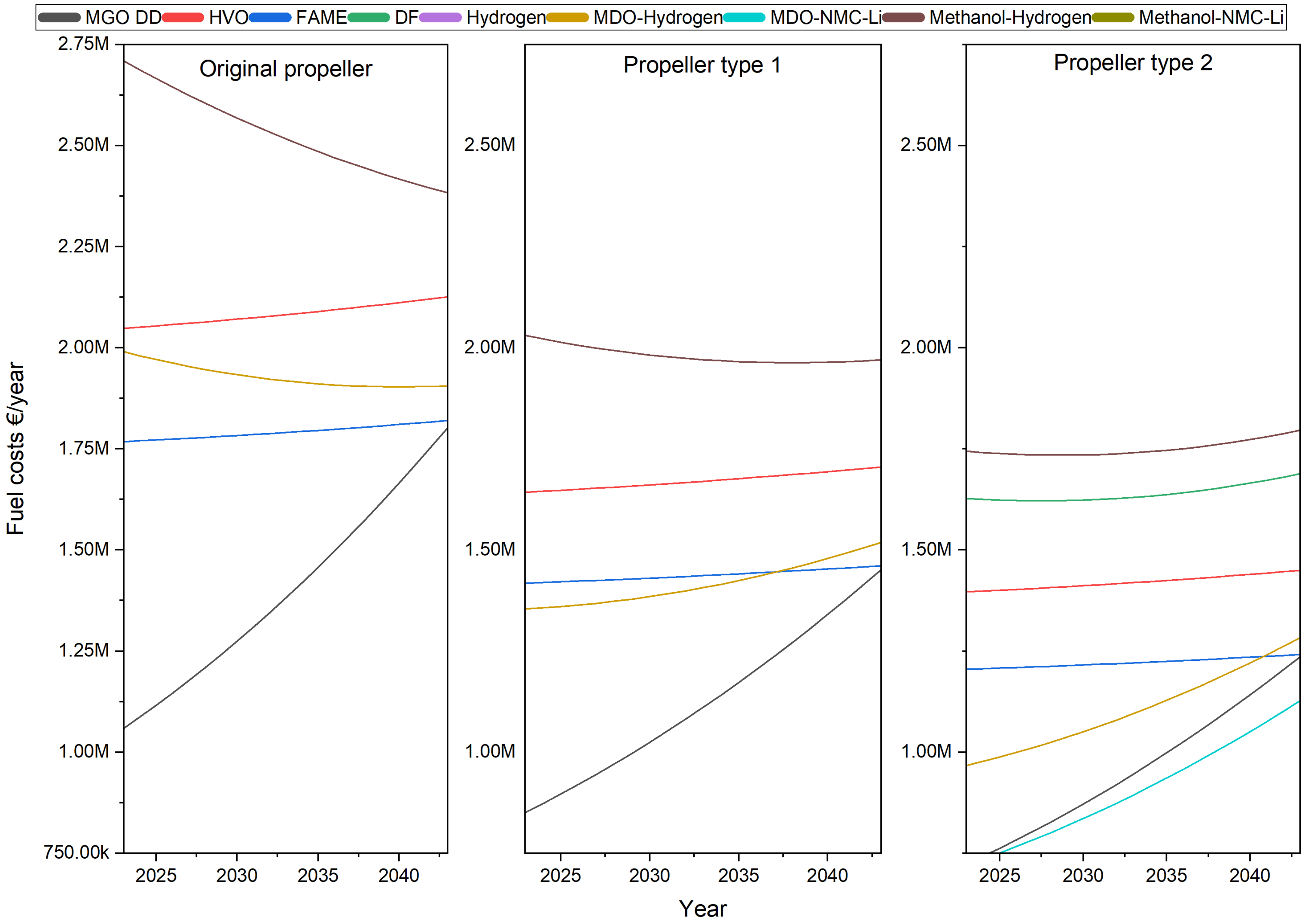


Figure E.4: Operational expenses, Continuous long cycle, high tax price

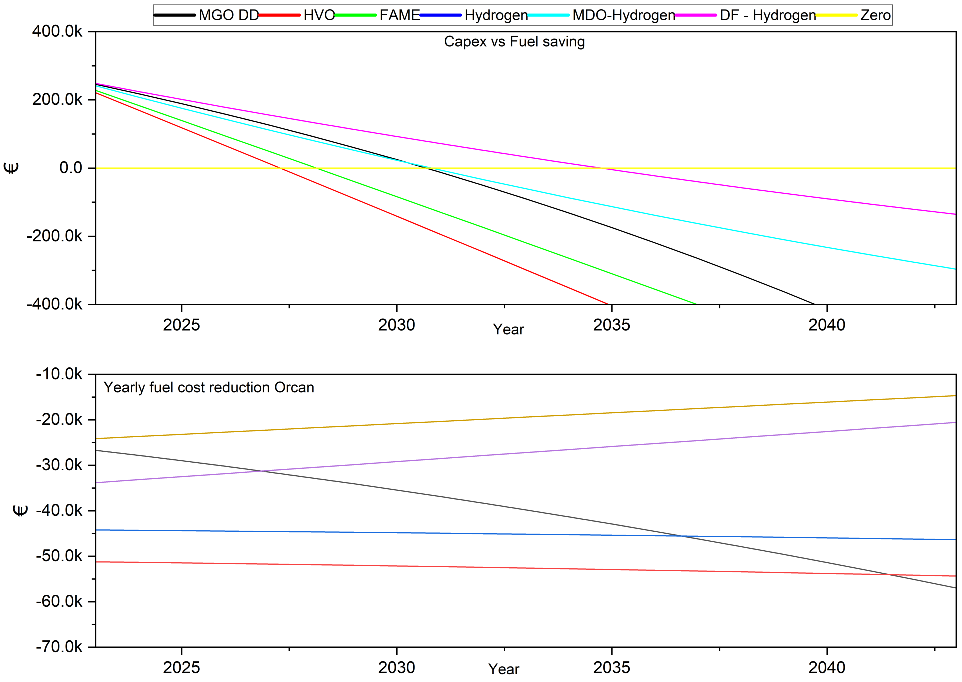


Figure E.5: High fuel price influence on ORCAN, Continuous long cycle

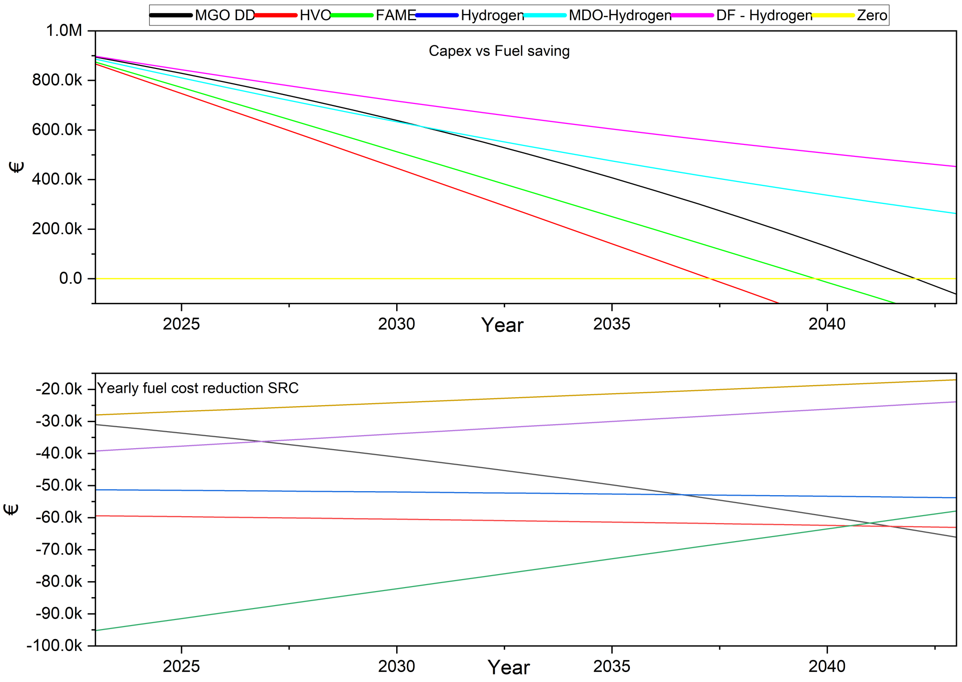


Figure E.6: High fuel price influence on SRC, Continuous long cycle

F

Concept drawings

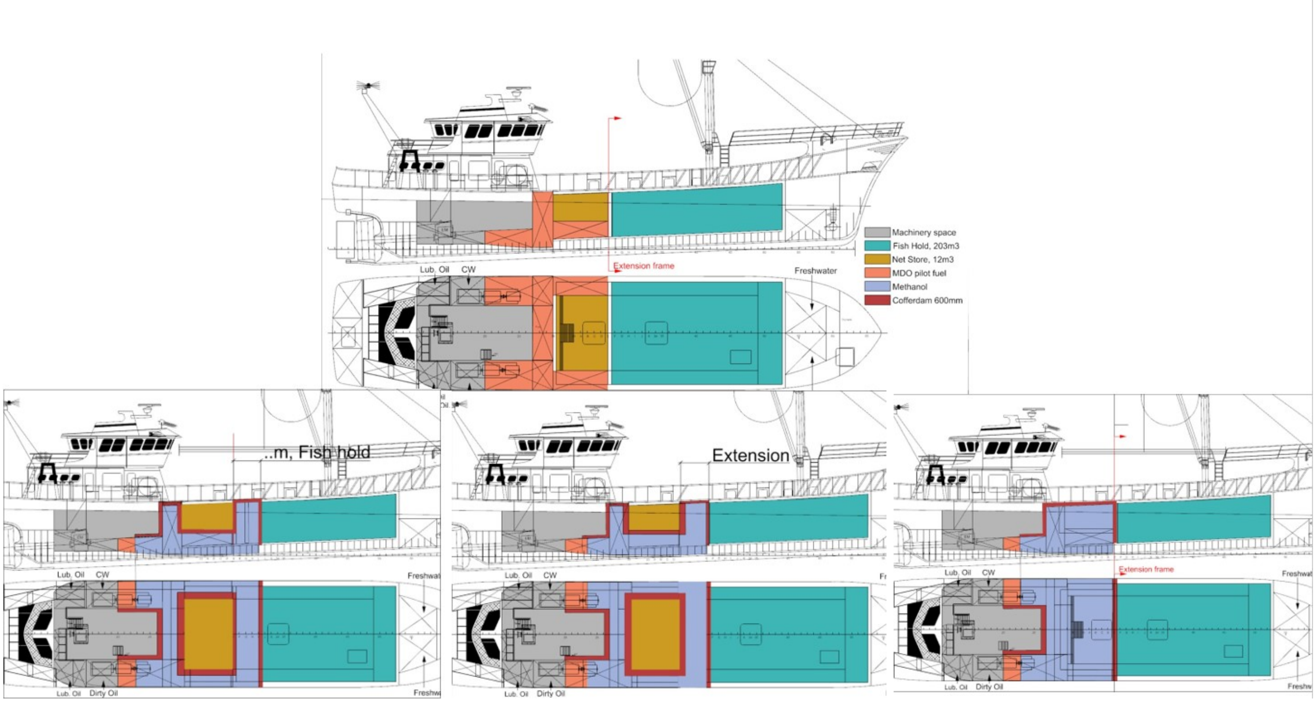


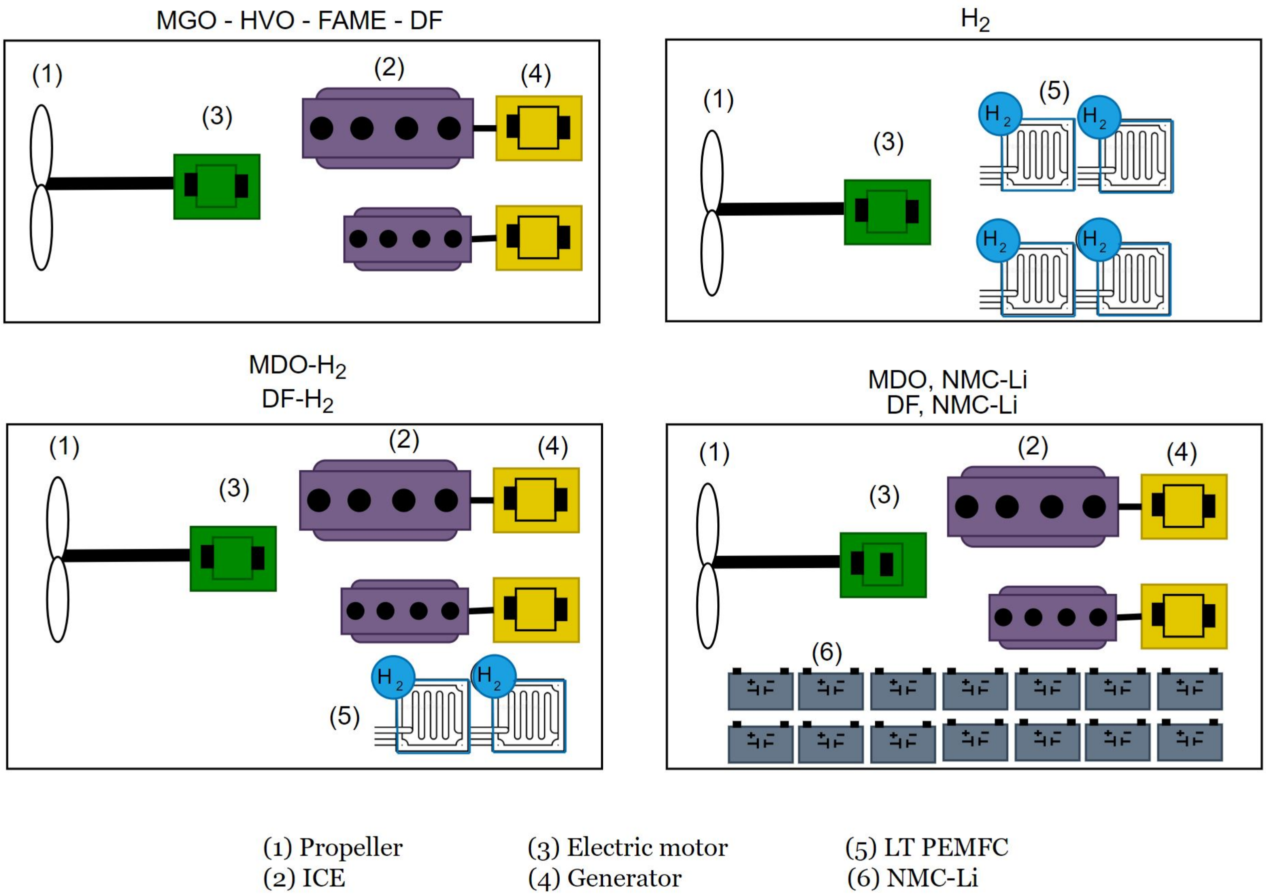
Figure F.1: Example, storage options for DF propulsion configuration[Padmos image]

Top: Original tank arrangement, including colour legend on the right.

Left: Using the original available storage volumes and the Fish hold for x meters to store the remainder of the fuel.

Middle: Using the original available storage volumes and extend the vessel with x meters to store the remainder of the fuel.

Right: Using the original available storage volume and the netstore. Extension with x meters is a secondary option if using the netstore is not sufficient.



MGO - HVO - FAME - DF

H_2

MDO-H_2
DF-H_2

MDO, NMC-Li
DF, NMC-Li

Figure F.2: Example, technical feasible configuration concepts

G

Scenario 3, additional results

Table G.1 illustrate that the use of the netstore generally does not prevent the vessel to be extended or fish hold to be used. If the use of the netstore can prevent hull extension, the numbers will change significant. Since the extension costs majorly are determined by labour, and this is hardly changing if the extension length is 0.6m or 0.9m. The last column illustrates how many more boxes the vessel can take if fuel is stores in the fish hold and the netstore together.

Table G.1: Relation between using netstore, capex reduction and potential lost capacity to store fish boxes

			Hull extension No netstore[m]	Hull extension Netstore used[m]	Capital cost reduction	Reduction in lost fish boxes
100hr	ICE	MGO DD	0	0	€ -	0
	ICE	HVO	0	0	€ -	0
	ICE	FAME	0	0	€ -	0
	ICE	DF	1	0.5	€ -36 000	170
	PEMFC	Hydrogen	3.1	2.5	€ -43 200	180
	MGO	Hydrogen(l)	0.9	0.4	€ -36 000	170
	MGO	NMC-lithium	2	1.6	€ -28 800	170
	Methanol	Hydrogen	1.2	0.7	€ -36 000	170
	Methanol	NMC-lithium	2.2	1.7	€ -36 000	170
Cont.	ICE	MGO DD	0	0	€ -	0
	ICE	HVO	0	0	€ -	0
	ICE	FAME	0	0	€ -	0
	ICE	DF	2.9	2.4	€ -36 000	170
	PEMFC	Hydrogen	n/a	n/a	n/a	n/a
	MGO	Hydrogen(l)	2.5	2	€ -36 000	170
	MGO	NMC-lithium	n/a	n/a	n/a	n/a
	Methanol	Hydrogen	3	2.5	€ -36 000	170
	Methanol	NMC-lithium	n/a	n/a	n/a	n/a