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NTNU
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Analysis of Strategies for GHG Emission Reduction in the LNG Shipping Industry

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Analysis of Strategies for GHG Emission Reduction in the LNG Shipping Industry

Cathrine Kabbe

Marine Systems Design
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Supervisor: Professor Stein Ove Erikstad
Co-supervisor: Hallvard Hersleth, Golar

Norwegian University of Science and Technology
Department of Marine Technology

Master Thesis in Marine Systems Design

Stud. techn. Cathrine Kabbe

"Analysis of Strategies for GHG Emission Reduction in the LNG Shipping Industry"

Spring 2020

Background

An increasing focus on climate change in the last couple of years has resulted in a desire and pressure to act more sustainability and in an environmentally friendly way. New regulations, requirements and pressure from the civil society, investors and customers make the shipping industry to focus on their environmental footprint. The ship owners have to systematically go through their operations in order to reduce their emissions and manage to communicate their work within this critical area. Regulations from policymakers as EU and IMO set specific requirements for ship owners to monitor, analyse and report vessel information data.

Golar owns and operates marine-based LNG midstream infrastructure and aims to develop world-class LNG infrastructure projects that will provide safe, competitive and sustainable ways of liquefying, transporting and turning gas into energy. They published their first ESG report in Q2 2020 and works systematically to improve vessel performance to reduce fuel consumption and emission.

Overall aim and focus

The aim is to develop an overall strategy to reduce GHG emissions cost-effectively for Golar. By analysing how different abatement actions and scenarios can influence the strategy in a long-term perspective.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Provide a state-of-the-art study of available strategies, measures and targets and the characteristics of these.*

2. *Formulate and discuss different goals for Golar to reduce their GHG emissions and comply with the regulations.*

3. *Describe the most promising characteristics found in (1) to develop a starting set to use in the decision model.*

4. *Develop a decision model to give an insight to the problem description. The deterministic optimisation model will be developed in Python and Gurobi.*

5. *Conduct a case study of different relevant scenarios based on the knowledge obtained from (1), (2) and (3).*

6. *Discuss the result and conclude by recommending an overall strategy for Golar.*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor. At Golar Management Hallvard Hersleth, Head of Maintenance and Performance, will be co-supervisor.

The work shall follow the guidelines given by NTNU for the MSc Master Thesis

Stein Ove Erikstad

Professor/Responsible Advisor

Summary

Marine transportation is a significant contributor to greenhouse gas (GHG) emissions. It is estimated that 80% of the volume of global trade is carried by sea. The International Maritime Organization (IMO) has developed an initial strategy to reduce GHG emissions from ships, aiming to reduce at least 50% of the total annual GHG emissions by 2050 (IMO MEPC 2018).

This thesis aims to develop an overall strategy to reduce GHG emissions cost-effectively for Golar. Golar owns and operates marine-based LNG midstream infrastructure. Golar has the last years worked to get an overview of their environmental impact. This work has led to their first Environmental, Social and Governance (ESG) report, published in the first half of 2020. Their LNG carriers emitted about 1 million metric tons CO_2 in 2019, and the majority of the CO_2-emissions are due to fuel consumption.

The thesis analyses how different abatement actions and scenarios can influence the strategy in a long-term perspective. The chosen approach is to make a decision model that structures the problem and gives a better understanding of the dynamics in a strategy like this. The thesis is limited to look at GHG and CO_2 emissions, due to already existing regulations for NO_x and SO_x. Further, are only Golar's sailing vessels, the LNG carriers, considered.

Three goal formulations, with different level of ambitions, have been developed. The lowest level equals today's requirement from the IMO. Further, will the medium level go beyond compliance with the requirements, and the highest level has even stricter requirements.

The decision model is a deterministic optimisation model where the objective function is to minimise the total costs for implementing a set of abatement actions. Time-periods and vessel groups are also sets in the optimisation model. The time perspective follows the same timeline as IMO's GHG study, where the time horizon is towards 2050. The period towards 2050 is divided into time-periods of five years, where period 0 equals 2025, period 1 is 2030 and up to period 5 which is 2050. The model uses three vessel groups to investigate how the selection of actions influence the vessel types. Three vessel groups based on engine type and age are used in the model. The first group is the vessels with a steam engine. These will be out of operation and the model in 2035, due to an assumption of a lifetime of 30 years. The dual-fuel diesel-electric (DFDE) vessel stays in operation throughout all of the periods. A third vessel group, newbuilds, replaces the steam vessels from 2035 and included in the operation from 2040. Alongside the sets, are the Golar's internal goals and requirements from the policymakers, the main parameters in the model.

A starting set was developed and contained the most promising abatement actions, associated reduction effects and a short description of each one. This set is the starting set used as input in the decision model. The opted actions used in this thesis are;

- Technical: air lubrication system, auxiliary systems, batteries (both full-electric and hybrid), hull design, propeller boss cap fin (PBCF), re-liquefaction system
- Operational: energy efficiency measures, hydrogen, LNG, speed reduction of 2 knots and voyage optimisation

Six scenarios with different requirements, goals, technology maturity and reduction effect were used in the case study. The results from the case study gave an objective value varying from 900 to 1300 million USD for the scenarios. Battery technology was the reference measure in the study. Battery hybrid, in combination with LNG or alternative fuels, were mostly selected. In the scenario where the battery technology has not matured for deep-sea shipping by 2050, was hydrogen as primary fuel selected. The case study revealed that a combination of technical and operational actions must be implemented to achieve the requirements from the policymakers and the internal goals. In the short-term perspective are hull coating, air lubrication systems, new auxiliary systems and speed reduction to recommend. These have a relatively low cost and the low to medium associated reduction effects are enough to achieve the short-term goals and regulations. However, to meet the long-term requirements did the results clearly show that new zero-emission technology and alternative fuels must get available.

One overall strategy and two alternative strategies, with different predictions for the future, are recommended to Golar. The main strategy has an overall cost of about 1000 million USD and follows a reduction plan with stricter regulations than IMO's strategy. The two alternative strategies have even stricter regulations. The first alternative has an optimistic approach regarding maturity in battery technology. The second alternative has a pessimistic path, assuming the battery technology would not mature at all. The shipowner should be willing to invest in technology and more expensive fuel alternatives. Such investment is partly related to a reduction of CO_2-emissions and partly of driving the development in the industry further. In combination with the predicted regulations and the importance of carbon-risk is it reasonable that all new vessels ordered from now should aim to have zero-emissions solutions. There are uncertainties of when the technologies are ready for deep-sea shipping. The shipowner can either take a chance of implementing the coming zero-emission technology now or wait and prepare for it and then do a smaller retrofit when the time is ready.

There are uncertainties regarding the cost and reduction effects in the input data for the different scenarios. Experience from the industry, literature review and predictions for the future is the basis of the input data. It is uncertainty about the future and therefore challenging to predict as the development of new technology happens fast. In order for the model and strategy to follow the development in the industry must the input data be updated when new information and knowledge about the cost and maturity of the new technology and alternative fuels are available.

Sammendrag

Marin transport er fortsatt en betydelig bidragsyter til klimagassutslipp på grunn av sin størrelse. Det anslås at 80% av volumet av global handel blir transportert på sjø. Den internasjonale sjøfartsorganisasjonen (IMO) har utviklet en innledende strategi for å redusere klimagassutslipp fra skip. Strategien tar sikte på å redusere minst 50% av de samlede årlige klimagassutslippene innen 2050(IMO MEPC 2018).

Denne oppgaven tar sikte på å utvikle en overordnet strategi for å redusere klimagassutslipp kostnadseffektivt for Golar. Golar eier og driver marinbasert LNG midtstrøms infrastruktur. Golar har de siste årene jobbet for å få oversikt over deres miljøpåvirkning i bransjen. Dette arbeidet har ført til deres første miljø-, sosial- og styringsrapport (ESG), publisert i første halvår av 2020. Deres LNG-carriere ga i 2019 ut rundt 1 million tonn CO_2, og flertallet av CO_2-utslippene skyldes drivstofforbruk.

Oppgaven analyserer hvordan forskjellige nedtrappingshandlinger og scenarier kan påvirke strategien i et langsiktig perspektiv. Den valgte tilnærmingen er å lage en beslutningsmodell som skal strukturere problemet og gi en bedre forståelse av dynamikken i en strategi som denne. Oppgaven er begrenset til å se på klimagass og CO_2-utslipp på grunn av noen forskrifter for NO_x og SO_x. Videre er det bare Golar's seilende skip, LNG-carriere som vurderes.

Tre målformuleringer, med forskjellig ambisjonsnivå, er utviklet. Det laveste nivået tilsvarer dagens krav fra IMO, mellomnivået går utover å overholde kravene, mens det høyeste nivået har enda strengere krav.

Beslutningsmodellen er en deterministisk optimeringsmodell der objektivfunksjonen er å minimere de totale kostnadene for å implementere et sett med reduksjonstiltak. Tidsperioder og fartøygrupper er også sett som påvirker optimeringsmodellen. Tidsperspektivet følger den samme tidslinjen som IMOs GHG-studie, der tidshorisonten er mot 2050. Perioden mot 2050 er delt inn i tidsperioder på fem år, der periode 0 tilsvarer 2025 og periode 6 er 2050. Modellen bruker tre fartøy grupper for å undersøke hvordan valg av tiltak påvirker fartøytypene. Tre fartøygrupper basert på motortype og alder brukes i modellen. Den første gruppen er skipene med en steam-motor. Disse vil være ute av drift og modellen i 2035, på grunn av en antagelse om en levetid på 30 år. Dieselmotoren med dual-dual diesel-electric (DFDE) holder seg i drift gjennom alle periodene. En tredje fartøygruppe, nybygg, erstatter skipene med steam-motor fra 2035 og inngår i operasjonen fra 2040.

Et startsett ble utviklet og inneholder de mest lovende reduseringstiltakene, med de tilhørende reduksjonseffektene og en kort beskrivelse av hvert tiltak. Dette settet blir brukt input i beslutningsmodellen. De valgte handlingene som brukes i denne oppgaven er;

- Tekniske: luftsmøringssystem, hjelpesystemer, batterier (både fullelektrisk og hybrid), skrogdesign, propell boss cap fin (PBCF), re-liquefaction system
- Operajonelle: energieffektiviseringstiltak, hydrogen, LNG, en hastighetsreduksjon på 2 knop og seilas optimalisering.

Seks scenarier med forskjellige krav, mål, teknologisk modenhet og reduksjonseffekt ble brukt i casestudien. Resultatene fra casestudien gav at målfunksjonen varierte fra 900 til 1300 millioner dollar for scenariene. Batteriteknologi var referansetiltaket i studien. Batterihybrid, i kombinasjon med LNG eller biodrivstoff, ble stort sett valgt. I scenariet hvor batteriteknologien ikke har modnet for havfart innen 2050, ble hydrogen valgt som primært drivstoff. Casestudien avdekket at en kombinasjon av tekniske og operasjonelle tiltak må iverksettes for å oppnå kravene fra beslutningstakerne og Golar's interne mål. På kort sikt er skrogbelegg, luftsmøringssystemer, nye hjelpesystemer og hastighetsreduksjon å anbefale. Disse har relativt lave kostnader og de lave til middels tilhørende reduksjonseffekter nok til å oppnå de kortsiktige målene og kravene. For å oppfylle de langsiktige målene viste imidlertid resultatene tydelig at ny nullutslippsteknologi og alternative drivstoff må bli tilgjengelig.

En overordnet strategi og to alternative strategier, med forskjellige spådommer for fremtiden, ble anbefalt til Golar. Den overordnede strategien har en samlet kostnad på rundt 1000 millioner dollar og følger en reduksjonsplan som er strengere enn IMOs strategi. De to alternative strategiene har enda strengere krav. Det første alternativet har en optimistisk tilnærming når det gjelder modenhet innen batteriteknologi. Det andre alternativet har en pessimistisk vei, da forutsatt at batteriteknologien ikke ville modnes. Rederen bør være villig til å investere i teknologi og dyrere drivstoffalternativer. Slike investeringer er relatert til en reduksjon av utslipp og en del av å drive utviklingen i industrien videre. I kombinasjon med forutsett regelverk og viktigheten av karbonrisiko er det rimelig at alle nye fartøyer bestilt fra nå, skal ha som mål å ha nullutslippsløsninger. Det er likevel store usikkerhet om når teknologiene er klare for havfart. Rederen kan enten ta en sjanse på å implementere den kommende nullutslippsteknologien allerede nå eller vente og forberede skipet på den og deretter gjøre en mindre ettermontering når tiden er klar.

Det er usikkerhet rundt kostnads- og reduksjonseffekter i inputdataene for de forskjellige scenariene. Erfaringer fra bransjen, litteraturgjennomgang og spådommer for fremtiden er grunnlaget for inputdataene. Det er usikkerhet om fremtiden og den er utfordrende å forutsi ettersom utviklingen av ny teknologi skjer raskt. For at modellen og strategien skal følge utviklingen i bransjen, må inngangsdataene oppdateres når ny informasjon og kunnskap om kostnadene og løpetiden for den nye teknologien og alternative drivstoff er tilgjengelig.

Preface

This master thesis is written at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU) in Trondheim during spring 2020. The thesis is the final part of obtaining a degree in *Master of Science* (Siv.Ing), specialising in in Marine Systems Design.

A specialisation project was written during fall 2019 and some parts have been used in this thesis. The background information and the parts about ESG (Environmental, Social and Governance) reporting are taken from the specialisation project.

The thesis has provided me with a lot of knowledge within the LNG shipping industry, and especially about the transition towards a greener industry which is a strong interest of mine. The future of the maritime industry is inspiring, many changes must occur in order to achieve the UN's Development Goals. The thesis has been written during COVID-19, and the process has, therefore been a bit more challenging than expected.

A special thanks to my supervisor Professor Stein Ove Erikstad, for excellent guidance throughout the process. I would also like to thank my co-supervisor from Golar Management Hallvard Hersleth for providing insightful information regarding their operations. I would also like to thank my family and friends for always supporting me both in good and tougher times.

Trondheim, 29th June 2020

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Abbreviations

BOG	=	Boil Off Gas
BAU	=	Business As Usual
CAPEX	=	Capital Expense
$CO_2 - e$	=	Carbon Dioxide Equivalents
CH_4	=	Methane
DFDE Engine	=	Dual-Fuel Diesel-Electric Engine
DWT	=	Deadweight Tonnage
EEDI	=	Energy Efficiency Design Index
EEOI	=	Energy Efficiency Operation Indicator
ESG Report	=	Environmental, Social and Governance Report
FLNGV	=	Floating Liquefied Vessel
FSRU	=	Floating Storage and Regasification Unit
ESCA	=	Emission Community Shipowners' Associations
ETS	=	Emission Trading Systems
EU	=	European Union
EU MRV	=	EU Monitoring Reporting Verification
GCU	=	Gas Combustion Unit
GHG	=	Greenhouse Gas
GRI	=	Global Reporting Initiative
GWP	=	Global Warming Potential
H_2	=	Hydrogen
HFO	=	Heavy Fuel Oil
IMO	=	International Maritime Organization
IMO DCS	=	IMO Data Collecting System
KPI	=	Key Performance Indicator
LBG	=	Liquid Biogas
LNG	=	Liquefied Natural Gas
LNGC	=	LNG Carrier
LSFO	=	Low Sulphur Fuel Oil
MBM	=	Market-Based Measures
MEPC	=	Marine Environment Protection Committee
MARPOL	=	International Convention for the Prevention of Pollution from Ships
MGO	=	Marine Gas Oil
NO_x	=	Oxides of Nitrogen
OPEX	=	Operational Expense

PBCF	=	propeller boss cap fin
PM_{10}	=	Particular Matter 10 Micrometers or Less in Diameter
SASB	=	Sustainability Accounting Standards Board
SEEMP	=	Ship Energy Efficiency Management Plan
SDG	=	Sustainability Development Goals
SO_x	=	Oxides of Sulfur

Chapter 1

Introduction

1.1 Motivation

An increasing focus on climate change in the last couple of years has resulted in a desire to act more sustainable. New regulations, requirements and demand from the civil society, investors and customers pressure the shipping industry to assess on their environmental footprint. The shipowners must systematically go through their operations in order to reduce their emissions and manage to communicate their work in this critical area. Regulations from policymakers as EU and IMO set specific requirements for shipowners to monitor, analyse and report vessel information data.

Baerekraft 100 is an annual report of Norway's 100 most prominent companies and their sustainability report (PwC 2019). The shipping industry came out as the worst of the industries disclosed, which shows the companies have not prioritised sustainability enough. Sustainability is rarely a part of the companies core strategy, and the effort to improve on this area has been rather low. With a transparent and correct approach, there are significant opportunities to take a leading position as a green and sustainable company. Implementation of abatement measures on the fleet is critical in order to reduce emissions. There exists much research on measures and strategies to use, however, it is challenging to manoeuvre in the sea of information and apply the ones that suit the company best. It is common to divide reduction measures into two categories, namely technical and operational measures. Typical technical measures include new technology, regulations, power and propulsion systems and hull design. Some of these apply for a retrofitted vessel, while others can only apply for newbuildings. Operational measures aim to reduce emissions during operations and applies both for existing and new built vessels.

In 2018 adopted the International Maritime Organization (IMO) under The International Convention for the Prevention of Pollution from Ships (MARPOL) an initial strategy to reduce greenhouse gas (GHG) emissions from ships. The strategy aims to reduce at least 50% of the total annual GHG emissions by 2050, which is equivalent to approximately 85% reduction of GHG per ship. The strategy will also pursue efforts to reduce the average carbon intensity (CO_2 per tonne-mile) by minimum 40% by 2030 and towards 70% by 2050 (IMO MEPC 2018). Efforts, regulations and action from the industry and policymakers like IMO have become a priority in the maritime transport towards a more sustainable industry. Also, to comply with the regulations, publishing sustainability reports and Environmental, Social and Governance (ESG) report are crucial if companies want to stay attractive to investors. In order to reach the reduction goals, involved parts in the shipping industry must be willing to change and take action.

In addition to the mandatory regulations from IMO and EU, are ESG guidelines a great tool to navigate which emission reduction measures to follow. Today's regulations are stricter for NO_x and SO_x emissions due to the human health and ecosystem. The CO_2 policies are motivated by reducing global warming and therefore, not prioritised equally. This lack of regulations, make ESG guidelines and standards as GRI and SASB necessary and makes it is easier for companies to reduce their GHG emissions.

If the world wants to meet the Paris Agreement must all industries contribute, including the shipping industry. It is a huge industry known for being conservative and slow. However, the transformation towards a greener shipping industry has started, and everyone has to contribute to reducing their emissions. Being green is important and can be crucial in order to be attractive and competitive in the future. IMO and the EU's ambitions are goal-based, and the operator has to make their plan to meet these reduction targets. There are numerous ways to cut the emissions for a shipowner. The challenge is to select the ones that fit with the company's core business and values, resulting in a long-term plan to prepare for future changes.

1.2 Objective

The aim is to develop an overall strategy to reduce GHG emissions cost-effectively for Golar. By analysing how different abatement actions and scenarios can influence the strategy in a long term perspective.

This thesis will investigate how the implementation of different abatement measures can influence the development of an overall strategy to reduce GHG emissions cost-effectively. There are many perspectives, approaches and dimensions about this problem and therefore hard to capture in a simple optimisation model. The chosen approach is to make a decision model that structures the problem and gives a better understanding of the dynamics in a strategy like this. The aim is to see how different scenarios can influence the strategy in a long term perspective. The scenarios are mainly dependent on the uncertainty and expectations of the future and the cost preferences of implementing such actions versus the gained reduction effects.

1.3 Limitations

The scope and objective of this thesis have following limitations:

- Will only consider LNG Carriers
- Focus on GHG emissions and mainly CO_2
- It is not a goal to build a decision model that gives one clear optimal result. It is a tool provided to get a better understanding of the problem and show how such a model can be used to make an overall strategy.
- The data used regarding cost and reduction effects are a mix of literature review, estimations and experience from the industry.

1.4 Structure of the Thesis

Figure 1.1 shows a visualisation of the thesis structure. The approach will be to look at the problem as a design problem. A strategy like this must be carefully tailored for Golar's resources and capabilities to have a full effect (Engert and Baumgartner 2016). The design process will follow a roadmap approach. Starting by designing goals, plot the pathway with abatement measures and actions to analyse interesting scenarios with a decision model.

The first part consists of background information about emission from shipping and then some information about Golar and what they do.

Chapter three presents a state-of-the-art study to get an overview of the different abatement actions and regulations that are available today and promising in the future. A SWOT-analysis summarises the study.

Chapter four presents the formulation of GHG reduction goals for Golar. The industry ambitions, along with a discussion of different types of goal formulations, is presented.

Chapter five presents a the most promising abatement actions and relevant regulations from the state-of-the-art study to be used in the decision model as a starting set.

Chapter six presents the developing of the decision model and the chosen approach to solve the problem.

Chapter seven presents the case study and results from the analysis of the different scenarios. The set of scenarios are dependent on expectations to the future and preferences regarding cost versus reduction effect and how they affect the optimal result.

The last two chapters are the discussion of the results with a recommendation to an overall strategy and conclusion and further work.

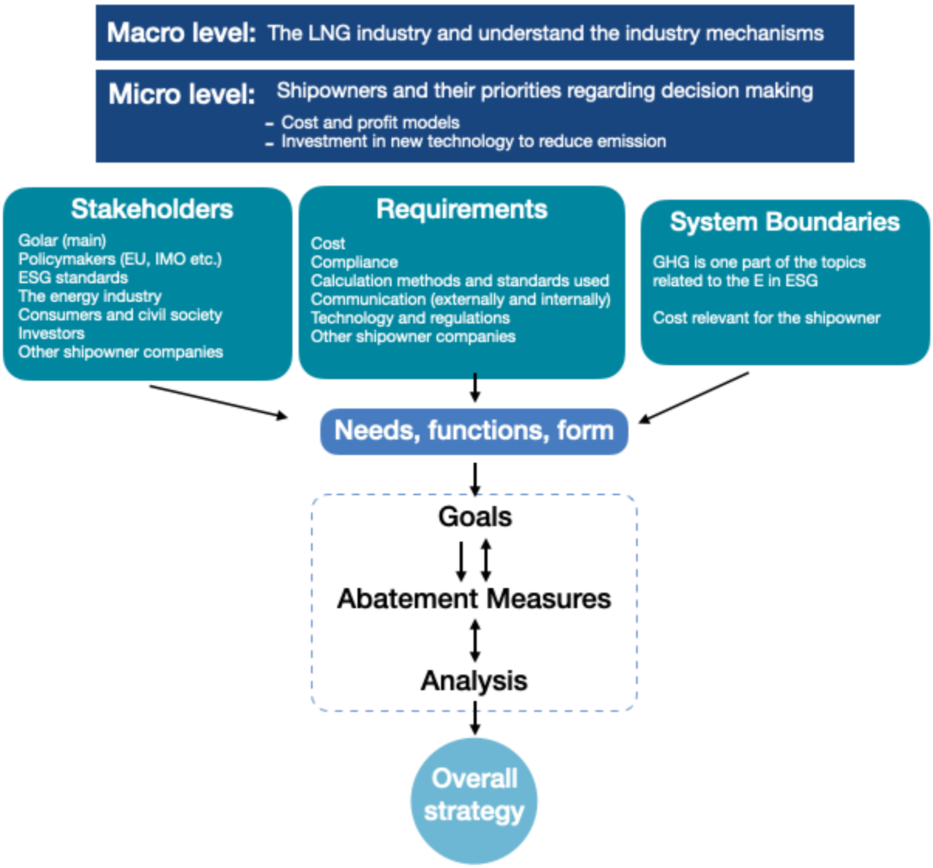


Figure 1.1: A process model of the thesis structure

Chapter 2

Background Information

The shipping industry is the most fuel-efficient in terms of fuel use per ton shipped, compared with other major transportation industries. Nevertheless, marine transportation is still a significant contributor to GHG emissions due to its size. It is estimated that 80% of the volume of global trade is carried by sea. In 2012 were emissions from international shipping (excluding military and fishing vessels) estimated to be 796 million tonnes (Mt) CO_2 and 816 Mt CO_2-e for GHG emissions, combining CO_2, CH_4 and N_2O (Smith et al. 2014). International shipping accounts for approximately 2.2% and 2.1% of the global CO_2 and GHG emissions on a CO_2 equivalent basis. Shipping also accounts for around 30% of total global NO_x emissions and 9% of SO_x emissions (Anderson et al. 2015). On the other side is it expected expansion in trade in the future because of the growing demand for merchandise and energy in developing countries, causing increasing environmental concern. Even though the global maritime trade expanded at a slower pace in 2018 than expected did the total volumes of trade still reach 11 billion tons (United Nations Conference on Trade and Development (UNCTAD) 2019). Figure 2.1 shows that CO_2 emissions are dependent on the ship size. The biggest greenhouse gas contributors within the maritime industry are CO_2, CH_4, N_2O (IPIECA 2016). These emissions are significant, where methane (CH_4) has a 28 times higher global warming potential (GWP) than CO_2 over a 100 years horizon (Anderson et al. 2015). GWP values are widely used as the default metrics to calculate CO_2-equivalents when calculation the consumption per transport work (Intergovernmental Panel on Climate Change (IPPC) 2014).

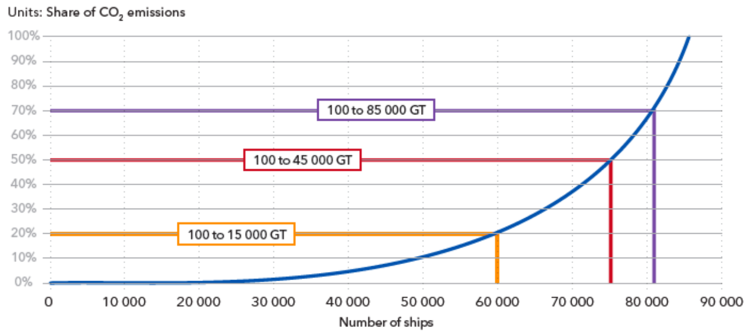


Figure 2.1: Accumulated CO_2 emissions from ships in 2018, analysed from observed AIS data for 86000 ships (DNV GL 2019a, p. 25)

In order to meet IMO's GHG ambition, does DNV GL (2019a) points out that new fuels and energy efficiency will play a vital role in the future. As seen in figure 2.2, is there a considerable gap to bridge in order to meet the goals. The Forecast has also introduced a CO_2 barometer for the world fleet. The barometer reflects the trend in the world fleet's CO_2-emissions, uptake of alternative fuels, development in technology and regulations must come in place to incentivise change. Even though ships have become more efficient the later years, shows the CO_2 barometer that the CO_2 emissions are still increasing. If the industry continues with business as usual, current policies and does not pick up the pace regarding transition to new technologes, alternative fuels and regulations, will the IMO's GHG strategy not be met.

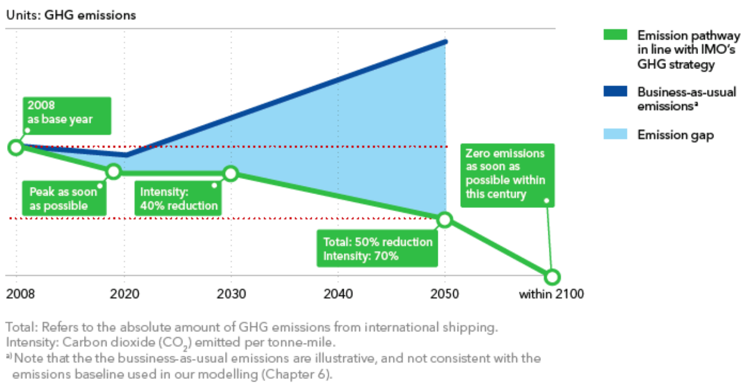


Figure 2.2: IMO strategy for major reductions in GHG emissions from shipping (DNV GL 2019a, p. 24)

2.1 Golar

Golar is a leading independent owner and operator of liquefied natural gas carriers(LNGC) and floating storage regasification units (FSRUs), and a pioneer developer of floating liquefied natural gas (FLNG) (Golar 2019). The LNG supply chain from grid to well can be seen in illustration 2.3 below, where Golar operates in all these segments. This thesis will concentrate its work within the shipping segment.

Figure 2.3: The LNG supply chain from grid to well (Golar 2019)

In 2019 consisted their operated fleet of 24 vessels; 17 LNG Carriers, six FSRUs and one FLNG vessel. The 17 LNG carriers can be divided into two groups based on the different engine types; dual-fuel-diesel-electric (DFDE) and steam turbines. Table 2.1 shows an overview of the vessels and their characteristics.

Table 2.1: Characteristics of the LNG carrier fleet

LNGC Fleet		
	Steam	DFDE
Number of vessels	6	11
Year build:		
2000	1	-
2003	2	-
2006	3	-
2013	-	2
2014	-	5
2015	-	4
Average cargo capacity (m^3)	140 000	160,000
Average Gross tonnage	98 000	102 000
Observed Distance in 2019 (nm)	350 000	850 000

Golar has the last years worked to get an overview of their environmental impact and to ensure that their emission calculations comply with all regulations and standards. This work has lead to their first ESG report, published in the first half of 2020. As a part of their ESG report, they have already done a considerable amount of work on the environmental, social and governance topics. They communicate that they want to take responsibility for their environmental footprint. They are using the SASB standard to present the workflow and calculations in a structured way in the ESG report. Air emissions and GHG emissions have the main focus in the environmental part of the report.

Golar is operating in the fossil fuel industry, and it is therefore essential to be transparent about the negative sides in the industry as well. However, natural gas is one of the cleaner fossil fuels and expected to have a critical role in the transition towards decarbonization. Positive roles LNG will play in the years to come is that it is applicable in both transport and power generation, and it is cheaper than alternatives.In according to the DNV GL (2019a), LNG is per today the only green fuel that is suited commercially and globally for deep-sea shipping. LNG is the most cost-efficient transition fuel available for consumption in large volumes. However, the bunkering infrastructure is still limited and must expand before LNG as ship fuel applicable for worldwide use. The price of LNG varies, and the market is yet not transparent. Even though LNG as fuel is not the best alternative, in the long run, is it the best we have now and necessary as a bridge fuel before the technology for carbon-free fuel are ready.

Looking at Golar's approach towards their ESG report, they have defined how they want their role in the industry to be in order to make an impact. Where the critical point is to minimise the environmental footprint within their operations. To achieve this they have identified five key areas; ”health, safety and security”, ”environmental impact”, ”energy efficiency and innovation”, people and community” and ”governance and business ethics”. From these areas, this thesis will have its focus on the ”Environmental impact” and ”Energy efficiency and innovation”. Golar has further identified six KPI's within the environmental area. These KPI's will be the base for the goals and different scenarios developed in this thesis.

- Air emissions: NO_x, SO_x and PM in *metric tonnes*
- Total energy consumption in *TJ*
- Gross global scope 1 in *tonnes* CO_2*-equivalents*
- Gross global scope 2 in *tonnes* CO_2*-equivalents*
- $\%$-energy consumed from HFO
- EEOI in CO_2 *emissions tonnes per* m^3 *nautical mile*

Note: Due to the limitation of GHG emissions is the first KPI, about air emission, outside of the scope.

Some of their current initiatives within the ”Environmental impact” are compliance with relevant regulations, monitoring and analysis fleet efficiency. The majority of Golar’s emissions are a result of fuel use. Their priority is to improve the efficiency of this by making smart decisions regarding the fuel mix and its volume. The vessels use LNG as their primary fuel. From the emission data in table 2.2, the HFO fuel consumption is only 14% of the fuel consumption for the entire LNGC fleet. Moreover, several initiatives to drive down fuel use even further, including a commitment to speed optimisation, engine loading, efficient voyage planning, and vessel trim monitoring, is introduced. As for the ”Energy efficiency and innovation” area, their program of converting old vessels to either FSRUs or FLNGs to extend their useful lives is excellent. Further, they are improving their energy efficiency by LNGC trim optimisation, using heat recovery steam generations (HRSGs) to recover heat waste energy from the liquefaction trains on the FLNGs. Lastly, they investigate the usage of hydro energy systems on their FSRUs to test in 2020.

The main costs for a shipowner company are the fixed costs as crew, fixed operations, service and maintenance on the vessels. The charterer pays the fuel costs. However, the fuel cost is essential when choosing, for instance, alternative fuels as an action to implement to reduce emissions. The charterer will pay as little as possible on this post.

2.2 Golar's Emission Data

Table 2.2 presents the metrics used to calculate the KPI's and the corresponding data from 2019. 2019 is chosen as the baseline year because the data collection to their energy/emission management had been more controlled and dedicated compared to earlier years.

Table 2.2: Emission calculations done by Golar for 2019 (Golar 2019)

	LNGC Fleet		
	Steam	DFDE	Total
Observed Distance (nm)	456,188	855,225	1,311,413
Fuel Cons, LNG (m^3)	281,492	325,735	607,228
Fuel Cons, HFO (MT)	29,062	38,411	67,472
Tot CO_2 Emission (Scope 1) (MT)	454,285	615,881	1,070,166
EEOI	-	-	11
Energy total (TJ)	8,423	11,323	19,746
Energy HFO (TJ)	1,215	1,606	2,820
Energy gas to GCU (TJ)	0	1,051	1,051
Energy LNG Total (TJ)			16,134
NO_x (MT)	1,106	4,987	6,094
SO_x (MT)	1,495	1,996	3,492
PM (MT)	245	333	578

The calculation methods that are used to get these values are based upon the SASB standards and IMO regulations and recommendations and are presented on Golar's sustainability page. This gives the reader full insight into the methodology, which is essential for the transparency of the data. A lot of the data are dependent on conversion factors, heating values, fuel quality, engine and manufacturing data and reported operational data.

The EEOI is defined as average CO_2 emissions per transport work and port operation and ballast voyages, as well as voyages which are not used for transport of cargo, such as voyage for docking service, are included within the calculation.

The result from the 2018 EU MRV reporting shows that the European shipping industry, including all ships sailing into, within and out of the EU, emitted 141 million tonnes of CO_2. Thus, the LNG sector contributed by 5.8 million tonnes emitted CO_2 (EU THETIS-MRV 2019). Transport and Environment has published a study on the EU shipping sector and its emissions. They have analysed 104 LNG Carriers and found that the average EEOI is 27.5 (Transport and Environment 2019, p. 15). The reliability of this value is debatable but can be used as benchmark. There are limited information or open data on this, except for the EU MRV. ”Maritime Forecast to 2050” from (DNV GL 2019a) estimated that the world fleet emitted a total of 870 million tonnes of CO_2 in 2018.

2.3 Preliminary Work

Some preliminary work has been done in order to decide the boundaries, defining the involved parts as stakeholders and the requirement for the process. The preliminary phase leads to a mapping of the needs, functions and forms, which will make the basis for the design phase. The macro perspective of this study is the LNG industry, which includes the understanding of the mechanisms in this industry and the role it has in sea transport. The most exciting part is the importance of LNG as a bridging fuel. The micro perspective is the understanding of the shipowners’ priorities regarding decision making, with a focus on sustainability and emission reduction. The companies’ cost and profit models drive the decisions and the focus on investments in new technology, and the cost regarding reducing their emissions.

Several stakeholders are identified. They can all influence the decision making in the process of designing the overall GHG reduction strategy. The primary stakeholder is Golar, but the stakeholders have different interests, and their role must also be considered in the decision-making process. The policymakers and investors have the most significant influence beside from Golar. Different stakeholders have different priorities, and may also have a different view/approach to risk as to the willingness to invest in new technologies and contribute to reducing barriers. The focus on the minimising cost can make conflicts for some stakeholders, while others may be more willing to invest in measures to reduce emissions. A decision tool can, therefore, be helpful to assist conflicts between stakeholders in a company. So the trade-offs and uncertainties can be more transparent for all parts. The system boundaries are limited to cost relevant for the shipowner, which means costs

paid by the cargo owner will not be considered in the decision making processes. The focus will be on GHG and more specifically CO_2 emissions, with limited to no focus on the air emissions. There are already quite strict mandatory regulations from IMO regarding air emissions. The GHG emissions do not have such precise regulation yet, but must nevertheless be reduced. It is also important to note that the GHG emissions are only one part of the topics related to the environmental aspect both in ESG reports and in sustainability reports. The regulations are essential requirements with high priority and must be followed.

Based on the work done in the project thesis, preliminary phase and brainstorming around the problem has a needs-functions-form table been developed- a part of an exercise in the early phase of the design process. The purpose is to get an overview of what the design problem requires. Tables 9.1 and 9.2 can be seen in appendix 9.1, which will along with the state-of-the-art, be the base for the process to build and develop the decision model.

Chapter 3

State-of-the-Art Study

There exist a lot of studies and research on emission reduction in the maritime industry. In addition to all this, emission controls, new technologies, stricter regulations and ESG standards are some of the subjects the shipowner has to take into account. This chapter aims to get an overview of state of the art to disclose the most promising abatement actions to implement.

Reduction measures and maritime emissions are commonly divided into two main categories; operational and technical (Psaraftis 2016; Lindstad et al. 2018). Operational measures include speed optimization, fleet management, weather routing and others that can impact the logistical operation. These measures aim at reducing emissions during operations both for existing and newbuild vessels. Technical measures are a broad category and are often divided into smaller sub-categories. These measures include energy-saving measures, cleaner and alternative fuels, more efficient ship hulls and designs, power and propulsion systems and compliance with EEDI. Some of the measures are considered for retrofitting, while others only can be applied through newbuildings (Psaraftis 2016; Lindstad et al. 2018). The following sections will describe some of these concepts.

3.1 Technical Measures

In this section, the technical measures will be reviewed. The focus is to find out the status of the measures when it comes to maturity, development, estimated cost and potenital reduction effect. Fuels and technologies used to reduce carbon emissions are identified as measures that will be game-changers towards decarbonisation (DNV GL 2020b, pp. 70–77).

3.1.1 Low Carbon Fuels

DNV GL (2020b) published in their *Technology Outlook 2030* that searching for alternative zero-emission fuels are necessary to cut CO_2 emissions. Especially because of the limitations of fully-electric solutions. Nevertheless, the uptake and use of such fuels are slow, and the availability and infrastructures are limited. Some of the fuels have a low energy density, safety issues and, most importantly, high CAPEX and OPEX. There are many uncertainties on the cost and availability of carbon-neutral fuels. Where properties as price, CO_2 emission factors and compatibility with different engines must be considered (DNV GL 2019a). Figure 3.1 shows the CO_2 emissions for the different fuels, where the GHG emissions are measured as CO_2-equivalents. Both fossil fuels and low carbon fuels are illustrated. The different and most applicable low carbon fuels will be further described in the following subsections. .

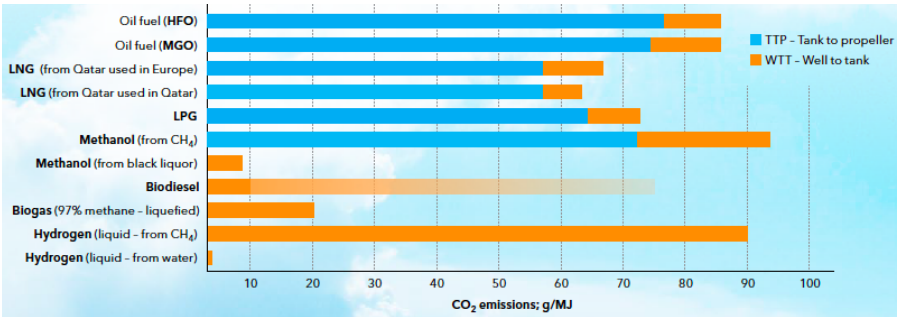


Figure 3.1: CO_2 emissions of fuel alternatives (DNV GL 2019b, p. 8)

LNG

DNV GL (2020b) in *Technology Outlook 2030* points out the urgent need to use fuels that can reduce the GHG footprint. LNG and LPG are the most cost-effective alternative today. They also reduce the emission of methane gas. In *Maritime Forecast to 2050* (DNV GL 2019a, p. 14) made an ”alternative fuel barrier dashboard”. It is an indication of the status of the different fuels where LNG is by now the most promising one. Technical maturity, fuel availability, rules, energy cost and volumetric energy density, are key barriers LNG has overcame. LNG is per today the only green fuel that is suited commercially and globally for deep-sea shipping and is now available in large volumes all over the world. The price of LNG fuel has reached a competitive feedstock price compared to alternative fuels. As for today, the price level is competitive with MGO but not directly with HFO. However, in 2020 HFO can not be used without a scrubber system. The price of new LSFO is expected to be higher than HFO. This makes LNG competitive with LSFO (DNV GL 2019b). LNG Carriers do already have the LNG on-board as cargo and are using the boil-off gas (BOG) and if needed, forced BOG, as fuel. When the ship is in ballast, it can use either the rest of the boil-off gas or some extra stored LNG as fuel instead of conventional fuel.

LNG is the fossil fuel that produces the lowest CO_2 emissions, with a reduction up to 20%. The realise of unburnt methane (CH_4) can reduce the benefit of GHG reduction from 25-15%, and reduces the benefit of using LNG as a bridging fuel over HFO and MGO (Lindstad 2013; DNV GL 2019b). CH_4 traps the heat 90 times more effective than CO_2, but this has a shorter life in the atmosphere (Hmiel et al. 2020). The CH_4 emissions might be reduced by using LNG as a fuel on high pressure two or four-stroke engines. Thus, the disadvantages will be more NO_x emissions which there already are strict regulations for (Lindstad 2013). In according to Gilbert et al. (2014) will there be no use for LNG in the longer term, due to the relative high CO_2 emission compared to zero-emission fuels, unless it is coupled with carbon capture storage (CSS). However, LNG is an essential transition fuel in the short term. If the industry is not capable of implementing such short term measures, can it be hard and even impossible to implement the longer-term measures.

Biofuel

There exists a large variety of processes to produce biofuels, involving different feedstocks and conversions. Biofuels are often a product derived from biomass or biomass residues converted into liquid or gaseous fuels. The most promising type for ships is biodiesel and liquid biogas (LBG), replacing MDO/MGO and fossil LNG respectively (DNV GL 2019b). Expansion of the use of marine biofuels requires the production to be based on lignocellulosic feedstocks (i.e. plant dry matter). That biodiesel and bioethanol can be made of lignocellulosic and waste makes it easier to make and may increase the availability for usage in shipping (DNV GL 2019a). Moreover, it is up to external drivers as the government's policies on waste management to decide the use of biowaste as any fuel (Gilbert et al. 2014).

Sustainable biofuels are flexible and can be fully substituting fossil fuel by either blending it with conventional fuels or using as drop-in fuels. Biofuels can be used directly in existing installations and engine systems with limited technical modifications and might be biofuel a good substitute for traditional fuel on the existing fleet (DNV GL 2019a). Biofuels have 25-80% CO_2 emission reduction potential if the biological origin of the fuel is carbon neutral. The CO_2 reduction potential has a wide range due to the life-cycle assessments for the various biofuels. The feedstock may differ in quality and type and is processed in different ways. For instance, has biofuel proceeded from palm oil a smaller reduction potential than from waste (DNV GL 2019b; Bouman et al. 2017). Hydrotreated vegetable oil (HVO) is currently available at commercial scale. By using waste oils and fats, very high GHG-reductions can be reached (DNV GL 2019a). Biofuels are one of the most promising technologies for delivering on the short-term cuts and will be mainly benefiting with slow steaming as an operational measure (Gilbert et al. 2014).

The price of biofuels is currently higher than for fossil alternatives. The market is still immature, poorly developed and the information about the prices are limited. Fortunately, is the market expected to grow, which leads to a significant potential for a reduction in price. The use of biofuels have to triple in order to meet the UN's Sustainability Goals for 2030. A falling cost and adaption by the shipping industry are drivers for this development. However, today's usage of biofuels in shipping is limited. (DNV GL 2019b).

Hydrogen and Ammonia

Hydrogen (H_2) produced from carbon-neutral energy resources by electrolysis of renewable energy or by reforming natural gas, is a promising fuel alternative. The emissions to air can be eliminated by using hydrogen in combination with fuel cells. Fuel cells are considered as the technology that needs to be in place to use the potential of H_2. Fuel cells in combination with batteries is a promising option in the future (DNV GL 2019a; DNV GL 2019b). The basic chemical reaction of H_2 is in a reaction with oxygen which results in energy and water. This gives no SO_x, NO_x or particles emissions as by-products and is, therefore, such a good alternative compared to traditional fuel. The energy used to make H_2 has to come from a renewable resource since the indirect CO_2 emissions must also be accounted for in the total emission calculation. To fully use hydrogen as fuel the ships must be designed so the H_2 can be stored and used safely (Gilbert et al. 2014; Lindstad 2013).

DNV GL (2020b) sees a minimal uptake of hydrogen before 2030, due to high costs and poor development. Zero-emission fuels as H_2 must play a vital role in the fuel-mix after 2030 for the industry to meet IMO's goals. The prices of H_2 is highly dependent on the sources of the energy used. For H_2 based on electrolysis, it is estimated that the cost will range between 1,170 to 2,770 USD per tonne of crude oil equivalent. While H_2 from reforming natural gas or biogas will vary from 800 to 2,170 USD per tonne of fuel oil equivalent. As a reference point is 70 USD per barrel of oil estimated to cost 510 USD per tonne of fuel oil equivalent (DNV GL 2019b).

Ammonia (NH_3) is pointed out as a highly potential fuel for the future for shipping, specially produced of H_2 from renewable resources. The price scenario for 2030 puts ammonia to vary (low to high range) between 1,800 to 2,300 USD per tonne of fuel oil equivalent. (DNV GL 2019b). The engines on today's market are not capable of burning ammonia. The bunkering infrastructure of ammonia is still poorly developed and seen as a barrier for its use as an alternative fuel (DNV GL 2019a).

3.1.2 New Technology

New technology consists of technologies and solutions applicable for both newbuildings and retrofitting, where the aim is to reduce CO_2-emissions and energy use.

Battery Technology

Today's battery technology has low energy density and therefore not good enough to store clean electricity form shore for pure electric operations on longer distances. It is successfully tested and implemented on ships operating on shorter distances that allow for frequent charging of the batteries. It is expected that fully battery-electric ships for trades over longer distances are applicable in the coming decade. However, these developments are quite slow and therefore not expected that battery power is a suitable solution for propulsion by 2045 for deep-sea shipping (DNV GL 2020b).

The emission potential by using batteries is enormous. Batteries have no emissions during operations. However, some parts of the life cycle are still not handled as good at it should. There are also several types of batteries, and especially the production and manufacturing process are energy-intensive. There have been several studies that have investigated the CO_2-equivalent emissions both for the battery itself and the system life cycle. Studies are done where batteries were compared with traditional drive configuration for the Norwegian NO_x Fund, on a hybrid platform supply vessel (PSV), and fully electric ferry gave overwhelming results. The environmental payback period for GWP on approximately 1.5 months for both vessel types when using the Norwegian electricity mix. By using the EU electricity mix the payback period for GWP was 2.5 month and under a year for the global energy mix (DNV GL 2019b).

Fuel Cells

Today's battery technology has low energy density and therefore not Fuel cells are available in small scale today. Where the lack of available suitable alternative fuels, hydrogen and methanol, is the critical factor for fuel cells to be adopted widely. (DNV GL 2019b). The main technical barriers for fuel cells are cost, vessel size, low power-to-weight ratio and efficiency at high loads (Gilbert et al. 2014).

A reduction of 30$\%$ CO_2 is possible when using hydrocarbon-based fuel due to the high efficiency of the fuel cell. There is expected a mass-production of fuel cells after 2022, which should make the production costs reach a competitive level. When the durability of the fuel cell reaches the same level as traditional combustion engines, and the primary fuels are competitive with MGO, will also the maintenance and operational costs be competitive (DNV GL 2019b). In a literature review done by DNV GL (2019a), it was found that the operation and maintenance costs were estimated to be two to eight times higher than for comparable diesel. The initial investment costs varied from 1,500 - 6000 USD/kW. The potential CO_2 reduction of using fuel cells can vary between 2-20$\%$ in according to a state-of-the-art study done by Bouman et al. (2017). Gilbert et al. (2014) points out 10-MW fuel cells as feasible by 2030 with appropriate infrastructure in place.

Power and Propulsion Systems

Power and propulsion systems is a big category. It includes the design of the power system and machinery, as more efficient propulsion and hybrid power solutions. The hybrid power solutions combine batteries with combustion engines to utilize the best of each technologies (Bouman et al. 2017). Promising technologies discussed in this category are counter-rotating propellers, propeller optimization to capture mote energy from the wake (Gilbert et al. 2014). Several trade-offs should be considered for engine designs features to achieve lower fuel consumption. A reduction in CO_2-emissions by reducing fuel consumption often conflict with the reduction of air emissions like NO_x, SO_x and PM which may be regulated (De Kat and Mouawad 2019).

In Bouman et al. (2017)'s state-of-the-art study the potential CO_2 reduction for different measures were identified from other studies. Hybrid power/propulsion has a potential of 2-45% reduction, while the power system/machinery has 1-35% reduction potential. The ranges are quite big due to its dependency on multiple factors.

3.1.3 Design

In Bouman et al. (2017), hull design is one of six mitigation groups identified as reduction measures with high mitigation potential. Aspects related to hull design can improve the hydrodynamic performance and minimise resistance, by hull dimensions and optimisation, shape and weight. Literature reviews identified that changing the vessel size has a CO_2 reduction potential of 4-83% and hull shape has a CO_2 reduction potential of 2-30%.

De Kat and Mouawad (2019) points out the importance of a vessel's anticipated operational profile when starting a new design project. The recent trends in slow steaming have led to new hull design that shows good results in waves and in varying loading conditions at a slower speed. De Kat and Mouawad (2019) summarise the owners choice when assessing hull optimisation in three groups. The first option is a standard package from the shipyard, which requires the least capital expense. The second option is to modify a well optimised hull form to fit with the expected operational profile. Lastly, is to develop new hull form.

3.2 Operational Measures

Operational measures aim to reduce emissions during operations on ship or fleet level. These measures can be implemented on all ship types, new-build and existing (Bouman et al. 2017).

3.2.1 Energy Efficiency Measures

Energy efficiency measures are installed to reduce the fuel and energy consumption onboard the vessel. The aim is to work towards a more optimal and conscious operation of ship systems. The measures may add an extra cost in training and motivating the crew, and to monitor the consumption. On the other hand, these actions may help to save energy, but it is not easy to assess the energy-saving potential (Buhaug et al. 2009). De Kat and Mouawad (2019) outline the importance of installing instrumentation to collect data onboard the vessel. So that the essential equipment and components to operate the vessel as efficient as possible in service. In order to evaluate the energy efficiency of the propulsion system, the fuel consumption and power, must the performance be tracked and logged.

The Energy Efficiency Operating Index (EEOI) is a voluntary monitoring tool that is provided in the Ship Energy Efficiency Management Plan (SEEMP) for companies to manage and operate the ship and fleet performance efficient over time (International Maritime Organization 2019a). The EEOI is a tool to improve voyage planning and manage performance by the measure fuel efficiency of the fleet. The index is defined as the ratio of the mass of CO_2 emitted per unit of transport work (IMO MEPC 2009).

3.2.2 Voyage Optimisation

Voyage optimisation consists of different operational measures to optimise the ship operation, constrained by logistics, scheduling, contracts and other constraints. The purpose is to find the optimum sailing route and speeds, sea conditions and deliveries according to contracts with the charterer. Weather routing, scheduling, ballast optimisation and trim optimisation are some of the typical issues. Voyage optimisation was identified to have a CO_2 reduction potential of 0.1-48% (Buhaug et al. 2009; Bouman et al. 2017).

3.2.3 Speed Optimisation

Eide et al. (2009) uses speed reduction as an operation measure. A common assumption is that fuel consumption of a vessel is proportional to the cube of the vessel speed. In reality, it varies with the individual ship design, and a vessel is often designed to operate at their hydrodynamic boundaries speeds. A reduction in speed within the boundary area gives the biggest reduction in fuel consumption and emissions (Bouman et al. 2017). By reducing the operational speed from, for example, 25 to 15 knots, total fuel consumption can be reduced by approximately 80%. In a short term perspective with high fuel prices, this is said to be the quick fix. However, it can also have positive long term impacts on the engine (Psaraftis 2016). The literature review done by Bouman et al. (2017), found that speed optimisation has a potential of CO_2 reduction from 1-60%. The cost of implementing this is often related to the lost transport capacity in terms of tonne-mile per day and then the ship's income. However, there is also the potential to save costs as a result of a reduction in fuel consumption (Buhaug et al. 2009; Eide et al. 2009). Speed reduction can apply for both new and existing ships. (Eide et al. 2013). In IMO's initial strategy is speed reduction, one of the key short-term measures (DNV GL 2020a).

Psaraftis (2019) identifies speed optimisation as an essential measure that because of the direct relationship between the economic and environmental criteria, and the relationship between a ship's CO_2 emissions and its speed. As an example, Psaraftis (2019) refers to a study done by Psaraftis and Kontovas (2009) that shows containerships are the top CO_2 emitters in the world fleet due to their relatively high design speeds (20-26 knots). Whether a ship can do slow steaming or not is depended on the trade pattern and charter contracts. Slow steaming also depends on the commercial aspects and market conditions of the destinations. Trades between Europe and Asia exemplify them. The cargo moves faster from Asia to Europe than in the opposite direction, due to a higher demand for Asian goods in Europe.

The imposition of speed limits is something that is highly discussed by countries and policymakers as (for many a controversial) measures to reduce GHG emissions. It was discussed at IMO/MEPC 72 and been included in the list of potential short-term measures toward IMO's 50% GHG reduction target. There are some difficulties regarding this measure. For instance, will a speed limit be superfluous when it is above the voluntarily chosen optimal speed. When the speed limit then is below the optimal speed, it will be challenging. This might influence and give distortions in the market, and costs may exceed the benefits of the speed reduction. The owners might get sanctioned twice by paying more for their cargo and longer transit times and consequently increased in-transit inventory costs (Psaraftis 2019). Psaraftis (2019) point out that speed reduction is not yet regulated. So for a shipowner will an economic viewpoint almost always get priority over the environmental benefits.

3.3 Regulations

According to Lindstad et al. (2018), have the policymakers have had a much bigger focus on making regulations for NO_x and SO_x-emissions. This is mainly due to the significant impact these emissions have on human health and eco-systems. The CO_2 related regulations are motivated by the need to reduce global warming, and thus takes longer time to implement. They have a lower priority as it does not affect humans and the local environment directly.

The two leading policymakers in the industry are the EU and IMO, while there are several ESG-standards to follow.

3.3.1 EU

ESCA (European Community Shipowners' Associations) (2020) points out the importance of EU taking the lead in the policymaking and regulatory processes for the international maritime sector. A clear, ambitious strategy must be provided to meet global reduction goals. This strategy, made by the EU, for a clean and competitive shipping industry, must involve all segments of the industry. As making EU in the lead in low- and zero-carbon technologies and fuels with a research and development funded by a CO_2- and fuel tax.

EU MRV

EU Monitoring, Reporting and Verification (MRV) of CO_2 emissions is a data collecting system that started 1 January 2018. EU MRV is a mandatory reporting system that is intended to be the first step in a process to collect and analyse emissions data. The system only focuses on CO_2 emissions from shipping within, into and out of the EU area. The EU Commission publishes the data and makes it available for everyone who wants to look. The regulation is only applicable for vessels transporting cargo or passengers for commercial purpose, which means that, e.g. offshore installation vessels and ice breakers do not need to report their activity. The vessels falling under the scope must report, on a per-voyage basis, parameters as; which port the vessel departures or/and arrives, including the date and time of departure or/and arrival. CO_2 emitted, distance travelled, time spent at sea and cargo carried must also be reported. Lastly, the amount and emissions factor for each type of fuel consumed in total and the transported work (distance travelled x cargo carried) shall be submitted. Also, the shipowner must monitor on an annual basis of aggregated data (DNV GL 2019d).

Emission Trading Systems (ETS) and Market-Based Measures (MBM)

The Emission Trading System (ETS) is an international fund based on the contribution from fuel consumption, among others as a part of market-based measures (MBM). MBM is an ongoing debate, where the EU is drivers to get this implemented. A highly discussed measure that is considered in the MBM is a CO_2-tax where the shipowner pays for the ship's CO_2-emission. EU MRV came into force in 2018 and seen as critical for the implementation of MBM in the future (Psaraftis and Woodall 2019). In an episode of Lloyd's List the Shipping Podcast (2020) about *Why the EU won't wait for IMO on climate change* member of the European Parliament(MEP) Jutta Paulus interviewed. She talks about the proposal from the European Commission that would forces all ships sailing inside, outside and within the EU to be a part of an emissions cap and trading system and contribute to a European maritime decarbonisation fund. They want to include the maritime industry in the already existing EU ETS. Either as a part of the existing program or as a separate one based on the MRV system. One of the suggestions is a CO_2-tax with a price of 25 EUR per tonnes CO_2 emitted. Paulus is also emphasises that actions must be taken now and the world cannot wait because policymakers have announced a fixed year for reconsidering e.g. a GHG reduction strategy.

The CO_2- and bunker tax are a hot topic with both supporters and opponents. The purpose of the proposal made by international associations is to make a maritime R&D fund. However, there are some structural challenges when establishing such taxes.

3.3.2 IMO

IMO's fourth GHG study will be published in 2020. The study includes an inventory of the current status in the industry, the global emissions and scenarios for future shipping emissions (United Nations Conference on Trade and Development (UNCTAD) 2019).

EEDI

IMO has adopted energy efficiency measures and established baselines for the amount of fuel different ship types can burn. According to International Maritime Organization (2019b), new vessels will be 30% more energy efficient by 2025 than those built-in 2014. Energy-efficient requirements were adopted in 2011 and entered into force in 2013. This regulation makes it mandatory to have an Energy Efficient Design Index (EEDI) for all new ships. It is an important technical measure which promotes the usage of more energy-efficient and less polluting engines, fuel and equipment (International Maritime Organization 2019a). EEDI is expressed as a ship's emitted grams of CO_2 per ship's capacity-mile. The smaller the value is, the more energy-efficient is the ship design. The calculation is done by a formula based on the technical design parameters for the given ship. In 2014 was the scope of EEDI extended to include LNG Carriers and ro-ro vessels as well. The index provides a specific figure for individual ship design and is expressed in grams of CO_2 per ship's capacity-mile.

These types of energy efficiency requirements will gradually become stricter. The only way to comply and fully meet the requirements will be through the improvement of design, power system and adopting low-carbon fuels (Bouman et al. 2017, p. 418). One of IMO's ambitions is to review EEDI with to make it stricter (DNV GL 2020a).

Lindstad et al. (2018) specifies problems related to policies as EEDI, which leads to unrealistic operative assumptions, a slowdown in new-building may result in older vessels being active longer and thus emits more. Speed limitations through power limitations make smaller vessels benefit from more generous EEDI limits.

IMO DCS

IMO Data Collecting System (DCS) on fuel consumption is a system where the data collection started 1 January 2019. All shipowners must collect the emissions data from fuel consumption. The scheme covers emission from shipping globally and is IMO's first step in a process to analyse emission data. The outcome of the scheme will be an annual report that IMO will produce and hand over to the Marine Environment Protection Committee (MEPC). It will be a report summarising the CO_2 emissions of aggregated fuel consumption from the worlds shipping fleet. The individual ship data will be kept confidential, thus only the aggregated fuel consumption will be disclosed (DNV GL 2019c).

The reporting is a requirement for all ships bigger or equal to 5000 gross tonnages (GT) trading globally. The first reporting must be submitted to an approved verifier by the end of March 2020. Each company has to deliver a monitoring plan where the collection and reporting method must be described in SEEMP Part II. This second part is an integrated part of the Ship Energy Efficiency Management Plan (SEEMP). Further, there are some details the reporting must contain. Firstly, abstract reports of all voyages must be logged, containing fuel consumption, distance travelled and hours underway used own propulsion. Secondly, the fuel balance reporting must contain the bunker delivery notes and the remaining-on-board fuel reports (DNV GL 2019c).

3.3.3 ESG Standards

To enlighten the environmental, social and governance (ESG) parts of the company is essential for companies due to the growing interest in green operations. The investors take the green economy and ESG issues into account when considering an investment. For a company operating in the fossil fuels industry, it is even more critical to demonstrate that they take the impact of climate changes and other parts of the ESG topics seriously. The ESG report shall communicate the company's strong ESG message with a precise alignment from the report to their strategy. A successful ESG strategy focuses on key issues and does often result in greater transparency on how these issues are managed and the quantitative metrics behind the performance (FrameworkESG 2019). There are a considerable amount of different standards, requirements and frameworks the company can use. It can be a time consuming and challenging process to choose the ones that fit with the organisational structure and strategies. The most accepted standards are; The Global Reporting Initiative (GRI), the International Integrated Reporting Council (IIRC), the Sustainability

Accounting Standards Board (SASB), the UN Global Compact, the CDP (formerly the Carbon Disclosure Project) (London Stock Exchange Group 2018). The GRI standards do not propose a calculation method or suggest specific formulas for the different KPIs. The company must find a proper calculation method, suitable assumptions and standards that have been used in order to calculate the emissions. The standard focuses on what the different sections should include. So each company must choose which ones to implement in their report based on what fits best with their strategies and goals (Global Reporting Initiative 2016). The GRI refer to some sources where calculation methods can be found and for what type of metrics the disclosure can include. On the other hand, suggests the SASB framework formulas, or refer to other regulations that can be used in order to calculate the emission (Sustainability Accoiunting Standards Board 2018).

Strategies regarding the company's GHG emissions recur in almost all regulations, standards and requirements. This topic has several accounting metrics and categories. However, those are related to the consumption of fuel and energy used in the whole value chain. The consumption is divided into three scopes, where scope 1 and 2 are carefully defined in order to avoid double counting. For the sustainability report and ESG related topics, is it also beneficial to discuss long- and short-term strategies on how to manage the emissions and emission reduction targets.

The Norwegian Shipowner Association recommends outlining clear ESG targets and the planned performance over a 3-5 years horizon. As a minimum, they recommend following accounting metrics: Global gross scope 1 and 2, GHG emission intensity, EEOI, GHG emission management, climate risk reporting and energy mix (Norwegian Shipowners' Association 2020). Gross global scope 1 (scope 1) covers direct emissions coming from sources the company owns or control. This means all on-site fossil fuel combustion from owned or controlled boilers or process equipment. Gross global scope 2 (scope 2) covers all indirect emissions from the energy that the company has purchased. Which include emissions resulting from e.g. heat and electricity (World Resources Institute (WRI) et al. 2004). The total amount of energy consumed is another metric. This covers energy consumption from all sources, including energy purchased from external sources and produced by the company. For example, direct fuel usage purchased electricity and heating/-cooling. This looks like a merged metric of scope 1 and scope 2 emissions (Sustainability Accoiunting Standards Board 2018).

3.3.4 Future regulations

IMO is currently focusing on finalizing short-term measures and making proposals for medium-term measures. The short-term approaches are expected to enter into force by the end of 2022. One technical, EEDI for existing ships (EEXI), and one operational measure, an enhanced SEEMP, was introduced. Other issues for medium-term are an International Maritime Research and Development Board (IMRB), GHG and carbon factors for fuels, methane emissions and EEDI Phase 4 entering into force after 2023. The most important element from the enhanced SEEMP is the mandatory documentation of a carbon intensity indicator (CII): a ships CO_2 emissions per transport work. The shipowner has to prove that it was reduced by at least 40% in 2030 compared to a comparable ship in 2008. As for today, it is not any clear description of consequences or sanctions if the CII is not met (DNV GL 2020a).

EU published the *European Green Deal* in December 2019, where the level of ambitions is high and aims for a climate-neutral Europe, including shipping, by 2050 (Commission 2019).

Energy Efficiency Existing Ship Index (EEXI)

The technical measure Energy Efficiency Existing Ship Index (EEXI) is a mandatory design improvement applicable for all ships. The EEXI is an enhancement of the EEDI which was only mandatory for new ships. With the EEXI, each ship has to improve its energy efficiency performance to a required EEXI level. It is a goal-based measure where the operators decide how to achieve the target. An option for design improvement is to use shaft/engine power limit where the ship reduces its speed and operates at a design speed limit. Another option is to change fuel or energy-saving devices or third, replace the existing ship with a new one. The calculation method of the EEXI is a simplified EEDI methodology, where the required EEXI for an LNG Carrier is a change of 30%, a reduction from the EEDI reference line. The EEXI will be applicable from the first annual or first renewal survey after entry into force. Due to the COVID-19 situation has the finalizing of this measure been put on hold (DNV GL 2020a).

3.4 Summary of State-of-the-Art Study

The shipping industry is known for being a conservative and slow industry where the willingness to change is low, and transitions to new technologies can take time. The quantification regarding CO_2 reduction and associated costs are hard to find. Most of the available data used in recent studies are based on the data from the *Second IMO GHG Study* (Buhaug et al. 2009) studies done by Lindstad (Lindstad et al. 2012; Lindstad 2013; Lindstad et al. 2018).

DNV GL (2020b) expect solid investments in alternative fuel technology in the near future. Together with changes in regulations from the policymakers, will help reduce barriers. Alternative fuels, in combination with energy efficiency measures, may lead to a reduction of GHG around 30% by 2030. A switch to low carbon fuels reacquires a clear strategy that considers how this transition can be cost-effective. Ideally, would this involve that technology as energy storage and conversion systems are flexible and accommodate both renewable and fossil fuels and minimise the degree of retrofitting.

3.4.1 SWOT - Analysis

Figure 3.2 presents the SWOT analysis that summarises the state-of-the-art chapter. The point of view is from the shipping industry, with the focus on the reduction of emissions.

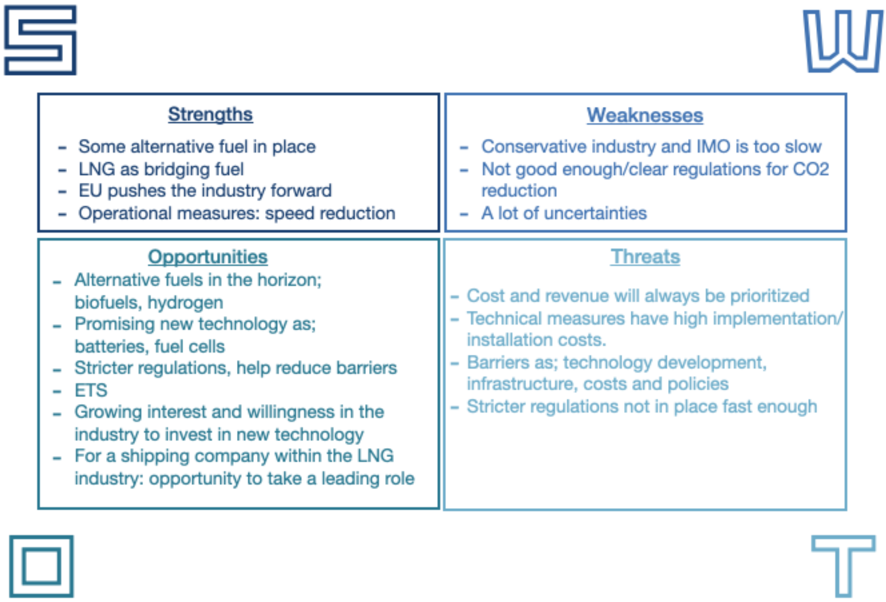


Figure 3.2: SWOT-analysis for a greener shipping industry

Chapter 4

GHG Reduction Goals

This chapter presents the process of designing emission reduction goals. It is challenging to decide and design goals without having any idea of the cost of implementing the measures needed to fulfil the goals. Several factors influence the process of designing goals. Firstly, the goals should be achievable but at the same time ambitious enough. External and internal stakeholders must be satisfied, from both an economical and environmental perspective.

Golar has sustainability as one of their main priorities. It is important for Golar to show that they want to make a difference and is committed to minimising their environmental impact. A summary of their focus areas and current initiatives can be seen in figure 4.1. The emission data from chapter 2.2, shows that Golar's total CO_2 emissions in metric tonnes are only 0.8 % of the total CO_2 emitted in the EU in 2018 and 18.5 % of the LNG industry in the EU. Note that not all of Golar's vessels operated within the EU and did not contribute equally due to different operational patterns. Can therefore assume that Golar did not contribute that much to the total LNG industry in EU. A comparison with the world fleet shows that Golar only contributed to 0.1 % of the CO_2 emissions. Golar's emission data is from 2019, while the data from the EU MRV from the 2018 data. Even though the data are from different years, gives it an insight into Golar's emissions compared to the industry.

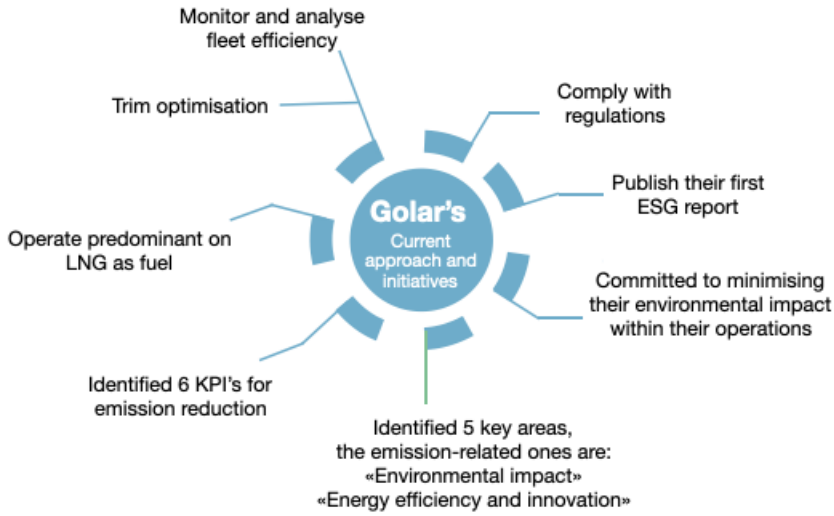


Figure 4.1: Summary of Golar's current approaches and initiatives

4.1 Industry Ambitions

The industry must act upon the Paris Agreement, an agreement signed by all parties in the United Nations Framework Convention on Climate Change (UNFCCC). They decided to reduce the GHG emissions and limit global warming below 2 °C below pre-industrial levels and limit the temperature increase towards 1.5 °C (UNFCCC 2015). Based on this IMO adopted the GHG reduction strategy in April 2018, reduce GHG emissions from ships. This strategy aims to reduce at least (compared to 2008) (IMO MEPC 2018). These goals apply to the entire world fleet, and the individual shipowner is free to interpret them. The tools given from IMO are goal-based and it is up to each operator to decide how to achieve the targets. The targets are as follows:

- 50% of the total annual GHG emissions by 2050. This requires approximately a 85% reduction of CO_2 emissions per vessel.
- 40% of the average carbon intensity (CO_2 per tonne-mile) by 2030 and towards 70% by 2050.

In December 2019, the EU released a strategy called the "European Green Deal" for the Union and its citizens as a response to the environmental challenges (Commission 2019). The strategy that aims is to transform the EU into a modern and resource-efficient society, with a competitive economy and simultaneously, no net emissions of GHG in 2050. The environmental ambition will not be achieved by Europe alone but depending on full mobilisation from all industries in the world. EU wants to adjust IMO's reduction goals to pursue a more ambitious strategy. They propose a reduction of emissions with 40% by

2030 compared to 2018, instead of IMO's compared to 2008. By changing the comparison year forward in time, where the vessels are more energy-efficient and emit less than they did in 2008, must the operators make an even more significant effort in order to reach the goal.

Another proposal in the Green Deal is to introduce a ”Climate Law” that should include all sectors, also the maritime industry. The commission will propose an extension of the ETS also to include the maritime sector, or develop a separate ETS for the shipping industry. Part of the income from the carbon tax will contribute to a European maritime decarbonisation fund to support innovation and development of new green technology within the maritime industry. The proposal is an invitation to the IMO, to join the ETS and develop a global measure for emissions (Lloyd's List the Shipping Podcast 2020). In Norway, the shipping industry shall reduce its absolute GHG emissions with 45 % by 2030 compared to 2005. The government are working on a strategy that will be published later in 2020 where they will further suggest a reduction of the GHG emissions towards zero-emissions in 2050 (Klima- og miljødepartementet 2019).

4.2 Goal Formulations

The process of designing reduction goals contains several aspects. In this thesis is the overall aim of introducing goals to reduce GHG emissions. The level of ambitions and the cost of reaching the goals are two factors that play essential roles. However, there are a handful of aspects and methods to consider when designing goals. The ones that are relevant for Golar and the rest of the stakeholders will be presented in this section.

The needs identified in table 9.1 and table 9.2 are the starting point to develop the goals. To *”Reduce GHG emissions”* and *”Beyond compliance or Comply with the regulations and ESG standards”* were decided to be the ambitions for the goals. To get a better understanding of the goals, is it smart to conduct an elucidation of what is required to reach the goals. This method emphasises the importance of getting an overview of the entire problem and thus be able to formulate the correct goals that meet the stakeholder's requirements. Andrews (2011) presents an interactive and iterative triad as a method on the way to create a successful strategy. This interaction is between: ”what the stakeholders want?”, second: ”what are the possible solutions” and third: ”what are the cost, timescale and risk of this?”. The overall aims decided above will be considered as the first step in this triad. The second step on this overall level is to come up with different goal formulations in order to find possible solutions to the first step. The last step is to evaluate these formulations related to cost, risk and time.

Lunenburg (2011) identifies four aspects of the goal-setting process. Firstly, specific and quantified goals are essential to motivate the employees. Secondly, the goals should be challenging but attainable and related to the level of ambition. Further, the goals must be accepted, meaning that the employees must be committed to the goals. The motivation within the entire company and willingness to contribute to meet the goals is a critical success factor. Lastly, deadlines and a timescale is an essential part of setting proper goals. The second GHG Study (Buhaug et al. 2009) addresses the influence of the current and future regulation, and their interactions in a decision process, and thus implemented in the goals. Such polices can be regarding CO_2-taxes and prohibiting of fossil fuels or fully decarbonisation.

The time scale of the goals is divided into three periods, similar to the industry ambitions time scale. These periods consists of short term (2-4 years), mid-term (within 10 years) and long-term (30+ years) goals. The long-term goal will typically be more ambitious than the short-term due to the timescale. The development in, for example, new technology, alternative fuels and more energy-efficient vessels in the long-term are different than in the short-term. Thus, a higher potential to reduce more emissions in the future. The importance of short-term goals must not be forgotten. Gilbert et al. (2014) points out that the urgency of a change is necessary in order to re-frame the options on the horizon and drive the development forward.

The goals will have various levels of ambitions. A minimum level of ambitions will have a smaller cost but consequently have a smaller reduction effect. On the other hand, there will very ambitious goals, have higher costs, but the reduction effects of reaching the goals will also be higher. Alongside the short-, mid- and long-term goals, are the overall aims further developed into four pillars showing Golar's approach and commitment related to reducing their GHG emissions. The pillars, displayed in figure 4.2, will be used as a supporting tool for the development of the goals and resulting strategy.

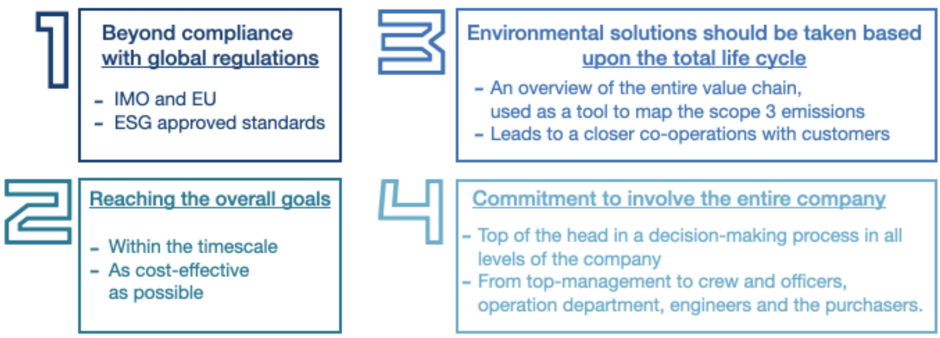


Figure 4.2: Four pillars to base the goals upon

In this thesis, a formulation of the goals as either relative or absolute targets is of relevance. The requirements from IMO have both relative intensity-based and absolute targets, with a comparison year. The intensity target is relative to a decided measure, while the absolute target is a total redaction of, for instance, GHG emissions. The operator can reduce the total GHG emissions by merely reducing the activity of the fleet and thus decrease the fuel consumption and CO_2 emitted. However, absolute targets will be included in the goals, as the industry aims to reduce the total GHG emissions with fifty percentage by 2050.

Carbon intensity ratio is a relative target and a necessary parameter in emission reduction. The intensity ratio describes the GHG emissions in the context of a company-specific metric, e.g. per vessel, per cargo capacity or nautical mile. Many companies track their environmental performance with the intensity ratio. It is often called the ”normalised” environmental impact data (World Resources Institute (WRI) et al. 2004). The intensity ratio is decided to be in metric tonnes emitted CO_2 per sailed nautical mile. Both voyages in laden and ballast are included, and the goal will be an incentive to reduce the ballast voyages. When the vessel is operating in ballast condition will the transported work be close to zero, but it should still be included since the vessel consumes fuel and thus emits. Consequently will the graph increase in ballast condition but it reflects the actual conditions. The EEOI is an index describing the ratio of the mass of CO_2 emitted per unit of transport work. The unit is very similar to the intensity ratio, but there is a vital difference. For the EEOI is the transported work only related to voyages in laden. EEOI is useful monitoring tool to see the direct improvements of energy-efficient and operational measures as route optimisation and to minimise ballast voyages.

The ESG related measures should also be taken into account. Metrics related to fuel and energy consumption are most common for GHG emissions. Regarding fuel consumption, is the scope 1 a metric which covers direct emissions from sources the company owns or control. scope 2 is also a widely used metric for CO_2 emissions. Scope 2 covers all indirect emissions from energy that the company has purchased, including emissions resulting from, e.g. heat and electricity (World Resources Institute (WRI) et al. 2004). *The total amount of energy consumed* is the metric associated with energy consumption. This metric includes energy consumption from all sources, including the energy produced by the company and energy purchased from external sources (Sustainability Accoiunting Standards Board 2018).

An alternative non-required goal-based measure could be to include a carbon budget. The budget is based upon cumulative emissions from a chosen base year. Then the cumulative emissions for the year are multiplied with the respective reduction target.

4.3 Presentation of the Goals

Three different goal alternatives have been designed and can be seen in table 4.1. One of the pillars is to comply or preferably go beyond compliance with global regulations. The global requirements and IMO targets have been used as a basis for all three. The three alternatives have different levels of ambitions; minimum requirement, medium level of ambitions and lastly a very ambitious level. Additionally is the work Golar has done in the making of their ESG report relevant to use as a basis. There is no point of introducing new measures they do not have in their energy management and emission calculation. Their main focuses for GHG emissions are total GHG emissions (scope 1) and energy consumed from HFO as absolute targets and EEOI as the intensity target.

Table 4.1: Alternative goal proposals with different levels of ambitions

	Alternative 1: Minimum Requirement	**Alternative 2:** Medium Ambitious	**Alternative 3:** Very Ambitious
Short-term by 2024		1. Reduce average carbon intensity with 25% compared to 2019	1. Reduce average carbon intensity with 40% compared to 2019 2. Reduce energy from MGO/MDO with 20 % compared to 2019
Mid-term by 2030	1. Reduce average carbon intensity with 40% compared to 2019	1. Reduce average carbon intensity with 50% compared to 2019	1. Reduce average carbon intensity with 70% compared to 2019
Long-term by 2050	1. Reduce average carbon intensity with 70% compared to 2019 2. Reduce 50% of the total GHG emissions	1. Reduce average carbon intensity with 75% compared to 2019 2. Reduce 80% of the total GHG emissions	1. Reduce average carbon intensity with 90% compared to 2019 2. Total GHG emissions towards zero emission

The baseline year is only a chosen reference point in time. As discussed before, Golar's baseline year is 2019 due to available data while IMO has used 2008 as the global baseline year. The consequences this gives is the emissions in 2019 most likely are less than in 2008 and hence must reduce more relative to this year. However, this is only beneficial for Golar and by using 2019 as a comparison year is even better than the EU's new proposal of changing this year from 2008 to 2018.

4.3.1 Evaluation

It is challenging to decide which one of the alternatives to choose without knowing the overall picture and cost of implementing the required actions. The benefit gained from implementing these goals is also of interest to understand. The benefits of the different alternatives include a smaller carbon footprint, which will be bigger, the more ambitious the goals are. With the information obtained this far in the thesis is it challenging to set a total cost of each formulation. Furthermore, are there many pathways with different abatement actions and number of factors influencing the decision of choosing the goal formulation. Costs and reduction effects have a more significant impact than others, for instance, regarding fuel prices, new technologies and design changes. The cost will be higher if Golar decides to reduce all GHG-emissions by 2040 than reducing half of the GHG emissions by 2050. On the other hand, is the benefit of being carbon-neutral also very high.

The high-level ambition is meant to be a preparation for stricter future regulation and thus will Golar be better suited for changes. High ambitions in the short-term establish good routines early, along with turning the right mindset that is required from the crew on on-board the vessels and employees in the offices to meet the ambition. Carbon-tax, for instance, is likely to be introduced globally soon, by setting high-level goals will also the cost be smaller due to the already low emissions.

To summarise the goals will total GHG emissions corresponds to ESG's scope 1 metric. EEOI is an individual relative target addresses voyages sailed with cargo, while the carbon intensity ratio covers all voyages in both laden and ballast. Lastly, is consumed energy which is an absolute goal and is an ESG metric Golar already has started to establish this metric.

The suggested goal formulations are a part of the preliminary work, and the decision model will help to get an insight in which of the alternatives that fit the final strategy.

Chapter 5

Actions, Regulations and Targets

This chapter will present an overview of the most promising abatement actions found in chapter 3 to meet the goals formulated in chapter 4, including a more detailed discussion of the most relevant actions and regulations. After obtaining more knowledge about the actions, is it also possible to get a better understanding of the reduction effects and associated costs. The motivation for implementing abatement actions is partly controlled by compliance with regulations and partly by the company's reduction goal. Compliance is about the given requirements from the policymakers, while the reduction goals are used to provide the annual report with data about total emission for the entire fleet.

5.1 The Development of a Strategy

This thesis aims to develop an overall strategy in order to make decisions for the long term. A strategy is a plan of actions developed to achieve success with the long-term goals formulated in chapter 4, which for Golar is to reduce GHG emissions towards 2050. As the state-of-the-art in chapter 3 shows, are there numerous actions to include in such a plan. To obtain a better knowledge of the decision problem, will it be taken one step down and investigate more detailed and specific plans. These will be called for tactical decisions, and are based on the framework decided on the strategic level. The decision model is a tool for the tactical level to model alternative actions to implement. Then the last level is an operational level which conducts the plans developed at the tactical level into the daily operations. In order to reduce emissions, must the framework developed in the overall strategy, actions found in the decision model be implemented in the daily operation. Figure 5.1 illustrates how these three levels influence each other.

Uncertainties about the future are present in a strategy like this. The strategy tries to predict how the next 30 years will be, and by breaking it down to the tactical level, Golar can get an overview of their opportunities within the next five to ten years. For instance, which plans and actions could be implemented today, and then start to implement them in

Figure 5.1: Assignment between strategic, tactic and operational level. (Adopted from (Kaufman 2013))

the daily operation, within the framework from the strategy. The strategy takes decisions based on data and information from the past, available now and tries to predict the future (Kaufman 2013).

5.2 Abatement Actions

The most common way to divide the reduction measures is into operational and technical control targets. Previous studies show that emissions can be reduced by 75 % towards 2050 by using today's technologies combining operational and technical measures (Lindstad et al. 2018). Quantitative and qualitative criteria must be considered for every action in order to get the full picture. As this thesis opts to find the most cost-effective abatement actions, is an identification of cost and reduction effect of each action needed. However, there can be challenging to find exact values so reasonable estimations based on the literature and Golar's experience from the industry will be used. Energy management will not be considered since Golar has already established good routines on this field. Therefore, will there not be any focus of further developing this action but rather look into new measures where Golar has little to none experience.

5.2.1 Speed Reduction and Voyage Optimisation

Speed reduction is a commercial, operational measure. In general, an action that is easy to implement, no installation costs and reduces fuel consumption. However, it is a bit more complicated due to the commercial part of it. Slow steaming leads to an extension in the voyage with extra days. Extra operational costs as crew, and loss of potential income is important factors to consider when reducing the speed. If there is a need for more LNG in the market, then the ship will not deliver as much LNG as it could have because of the reduction in speed. Another option for the LNG carrier is to always sail in optimal speed which corresponds to the use the available BOG. This will also decrease or minimise the amount of BOG that goes to the gas combustion unit (GCU), which, in reality, is waste. A trade-off between the loss in income and how much it gains in emission and fuel reduction must be evaluated. For an LNG carrier will the cost in delay be higher than the gain in consumption. The vessel uses the BOG from the LNG cargo and thus no fuel cost. However, if the fuel switches to an alternative low carbon fuel will the costs apply. All over is it the cargo owner/charterer that pays for the fuel, and this thesis only considers costs related to the shipowner.

Voyage optimisation and especially minimising voyages in ballast condition can be challenging. The LNG shipping market is based on the transportation of LNG from one source of production of natural gas to destinations where there is a need for gas. If the vessel is on a long-term fixed contract, is it be challenging to bring LNG on the voyage back to the source. However, if the vessel is in the spot-market, the operational department can try to optimise the routes for minimising the ballast voyages. Voyage optimisation is also including the cost of weather routing services.

5.2.2 Batteries

From the state-of-the-art in chapter 3, is battery power not applicable as propulsion for deep-sea shipping before at least 2045. An interesting aspect for an LNG carrier that already uses LNG as primary fuel is to use batteries as storage for the remaining BOG, in a hybrid-power system. Then the BOG can be used at a later time when it is needed for instance, in ballast voyages. Also, will the extra BOG not be sent to the GCU as waste. Such an installation will not need as much space as a battery delivering 100% of the propulsion power. This benefit makes this option more relevant in the shorter term. If the installation cost is not too high, and there is enough space in the engine room, batteries could be installed on both existing and newbuild vessels. The battery prices has an initial cost and will be considerably high until the full-scale development is in place.

To only use batteries in deep-sea shipping will not be available shortly. Several factors need to be in place before this can happen if it will happen at all because other technologies as hydrogen reach maturity before batteries. The size of the batteries required of the batteries in order to deliver the power needed to sail these long-distance voyages is a considerable challenge. An evolution in the battery technology must happen to minimise the volume and weight of the batteries. An example calculation to see whether deep-sea all-electric is possible has been conducted. The key characteristics for a nickel manganese cobalt oxide (NMCO) battery with today's technology are taken from *Maritime Forecast to 2050* by DNV GL (2019a, p. 50). For a vessel with 300,000 DWT and 1500 tonnes bunker, is the estimated volume of the batteries around 5350 m^3 and associated weight be 13,300 tonnes. The values used in this example can be found in appendix 9.1. Based on this is it realistic to believe that the usage of batteries will be a hybrid solution towards 2050. On the other side, are there coming more incentives and money in developing better battery technology, so if it becomes profitable might fully-electric solutions be available closer to 2050. The starting set will include the hybrid solution and assume a reduction effect of 50%, because of the part of the total voyage it can be applied.

5.2.3 LNG

LNG is the primary fuel for Golar's vessels. Since the LNG also is the cargo and the BOG from the LNG is the fuel, is the vessel saving fuel costs during cargo operations. The use of LNG as the only fuel during their long voyages is not enough to achieve internal and external goals. Also, must the emissions from CH_4 be considered as high for such voyages.

5.2.4 Biofuels

LBG can be used on today's system without any significant modifications. It is one of the most promising fuel to replace LNG. The expected price of biofuels when the market is fully developed is to be on par or lower than other alternative fuels, but higher than the conventional fossil fuels. However, it is not expected that this will happen within the next ten years (DNV GL 2019b). The market is still immature, and the use of biofuels shortly will lead to a high operational cost. The initial costs related to biofuels are the same as for LNG, and since Golar already has this on their vessels will this cost be zero. Today's usage of biofuels in shipping is limited.

5.2.5 Hydrogen

The production of H_2 have to be from renewables in order to obtain zero CO_2-emissions. This requirement makes the price is dependent on the electricity price, which remains fairly constant. However, the production costs will be reduced in the future. The reduction is due to the lower investment costs of electrolysers and use of carbon capture and storage (CCS) for H_2 produced from natural gas and fossil fuels. Regarding the cost of ammonia (NH_3), a fixed percentage of the H_2 price will be assumed (DNV GL 2019b). An LNG carrier can use a mix of hydrogen and LNG as fuel. An assumption that the vessel can use the existing equipment and only needs to install storage tank and pumps is made.

5.2.6 Hull Design

Changing the hull design to get more efficient vessels and minimise resistance from the hull will is relevant for both existing and newbuidings. The most promising action is to install a new bulb, but these are typically optimised for a service speed at 19.5 knots. Golar's vessels operate at a service speed between 13-19 knots, so it might not be as energy-efficient for lower speeds. Hull coating is another measure to consider. It can follow the five-year docking interval. Both the hull coating and the new bulb is included in the hull design-action taken into the model. Air lubrication system is a measure that exists and can be installed. It is a system that uses air bubbles to reduce the resistance between the hull and seawater.

5.2.7 Power and Propulsion Systems

The range of reduction potential is quite prominent in this group, due to a lot of different solutions. One option for Golar could be to do a retrofit and change their low-pressure 4-stroke DFDE into a high-pressure 4-stroke DFDE. This change of the engine would minimise the unburnt methane slips the low-pressure engine have and thus make LNG a cleaner fuel. A hybrid power system might be an even better option and is equal to the battery solution discussed above.

PBCF (propeller boss cap fin) exists on Golar Crystal and is a propeller that increases the propulsive efficiency with approximately 1%. The auxiliary systems as pumps, fans, compressors can be upgraded in addition to installing more efficient equipment as smaller engines. Re-liquefaction systems can liquefy the BOG and return the LNG to the cargo tanks and thus reduce waste the unused BOG and make LNG storage commercially good. The re-liquefaction system can have a capacity of 1.4 MT LNG per hour.

5.2.8 Energy Efficiency Measures

Energy efficiency measures are measures that reduce the vessel's fuel and energy consumption. An issue is the unused BOG that goes to the GCU as waste. Therefore, one measure can be to reduce the GCU usage, because according to data from Golar, is 7% of the energy burned in the GCU. Other alternatives are to install equipment that collects the essential data to improve the energy-efficiency.

5.2.9 Fleet Renewal

Fleet renewal is also an option by deciding to take the older vessels out of operation and replace them with zero-emission vessels. Another alternative for the new vessels is to be prepared for the new technology and thus do a retrofit when it has matured enough to be applicable for deep-sea shipping. Average newbuilding price for an average LNG vessel in the 2007 fleet was estimated to be 162 million USD. (Lindstad et al. 2012).

5.3 Regulations and Policies

A declining intensity ratio reflects a positive environmental performance in the company. The shipowners decided the intensity ratio themselves. In this thesis is this metric tonne emitted $CO_2 - e$ per sailed nautical mile. As specified in the discussion of the goal formulation, in section 4.2, includes the intensity ratio all voyages.

$$\text{Carbon Intensity Ratio} = \frac{\text{mt}CO_2\text{emissions}}{\text{sailed nm}} \tag{5.1}$$

The EEOI formula is from MEPC's voluntary guideline for the usage of EEOI (IMO MEPC 2009). It calculates the vessels CO_2 emissions for voyages sailed with cargo.

$$\text{Average EEOI} = \frac{\sum_i \sum_j (FC_{ij} \cdot C_{Fj})}{\sum_i (m_{\text{cargo},i} \cdot D_i)} \tag{5.2}$$

i = voyage number
j = fuel type

FC_{ij} = mass of consumed fuel *j* on voyage *i*
C_{Fj} = conversion factor for fuel type *j*
$m_{cargo,i}$ = cargo carried (tonnes) on voyage *i*
D_i = distance travelled on voyage *i* in nm

As for now, EEDI is the only established regulation applied for CO_2-emissions. Which again does not apply to older ships. However, as said, IMO is working on a new indicator called EEXI, which also applies for older existing ships. The problem with EEDI is according to Lindstad et al. (2018) that it is not an excellent goal-based measure. It gives wrong and unrealistic operative assumptions due to the design speed, design load and still water conditions. A vessel operates mostly at speed different than the design speed, due to fuel prices, market conditions and contracts. This wrong adoption of EEDI can in some cases result in the existing vessel being active longer than it should and used more intensively, again resulting in a less efficient and higher emitting vessel. Must have this in mind when the calculation and usage of EEXI starts. The EEXI reference line for LNG vessels is a change of 30% reduction from the EEDI reference line (DNV GL 2020a).

Regulation 21 in MEPC.203(62) (IMO MEPC 2011) provides a guideline to verify that the vessel's attained EEDI is lower than the required EEDI reference line for each ship type. The required EEDI is the regulatory limit the company must follow (Polakis et al. 2019).

A CO_2-tax is not developed yet, but it might be regulation that will be established soon. There are a lot of structural decisions to make before this is taken into actions. These are questions like, who is going to pay? Is it the cargo owner or the shipowner? Where should the tax be paid? To the flag state or the IMO or the EU? The most likely upcoming CO-tax will, in this case, be used in the case study to evaluate the cost of operating with BAU if this tax was set into action today.

5.4 ESG Targets

Scope 1, EEOI and total energy consumed are the most relevant metrics for this thesis by looking at Golar's work with their ESG report. Another focus area that is recommended to start to establish is the scope 2 metric. These metrics are used to calculate emissions and energy consumed. So the implementation of abatement actions contributes to driving these metrics down closer towards the reduction goals and global regulations.

5.5 Starting Set

The starting set presents an overview of the most promising abatement actions, associated reduction effects and a short description. This set is the starting set for the decision model and the input is classified as medium and will thus be the reference data. The reduction effect is in percentage due to big range in the nature of the abatement actions and possible interaction effects. It must be noted that technical measures like battery systems are zero-emission alternatives when the technology is mature for deep-sea shipping. Thus, is the reduction effects when the technologies are fully developed presented. The reduction effects are mainly obtained from Balland et al. (2012), Buhaug et al. (2009) and Bouman et al. (2017). Data not found in the literature are estimations based on Golar's experience. IMO has created 10 groups to avoid measures from the same group being used together and measures from different groups not excluding each other. These 10 groups are: (1) propeller maintenance, (2) propeller/propulsion system upgrades, (3) hull coating and maintenance, (4) voyage and operations options, (5) main engine retrofit, (6) retrofit hull improvements, (7) auxiliary systems, (8) other retrofit options, (9) speed reduction, (10) air lubrication (Buhaug et al. 2009). Note that there are some cases, especially within the voyage and operation option (4) that is challenging. For instance can voyage optimisation, biofuels and energy-efficiency measures be implemented at the same time, while with this grouping will these exclude each other and only one of the measures could be chosen.

Table 5.1: Reference values for the abatement actions, in alphabetic order

Action	**Type**	**ESG**	**Expected maturity**	**Potential CO_2 reduction (%)**	**Group**
Air lubrication system	T	Energy consumed, scope1, EEOI	Now	0-10	10
Auxiliary systems	T	Energy consumed	Now	0-10	7
Batteries	T	Energy consumed, scope1, EEOI	2050	100	5
Biofuels	O	Energy consumed, scope1, EEOI	2030	19-88	4
Energy efficiency measures	O	Energy consumed	Now	1-10	4
Hull design	T	Energy consumed	Now	2-30	3
Hybrid Batteries	T	Energy consumed, scope1, EEOI	2040	50	5
Hydrogen	T	Energy consumed, scope1, EEOI	2030	100	4
LNG (primary fuel)	O	-	Now	5-30	4
PBCF (propeller boss cap fin)	T	Energy consumed	Now	1-8	2
Re-liquefaction	T	Energy consumed, scope1, EEOI	Now	2-10	8
Speed Reduction 2 knots	O	Energy consumed, scope1, EEOI	Now	1-60	9
Voyage optimisation	O	Energy consumed, scope1, EEOI	Now	0.10-48	4

Chapter 6

Decision Model

This chapter contains a description of a decision model to evaluate and benchmark alternative scenarios for emission reduction. Figure 6.1 shows the pathway of the development of the model. The purpose is to use the model as a supporting tool in the decision-making process and a fundamental understanding of the overall problem in this thesis. To obtain an understanding of how certain input variables affect the implementation of the different actions and develop over time. Furthermore, to get an overview of the total cost and CO_2 reduction effect by implementing these actions. It is a simple model where the results are a guideline on the road towards an overall strategy and do not provide the final answer.

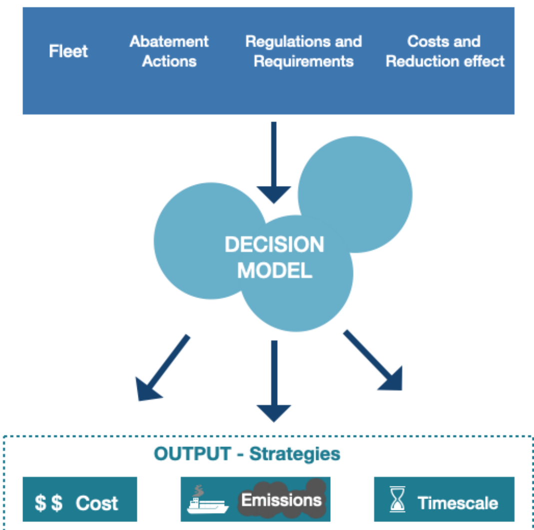


Figure 6.1: The model pathway

Future regulations are essential criteria a shipowner must follow, and consequently, something the model must take into account. It is expected an introduction of stricter regulations soon due to the increasing focus on CO_2 emissions from the policymakers and industry itself. It is a considerable uncertainty related to how strict they will be. Besides uncertainty of future regulations, will other qualitative factors impact each of the abatement actions. Qualitative factors to consider when recommending an overall strategy are the risk of implementing them, the maturity of the new technologies and uncertainty of the development, industry standards and regulations from the policymakers. These are not included in the model but discussed with the results.

There are some assumptions and simplifications regarding the development of the model. As mentioned earlier, is this thesis limited to only consider CO_2-emissions, which also applies for the model. The lifetime of a vessel is set to be 30 years. When a vessel gets older and goes out of operation, is it also the end of the emission calculation for that vessel. Another assumption is that seaborne trade and transport of the LNG demand remain constant. A simplification made is the lifetime of the abatement action. If a technical measure is implemented, will it not be re-installed or upgraded with a new initial cost at a later time. The cost is only relevant for the shipowner, which means cost related to the cargo is not considered. Another simplification is that all future values are known. Furthermore, are the period of pay-back and financing related to the implementation and initial cost of the abatement measures not considered. Different approaches will be made in the analysis to see how the prediction of the future influences the decision-making.

6.1 Deterministic Optimisation Modelling

An deterministic optimisation model is used to solve a real problem by creating a simplified problem in order to find the best alternative in a decision-making situation. The purpose is to get an insight into the system in order to find solutions to the problem. It aims to solve minimise or maximise a decided objective value by using decision variables. The values of the decision variables are restricted by a set of constraints representing physical, technical and economic limits of the problem are described. Furthermore, linear programming problem (LP) is a problem where all functions are linear and all variables are continuous (Lundgren 2010). Deterministic optimisation is one approach of optimisation within mathematics and follows linear algebra. The opposite classification of deterministic optimisation is stochastic or probabilistic optimisation. Deterministic optimisation does not take future uncertain data into account (Cavazzuti 2013).

The what-if analysis, scenario analysis and sensitivity are all techniques that explore a variety of future scenarios without including uncertainty in the modelling (King and Wallace 2012). A mix of sensitivity analysis and scenario analysis will be used to evaluate the model and solution by varying the parameter values. Different scenarios will be developed to see how much the input values can vary and still have a stable solution (King and Wallace 2012). However, it must be noted that the purpose of this model is to assist the decision process and the result from the modeling might not be the final recommendation of the overall strategy.

6.2 Model Description

The pathway model in figure 6.1, outlines the importance of four input categories the model is dependent on in order to get a valuable result. The goals from chapter 4 play an essential role in realising the required reduction effects. The three different levels of ambitions will be tested and compared to find the most significant reduction effect for the implemented actions to a minimised cost. This model is a flexible tool, so the information provided for each group will change during different runs of the model, based on the scenarios.

The time perspective follows the same perspective as IMO's GHG study, where the time horizon is towards 2050. The period towards 2050 is divided into time-periods of five years, where period 0 equals 2025, period 1 is 2030 up to period 5 which is 2050. Other options could be to use smaller intervals as ten periods of three years each, or bigger with an interval of ten years in each period. The development of technology and infrastructure can go fast, and a lot can happen in ten years. Although five years is also quite a big interval, requires a three-year interval, many guesstimations on the input data where the level of uncertainty already is high.

6.2.1 Fleet Information

There are several ways to provide the model with information about the fleet. One way to systematise this is to consider the fleet as one single vessel and then aggregate it or divide the fleet into vessel groups. Then the model will treat each group individually and customise the plan for those groups regarding cost and emission. Particular actions will have a different effect and cost for each group. The division of the groups has several options, like vessel type, machinery, the vessel's operation and trade pattern or age. A division could be to choose the machinery types since Golar has two engine types in their carrier fleet; DFDE and steam engines. On the other side, there would only be two groups, which may decrease the level of detail, instead of having four to six groups to increase the level of detail. Thus, could the engine type also be a sub-category within another vessel group. The vessels operational type is also an interesting perspective, which can have various focus areas such as short sea vs deep sea and the trading pattern. The operational alternative includes where the vessel operates, for instance, within Europe, where regulations are expected to be stricter soon or routes where the infrastructure for alternative fuel is not equally developed. The last alternative is to group the vessels after their age. An assumption is that an older vessel is less efficient and emits more the older it gets. This category gives a proper division of the fleet, where an action implemented on a relatively new vessel might have less effect on an older vessel. Further, the shipowner can get a better insight into the fleet, and where it is most cost-effective and beneficial to implement the different abatement actions.

The chosen vessel groups for further use in this thesis is the existing fleet, and more specifically, the engine types and newbuildings. The two engine types have different opportunity areas regarding the implementation of abatement actions. There will also be a possibility to include a third group, namely new vessels. These will again have even more options for new technology than an old steam vessel in the existing fleet. The characteristics of the vessel groups can be seen in table 6.1.

Table 6.1: The vessel group characteristics

	Group 1: New Vessels	**Group 2:** Existing Fleet	**Group 3:** Existing Fleet
Time Domain	within 5 years	0-30 years	0-30 years
Engine Type	-	DFDE	Steam
# of vessels	-	11	6
Age range	-	5-7y	14-20y

The input data will handle the different ages of the vessel types. The steam vessels in the existing fleet, will according to earlier assumptions, be out of operation within 10-15 years. After 2035 will steam vessels be replaced with new vessels- either same as the DFDE types or new design suited for new technologies. One way to handle this is by replacing the steam vessels with the third vessel group, newbuilds, from 2035. Regarding the DFDE vessels, a simplification is made so that they will stay in operation throughout the period.

6.2.2 Abatement Actions

There are many abatement actions to choose between. The level of detail in the measures can vary depending on the available information. The shipowner's willingness to implementing such measures in the first place is essential. This thesis will include the measures at a system level due to the objective of making an overall strategy. Furthermore, is the model a tool to get an understanding of the big picture and thus not needed to be extremely detailed in the choose of the measures to use in the model.

Interactions between abatement actions happen. For instance, do NO_x reduction actions through technology standards tend to result in higher fuel consumption which gives more CO_2-emissions. Similarly happens with the SO_x rules, and gives conflicting interests. Nonetheless, comparable situations will most likely happen between the actions for reducing CO_2-emissions as well. Fuel consumption is one of the main targets that a shipowner wants to reduce when implementing actions to reduce emissions (Lindstad et al. 2018). These interaction effects between the actions can be challenging to account for but important. They can apply for the costs, period of implementation, emission reduction effect and type of action; technical or operational.

It can be interesting to disclose if some of the actions work poorly together, or if the effect of implementing two actions at the same time cancel out each others effect. The effects can reveal how the actions interact, affect each other and if there are any compatibility issues. However, a study done by Balland et al. (2012) points out that including the interaction effects and will give underestimated reduction effects. While by summing them, same as not including them, will always overestimate the effects. Interaction effects also seem to be more common for air emission controls than for GHG. To include it or not will be a trade-off between the uncertainties in the parameter values and minimising error in the result when considering these effects. The effects are included in the model with an interaction matrix, only considering the second-order effects. In the same study done by Balland et al. (2012), they found that including higher-order effects gave a minimal error compared to the uncertainties in the parameters.

6.2.3 Goals, Regulations and Policies

The model aims to make a flexible tool and include varying strictness of the requirements. A simplification that is done is to include the regulations as the total reduction of emissions in each period. It is hard to predict the future and thus much uncertainty regarding future regulations. As for today is the EEDI, the regulation that discloses the CO_2-emissions. EEDI applies for new vessels and has therefore not been applicable for Golar. The new index for existing vessels (EEXI) will most likely enter into force by 2023 and will be included in the requirements. In addition to this, there exist some indications of new regulations coming soon. An ambition is to go beyond compliance with the regulations. By doing so, Golar can easier adapt and comply with new and stricter regulations in the future. The requirements from the policymakers are both relative and absolute targets. The choice is to use relative targets and the carbon intensity ratio. Since the model is evaluating one vessel in each vessel group, are the goals and regulation targets for each vessel and not for the total emission for the entire fleet. The three different levels of the goals, formulated in table 4.1, will be tested in the case study.

The ESG standards will not be considered as requirements since the ESG reporting is voluntary and mainly for satisfying investors and customers.

6.2.4 Costs and Reduction Effect

The cost of implementing an abatement action consists of an operational (OPEX) and initial (CAPEX) cost. Operational costs include maintenance, training of personnel and lost revenue, and initial costs are related to the installation of the measure and the design of it. Considering the two main categories of reduction measures, the assessment of costs and reduction is quite different. Technical measures often have a high investment cost, while the operational costs are moderate and potential emission reduction effect is significant. The operational measures tend to have a lower investment cost, moderate operational costs, and a relatively small potential emission reduction. However, an operational measure can give a reasonably good effect on the fleet's emission reduction in the short term (Eide et al. 2011).

Projecting the fuel price of the alternative fuel types can be challenging because several of these fuels are not available yet. Thus, if they are, they are often expensive due to the poor development in infrastructure and also in many cases fuel converters (DNV GL 2019a). The information about the cost is a mix gathered from relevant sources, previous studies and experience from Golar. A simplification is to assume constant CAPEX towards 2050. An exception is for new technologies in an early phase where the prices will decrease as soon it reaches large-scale volumes. The fuel prices are given in USD/MT and dependent on fuel consumption. Average annual fuel consumption has been taken from both of the vessel types. OPEX related to the rest of the actions is annual USD per vessel.

The reduction effects are estimations gathered from manufacturers, previous studies and Golar's experience in the industry. The wide range in potential effects from each action makes the uncertainty in the numbers high. To solve this, and get an understanding of the effects and respective costs, will scenarios with different levels of the reduction effects be evaluated. The interaction effects by implementing the actions are limited to the second-order effects based on the study done by Balland et al. (2012).

6.3 The Mathematical Optimisation Model

Table 6.2: Notation for the optimisation model

	Sets
I	Abatement actions, indexed by *i*
V	Vessel group, indexed by *v*
T	Time domain, indexed by *t*
	Parameters
C_{ivt}	Total cost for implementing action *i* on vessel group *v* per time *t*
C^{I}_{ivt}	The Initial cost for implementing abatement action *i* on vessel group *v* per time *t*
R_{ivt}	Reduction effect by implementing abatement action *i* on vessel group *v* per time *t*
G_{vt}	Goals for the emission reduction on vessel group *v* per time *t*
K_t	Regulations and requirements applying from/in time *t*
I^{E}_{ij}	Emission reduction interactions between action *i* and *j*
δ_i	Indicates whether the action is technical or operational, representing continuity when implementing abatement action *i*
	Variables
x_{ivt}	Binary variable representing the decision of implementing action *i* on vessel group *v* at time *t*
y_{ivt}	Binary variable representing having abatement action *i* implemented on vessel group *v* at time *t*
z_{ijvt}	Binary variable representing the decision of installing both actions *i* and *j*

Model formulation:

$$\min \sum_{t\epsilon T}\sum_{v\epsilon V}\sum_{i\epsilon I} C_{ivt}x_{ivt} + \sum_{t\epsilon T}\sum_{v\epsilon V}\sum_{i\epsilon I} C^{I}_{ivt}y_{ivt} \tag{6.1}$$

subject to:

$$\sum_{i\epsilon I} R_{ivt}x_{ivt} - \sum_{i\epsilon I}\sum_{j\epsilon I|j>i} I^{E}_{ijvt}z_{ijvt} \geq G_{vt} \qquad v\epsilon V, t\epsilon T \tag{6.2}$$

$$\sum_{i\epsilon I}\sum_{v\epsilon V} R_{ivt}x_{ivt} - \sum_{i\epsilon I}\sum_{j\epsilon I|j>i} I^{E}_{ijvt}z_{ijvt} \geq K_{t} \qquad t\epsilon T \tag{6.3}$$

$$x_{ivt} + x_{jvt} - 1 \leq z_{ijvt} \qquad i, j\epsilon I, v\epsilon V, t\epsilon T \tag{6.4}$$

$$x_{ivt} + x_{jvt} \geq 2z_{ijvt} \qquad i, j\epsilon I, v\epsilon V, t\epsilon T \tag{6.5}$$

$$x_{ivt} - x_{iv(t-1)} - M(\delta_i - 1) \geq 0 \qquad i\epsilon I, v\epsilon V, t\epsilon T\backslash\{1\} \tag{6.6}$$

$$\sum_{t'\epsilon[0,t+1]} y_{ivt'} \geq x_{ivt} \qquad i\epsilon I, v\epsilon V, t\epsilon T \tag{6.7}$$

$$y_{iv(t-1)} \leq x_{iv(t-1)} \qquad i\epsilon I, v\epsilon V, t\epsilon T\backslash\{1\} \tag{6.8}$$

$$x_{ivt}\epsilon\{0, 1\} \qquad i\epsilon I, v\epsilon V, t\epsilon T \tag{6.9}$$

$$y_{ivt}\epsilon\{0, 1\} \qquad i\epsilon I, v\epsilon V, t\epsilon T \tag{6.10}$$

$$z_{ijvt}\epsilon\{0, 1\} \qquad i, j\epsilon I, v\epsilon V, t\epsilon T \tag{6.11}$$

The objective function 6.1 is to minimise the total costs for implementing a set of abatement actions. Where the first part is the operational costs (OPEX), and the second part is the initial costs (CAPEX).

Constraint 6.2 ensures that the total reduction effect given by the implemented abatement actions and their interaction effects satisfy the company's reduction goal for each vessel group per time-period. It is assumed that the reduction goal is constant for each time-period. Constraint 6.3 makes sure that the Golar complies with the reduction requirements for each time-period made by the policymakers.

Constraints 6.4 and 6.5 make sure the interaction effects are taken into account by linking the decision variables.

Constraint 6.6 makes sure the model remains linear when it takes the continuity of the abatement actions into account. It ensures that the implementation of one action in one time period continues in the following as well. However, there are some measures, typically operational, that do not need to have this continuity. A binary indicator parameter decides whether the action needs continuity or not, dependent on the type of action. This parameter is decided in the input-file.

Constraints 6.7 and 6.8 ensure that the initial costs (CAPEX) will be added to the operational costs (OPEX) only the first time the action is implemented on the vessel.

Lastly, constraints 6.9 - 6.11 are binary decision variables.

Chapter 7

Case Study

This chapter consists of a case study to get a more in-depth insight into the decision problem. The study will take a look at how a relative change in the input values influences the results. The case study is a part of demonstrating the usage of the model and the purpose of it.

7.1 Description of the Case

The case study uses the uncertainty related to the development in the infrastructure and maturity of batteries for full-electric power as a basis. The aim is to use the input data to get a feeling of how the result changes by testing different scenarios.

There is some background information that should be established before the case study is conducted. Firstly, the primary fuel types are LNG and LSFO. LSFO is required as a minimum from the policymakers unless the company installed scrubbers instead. However, Golar sails on LNG whenever they can and then switches to LSFO. From their ESG calculations was the consumption from HFO 11% of the total fuel consumption in 2019, which can be aimed to be close to zero. Biofuels (including biogas) and hydrogen are the alternative fuel types considered in this case study and are assumed ready for full-scale use in 2030. However, it must be noted that the operational cost for these fuel types is still high compared to traditional fuel and LNG. Another assumption is that the vessels operate 300 days during a year. The study is also considering one vessel for each vessel group. Hence, it requires an aggregation of the costs and reduction effects to apply the results on a fleet level.

The goals and requirements use the relative targets in the model and prevent Golar from cutting total emissions by only reducing their activity. Table 7.1 shows the associated values represented by low, ref and high for the requirements and goals that vary in each the scenarios. High, reference and low goals are equivalent to the very ambitious, medium and low ambitious respectively. The low scenario, for both the goals and requirements, equals IMO's strategy. As can be seen, is the goals slightly more conservative than the requirements in this case study.

Table 7.1: Carbon intensity targets for the requirement and goals used in the scenarios, in percentage

Time Period		**Requirement**			**Goals**		
Year	Number	Low	Ref	High	Low	Ref	High
2025	0	20	25	30	35	40	60
2030	1	30	35	40	40	50	60
3035	2	40	50	55	45	60	80
2040	3	50	60	65	55	70	80
2045	4	60	65	70	60	75	90
2050	5	70	75	85	70	75	90

Lastly, must the evaluation of the steam vessels lifetime and they going of operation in 2035, and newbuildings take over, be considered. The cost of building a new vessel is not included in the study. However, an assumption of the price for an LNG carrier today, without new technology installed is around 200 mUSD. Further will technical actions like hull design have no initial cost, as this is included in the building cost of a newbuild vessel. A limitation is that the OPEX and CAPEX in each time-period are constant throughout each period of five years.

A total of 12 abatement actions for reducing CO_2 emissions are considered in the study. The costs and reduction effects are numbers found in the literature, experience from the industry and predictions of future development in the prices and potential effects. The measures are a mix of operational and technical measures, where some are specific, while others are more like an overall policy. An example of such policy is the hull design including hull coating and bulb, and energy efficiency measures, including all measures that reduce the energy consumed. The costs of the speed reduction, include the reduced freight transported in addition to a cost per hours delayed. Furthermore, LNG is included in this starting set. LNG is Golar's primary fuel, and included in the starting set. It is an action for cutting the amount of fossil fuel as LSFO and MGO that can be used today.

The interaction effects are taken into account and make sure that the reduction effects are relative to each other. These interaction effects do also consider the compatibility between the measures and ensure that the vessel will not use, for instance, hydrogen, biofuels and LNG as fuels in the same time interval. Another impact it has is regarding speed reduction. It makes no sense to implement a speed reduction of 1.5 knots and 3 knots at the same time for one vessel. The compatibility needs to be studied in more detailed in order to implement this in the model. Therefore, will this case study only consider one scenario of speed reduction. The interaction effects for measures within the same IMO group will be handled in the input-file, and biofuels and hydrogen will not be chosen in the same period.

7.2 Scenarios

Six scenarios are chosen, and the characteristics are displayed in table 7.2. The aim is to see how the solution changes by varying the parameter values. The reference levels are based on the starting set from section 5.5, where a middle value of that range is used. Uncertainties regarding the maturity of batteries for deep-sea shipping and when this technology reaches full-scale level and can provide the vessel with 100% power is the reference measure in the case study.

The case study starts with the first scenario as the reference scenario. Each abatement measure have gotten an associated potential reduction effect, initial cost and operational cost, for each time-period and vessel group. The steam vessel reaches its lifetime during period 2, between 2035 and 2040, and will, therefore, be taken out of operation. Golar orders newbuildings in order to replace the steam vessels. These will be accounted for in the model from 2040. Scenario 1 assumes that battery hybrid is available on the market from 2040, which is the reference point for the other scenario. The second scenario assumes that batteries are not ready for deep-sea shipping by 2050, and batteries are therefore not an alternative.

Table 7.2: Scenarios for the case study

Scenario	Characteristics	Requirements	Goals
1	Battery hybrid is ready from 2040	Ref	Ref
2	Batteries are not possible before 2050	Ref	Ref
3	Batteries are ready from 2045	High	Ref
4	-3% change in reduction effect	Low	Low
5	Battery hybrid is ready from 2035	Ref	Ref
6	+3% change in reduction effect	High	Ref

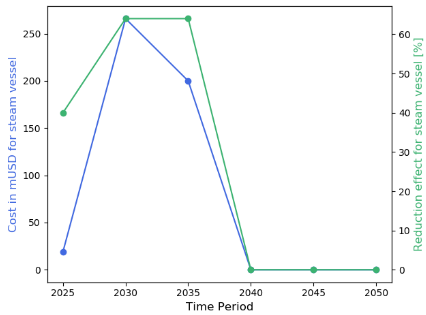
7.3 Results

The objective value is the price for operating and install these measures for three vessels over 50 years. Table 7.3 shows the objective value for implementing the selected abatement actions in the given periods. For the technical measures will the initial cost only apply the first time, it is implemented. The rest of the periods will have an annual operational cost, which is low compared to the operational cost for the operational measures.

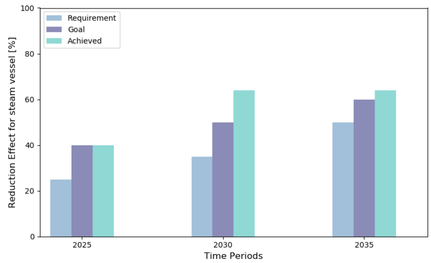
Table 7.3: Results from scenario 1, with battery hybrid available from 2040

Objective value:	1100 million USD	
Vessel type	**Abatement Actions**	**Implementation Period**
Steam	Biofuels	1,2
	Hull design	0,1,2
	Speed reduction, 2 knots	0
	LNG	0
	Voyage optimisation	0
DFDE	Biofuels	2,4,5
	Hull design	0,1,2,3,4,5
	Speed reduction, 2 knots	1
	Battery hybrid	3,4,5
	LNG	1,3
	Propeller boss cap fin	0,1,2,3,4,5
	Voyage optimisation	0,1,3
	Auxiliary systems	0,1,2,3,4,5
	Re-liquefication	0,1,2,3,4,5
Newbuilding	Biofuels	4,5
	Hull design	3,4,5
	Battery hybrid	3,4,5
	Energy efficiency measures	5
	LNG	3
	Air lubrication system	3,4,5
	Propeller boss cap fin	3,4,5
	Voyage optimisation	3

The figures 7.1, 7.2 and 7.3 display the cost versus the reduction effect in each time-period. The DFDE vessel, 7.2a, has a high cost in 2035 due to installation of hybrid batteries. However, in order to comply with the medium-strict regulations, must the vessel also use biofuels in 2045, which has high operational costs. There will also be an additional building cost for building the new vessel, excluding the cost for extra equipment for a low emission vessel.

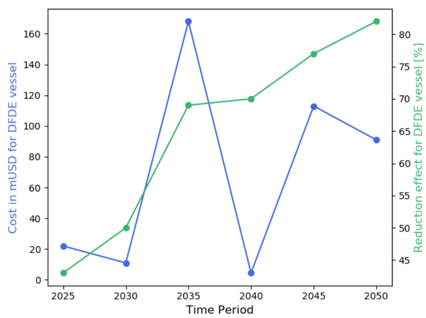


(a) Cost in million USD versus percentage reduction effect for each time period

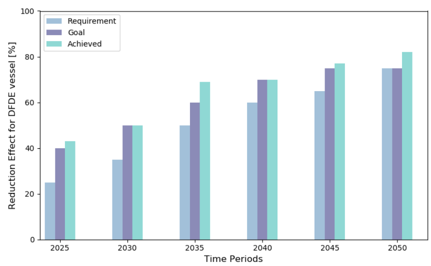


(b) Overview of achieved reduction effect seen against the targeted goals and regulations for each time period

Figure 7.1: Results from the scenario 1 for steam engines

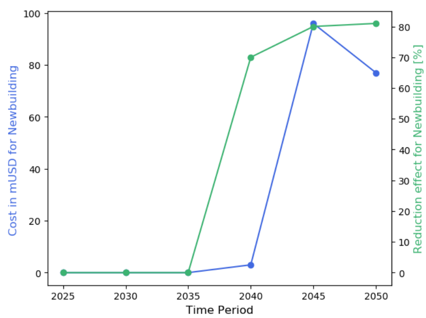


(a) Cost in million USD versus percentage reduction effect for each time period

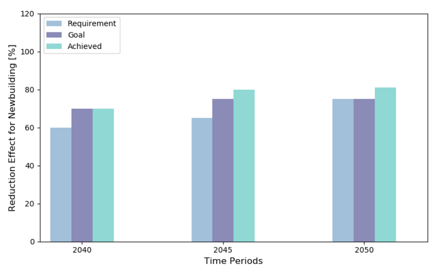


(b) Overview of achieved reduction effect seen against the targeted goals and regulations for each time period

Figure 7.2: Results from the scenario 1 for DFDE engines



(a) Cost in million USD versus percentage reduction effect for each time period



(b) Overview of achieved reduction effect seen against the targeted goals and regulations for each time period

Figure 7.3: Results from the scenario 1 for newbuildings

In table 7.4 are the total costs for each scenario displayed. Interestingly, scenario 5 and 6 have the lowest objective value. The cost for the DFDE vessel is slightly lower than for the other scenarios. This difference is because battery hybrid is ready from 2035 in scenario 5, compared to in 2040 as for the other scenarios. Also, has scenario 6 an increased potential reduction effect compared to scenario 1. Scenario 3, where it assumes full-electric batteries from 2045, does not select to use batteries but hydrogen instead. Hence, will the operational costs for sailing on hydrogen be bigger for scenario 3 than scenario 5 and 6. The hydrogen opted before batteries because it is required high emission reductions in period 3 (2035) and the batteries are not available at that time. There is some initial costs of using hydrogen, due to new tanks and pumps, will the model continue to choose hydrogen until 2050. However, for the newbuild is the battery chosen as soon as it is available on the market. It is also interesting to see that scenario 4 has a low requirement and goal targets, but it is not the cheapest option. This scenario will not be looked further into since the objective is to find the most cost-effective solution and go beyond compliance with the regulations.

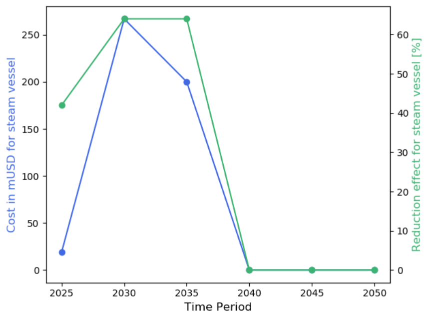
Table 7.4: Total cost, excl building cost, in 2050 for implementing the selected abatement actions for the different vessel groups for each scenario. All costs are in million USD.

Scenario	Objective value mUSD	Steam	DFDE	Newbuild
1	1100	500	400	200
2	1300	500	500	300
3	1100	500	500	100
4	1100	500	350	250
5	900	500	200	200
6	900	500	200	200

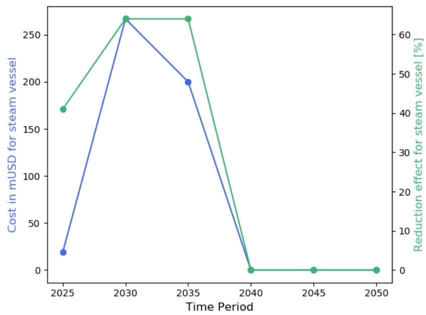
Presentation of the Scenarios

Based on table 7.4 and the scenario information in table 7.2, will scenario 2,3,5 and 6 be closer investigated in this subsection. As mentioned above, will scenario 4 not be evaluated further due to the relatively high cost with low requirement and goals. This subsection presents all scenarios for each vessel group, firstly the cost against reduction effect, and then the achieved reduction effect together with the targeted requirements.

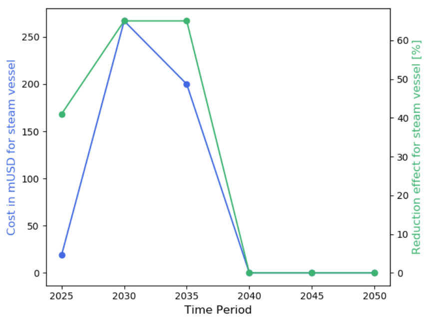
The results from the steam vessels are presented in figure 7.4 below. These vessels have an estimated operating life until 2035, where newbuildings will replace them. Common for the steam vessels is the use of operational measures and replace LNG with biofuels when that is available in full scale. The hull design is another measure that is chosen for all scenarios, even though the vessel will be out of operation within ten years. However, small improvements like new bulb and hull coating can be made in combination with the next dry docking.



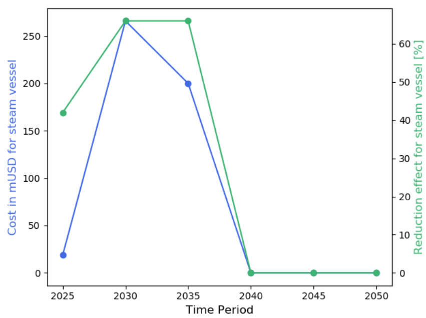
(a) Scenario 2 where batteries will not reach full scale use before 2050



(b) Scenario 3 with high regulations and full-electric operation with batteries are mature in 2045



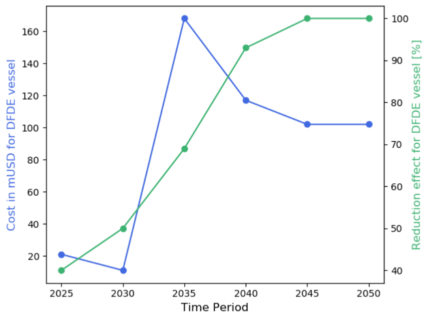
(c) Scenario 5 with reference values and battery hybrid available from 2035



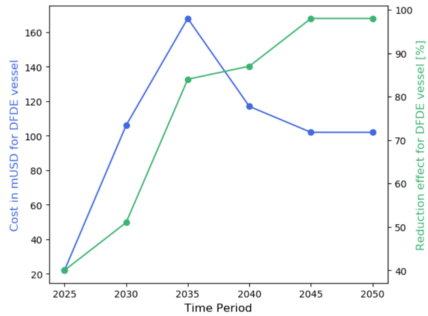
(d) Scenario 6 with high reduction effect and regulations and battery hybrid from 2040

Figure 7.4: Cost in million USD versus percentage reduction effect for each time period for vessels with steam engines

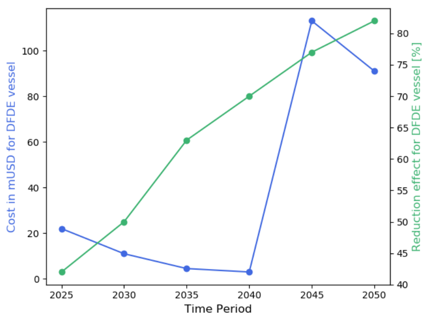
The plots in figure 7.5 show how the use of biofuels or hydrogen influence the cost picture. It is even more explicit for a LNG carrier, BOG from the LNG is used as fuel and thus not any additional fuel cost.



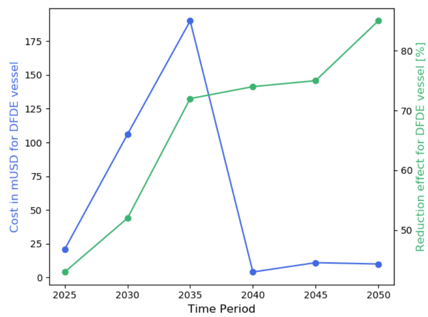
(a) Scenario 2 where batteries will not reach full scale use before 2050



(b) Scenario 3 with high regulations and full-electric operation with batteries are mature in 2045



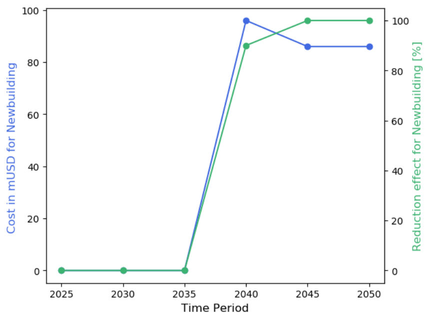
(c) Scenario 5 with reference values and battery hybrid available from 2035



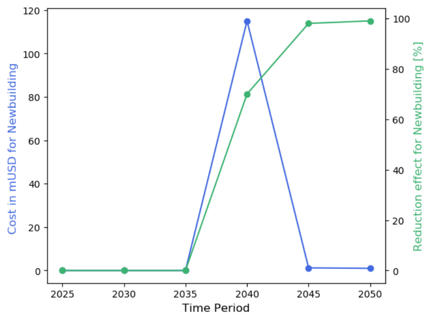
(d) Scenario 6 with high reduction effect and regulations and battery hybrid from 2040

Figure 7.5: Cost in million USD versus percentage reduction effect for each time period for vessels with DFDE engines

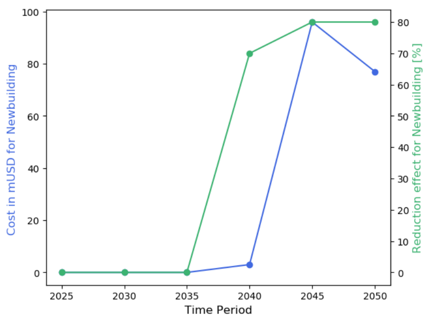
The newbuildings will take over the operation for the steam vessels and are therefore not considered before 2035. Scenario 5 and 6, figure 7.6c and 7.6d respectively, have a low cost in 2040 because it is assumed that the installation cost of battery hybrid systems have been reduced by 2040. The use of biofuels from 2045 increases the cost again.



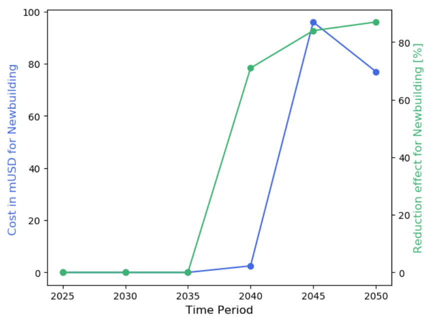
(a) Scenario 2 where batteries will not reach full scale use before 2050



(b) Scenario 3 with high regulations and full-electric operation with batteries are mature in 2045



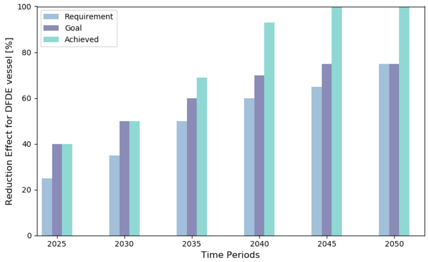
(c) Scenario 5 with reference values and battery hybrid available from 2035



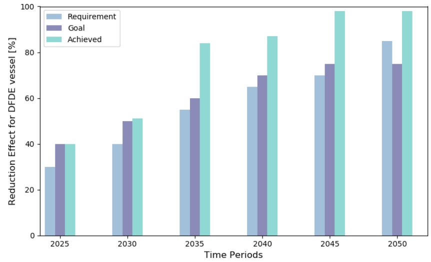
(d) Scenario 6 with high reduction effect and regulations and battery hybrid from 2040

Figure 7.6: Cost in million USD versus percentage reduction effect for each time period for newbuildings

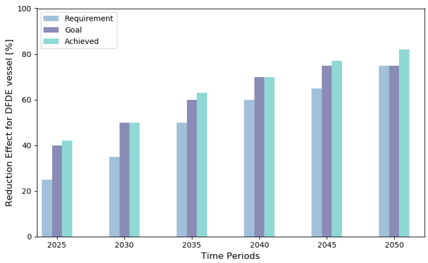
The plots in figure 7.7 show the achieved reduction effect in each time period together with the required goals and regulations for a DFDE vessel. Scenario 2 and 3, figure 7.7a and figure 7.7b, have a higher achieved reduction effect than required. This is due to the use of green hydrogen from electrolysis which is a zero-emission fuel type.



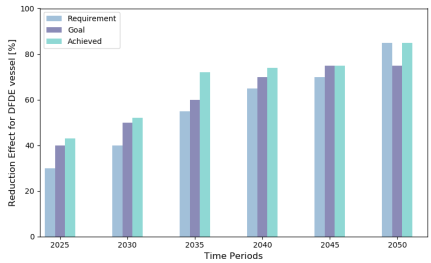
(a) Scenario 2 where batteries will not reach full scale use before 2050



(b) Scenario 3 with high regulations and full-electric operation with batteries are mature in 2045



(c) Scenario 5 with reference values and battery hybrid available from 2035



(d) Scenario 6 with high reduction effect and regulations and battery hybrid from 2040

Figure 7.7: Overview of achieved reduction effect against the targeted goals and regulations for each time period for vessels with DFDE engine

7.4 Comments on the Results

The results will be compared to a case with BAU operation and a CO_2-tax. An assumption for the tax price is similar to the EU's suggestion of 25 EUR per tonnes CO_2 emitted. Further, is the cost estimated to increase by 5% annually.

A DFDE vessel will be used in the comparison between the scenario 1 and the BAU with acceptance of an assumed CO_2-tax. The average emitted CO_2 for a DFDE vessel in 2019 was 56,000 MT, equals a cost of 1.4 million EUR The emissions are assumed to stay constant, but they still have to meet the required IMO reductions in 2030 and 2050 for the total annual GHG emissions, where 50% must be reduced in 2050 and assuming a reduction of 20% in 2030. Table 7.5 shows the CO_2-emissions with BAU for a DFDE vessel and associated costs, summarised for each five-year period.

Table 7.5: Comparison of the scenario 1 and BAU with CO_2-tax. (The currency conversion is 1 EUR equals 1.13 USD)

Year	**CO_2 emission MT**	**Cost BAU mUSD**	**Cost scenario 1 mUSD**
2025	280000	13	22
2030	268800	12	11
2035	224000	13	168
2040	224000	16	5
2045	224000	20	113
2050	201600	23	91
Total	1400000	97	408

The high cost for the scenario 1 is due to the implementation of expensive technologies. The hybrid batteries and the use of biofuels, which still has a high operating cost. It is assumed that this price will decrease when the market and infrastructure grow and reaches full-scale. As seen in table 7.5 are there periods the cost of implementing abatement measures are close to a BAU.

Chapter 8

Discussion

This chapter discusses the result from the case study and the knowledge obtained throughout the thesis. The case study took the problem one step down and structured the problem. The discussion will go back again and discuss the overall problem. Finally, will the work be summarised in a recommendation of an overall strategy for Golar.

The results from the case study showed that batteries were mostly selected. In the case where the battery technology was not mature for deep-sea shipping by 2050, was hydrogen as primary fuel selected. In combination with the predicted regulations and the importance of carbon-risk is it reasonable that all new vessels ordered from now should aim to be zero-emissions. However, there are uncertainties regarding the technologies and when they are ready for deep-sea shipping. The shipowner can either take a chance on the coming zero-emission technology or wait and prepare space for it and then do a smaller retrofit when the time is ready. The results from the case study did reflect that the older vessels were recommended to select operational measures or alternative fuels. Such a recommendation seems reasonable since it might not be cost-efficient to retrofit a vessel that will go out of operation in 5 to 10 year.

As this thesis shows are there numerous ways to reduce the emissions from a vessel. Nevertheless, is this work limited to consider just a few of the possible measures, in addition to only consider CO_2 emissions. The case study gave a better life cycle perspective on the different measures and when to implement them. It further reveals that when the reduction requirements are lower, generally in the short-term, are operational measures preferred because of medium to low operational costs and close to no initial cost. If higher reduction effects are desired earlier must technical measures also be implemented in an earlier phase. The decision regarding what type of actions to choose depends on several things. For instance, should the vessel's docking plan be taken into consideration. If a retrofit could be combined with the next scheduled dry dock and then assess which measures the yard can install or build. A new and more optimised bulb for energy efficiency and reduce the resistance, or an air lubrication system or replace the propeller with a PBCF type are some alternatives. Another even more proactive solution is to retrofit the vessel for future technology as making it ready for hydrogen by install storage tanks and pumps or for batteries. High reduction cuts in a relatively short period of time require more actions. A mix of operational measures, traditional well developed technical measures and new technology must be considered. The willingness to take risks as a shipowner and invest in new and uncertain technologies and solutions are essential to obtain such reduction cuts. The ESG standards and guidelines are an excellent complementary tool to extend some of the measures to involve the entire supply chain, as the scope 3 does. Inclusion of the entire supply chain includes evaluation of decisions taken outside of the shipping segment itself as well. This contains an evaluation of, for example, the suppliers and yards and their environmental footprint. Such metrics help to establish even better routines within the company and change the attitude of green thinking in all levels in the company.

The middle-aged vessels, planning to stay in operation for the next 20-30 years, have many opportunities when it comes to reducing emissions. Firstly, some of these vessels are already some years old and have not the newest design and thus emits a fear bit. The case study also suggested implementing the technical measures in an early phase of the period in combination with a retrofit. The continuity constraint in the model caused the early implementation and contributes to the total reduction in the long term as well. However, the uncertainty in the data used for OPEX, CAPEX and reduction effect must be taken into account. This may have influenced the selection of technical alternatives as auxiliary systems, new propeller and air lubrication systems instead of alternative fuels. Today's prices for alternative fuel as biogas is very high, and hard to justify a choice like this at this stage. Especially when it is the cargo owner that pays for it and cost minimisation is often a top priority. In addition to the high prices, are there also problems regarding today's poorly developed infrastructure and availability. With this in mind, is a reasonable approach to focus on the operational measures, in combination with the best developed technical ones. This means that measures as energy efficiency, voyage optimisation and speed reduction, if possible within the frame of the contracts, should have the main focus in the short-term. And then implement the new technology as batteries, biofuel or hydrogen as soon as this is possible for deep-sea shipping.

The motivation behind implementing a strategy like this, besides, reducing the CO_2 emissions and comply with today's regulation, is to be an attractive company for the investors and society and prepare for future stricter regulations. One of these stricter regulations can be the CO_2 tax. It is expected to be enforced globally and will increase annually. A trade-off between the costs of starting the process towards cutting the emissions now or wait and pay more tax must be evaluated. The company's carbon risk will also influence the decision. Golar operates in a fossil fuel industry and thus has a quite high carbon risk. This makes it even more critical to implement such a strategy and avoid a negative reputation by paying the company out of the ongoing environmental crisis. It is also a cost related to a negative reputation and being poorly liked by society and investors, which is desirable to avoid. Golar has started to reduce their CO_2-emissions and wants to take their part in the transformation towards a greener industry. That does not mean that they can implement all the best and most expensive technologies and actions now. A shipowner will always take the decisions from an economic perspective.

The CO_2-tax is a discussed topic with to much uncertainty for the organisational structure of it. To choose a solution with a close to business as usual operation with minimal reductions in CO_2 -emissions and paying the tax, can look like the most cost-effective solution. However, the cost of negative revenue and missing investments due to a poorly developed reduction strategy might be much higher in the long-term than the cost of implementing the measures.

The final recommendation will relay on two perspectives. Partly on the expectations and predictions for the future, regarding the development of the new technologies and infrastructures, and new and possibly stricter regulations. The second part relays on the different preferences in cost versus reduction and the level of ambition Golar wants to have. A decision of how much they are willing to pay to meet these ambitions is a strategical choice the top management has to make. Again is it hard to predict the future and the uncertainty is significant. These two perspectives will influence each other on the path to find the optimal result. The model gave an insight that stricter regulations and a higher level of ambitions resulted in higher costs. As a result, should the actions be implemented sooner. However, the problem is not that straight forward and has not an obvious answer, where the decision-basis can be flawed. Decisions are taken daily without knowing all of the information by the management. It should, therefore, not be a problem of making a decision based on the same information for environmental purposes. The process can also be handled dynamically with a more on-the-spot approach by having a minimal level of ambitions and wait to act before the upcoming regulations are confirmed. It is important to have in mind that this can be as expensive as being an early adopter and start the transformation right away. To summarise is it challenging to predict the future except the increasing focus on acting more environmentally friendly and cutting emissions, both in the shipping industry and the world in general.

8.1 Uncertainties in the Model and Input Data

There are different approaches to consider qualitative factors in the decision-making process. One solution is to do a weighting of different factors and barriers that have an impact on each of the abatement measures. Future regulations, risk of implementing the actions, uncertainty and maturity of new technologies, cost and associated emission reduction are some of the factors that have a vital role. The weighting will again be influenced by the risk profile and the shipowner's priorities. A risk-averse owner takes close to no risk, and the investment in new uncertain technology will not be considered. On the other side, are a risk-neutral or risk-prone owner one who prioritises opportunities in reducing emissions over the associated risk in the high cost. The model does only consider one vessel for each vessel group, based on the encouraging from IMO to look at the individual vessels. Thus, another option is to implement a strategy that focuses on the vessel types individually. Essential factors in such a division are age, engine types and operational pattern.

One of the critical risks is the development in new technology and when it is ready for deep-sea shipping. The initial cost related to these technologies is high because of the small-scale implementations and manufacturing, poor development or infrastructure. However, as soon as these technologies are fully scaled will also the initial cost decrease fast. The question of whether an owner should be an early adopter, upgrade and install a measure today or wait until it has been a requirement to have this measure on-board the vessel must be decided. Where the obvious answer, if the company has the economy and willingness to do so; yes they should.

There are some uncertainties regarding the cost and reduction effects in the input data for the different scenarios. The parameters can vary from the ones assumed here, but these parameters tell what type of information required in decision problems like this. These uncertainties are related to the challenge of assuming cost for technology not yet fully developed and matured. When information regarding cost and reduction effect is available, should also the associated input parameters and new and less uncertain knowledge and understanding are obtained.

A question to ask is whether a deterministic optimisation model is an appropriate tool for this type of problem. The decision problem has many uncertain factors, and it has not one correct solution. An alternative could have been to use a stochastic optimisation model in order to include the uncertainties. The decision problem is a combination of predictions for the future and the company's ambitions of cutting emissions versus cost, and thus challenging to model and get one correct answer. Nevertheless, formulating the problem as a deterministic model gives a structured overview of the problem. The definition of constraints and input parameters are helpful to obtain an understanding of the requirements, such as how goals and regulations play a critical part. Furthermore, knowing how the problem is changing over a time when the different factors as regulations and technology changes are key factors to understand. To obtain this type of knowledge of the problem is the deterministic optimisation model, a suitable tool and gives valuable insight to the overall problem.

8.2 Presentation of Recommended Overall Strategy

The last step in this design process is to present the overall goals and strategy for internal and external use. The strategy gives Golar a plan for the implementation of the measures, and the expected reduction over each time-period. The recommendations are based upon the insight the model gave for the different scenarios, and further adjusted by combining some of the results, to suit Golar's profile. The external plan represents the overall goals on the strategic level, as seen in figure 5.1, while the internal communication plan is on the tactical level. The plan of when and what types of measures to implement should be presented to all in the organisation to get an overview and understanding of Golar's emission reduction strategy.

A summary of the background information and assumptions for each of the strategy is made and can be seen in figure 8.1. Figure 8.2 shows the primary strategy, while figure 8.3 and 8.4 represents the alternative strategies considering specific scenarios for the development in technology and future regulations. The overall strategy assumes medium strict regulations, which represent stricter than today's IMO strategy. The reduction requirements used in the strategy can be seen in figure 7.1 in chapter 7. The alternative strategies are based upon stricter regulations than IMO's, while the first alternative has an optimistic approach regarding maturity in battery technology. The second alternative has a pessimistic path, assuming a high cost of hydrogen and biofuels throughout the period and the hybrid technology would not mature.

For the external communication will an overview of the chosen reduction goals and the associated pillars be presented in figure 8.5. The goals have a medium level of ambitions, which corresponds to beyond compliance with IMO's requirement. This is recommended for Golar to be one step ahead and prepared for stricter regulations in the future that are highly anticipated. It was decided not to define too many goals in order make sure these are achievable and easy for the employees to follow.

Once more must it be noted that the cost and reduction effects have high uncertainties and are based upon estimations and future predictions of the development in the different markets.

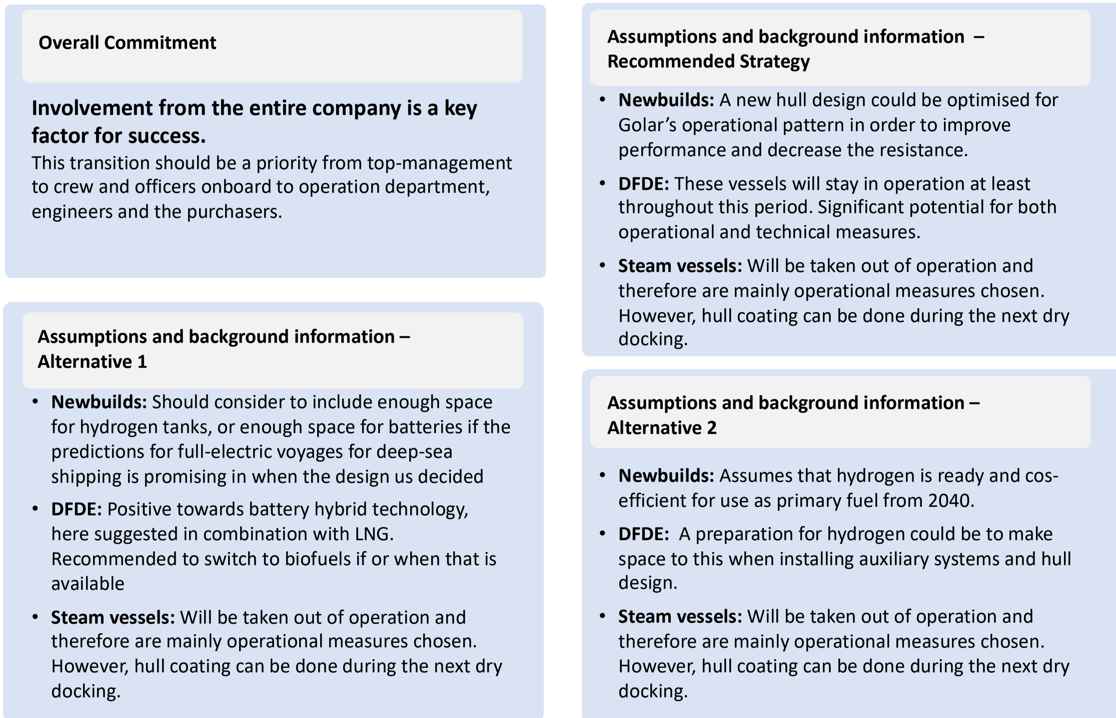


Figure 8.1: Assumptions and background information for the recommended strategy and the two alternatives

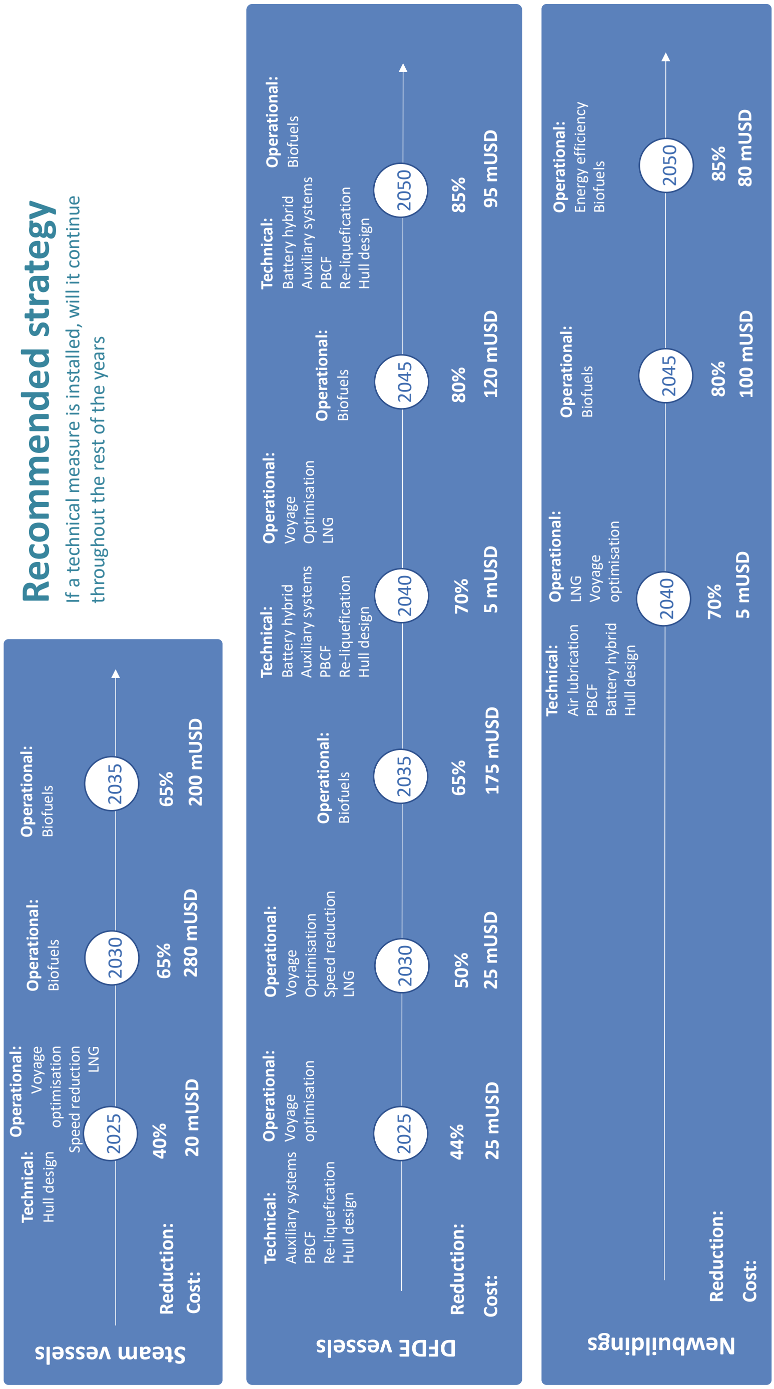


Figure 8.2: Recommended overall strategy

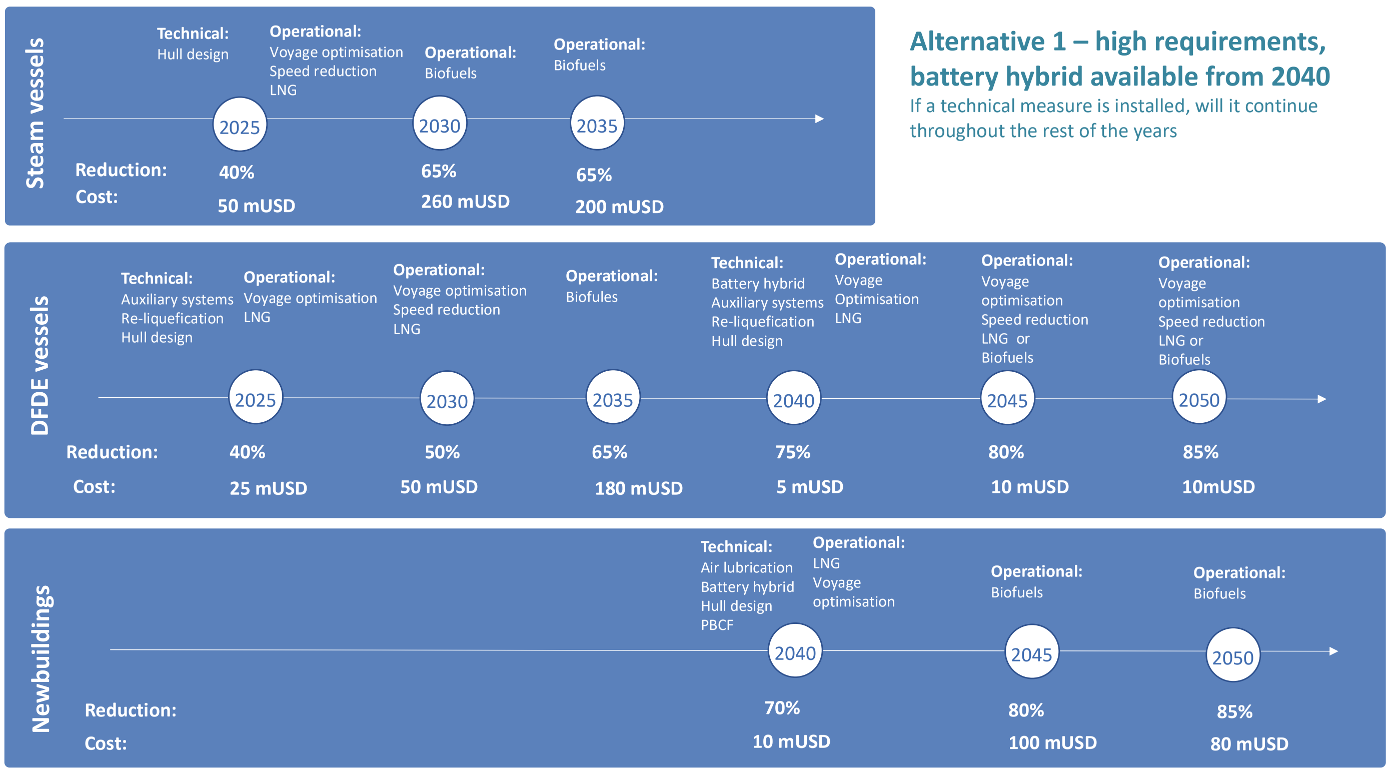


Figure 8.3: Alternative 1 - high requirements, battery hybrid available from 2040

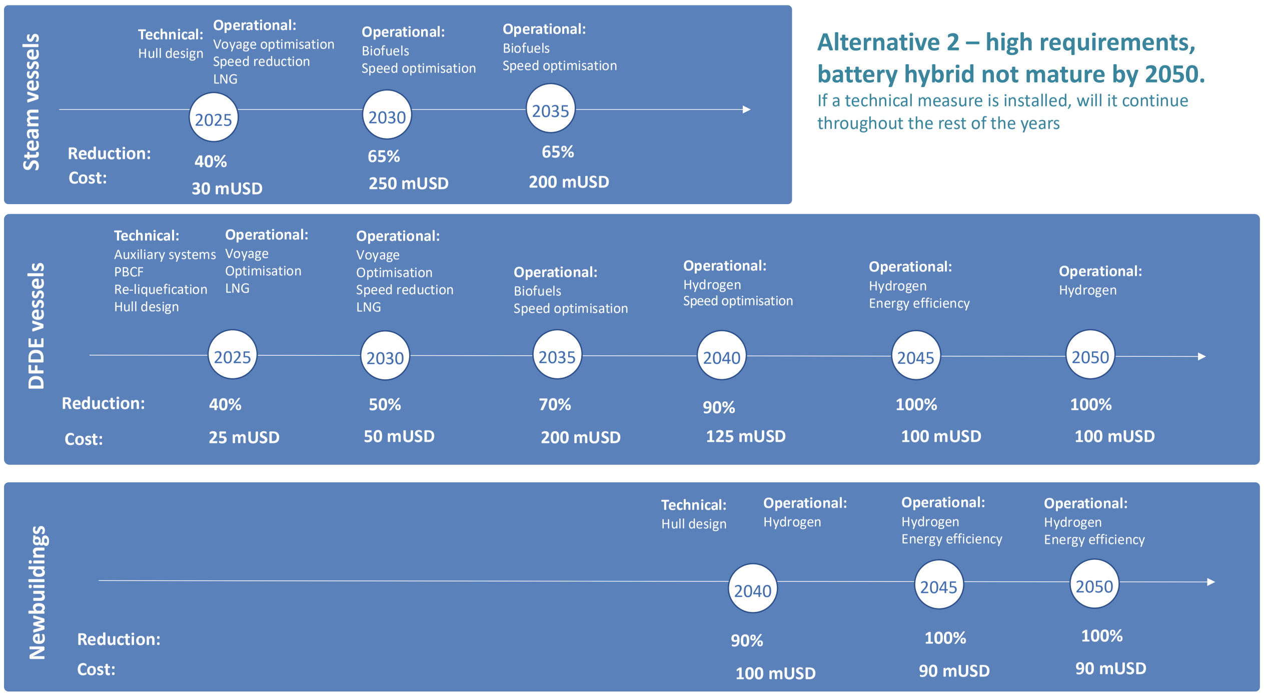


Figure 8.4: Alternative 2 - high requirements, battery hybrid not available by 2050

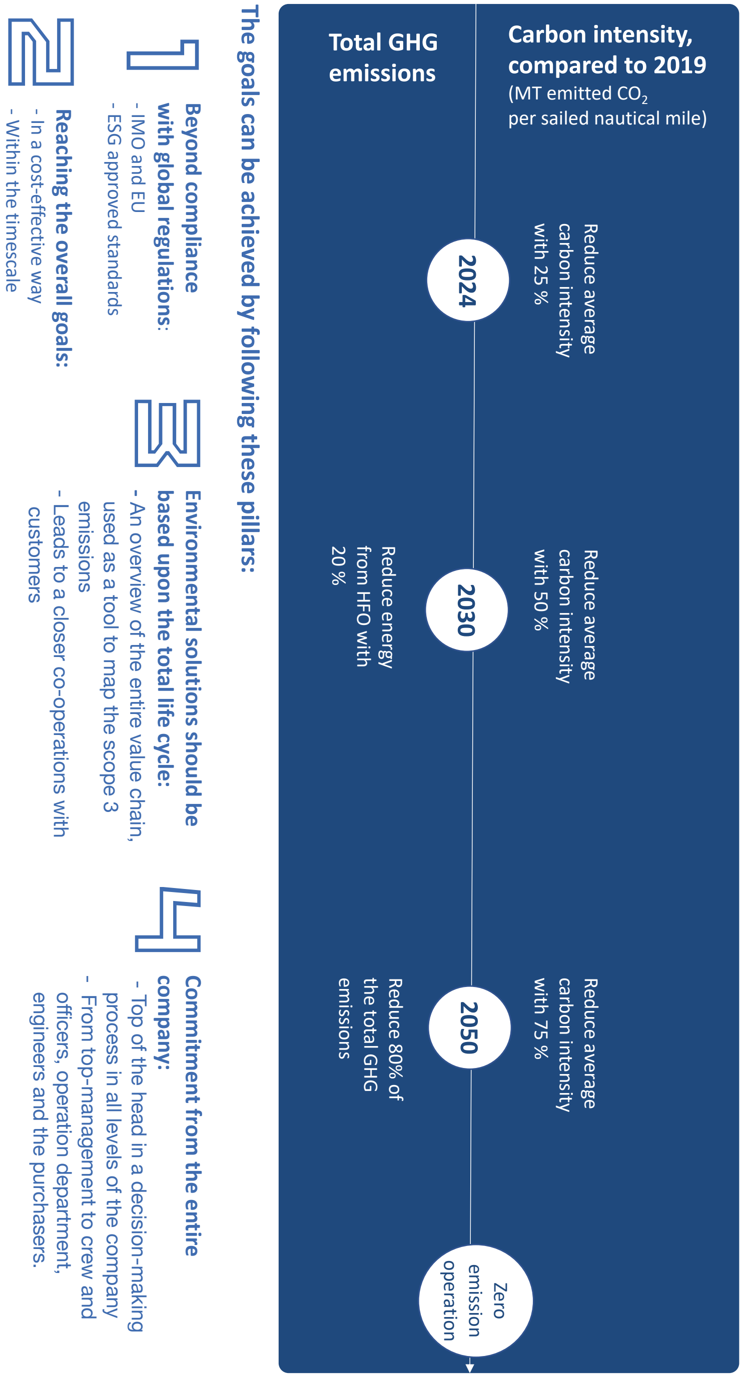


Figure 8.5: The recommended goals with associated pillars that should be followed to achieve the goals

Chapter 9

Conclusion and Further Work

This master thesis has developed and evaluated an overall strategy to reduce GHG emissions cost-effectively for Golar. An analysis of how different abatement actions and scenarios can influence the strategy in a long term perspective is conducted. A deterministic optimisation model was developed in order to take one step down from the strategic plane to a tactical plane, and investigate each of the chosen abatement actions. The objective function is minimising cost, while the main constraints ensure compliance with GHG emission regulations and Golar's goals for emission reduction.

The results from the analysis give the shipowner an insight into the field of reducing GHG emissions. The development of new technology must go faster if the industry, as a total, is going to achieve IMO's requirements must. The cost, and especially for zero-emission fuels, need to fall and become competitive with fossil fuel.

The state-of-the-art study provided information about the operational and technical abatement actions, in addition to today's most relevant and also upcoming regulations not yet forced into action. The most relevant standards and measures from the ESG-reporting system were also conducted. The ESG measures, like the gross global scopes, are a helpful tool for systematising and calculate the total emissions. At the same time, IMO regulations require a reduction in both carbon intensity and total GHG emission for a vessel and on a fleet level. These are mandatory regulations a shipowner has to follow. To summarise the findings from the abatement actions are the technologies and alternative fuels still in the start phase of its development. The infrastructure is weak, particularly for deep-sea shipping. Operational measures like voyage optimisation and speed reduction can give a medium potential reduction effect with associated low costs. Hence, these measures are essential for the short-term perspective. On the other side is such measures highly dependent on the market and the commercial side.

Three goal formulations were developed based on the regulations from IMO and the EU and Golar's CO_2-emission data and their previous work on this field. The final recommendation was the medium level of ambition and thus beyond compliance with the regulations. The purpose is to be prepared for stricter regulations in the future, which are highly anticipated. Four pillars were also developed for Golar to use as a support for their commitment to the goals. Further, was a starting set developed. This set is based on the knowledge obtained from the state-of-the-art study, the proposals of the different ambitious goals and the most promising actions relevant for Golar. The starting set was further used as a basis for the input parameters to the decision model.

The deterministic optimisation model gave a valuable insight into the decision problem of selecting abatement actions to a minimum cost. The aim was to structure the problem to reveal what the shipowner's decisions are constrained by, and the required information to support the decisions. This model was deterministic and not considering uncertainties, even though this problem is highly connected to the future and the uncertainties of new technology and regulations. This was to some extend handled by different scenarios where future requirements and development in new technology were taken into account. The case study had six different scenarios the development in battery technology as a reference. Battery hybrid, in combination with LNG or alternative fuels, were mostly selected. In the scenario where the battery technology has not matured for deep-sea shipping by 2050, was hydrogen as primary fuel selected. To meet the long-term requirements did the results clearly show that new zero-emission technology and alternative fuels must get available.

A conclusion to draw is that a combination of technical and operational actions must be implemented in order to reduce CO_2-emissions and achieve the requirements from the policymakers and internal goals. Today's status quo regarding new technology and zero-emission fuels shows that they are not ready for deep-sea shipping shortly and therefore not cost-efficient to invest in such measures. Moreover, the shipowner must be willing to invest in such technology and more expensive fuel alternatives. Such an investment is related to a reduction of emission and contribute to driving the development in the industry further. In the short-term perspective is measures as hull coating, air lubrication systems, new auxiliary systems and speed reduction ready to be implemented. They have relatively low cost and the low to medium associated reduction effects enough to achieve the short-term goals and regulations.

9.1 Further Work

During the work with this thesis has it emerged several interesting aspects that could have been included in the work.

Firstly, could it be interesting to expand the model to a stochastic optimisation problem. Then the probability of different scenarios would be taken into account in the model. This could give an even more in-depth insight into the problem and the changes over time. An additional area is also to expand the different scenarios where the variation in cost could have a more significant focus.

The machinery configuration could either be included in more detailed or explored as a individual case. It is interesting to see the requirements and set-up in machinery systems, room and required space and equipment for the different technologies. And further how the initial- and operational cost picture would looked like and potential reduction effect.

Fleet renewal versus retrofitting could be included as an option within one vessel group. This may influence the total emission picture, which also could be looked at, in addition to a per vessel basis. Adding this can give another perspective to the problem, and the recommended strategy might change with those expansions.

A more detailed investigation of the interaction effects and the IMO groups is a field that needs more study. The IMO groups are established to avoid the effect of the interaction between the measures within one group. The order of implementation of the different actions can also influence each other and the reduction effects to some degree.

A compelling case to look deeper into is voyage optimisation and speed reduction. By including the commercial side and the effects, they see by implementing such measures. The cost of the voyage being longer and the problem regarding who should pay for this extra cost. An extra cost both loss in freight and also crew costs. This can be tested with different speeds by using the speed - fuel consumption curve.

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A - Needs, functions and form - Table

Table 9.1: Part 1: Needs, function and form overview

Needs	Functions	Form
1. Reduce GHG emissions	Alternative fuels towards zero emissions	Infrastructure and availability LNG Biofuels Hydrogen and Ammonia Technological development
	Operational control	Speed reduction Voyage optimisation Engine loading Vessel trim monitoring GHG emission management Fleet management
	Fleet	Newbuilding Retrofitting
	Uncertainties/ Climate related risk	New technology Cost Major shift in consumer behaviour Future regulations
	New technology	Alternative fuel Batteries Battery hybrid power systems Machinery for alternative fuel
	Cost	Beneficial for ship owners Fuel prices New technologies Installing/changing to CO_2 reduction equipment Operational changes
	Energy Management	Reduce energy efficiency measures New energy efficient design Energy from renewable Reduction in fuel consumption
	New design	Energy efficient newbuldings Hull shape Vessel size Cost Design speed Hull Coating

Table 9.2: Part 2: Needs, function and form overview

Needs	**Functions**	**Form**
2. Comply with regulations and ESG standards	New regulations from policy makers	Carbon tax Fuel tax Stricter requirements for CO_2 emission Extension of EU MRV system Cost beneficial to use low emission fuel Stricter regulations
	ESG standards and measures	Gross global scope 1 and 2 Consider scope 3 GHG emissions

B - Deep-Sea all-electric vessel, an example calculation

Size	Value	Unit	Comment
Vessel size	300000	dwt	
Tonnes bunkers today	1500	tonn	HFO or similar
Energy density	42.7	GJ/tonn	BTU
Energy density	11.9	MWh/tonn	
Energy density	11.9	kWh/kg	
Saved energy onboard	17792	MWh	BTU
Efficiency engine	45 %		
Saved usable energy onboard	8006	MWh	
Factor improvement	3		
Specific volumetric energy density	1.5	kWh/l - MWh/m3	
Specific gravimetric energy density	0.6	kWh/kg - MWh/tonn	
Volume batteries	**5338**	**m3**	
Weight batteries	**13344**	**tonn**	
40' - 1,5 MWh, 67,7 m3	0.0222	MWh/m3	
	361349	m3	1,5 MWh i 40' container
	80063	tonn	15 tonn per 40'
	5338	**number of containers**	

Figure 9.1: Deep-sea all-electric vessel - an example calculation

C - Optimisation Code in Python

```
import pandas as pd
import gurobipy as gp
from gurobipy import GRB
import numpy as np


# Read input data, Medium-low ambitious
excel_file = "input_ref.xlsx"
df = pd.read_excel(excel_file)

df_input = pd.read_excel(excel_file, sheet_name=1)
df_reg = pd.read_excel(excel_file, sheet_name=8)
df_goals = pd.read_excel(excel_file, sheet_name=9)
df_inter_eff = pd.read_excel(excel_file, sheet_name=2,
                             header=None)
df_inter_eff1 = pd.read_excel(excel_file, sheet_name=2)
df_inter_cost = pd.read_excel(excel_file, sheet_name=3,
                              header=None)
df_inter_cost1 = pd.read_excel(excel_file, sheet_name=3)

# ---------------------------------------------------------
# ---------------------- SETS -----------------------------
# ---------------------------------------------------------

set_actions = [rows.Action_int
               for index, rows in df.iterrows()]
set_VG = [rows.Vessel_Groups
          for index, rows in df.iterrows()
          if rows.Vessel_Groups != "None"]
set_TP = [rows.Time_Periods
          for index, rows in df.iterrows()
          if rows.Time_Periods != "None"]

# ---------------------------------------------------------
# -------------------- PARAMETERS -------------------------
# ---------------------------------------------------------

M = 10000

indicator_var = {rows.Action_int: rows.Indicator_Var
                 for index, rows in df.iterrows()}
```

```
# -------------------------- Cost -------------------------
# Operational cost for actions i in vessel group v
cost_tot = {(rows.Action_int, rows.Vessel_Group,
             rows.Time_Period): rows.OPEX
            for index, rows in df_input.iterrows()}


# Installation cost for implement action i on
# vessel group v in time period t
cost_inst = {(rows.Action_int, rows.Vessel_Group,
              rows.Time_Period): rows.CAPEX
             for index, rows in df_input.iterrows()}

# ----------------- Reduction effect ----------------------
# Reduction for actions i in vessel group v

red_effect = {(rows.Action_int, rows.Vessel_Group,
               rows.Time_Period): rows.Reduction
              for index, rows in df_input.iterrows()}


# ----------------------- Goals ----------------------------

goals_red = {(rows.Vessel_Group, rows.Time_Period):
                 rows.Goals_ref_Carbon
             for index, rows in df_goals.iterrows()}


# --------------------- Regulations -----------------------
# Regulation and requirements [% reduction]
# total for each time period

req_step1 = df_reg[["Time_Period",
                    "Reduction_Req_high"]].dropna()
reg_req = {rows.Time_Period: rows.Reduction_Req_high
           for index, rows in req_step1.iterrows()}


# ---------------- Interactions Effects --------------------

inter_step1 = df_inter_eff.values[1:, 1:]
inter_eff = {(idx[0], idx[1], rows2, rows): x
             for idx, x in np.ndenumerate(inter_step1)
```

```
             for rows2 in set_VG
             for rows in set_TP}

# -----------------------------------------------------------
# ----------------------- MODEL ----------------------------
# -----------------------------------------------------------

# Create a new model
m = gp.Model("master1")

# ------------------- DECISION VARIABLES -------------------

x_ivt = m.addVars(((i, v, t)
                   for i in range(len(set_actions))
                   for v in set_VG for t in set_TP),
                  vtype=GRB.BINARY, name="x_ivt")

y_ivt = m.addVars(((i, v, t)
                   for i in range(len(set_actions))
                   for v in set_VG for t in set_TP),
                  vtype=GRB.BINARY, name="y_ivt")

z_ij = m.addVars(((i, j, v, t)
                  for i in range(len(set_actions))
                  for j in range(len(set_actions))
                  for v in set_VG for t in set_TP),
                 vtype=GRB.BINARY, name="z_ij")


# ------------------- SET OBJECTIVE ------------------------

objective = (gp.quicksum(cost_tot[i, v, t] * x_ivt[i, v, t]
                         for i in set_actions
                         for v in set_VG
                         for t in set_TP)
             + gp.quicksum(cost_inst[i, v, t] * y_ivt[i, v, t]
                           for i in set_actions
                           for v in set_VG
                           for t in set_TP)
             )

m.setObjective(objective, GRB.MINIMIZE)
```

```python
# -------------------- ADD CONSTRAINTS ---------------------
# 1) The reduction goal for each time
# period and vessel group is realised and the
# total reduction is bigger or equal to the goals.

m.addConstrs(((gp.quicksum(
    red_effect[i, v, t] * x_ivt[i, v, t]
    for i in set_actions for v in set_VG)
               -
               gp.quicksum(
                   inter_eff[i, j, v, t] * z_ij[i, j, v, t]
                   for i in set_actions
                   for j in set_actions
                   if j > i
                   for v in set_VG
               )
               )
              >= reg_req[t] for t in set_TP), name="Req")

# 2) The implemented action must satisfy the regulations

m.addConstrs(((gp.quicksum(red_effect[i, v, t]
                           * x_ivt[i, v, t]
                           for i in set_actions)
               -
               gp.quicksum(
                   inter_eff[i, j, v, t]
                   * z_ij[i, j, v, t]
                   for i in set_actions
                   for j in set_actions
                   if j > i
               )
               )

              >= goals_red[v, t]
              for v in set_VG
              for t in set_TP), name="Goals")

# 3) Linking the interaction variable to the implementation
# variable

m.addConstrs((x_ivt[i, v, t] + x_ivt[j, v, t] - 1
              <= z_ij[i, j, v, t]
```

```
                 for i in set_actions
                 for j in set_actions
                 for v in set_VG
                 for t in set_TP), name="LinkBin1")

m.addConstrs((x_ivt[i, v, t] + x_ivt[j, v, t]
                 >= 2 * z_ij[i, j, v, t]
                 for i in set_actions
                 for j in set_actions
                 for v in set_VG
                 for t in set_TP), name="LinkBin2")

# 4) Action continuity constraint

m.addConstrs((x_ivt[i, v, t] - x_ivt[i, v, (t - 1)]
                 - M * (indicator_var[i] - 1)
                 >= 0
                 for i in set_actions
                 for v in set_VG
                 for t in set_TP[1:]), name="Continuity")

# 5) The investment and installation cost (CAPEX) will
# only be
# accounted for the first time
# the action is implemented.

m.addConstrs((gp.quicksum(y_ivt[i, v, t1]
                               for t1 in range(0, t + 1))
                 >= x_ivt[i, v, t]
                 for i in set_actions
                 for v in set_VG
                 for t in set_TP), name="CAPEX")

m.addConstrs((y_ivt[i, v, t - 1]
                 <= x_ivt[i, v, t - 1]
                 for i in set_actions
                 for v in set_VG
                 for t in set_TP[1:]), name="CAPEX2")


# ----------------------------------------------------------
# ---------------------- SOLVING THE MODEL -----------------
# ----------------------------------------------------------
m.optimize()
```

D - Results from the Case Study

Table 9.3: Results from scenario 2, batteries are not available on the market by 2050

Objective value:	1300 million USD	
Vessel type	Abatement Actions	Implementation Period
Steam	Biofuels	1,2
	Hull design	0,1,2
	Speed reduction, 2 knots	0
	LNG	0
	Voyage optimisation	0
DFDE	Biofuels	2
	Hydrogen	3,4,5
	Hull design	0,1,2,3,4,5
	Speed reduction, 2 knots	1
	LNG	0,1
	Propeller boss cap fin	1,2,3,4,5
	Voyage optimisation	0,1
	Auxiliary systems	0,1,2,3,4,5
	Re-liquefaction	0,1,2,3,4,5
Newbuilding	Hydrogen	3,4,5

Table 9.4: Results from scenario 3, high requirements and batteries are available for full-electric use in 2045

Objective value:	1100 million USD	
Vessel type	Abatement Actions	Implementation Period
Steam	Biofuels	1,2
	Hull design	0,1,2
	Speed reduction, 2 knots	0
	LNG	0
	Voyage optimisation	0,1
DFDE	Biofuels	2
	Hydrogen	3,4,5
	Hull design	0,1,2,3,4,5
	Speed reduction, 2 knots	1
	Energy efficiency measures	4
	LNG	0,1
	Propeller boss cap fin	0, 1,2,3,4,5
	Voyage optimisation	0,1
	Auxiliary systems	0,1,2,3,4,5
	Re-liquefaction	0,1,2,3,4,5
Newbuilding	Biofuels	3
	Batteries	4,5
	Energy efficiency measures	4
	LNG	4
	Air Lubrication system	3,4,5
	Propeller boss cap fin	3,4,5
	Voyage optimisation	3

Table 9.5: Results from scenario 4, reduced reduction effect, low regulations and goals and battery hybrid from 2040

Objective value:	1100 million USD	
Vessel type	Abatement Actions	Implementation Period
Steam	Biofuels	1,2
	Hull design	0,1,2
	Speed reduction, 2 knots	0
	Voyage optimisation	0
DFDE	Biofuels	2
	Hydrogen	3,4,5
	Speed reduction, 2 knots	1,2
	Energy efficiency measures	3,4
	LNG	0,1,2
	Air Lubrication system	0,1,2,3,4,5
	Propeller boss cap fin	1,2,3,4,5
	Voyage optimisation	0,1,2
	Auxiliary systems	0,1,2,3,4,5
	Re-liquefaction	0,1,2,3,4,5
Newbuilding	Hydrogen	3,4,5
	Energy efficiency measures	4

Table 9.6: Results from scenario 5, battery hybrid available from 2035

Objective value:	900 million USD	
Vessel type	Abatement Actions	Implementation Period
Steam	Biofuels	1,2
	Hull design	0,1,2
	Speed reduction, 2 knots	0
	LNG	0
	Voyage optimisation	0
DFDE	Biofuels	4,5
	Hull design	0,1,2,3,4,5
	Speed reduction, 2 knots	1
	Battery hybrid	2,3,4,5
	Energy efficiency measures	2
	Propeller boss cap fin	0, 1,2,3,4,5
	LNG	0,1,3
	Voyage optimisation	0,1,3
	Auxiliary systems	0,1,2,3,4,5
	Re-liquefaction	0,1,2,3,4,5
Newbuilding	Biofuels	4,5
	Hull design	3,4,5
	Battery hybrid	3,4,5
	LNG	3
	Air Lubrication system	3,4,5
	Propeller boss cap fin	3,4,5
	Voyage optimisation	3

Table 9.7: Results from scenario 6, increased reduction effects, high regulations with battery hybrid from 2040

Objective value:	900 million USD	
Vessel type	Abatement Actions	Implementation Period
Steam	Biofuels	1,2
	Hull design	0,1,2
	Speed reduction, 2 knots	0
	LNG	0
	Voyage optimisation	0
DFDE	Biofuels	2
	Hull design	0,1,2,3,4,5
	Speed reduction, 2 knots	1,4,5
	Battery hybrid	3,4,5
	LNG	0,1,3,4,5
	Voyage optimisation	0,1,3,4,5
	Auxiliary systems	0,1,2,3,4,5
	Re-liquefaction	0,1,2,3,4,5
Newbuilding	Biofules	4,5
	Hull design	3,4,5
	Battery hybrid	3,4,5
	LNG	3
	Air Lubrication system	3,4,5
	Voyage optimisation	3