Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Economics and Management
Dept. of Industrial Economics and Technology Management

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Strategic Fleet Renewal of Norwegian Fisheries with Environmental Considerations

Master's thesis in Industrial Economics and Technology Management
Supervisor: Peter Schütz
Co-supervisor: Mohamed Kais Msakni
June 2023

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Preface

This Master's thesis marks the conclusion of my studies at the Norwegian University of Science and Technology (NTNU). The thesis has been written in partial fulfilment of the requirements for the degree of Master of Industrial Management with a specialization in Applied Economics and Optimization. The work has been conducted during the spring semester of 2023 and is written in collaboration with the ZeroKyst project.

I would like to express my sincerest gratitude to my supervisors Associate Professor Peter Schütz and Doctor Mohamed Kais Msakni, both by the Department of Industrial Economics and Technology Management (IØT) at NTNU, for their invaluable guidance, support and thorough feedback during my work. Thank you for contributing your time and expertise to this thesis. I would also like to thank Torstein Aarseth Bø, Researcher for SINTEF Ocean - Energy and Transport, for all the time he set aside in order to help me develop a realistic case study through in-depth discussions on the Norwegian fishing fleet, propulsion systems and the possibilities inherent in future technology. Finally, I would like to thank my family and friends for their unwavering support and encouragement throughout my studies at NTNU.

The ongoing ZeroKyst project is working to implement a green technology change in the fisheries and aquaculture industry. The project aims to demonstrate that both new and existing vessels in the seafood industry can become zero-emission, and contribute to a 50% cut in CO2 emissions from fishing and aquaculture vessels by 2030. I hope that this thesis will contribute to this work and that it may prove useful to researchers, practitioners, and policy-makers alike.

Trondheim
11^{th} of June 2023

Helle Hagli Sønnervik

Abstract

Under the Paris Agreement Norway has committed to reducing Greenhouse Gas Emissions (GHG) by at least 55% by 2030 compared to 1990 levels. Additionally, Norway has a legally binding goal to become a low-emission society by 2050, aiming for a 90-95% reduction in emissions compared to 1990 levels. Norwegian industries, including the fisheries sector, face increasing pressure to reduce their climate impact. As a significant contributor to Norway's total CO2 emissions, Norwegian fisheries play a crucial role in achieving national climate goals. To meet these challenges, a comprehensive effort is needed to implement low- and zero-emission solutions in the Norwegian fishing fleet. ZeroKyst is a project that aims to contribute to a 50% emissions reduction from fishing and aquaculture vessels by 2030. This is accomplished through the development of a hybrid zero-emission powertrain and vessel that incorporates battery and fuel cell technology.

For this master's thesis, we formulate and solve a mathematical optimization problem for the strategic renewal of the Norwegian fishing fleet in order to provide decision support to decision-makers. We formulate the deterministic Fishing Fleet Renewal Problem with Emission Constraints (FFRPEC), which takes into account emission reduction targets for the period 2023-2050. The objective is to minimize the discounted total costs associated with fleet renewal and operation of the Norwegian fishing fleet. From solving the model, we obtain a detailed schedule specifying the timing of replacing a certain number of vessels with a specific propulsion system within a sub-fleet, as well as the propulsion system to be used as a replacement.

The parameter values used in the model are calculated using data regarding the existing fishing fleet and cost information associated with propulsion system components and associated energy storage, such as combustion engines, batteries and fuel cells. We conduct an extensive scenario analysis on uncertain parameters such as the fuel prices of Marine Gas Oil (MGO), battery power, hydrogen and ammonia, CO2 tax price-trajectories, costs of the mentioned propulsion system components, as well as shipyard capacities. The analysis aims to identify the potential impact of the relevant parameters on the resulting fleet renewal schedule.

We highlight three key findings from our analysis:

(1) *Zero-emission propulsion is economically unfavourable*

(2) *Penalizing the use of conventional fuel incentivizes earlier renewal of the fleet*

(3) *Immediate action must be taken to initiate the renewal of the ocean-going fishing fleet to achieve emission reduction targets in a cost-effective manner*

Sammendrag

Norge har under Parisavtalen forpliktet seg til å redusere utslippene av klimagasser med minst 55% innen 2030 sammenliknet med utslippsnivået i 1990. I tillegg har Norge et lovfestet mål om å bli et lavutslippssamfunn innen 2050 hvilket innebærer en utslippsreduksjon på 90-95% sammenliknet med utslippsnivået i 1990. Norsk industri, inkludert fiskerinæringen, står derfor overfor økende press for å redusere sin klimapåvirkning. Som en betydelig bidragsyter til norges totale utslipp, spiller norsk fiskeri en viktig rolle i å oppnå nasjonale klimamål. For å møte disse utfordringene er det nødvendig med en omfattende innsats for å implementere lav- og nullutslippsløsninger i den norske fiskeflåten. ZeroKyst er et pågående prosjekt som ønsker å bidra mot 50% utslippskutt fra fiskeri- og havbruksfartøy innen 2030. Dette gjøres blant annet gjennom utviklingen av en hybrid nullutslipps drivlinje og -fartøy, bestående av batteri og brenselcelleteknologi.

I denne masteroppgaven formulerer vi og løser et matematisk optimeringsproblem for strategisk fornyelse av den norske fiskeflåten for å kunne gi beslutningsstøtte til sentrale beslutningstakere. Vi definerer det deterministiske Fornyelsesproblemet for Fiskeflåten med Utslippsrestriksjoner (FFRPEC), som hensyntar mål for utslippsreduksjon i perioden 2023-2050. Objektivet er å minimere den diskonterte totale kostnadene knyttet til fornyelsen og drift av den norske fiskeflåten. Ved å løse modellen oppnår vi en detaljert plan som angir tidspunktet for utskifting av et bestemt antall fartøy med et spesifikt fremdriftssystem innenfor en sub-flåte, samt hvilket fremdriftssystem som skal benyttes som erstatning.

Parameterverdiene som benyttes i modellen er beregnet ved hjelp av data vedrørende den eksisterende fiskeflåten og kostnadsinformasjon knyttet til fremdriftssystemkomponenter og tilhørende energilagring, som forbrenningsmotorer, batterier og brenselceller. Vi gjennomfører en omfattende scenarioanalyse av usikre parametere som prisene på marin gassolje (MGO), batterikraft, hydrogen og ammoniakk, prisbaner for CO2-avgift, kostnader av nevnte fremdriftssystemkomponenter, samt verftskapasitet. Analysen tar sikte på å identifisere den potensielle effekten de relevante parametrene har på den resulterende flåtefornyelsesplanen.

Vi fremhever tre nøkkelfunn fra vår analyse:

(1) *Bruk av nullutslipps fremdriftssystemer er økonomisk ugunstig*

(2) *Å straffe bruken av konvensjonelt drivstoff incentiverer tidligere fornyelse av flåten*

(3) *Fornyelsen av havfiskeflåten bør initieres umiddelbart for å oppnå utslippsreduksjonsmål på en kostnadseffektiv måte*

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List of Abbreviations

B&B Branch-and-Bound

B&C Branch-and-Cut

CAPEX Capital Expenditures

COP Conference of the Parties

DP Dynamic Programming

ECA Emission Control Area

EEA European Economic Area

ESR Effort Sharing Regulations

EU-ETS EU Emissions Trading System

FFRPEC Fishing Fleet Renewal Problem with Emission Constraints

FRP Fleet Replacement Problem

GHG Greenhouse Gas Emissions

IEA International Energy Agency

IP Integer Programming

LHV Lower Heating Value

LNG Liquid Natural Gas

LP Linear Programming

MARPOL International Convention for the Prevention of Pollution from Ships

MFRP Maritime Fleet Renewal Problem

MFSMP Maritime Fleet Size and Mix Problem

MGO Marine Gas Oil

MIP Mixed-Integer Programming

O&M Operation and Maintenance

OPEX Operational Expenditures

OR Operational Research

PFRP Parallel Fleet Replacement Problem

PRP Parallel Replacement Problem

RSW Refrigerated Sea Water

SRP Series Replacement Problem

VRP Vehicle Routing Problem

Chapter 1

Introduction

Every year, the fishing industry is responsible for great value creation through significant export revenues and employment effects. As of today, more than 5,600 fishing vessels participate in the capture of fish within Norway's maritime borders. However, the Norwegian fishing fleet contributes to significant CO2 emissions through the combustion of Marine Gas Oil (MGO) used for propulsion and auxiliary power. According to the Directorate of Fisheries, the total CO2 emissions from the Norwegian fishing fleet amounted to 1.1 million tonnes in 2021, corresponding to ∼2.7% of Norway's yearly emissions of CO2 and other greenhouse gases (SSB, 2023).

Norwegian Climate Policy

Norwegian climate policy is closely linked to the one of the EU through the European Economic Area (EEA) agreement and the EU Emissions Trading System (EU-ETS) that Norway has participated in since 2008. In 2019, Norway entered into a climate agreement with the EU, submitted to the Paris Agreement, to reduce net Greenhouse Gas Emissions (GHG) emission by at least 40% from 1990 to 2030. Today, both the EU and Norway have submitted reinforced emission reduction targets, and the EU has presented its climate package *Fit for 55.* Fit for 55 was presented in July 2021 by the EU commission and is a legally binding climate change package that commits EU and EEA member states to reduce net GHG emissions by at least 55% by 2030, compared to 1990-levels (Regjeringen, 2023). Additionally, Norway's Climate Act states that Norwegian emissions must be cut by 90-95% by 2050, compared to 1990-levels (Norsk Klimastiftelse, 2022).

A distinction is made between quota-obliged and non-quota-obliged emissions. Most of the emissions from oil and gas extraction, industry, and aviation are subject to quotas, i.e. they are covered by the EU-ETS (Miljødirektoratet, 2023). The goal of Fit for 55 is that the quota system will contribute to a 61% emission reduction in 2030 compared to 2005 (Miljødirektoratet, 2021). Non-quota obliged emissions, on the other hand, are not included in EU-ETS and include GHG emissions from transport, agriculture, heating in buildings, and fisheries. These emissions are regulated through, for example, taxes, fees, subsidies, and other schemes that lead to lower emissions. Individual countries do not have targets for reducing quota-obliged emissions as these are market-driven. Consequently, the focus is often on the non-quota obliged emissions in analyzes of which measures and tools can be implemented to reduce emissions nationally (Miljødirektoratet, 2023).

For Norway, the EEA cooperation with the EU entails an obligation to keep emissions in the non-quota sector, including the fishing industry, below a given overall level in the period 2005-2030. The level is determined through the EU's Effort Sharing Regulations (ESR) which is being revised through the Fit for 55 package. The current effort distribution obliges Norway to cut non-quota emissions by 40% by 2030 from 2005 levels. However, if Norway is to participate in the enhanced version of the effort distribution, Norway will receive an obligation to cut emissions by 50% in the non-quota sector (Regjeringen, 2023).

The ZeroKyst Project

In order for the Norwegian fishing industry to contribute to Norway's emission reduction targets for 2030 and 2050, several actors have joined forces on the so-called ZeroKyst project. The project is a collaboration between industry (shipbuilders, shipyards, energy, and infrastructure suppliers), municipalities, and research partners such as SINTEF and NTNU, with Selfa Arctic AS as the project owner. The project aims to contribute to a 50% emissions reduction from fishing and aquaculture vessels by 2030 and has a value creation potential of 100 billion NOK. ZeroKyst deals with developing and constructing zero-emission vessels, a zero-emission propulsion system, and developing necessary services for the fisheries and aquaculture industry. Additionally, the project deals with the construction of regional infrastructure in Lofoten onshore power and hydrogen supply (ZeroKyst, 2023). ZeroKyst consists of five sub-projects with an associated objective:

- **Zero-emission propulsion system** - Develop a flexible and standardized propulsion system to be sold for use in over 6,000 vessels in the fishery and aquaculture industry
- **Zero-emission vessels** - Develop and demonstrate a zero-emission vessel concept
- **Flexible and competitive hydrogen supply** - Develop solutions for production, storage, and bunkering of hydrogen to ensure a predictable supply to the maritime sector. Develop circular solutions to enable fish hatcheries to utilize heat and oxygen from hydrogen production plants
- **Regional energy infrastructure** - Develop and implement infrastructure for zero-emission energy, adapted to the fishing flotilla's operations, with a possible expansion to other vessel categories
- **Collaborative and knowledge-building project** - Develop technology, models and analyses of propulsion systems, infrastructure, security and sustainability, to enable a 50% emissions reduction from fishing and aquaculture vessels by 2030

Figure 1.1 demonstrates the deliveries of the five sub-projects of ZeroKyst.

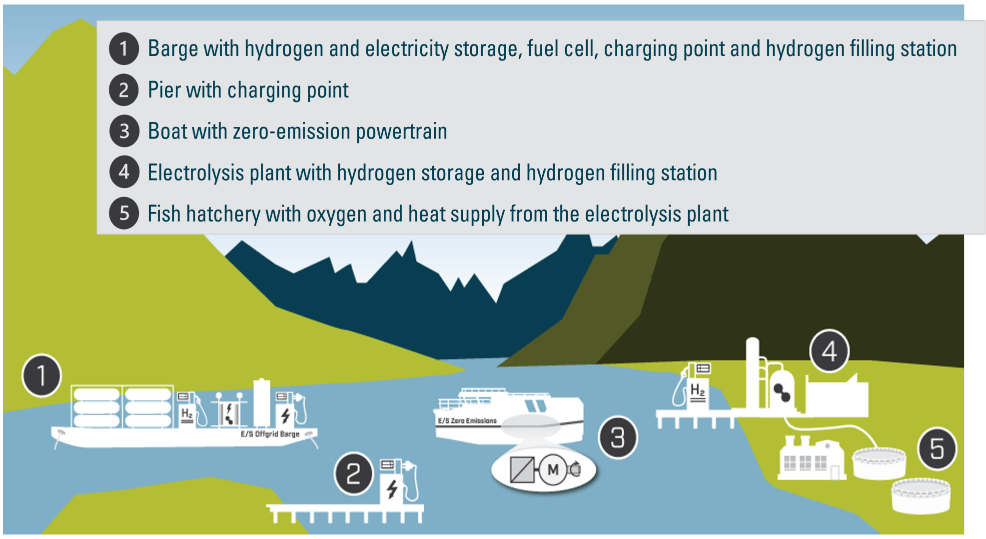


Figure 1.1: Illustration of the ZeroKyst project with solutions for electric-hydrogen hybrid vessels, mobile energy supply and infrastructure in Lofoten (ZeroKyst, 2023).

In order to comply with the Norwegian Climate Act and ZeroKyst's emission reduction targets, a growing share of the Norwegian fishing fleet must become low- and zero-emission. Nevertheless, the lifespan of Norwegian fishing vessels implies that renewals must happen earlier than the vessels' economic lifetime in order to meet emission reduction targets. This creates strategic challenges related to determining the optimal utilization time of a specific vessel and in what way the relevant vessel may be renewed.

This thesis starts by presenting useful background information regarding the Norwegian fishing industry, including fishing gear and vessels in today's fishing fleet, emissions, and propulsion alternatives in Chapter 2. In Chapter 3, the strategic problem is set into a theoretical perspective when we introduce relevant literature within the field of Operational Research (OR). Chapter 4 presents the problem description, while Chapter 5 presents the mathematical formulation of the Fishing Fleet Renewal Problem with Emission Constraints (FFRPEC), as well as the and modelling assumptions. In Chapter 6 all aspects of the work done prior to the FFRPEC are presented in a case study. This includes all the calculations made to form a data basis and parameter values for the problem. Furthermore, the computational study is presented in Chapter 7. Lastly, suggestions for future research and concluding remarks are presented in Chapter 8.

Chapter 2

Background

This chapter provides an overview of key aspects associated with the fleet renewal of Norwegian fisheries. In Section 2.1, the Norwegian fishing industry is presented in relation to value creation, fishing gear and the characteristics of the current fishing fleet. Furthermore, the emissions from the fishing industry, as well as emission reduction targets and regulations that the industry must comply with, are presented in Section 2.2. Finally, in Section 2.3, fleet renewal considerations are presented together with zero- and low-emission propulsion alternatives for the Norwegian fishing fleet.

2.1 The Norwegian Fishing Industry

Throughout Norwegian history, fisheries have created livelihood for large parts of the population along the coast, and provided Norway with significant export revenues for several hundred years (Dørum and Hallenstvedt, 2023). In 2021, the Norwegian fishing fleet caught 2.59 million tonnes of fish. In the same year, the employment effects from the activity in fishing were around 18,800 people. The total value creation of the Norwegian fishing industry in 2021 amounted to 21.4 billion NOK, whereas 13.8 billion NOK was created directly by the fishing fleet, while 7.6 billion NOK was ripple effects from suppliers (Iversen et al., 2022). Norway has established a large exclusive economic zone around its coast, in addition to two fishery protection zones of 200 nautical miles around Svalbard and Jan Mayen, illustrated in Figure 2.1. These are large sea areas where Norway has legal power over the activity that takes place within the maritime borders, such as rights to fishing and shipping. (Henriksen and Helgesen, 2022).

Statistics from the Norwegian Directorate of Fisheries show that there were 5,611 brand-registered fishing vessels in 2022 (Fiskeridirektoratet, 2023). A brand-registered vessel is a vessel where the owner has the right to participate in fishing with the relevant vessel within Norway's maritime borders (Regjeringen, 1999). Most vessels are registered in northern Norway in the counties Troms og Finnmark and Nordland. Many are also registered in Vestland County (Fiskeridirektoratet, 2023). The Norwegian fishing fleet can be categorized in two ways. One is to divide the fleet according to where the relevant vessels practice fishing. The Norwegian fishing fleet is usually divided into the ocean-going and coastal fishing fleet (Hallenstvedt, 2020). Ocean-going fishing is carried out on the open sea and on the fishing banks, in contrast to coastal fishing, which is carried out in the fjords, along the coast and near coastal banks (Hallenstvedt, 2020). In Norway, the Fisheries Administration sets the limit between the ocean-going fishing fleet and the coastal fishing fleet at a vessel length of 28 metres or at a cargo space size of $500m^3$ (Johnsen, 2019). Fishing can only be carried out from brand-registered fishing vessels with an assigned fishing quota based on the length group in that the relevant vessel belongs. Another way of categorizing the fishing vessels is to divide the Norwegian fishing fleet by which fishing gear is used, which in turn relates to what fisheries the respective vessel is involved in. Examples of such gear are seines, various trawls, nets and lines.

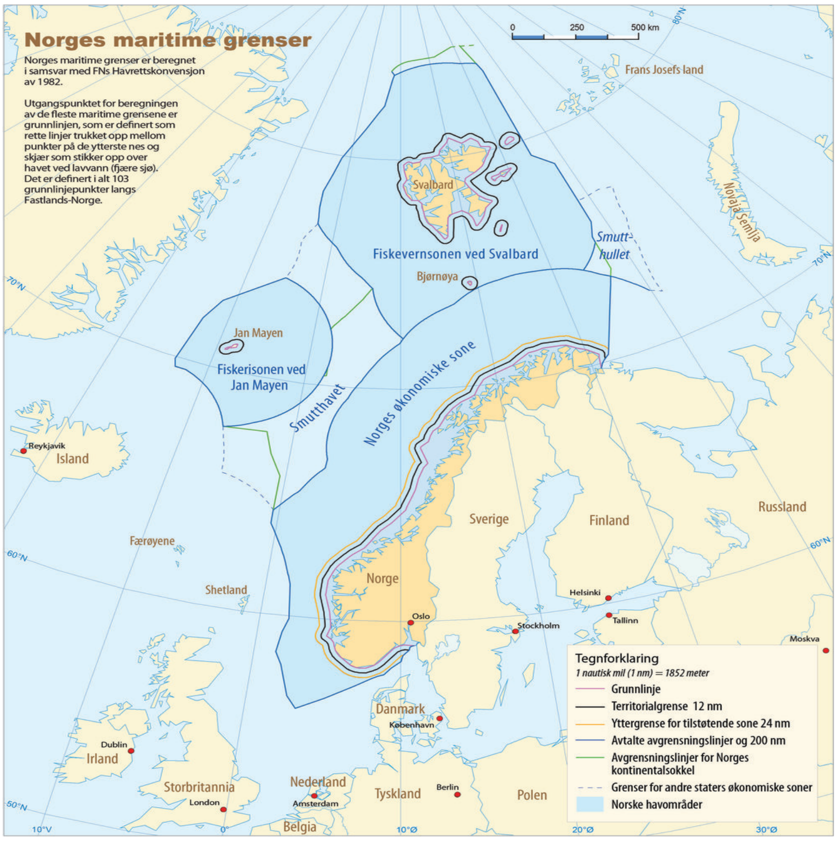


Figure 2.1: Norway's maritime borders (Henriksen and Helgesen, 2022)

2.1.1 Fishing Gear

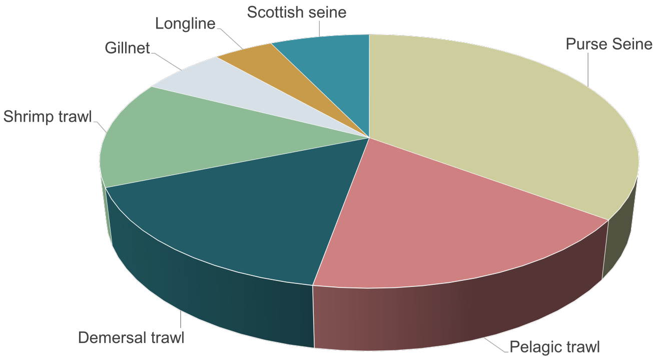
A broad distinction is usually made between pelagic and demersal fisheries. Pelagic fish are species such as herring, sprats and mackerel that usually find their food, e.g. plankton, in the surface layers of the sea. Demersal fish, on the other hand, live and feed on or near the bottom of the sea. These are species such as cod, haddock and flatfish and are also referred to as bottom fish or groundfish (Chattopadhyay and Adhikari, 2014). Which fish species a vessel is to catch provides requirements for what gear the relevant vessel should have installed on board. Figure 2.2a provide an overview of the total catch in tonnes distributed on some widely used fishing gear within Norwegian fisheries. We distinguish between the catch caught by the ocean-going and the coastal fishing fleet with the relevant gear. The numbers are calculated based on data retrieved from The Norwegian Directorate of Fisheries and the details on the calculation are provided in Section 6.3. The distribution of the total catch is also illustrated by Figure 2.2b. In the following section, a brief explanation of the working principles of the different types of fishing gear is given.

Passive Fishing Gear

The Norwegian Directorate of Fisheries defines passive fishing gear as a fishing device where the fish seek out the gear in order to be caught, such as gillnets and longlines, and is often referred to as conventional fishing gear. A gillnet is a large net with floaters attached to the top and weights attached to the bottom, illustrated in Figure 2.3a (bottom-set gillnet). The length and height of the gillnet vary according to the type of fish one wants to catch, as does the mesh size. Gillnets are typically used to catch demersal bottom fish such as cod, halibut, pollock and monkfish, and are primarily used by the coastal fishing fleet, but also by larger ocean-going vessels (Fiskeridirektoratet, 2010). Longline fishing, on the other hand, can be used to target both pelagic and demersal fish, depending on whether the rig is set in the midwater or on the seabed, respectively. A longline consists of either a long, light rope or a nylon monofilament, to which multiple branch lines with

Gear type	**Tonnes caught**
Purse seine	Ocean-going fleet: 731,363 Coastal fleet: 107,322 **Total catch: 838,685**
Pelagic trawl	Ocean-going fleet: 419,461 Coastal fleet: - **Total catch: 419,461**
Demersal trawl	Ocean-going fleet: 381,543 Coastal fleet: - **Total catch: 381,543**
Shrimp trawl	Ocean-going fleet: 321,423 Coastal fleet: 4,810 **Total catch: 326,233**
Scottish seine	Ocean-going fleet: 90,774 Coastal fleet: 79,256 **Total catch: 170,030**
Gillnet	Ocean-going fleet: 17,569 Coastal fleet: 127,152 **Total catch: 144,721**
Longline	Ocean-going fleet: 51,205 Coastal fleet: 51,293 **Total catch: 102,498**

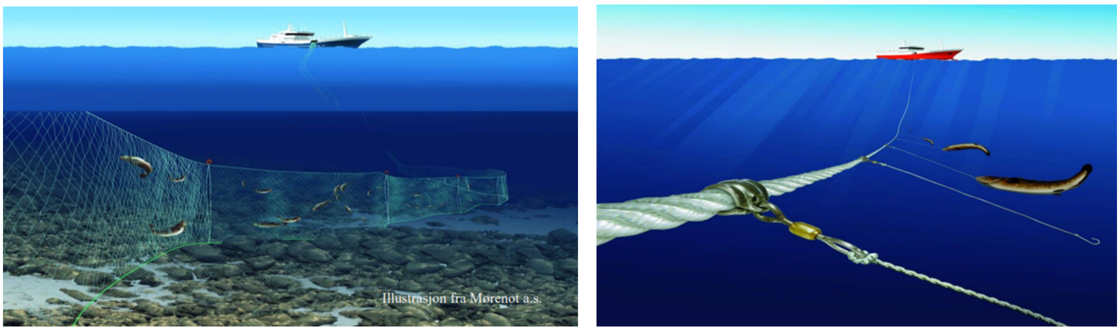
(a)



(b)

Figure 2.2: Tonnes fish caught in 2022 distributed by fishing gear and fleet (Fiskeridirektoratet, 2022b, Fiskeridirektoratet, 2022a)

baited hooks are attached at regular intervals. The main line may be up to many miles long (Seafish, 2023b). Figure 2.3b illustrates a longline during hauling.



(a) A bottom-set gillnet used for demersal fishing (Fiskeridirektoratet, 2010)

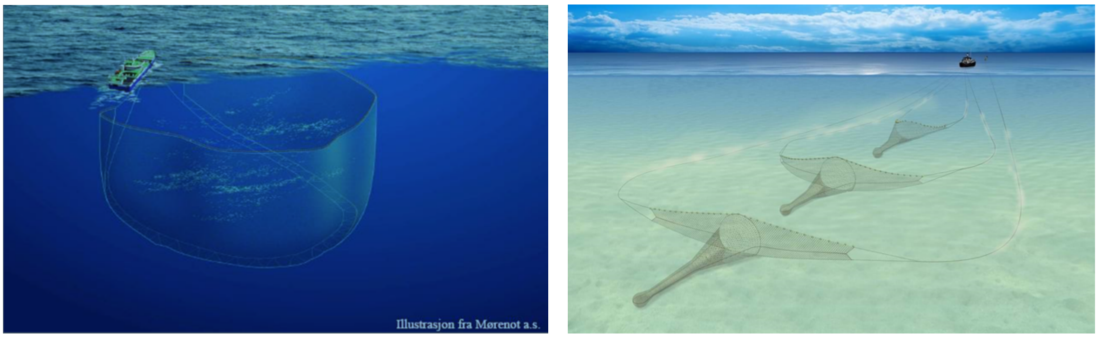
(b) A longling during hauling (Fiskeridirektoratet, 2010)

Figure 2.3: Passive fishing gear: Bottom-set gillnet and longline

Active Fishing Gear

Active fishing gear is defined as a fishing device where the gear must seek out the fish in order to catch it, such as closing nets, seines, and trawls (Fiskeridirektoratet, 2010). A purse seine is a large closing net used to surround a shoal of primarily pelagic fish such as mackerel, herring, and capelin. Once the net is cast, the bottom is snarled together so that it forms a large cup shape, before it is hauled onboard the vessel (Seafish, 2023d). A purse seine differs from a gillnet, in that a purse seine encloses fish, whereas a gillnet directly snares fish (Wikipedia, 2022). Figure 2.4a illustrates how a purse seine is cast around a school of fish.

A seine, on the other hand, resembles a trawl and is primarily used for fishing bottom fish such as flounder, cod, haddock and other demersal fish species. It is used at the bottom of relatively shallow water (up to 100 metres) (Wikipedia, 2021). In Norway, the Scottish variant is primarily utilized, and the extension and length of the lines vary with the depth and seabed conditions (Fiskeridirektoratet, 2010). The Scottish seine is typically used for fishing close to the coast, often in combination conventional fishing gear such as gillnets and longlines. Also, due to its similarities with both trawls and purse seines, new combinations can be suitable in the future (Vestre, 2020). Figure 2.4b illustrates how a Scottish seine is hauled along the seabed with weighted ropes attached to each end of the net. The vessel retains position while using its engine power to haul the seine in, implying that it is never towed long. Consequently, relatively little energy is needed so that it may be operated from lower-powered vessels (Seafish, 2023e).

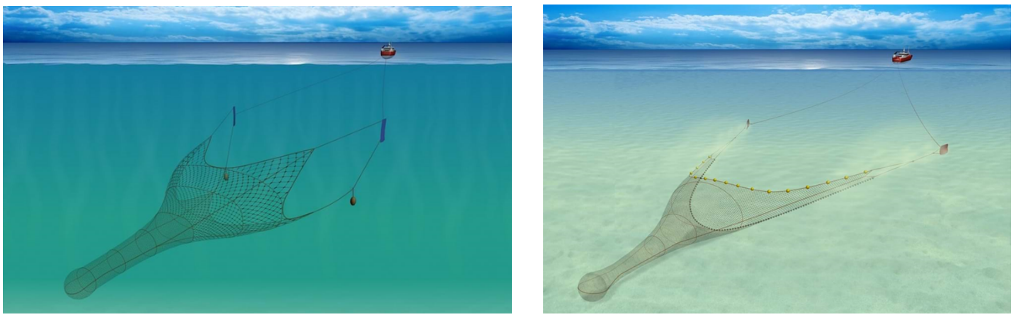


(a) A purse seine cast around a school of fish (Fiskeridirektoratet, 2010)

(b) A Scottish seine hauled along the seabed (Seafish, 2023e)

Figure 2.4: Active fishing gear: Purse seine and Scottish seine

Trawls are another example of active fishing gear. For the trawler vessel group, a distinction is made between pelagic and demersal trawl, hereby referred to as bottom trawl. This is due to the difference in both how the catch is handled onboard, and how the different types of trawls operate. A bottom trawl is towed along or close to the seafloor, while pelagic trawling is characterised by the trawl not coming into contact with the seabed (Fiskeridirektoratet, 2010). The pelagic and bottom trawl are illustrated in Figure 2.5a and Figure 2.5b, respectively. In addition, there are also shrimp trawls. These trawls are significantly smaller and have a smaller mesh size than the pelagic and bottom trawl. The shrimp trawl typically operates near the seabed (Wikipedia, 2020).



(a) A vessel towing a single pelagic trawl (Seafish, 2023c)

(b) A bottom trawl hauled along the seabed (Seafish, 2023a)

Figure 2.5: Active fishing gear: Pelagic and bottom trawl

2.1.2 The Fishing Fleet

As previously mentioned, the Fisheries Administration sets the limit between the ocean-going fishing fleet and the coastal fishing fleet at a vessel lenght of 28 metres or at a cargo space size of $500m^3$. As of today, the ocean-going fishing fleet makes up 4.6% of the total fishing fleet, while the remaining 95.4% are considered coastal vessels (Fiskeridirektoratet, 2023). This implies that the ocean-going and coastal fishing fleet comprises 258 and 5 353 fishing vessels, respectively. The ocean-going and coastal fishing fleet may be further divided into sub-fleets based on which fishing gear and consequently what type of fisheries the relevant vessel participates in. The ocean-going fishing fleet can be divided into the sub-fleets purse seiners, conventional ocean-going vessels, pelagic and bottom trawlers, while the coastal fleet may be divided into conventional coastal vessels, coastal seiners and shrimp trawlers (Thompson and Thompson, 2021). There is little distinction between the purse seiners and the coastal seiners, besides the length of the vessels (Fiskeridirektoratet, 2010).

The Ocean-going Fishing Fleet

Figure 2.6 illustrates the distribution of the ocean-going fishing fleet between the sub-fleets, given as purse seiners, bottom and pelagic trawlers, and conventional ocean-going vessels, according to Fiskeridirektoratet (2019). The survey was based on a population of Norwegian fishing vessels that exceed the minimum requirement for yearly catch income for the relevant vessel group. The minimum income requirement varies with the size of the vessel. The population constitutes 84.6% of the total catch quantity and 91.8% of the total catch value of the Norwegian brand-registered fishing fleet.

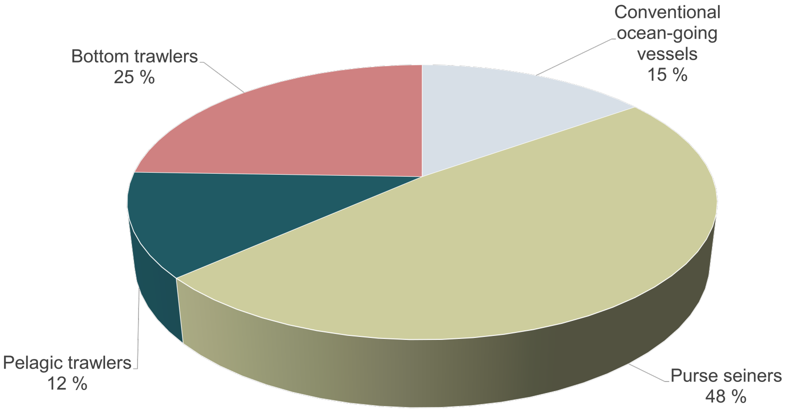


Figure 2.6: Distribution between sub-fleets in the Norwegian ocean-going fishing fleet (Fiskeridirektoratet, 2019). There were 258 ocean-going vessels in 2022 (Fiskeridirektoratet, 2023)

As can be seen from Figure 2.6, the majority of ocean-going fishing vessels use a purse seine as their main type of fishing gear and are thus referred to as purse seiners, illustrated in Figure 2.7a. Purse seiners operate in the pelagic fisheries, catching fish such as herring, mackerel, and capelin. The typical sailing time, i.e. the time between two port calls, is between three to seven days (Valland, 2021). The modern purse seiners are amongst the most efficient fishing vessels in use in Norway today. Many purse seiners also have a pelagic trawl for when it is unsuitable to use the purse seine. This is often referred to as having combined gear (Vestre, 2020). Furthermore, conventional ocean-going fishing vessels account for about 15% of the Norwegian ocean-going fishing fleet. These are vessels that predominately utilize conventional fishing gear such as longlines and nets (Vestre, 2020). The Norwegian ocean-going fishing fleet, however, mainly has longlines as their main gear rather than nets and Scottish seines, which as previously mentioned is commonly used in combination with conventional fishing gear, (Fiskeridirektoratet, 2023). These vessels are referred to as longliners and the typical sailing time is usually between one to three days (Valland, 2021). Figure 2.7b illustrate a 66.90 metres long ocean-going longline vessel *Cape Arkona*. The vessel has an automatic baiting system and about 62,000 hooks (FiskerForum, 2018). The Norwegian longliner fleet primarily catches cod and other demersal fish (Fiskeridirektoratet, 2023).

Trawlers account for about 37% of the ocean-going fishing fleet. In 2019, the Norwegian ocean-going trawl fleet consisted of 17 pelagic and 34 bottom trawlers. Figure 2.8a and Figure 2.8b illustrate

(a) The 64.2 metres long purse seiner *Fiskebas* (Fiskebas, n.d.-b)

(b) The 66.9 metres long longliner *Cape Arkona* (FiskerForum, 2018)

Figure 2.7: Ocean-going purse seiner and conventional vessel

a pelagic and bottom trawler, respectively. For bottom trawlers, it is cod that makes up the largest share of the total catch and has the highest first-hand value (nominal) (Fiskeridirektoratet, 2019). However, the bottom trawler is well-suited for combined operations, and many bottom fish trawlers have combined operations with the use of shrimp trawls as well. Bottom trawlers with combined operations in the Barents Sea, typically catch shrimp after the main cod season is over, meaning from early May until approximately the start of September (Vestre, 2020). As of 2022, the ocean-going fishing fleet accounted for approximately 99% of the Norwegian fishing of shellfish, i.e. shrimp, crayfish, crab and lobster (Fiskeridirektoratet, 2022b). The typical sailing time of a pelagic and bottom trawler is 7-28 and 7-14 days, respectively (Valland, 2021).

Vessels that predominantly catch demersal species typically have large freezers onboard, along with processing equipment. Pelagic species are rarely processed at sea. Instead, the catch is stored on so-called Refrigerated Sea Water (RSW) tanks and pumped directly from the vessel to the landing site. This allows ocean-going fishing vessels to operate at sea for weeks at a time. For example, a freezer trawler can stay in the field for four to five weeks (Thompson and Thompson, 2021).

(a) The 65 metres long pelagic trawler *Cetus* (Fiskebas, n.d.-a)

(b) The 65.5 metres long research vessel and bottom trawler *RV Celtic Explorer* (Eurofleets, n.d.)

Figure 2.8: Pelagic and bottom trawler

In terms of age, statistics from the Directorate of Fisheries from 2022 have been used to determine the age distribution as well as the average age of the Norwegian ocean-going fishing fleet. As of 2022, approximately 5.0% of ocean-going vessels were built before 1970, i.e. above 50 years old. 4.6% of ocean-going vessels were built between 1970 and 1979, and 10.0% of the fleet was built between 1980 and 1990. Furthermore, 17.3% was built between 1990 and 2000, and 25.8% was built between 2010 and 2019. Finally as much as 37.3% of the fleet is built after 2010, i.e. 13 years and younger. The average age of the ocean-going fleet in 2022 was approximately 20 years (Fiskeridirektoratet, 2023).

The Coastal Fishing Fleet

In the same manner as for the ocean-going fishing fleet, the distribution of the coastal fishing fleet between the sub-fleets, given as conventional coastal vessels, coastal seines and shrimp trawlers are found from Fiskeridirektoratet (2019). Figure 2.9 illustrates the resulting distribution.

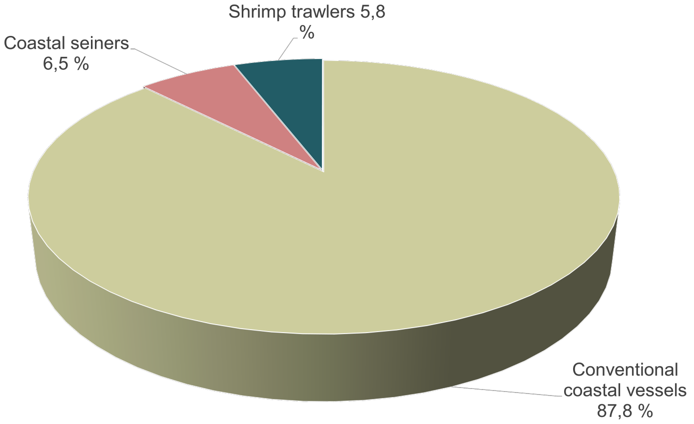


Figure 2.9: Distribution between sub-fleets in the Norwegian coastal fishing fleet (Fiskeridirektoratet, 2019). There were 5 353 coastal fishing vessels in 2022 (Fiskeridirektoratet, 2023)

Figure 2.9 shows that the conventional coastal fishing vessels constitute the majority of the coastal fishing fleet. These are fishing vessels that use conventional fishing gear such as gillnets and longlines, primarily used for catching demersal species, but also some pelagic. The most important coastal fishery in terms of quantity and value is cod fishing (Johnsen, 2019). According to statistics from the Norwegian Directorate of Fisheries, the conventional coastal fishing sub-fleet accounted for approximately 36.3% of the total catch of cod in 2022. This includes the catch with Scottish seines (Fiskeridirektoratet, 2022b). Figure 2.10a illustrates the conventional coastal vessel *MS Stormhav* which catches demersal fish using longline and gillnet. The vessel has space for approximately 45.000 hooks, a processing department on the main deck, and a combined cold and freezer room of $206m^3$ (Skipsrevyen, 2020). The coastal fishing fleet primarily delivers fresh fish, but an increasing number of large coastal vessels are installing freezers on board (Johnsen, 2019). Furthermore, coastal seiners constitute about 6.5% of the coastal fishing fleet, which implies about 348 vessels. As previously mentioned, the coastal seiners use a purse seine as their main gear targeting pelagic fish such as herring, mackerel, and capelin. The coastal seiners account for about 12.8% of the total catch with purse seines of pelagic fish. Finally, shrimp trawlers constitute about 5.8% of the Norwegian coastal fishing fleet. The 23.95 metres long shrimp trawler *Bona Fide* is pictured in Figure 2.10b. This form of trawling operation takes place along the seabed in the same manner as bottom trawling. Even though the coastal shrimp trawler fleet is significantly larger than the ocean-going bottom trawler fleet, with approximately 310 vessels against 34 (some with combined bottom and shrimp trawling operation), the coastal shrimp trawler fleet constitutes only 1% of the total catch of shellfish (Fiskeridirektoratet, 2022b). Consequently, shrimp trawlers are disregarded further in this thesis.

Within the Norwegian coastal fishing fleet, the Directorate of Fisheries distinguishes between four different length groups. Below 11 metres (83.9%), 11-14.99 metres (12.4%), 15-20.99 metres (1.9%) and 21-27.99 metres (1.8%) (Fiskeridirektoratet, 2023). Most fishing vessels below 15 metres fall under the category of fishing vessels called smack. A smack is a light fishing and transport boat, typically half-decked and with a wheelhouse. This type of vessel is particularly used in northern Norway for line, net and hook fishing in coastal waters, and the crew size on board usually ranges from one to three people (Rabbevåg, 2021).

In the same manner as for the ocean-going fishing fleet, statistics from the Directorate of Fisheries from 2022 are used to determine the age distribution as well as the average age of the Norwegian coastal fishing fleet. As of 2022, approximately 3.3% of coastal vessels were built before 1970, i.e.

(a) The 27.99 metres long conventional coastal vessel *MS Stormhav* (Skipsrevyen, 2020). Foto: JK Foto

(b) The 23.95 metres long shrimp trawler *Bona Fide* (Maritime, 2018)

Figure 2.10: Conventional coastal vessel and coastal shrimp trawler

above 50 years old, while 15.5% of today's coastal fleet was built in the period 1970-1979. During the 1980s, as much as 33.2% of the coastal fleet was built. Furthermore, 12.4% of the fleet was built between 1990 and 2000 and 14.2% between 2000 and 2009. Finally, 21.3% of the coastal fleet was built after 2010, i.e. 13 years and younger. The resulting average age of the coastal fishing fleet in 2022 was approximately 30 years (Fiskeridirektoratet, 2023).

2.2 CO2 Emissions from Norwegian Fisheries

As of today, the Norwegian fishing fleet predominantly uses MGO for propulsion and auxiliary power (Leira, 2018). In 2021, 1,952 million litres of MGO was sold in Norway (SSB, 2023). This constitutes about 23.5% of the total sale of petroleum products in Norway according to Statistics Norway (SSB). The CO2 emissions of the Norwegian fishing fleet are a direct result of fuel consumption. According to statistics presented by the Directorate of Fisheries, the total CO2 emissions amounted to 1.1 million tonnes in 2021, which corresponds to $\sim$ 2.7% of Norway's yearly emissions of CO2 and other GHG (SSB, 2022). It should be noted that there are varying estimates of overall CO2 emissions from Norwegian fisheries due to different calculation methods. Nevertheless, this thesis uses the figures presented by the Directorate of Fisheries.

2.2.1 Fuel Use Intensity

There may be considerable differences in the operational profile of each sub-fleet within both the ocean-going and coastal fleets and the operational pattern of a fishing vessel is a significant determinant of its fuel consumption. According to Thompson and Thompson (2021), the fuel consumption varies mainly due to four parameters.

- **Distance** - Travel distance to the fishing field
- **Type of fishing gear** - Active or passive
- **Accessibility** - Bottom fishing or closer to the surface
- **Seasonality** - Seasonal or year-round fishing

These parameters help determine the fuel use intensity of the relevant vessel based on the main gear, i.e. the fuel consumption per kg of fish caught. Figure 2.11 illustrates the development in fuel use intensity from 2001 to 2019. Bottom trawlers and conventional ocean-going vessels have the highest fuel consumption per kilogram of fish caught. For the other vessel classes, the fuel use intensity is relatively lower and less fluctuating in the relevant period (Thompson and Thompson, 2021).

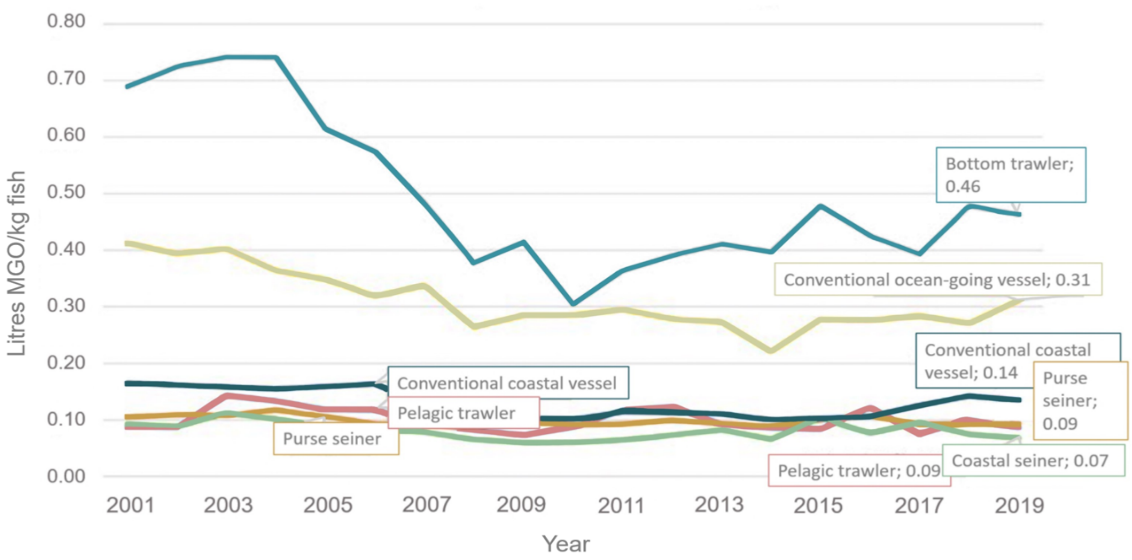


Figure 2.11: Fuel consumption per kilogram caught fish from the various sub-fleets of the ocean-going and coastal fishing fleet (Thompson and Thompson, 2021)

The Coastal Sub-fleets

Coastal fishing vessels engaged in net or line fishing, i.e. conventional fishing, typically have a short travel distance to the fishing field and use little energy to set and pull the gear. In general, the use of passive fishing gear contributes to stable and relatively low energy consumption (Thompson and Thompson, 2021). According to SINTEF, the energy use of a small coastal smack is divided so that 30% is related to fishing, while 70% is related to movement from and to the fishing field, often referred to as steaming. For vessels between 15 and 21 metres, the distribution between fishing and steaming is more evenly distributed (Aarsæther et al., 2018). However, as coastal vessels do not travel far to the fishing field, the overall energy requirement related to steaming and fishing is relatively low. In addition, many coastal vessels have a relatively short season. For example, during the scree fishing season, they run around the clock, while being docked or used for local fishing for the rest of the year. This contributes to a lower fuel use intensity, i.e. more energy-efficient fishing.

According to Figure 2.11, coastal seiners are the sub-fleet with the lowest fuel use intensity, despite the more energy-intensive nature of the active fishing gear purse seine compared to passive fishing gear. This can be explained by the fact that, as of today, the purse is the most efficient fishing gear available in terms of catch quantity as of today. In addition, coastal seiners have a short travel distance to the fishing field.

The Ocean-going Sub-fleets

For ocean-going sub-fleets such as pelagic trawls and purse seiners, it is the steaming that to the greatest extent contributes to the fuel use intensity. The fishing gear provides highly efficient fishing in terms of catch quantity, but as the fishing field typically is distant, the overall energy efficiency decreases (Thompson and Thompson, 2021). On average, purse seiners and pelagic trawlers are among the vessels with the lowest fuel use intensity, as can be seen in Figure 2.11 This is because even though the steaming is energy consuming, the vessels in question fish large quantities of pelagic fish in a short time, which leads to high energy efficiency.

Bottom trawlers and conventional ocean-going vessels are the two sub-fleets with the highest fuel consumption per kilogram of caught fish. This is mainly due to the fact that they fish in distant waters. There are large variations in the total fuel consumption depending on where the fishing takes place and the weather conditions. A bottom trawler that is to deliver fresh cod from the

Barents Sea for reception on land must travel far and often to keep the fish fresh. In addition, bottom trawling requires considerable traction from the vessel when dragged along the seabed, making it an energy-intensive operation. Finally, cod trawling is year-round fishing, contributing to the relatively higher energy efficiency compared to for example seasonal scree fishing (Thompson and Thompson, 2021).

Estimating Fuel Use Intensity

The fuel intensities of the various sub-fleets as of 2019 are assumed to be reasonable estimates for the fuel use intensity of today's fishing fleet. Based on the information presented in Figure 2.11, it appears that the fuel consumption per kg of caught fish has remained constant over the years for conventional coastal vessels, purse seiners, coastal seiners, and pelagic trawlers. This suggests that it is reasonable to assume that this trend has persisted to the present day.

For the bottom trawler fleet, the fuel use intensity has fluctuated greatly since 2001, whereas the conventional ocean-going fleet has seen a gradual decrease up until 2014, before starting to rise again. The decline for both sub-fleets at the beginning of the relevant period may be explained by the fact that considerable investments were made in new vessels in the ocean-going fleet during this time, which can have resulted in more energy-efficient vessels (Fiskeridirektoratet, 2023). The gradual increase from around 2012 on the other hand may result from the decrease in total catch of the two sub-fleets as of 2011 (Fiskeridirektoratet, 2022b).

2.2.2 Fuel Consumption

From Fiskeridirektoratet (2019), the Norwegian Directorate of Fisheries has estimated the annual fuel consumption of the ocean-going and coastal fishing fleet using financial figures of the population described in Section 2.1.2. The development from 2001 to 2019 is illustrated in Figure 2.12 (Thompson and Thompson, 2021).

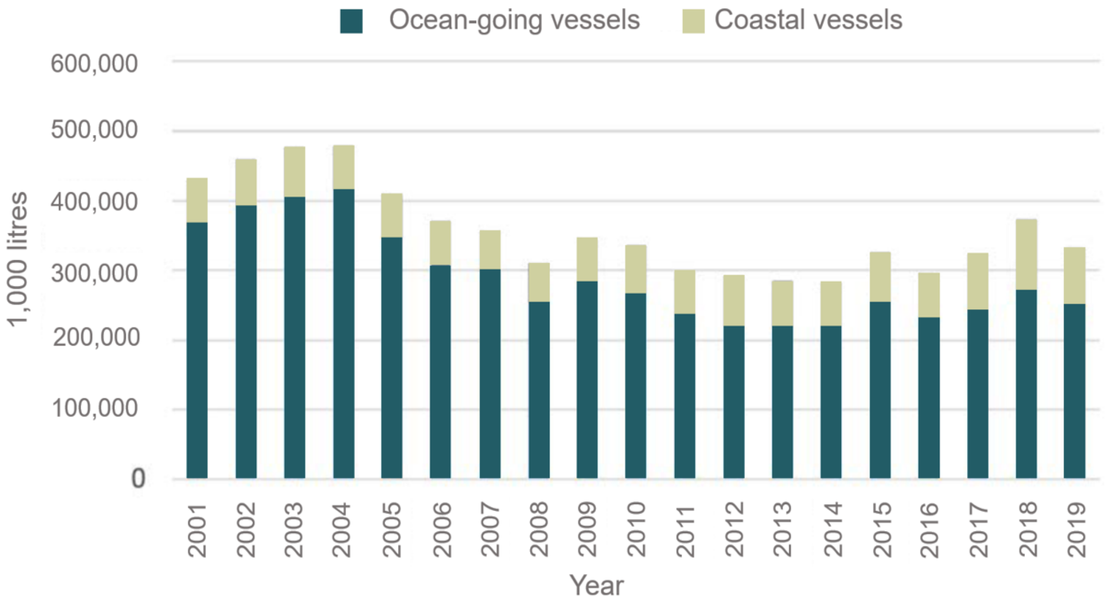


Figure 2.12: Historical fuel consumption of ocean-going and coastal fishing vessels included in the population in Fiskeridirektoratet (2019) (Thompson and Thompson, 2021).

From Figure 2.12, it is apparent that the ocean-going fishing fleet consumes the most fuel, even though the fleet comprises significantly fewer vessels than the coastal fishing fleet. In 2019, the coastal fishing fleet accounted for 25% of the total fuel consumption of the Norwegian fishing fleet, an increase from 19% in 2005. Conventional coastal fishing vessels account for the majority of the increase. For the ocean-going fishing fleet, there has been a major decrease in fuel consumption from the year 2001 until 2013-2014, after which have risen until today. In 2019 the ocean-going fleet used 30 million more litres of fuel than in 2014. This corresponds to an increase of 14% (Thompson and Thompson, 2021). The increase in total fuel consumption from 2014 comes despite the fact that the total number of vessels in the combined Norwegian fishing fleet has been gradually declining during the same period of time. However, the total engine power of the fleet has increased, being directly correlated with fuel consumption (Fiskeridirektoratet, 2023).

2.2.3 Combined CO2 Emissions

In the same manner that the total fuel consumption of the combined fishing fleet has been increasing as of 2014, so have the CO2 emissions from Norwegian fisheries. The development in CO2 emission from the Norwegian fishing fleet according to Fiskeridirektoratet (2019) is presented in Figure 2.13 (Thompson and Thompson, 2021).

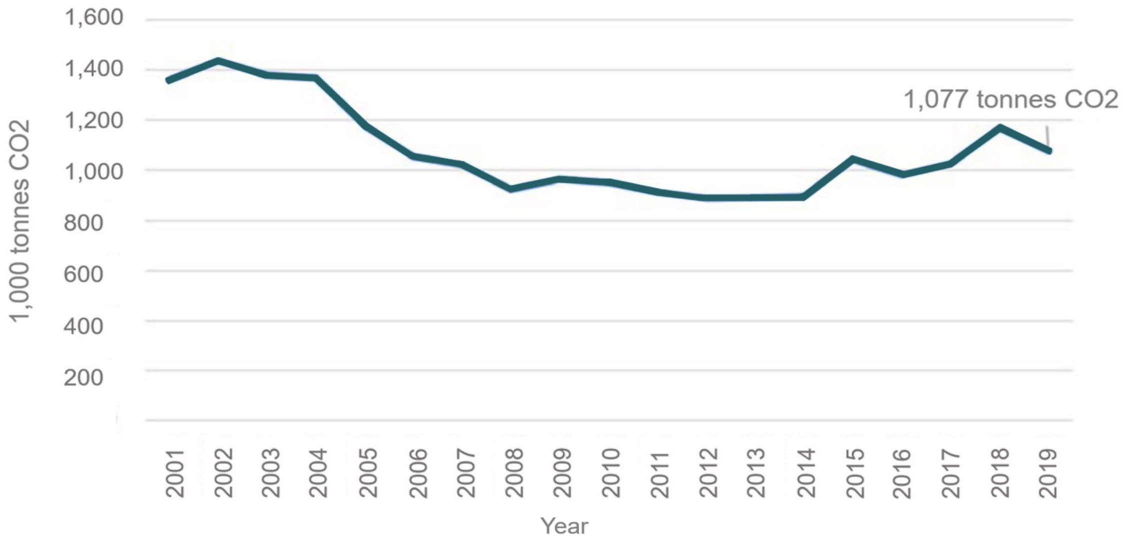


Figure 2.13: CO2 emissions from the combined Norwegian fishing fleet adjusted upwards to account for catch fished by vessels not included in the population in Fiskeridirektoratet (2019) (Thompson and Thompson, 2021).

It is evident that the CO2 emissions in Figure 2.13 follow the same development as the historical fuel consumption in Figure 2.12. Furthermore, according to the data provided by the Directorate of Fisheries, CO2 emissions from the combined Norwegian fishing fleet have continued to rise, reaching 1.1 million tonnes in 2021.

2.2.4 Emission Reduction Targets and Regulations

The goal of the ZeroKyst projects is to contribute to a 50% emission reduction from fishing and aquaculture vessels by 2030. This goal is based on Norway's climate target to the UN, as well as the Norwegian Climate Act. At the last Conference of the Parties (COP) meeting in Sharm el-Sheik, Egypt, in November 2022, the Norwegian Prime Minister, Jonas Gahr Støre, announced that Norway has submitted an enhanced climate target to the UN of reducing CO2 emissions by 55% by 2030 compared to 1900 levels (Regjeringen, 2022a). Additionally, Norway's Climate Act states that Norwegian emissions must be cut by 90-95% by 2050, compared to 1990 levels (Norsk Klimastiftelse, 2022). For the non-quota-obliged sector, this implies a commitment to cutting the emissions by 40% by 2030 compared to 2005 levels. The non-quota-obliged emissions are those not covered by the EU-ETS and include sectors such as transport, agriculture, heating in buildings and fisheries. The CO2 emissions from these sectors are regulated through, for example, taxes, fees, subsidies and other schemes that aim to reduce emissions (Regjeringen, 2023).

In order to reverse the trend in CO2 emissions from Norwegian fisheries, a full CO2 tax was introduced in 2020 for the Norwegian fishing fleet. At the same time, a compensation scheme was introduced relative to the vessel's share of the turnover in the sub-fleet to which the vessel belongs. The purpose of compensating based on catch value, and not fuel consumption, is to stimulate more energy-efficient fishing (Thompson and Thompson, 2021). Thompson and Thompson (2021) argues that a CO2 tax in a closed market works well, but that a CO2 tax in an open market with alternative purchasing options for fuel does not work well. The report state that with the average fuel price in Europe in 2019 of 5.11 NOK/litre, the tax rate provides a price difference between Norway and Europe of 24%. As a consequence, fishermen may choose to bunker outside of Norway as long as the cost of transport and alternative cost does not exceed 24% of the cost of bunkering in Norway. For example, a large vessel may typically bunker about 500,000 litres at a time, which entails a saving of 790,000 NOK per bunkering. The journey will have to be relatively long for it not to be commercially profitable to bunker outside of Norway.

Figure 2.14 illustrates the perceived development of the CO2 tax on top of the average fuel price for fishing vessels in 2019. The CO2 tax is set in the state budget annually. In the message *Klimaplan 2021-2030*, the government announces the ambition for a gradual escalation of the CO2 tax to 2,000 per tonne CO2 in 2030 (Thompson and Thompson, 2021). Recalculated in NOK per litre of MGO, this amounts to approximately 5.32 NOK/litre. Note that Figure 2.14 is for illustrative purposes and that the price of MGO is also expected to increase.

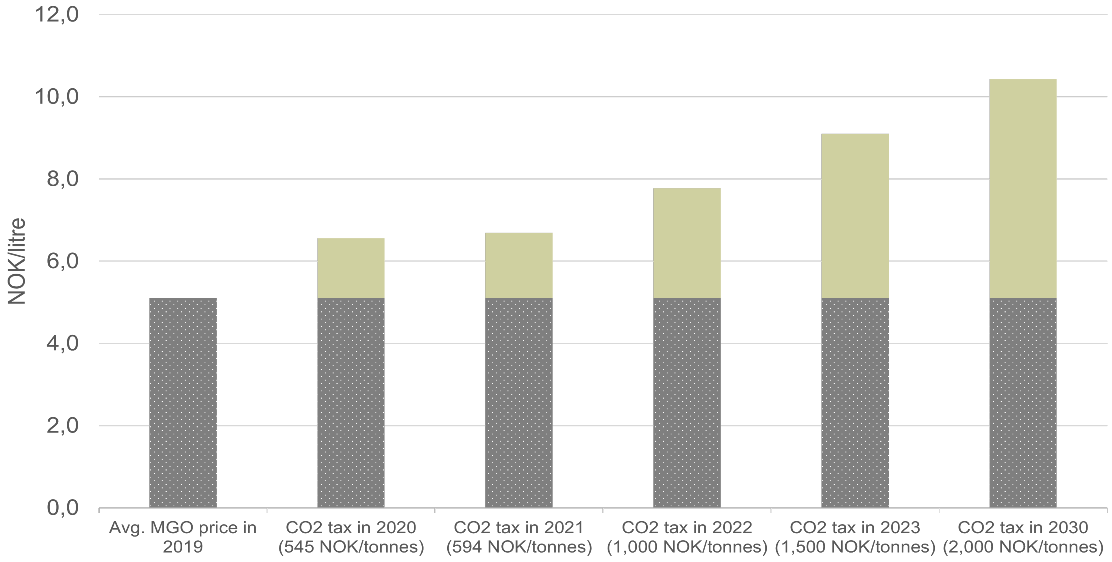


Figure 2.14: The CO2 tax expressed in NOK/litre MGO on top of the average fuel price in Europe in 2019 (Thompson and Thompson, 2021).

When the full CO2 tax and support scheme first was introduced in 2020, fishermen were able to receive compensation for the CO2 tax even when they had bunkered abroad. This was recognized as a weakness of the support scheme and consequently, as of 2022, the support scheme covers only Norwegian registered fishing vessels that bunker Norwegian excise duty fuel. In addition, the support scheme is planned to be phased out in order to speed up the transition to zero-emission fisheries (GarantiKassen, 2020). The increase in CO2 tax and decrease in compensation, combined with a reduced incentive for fishermen to bunker outside Norway's national borders implies an ever-increasing need for low- and zero-emission alternatives for propulsion within the Norwegian fishery industry.

2.3 Transition to Zero-Emission Fisheries

Based on statistics from the Directorate of Fisheries, the total CO2 emissions from the Norwegian fishing fleet amounted to approximately 1.2 million tonnes in 2005, as shown in Figure 2.13. ZeroKyst's goal of reducing emissions by 50% by 2030 compared to 2005 levels thus corresponds to an emissions cap of 600,000 tonnes in 2030. In addition to the 50% reduction goal of ZeroKyst, Norway's Climate Act states that Norwegian emissions must be cut by 90-95% by 2050, compared to 1990 levels (Norsk Klimastiftelse, 2022). According to statistics from SSB, a 95% reduction compared to 1990 levels corresponds to an emissions cap of 40,000 tonnes in 2050 (Stakeholder AS, 2022).

In order to reduce the CO2 emissions from Norwegian fisheries it is necessary to investigate technical and operational measures to reduce fuel consumption and emissions from fishing vessels. This will require a targeted investment in fleet renewal. The phasing in of low- and zero-emission technology is amongst the key measures that can contribute to a significant reduction in CO2 emissions by 2030 (Thompson and Thompson, 2021). In the following subsections, we present the necessary considerations related to fleet renewal, as well as various propulsion alternatives.

2.3.1 Fleet Renewal Considerations

In order to accomplish ZeroKyst's emission reduction target of 50% by 2030, as well as the Climate Act's target of 90-95% emission reduction by 2050, a growing share of the Norwegian fishing fleet must be low- and zero-emission fishing vessels. Nevertheless, the lifespan of coastal and ocean-going fishing vessels implies that renewals must happen earlier than the vessels' economic lifetime in order to meet emission reduction targets. This creates strategic challenges for decision-makers related to the utilization, replacement, or retrofitting of fishing vessels in the context of reducing CO2 emissions. The decision-makers considered to be the most relevant are the fishermen themselves, as well as policy-makers.

Firstly, decision-makers need to determine the optimal utilization time of a specific vessel. This involves balancing the need for continued operation of the vessel with the desire to minimize its carbon footprint. By renewing the relevant vessel with low- or zero-emission technology through replacement or retrofitting, the CO2 emissions associated with the operation are reduced. However, the timing of such renewal must be carefully considered to ensure that it is both economically viable and environmentally beneficial. Secondly, after determining the optimal utilization time of a specific fishing vessel, decision-makers face the choice of either replacing or retrofitting a vessel and with what low- or zero-emission technology, to reduce CO2 emissions. Retrofitting a vessel with new and emission-reducing technologies can be a practical approach to cutting emissions. However, retrofitting may not always be feasible or economically viable. In such cases, vessel replacement may be a better option. Further elaborations on vessel retrofitting and replacement in the context of reducing CO2 emissions in the fishing industry, as well as low- and zero-emission technology alternatives, will be expounded upon in the subsequent subsections of this thesis.

In summary, decision-makers in the fishing industry face complex strategic challenges when making decisions related to reducing CO2 emissions, including determining the optimal vessel utilization time, deciding on whether to replace or retrofit vessels, with what emission-reducing technology and identifying the best timing for making these investments. This involves taking into account political goals and incentives, such as emissions reduction targets and subsidies for the adoption of green technologies, as well as costs and revenues related to fleet operation and renewal. External factors such as the capacity of shipyards and access to fuel must also be taken into account. The relevant decision-makers, the fishermen and the policy-makers can be expected to emphasize different aspects of fleet renewal. While policy-makers are primarily focused on value-creation from fisheries, political emission reduction targets and how to provide incentives for emission-reducing investments, fishermen are more concerned with the practical implications of vessel renewal on their daily operations and the associated costs.

Political Goals and Incentives

There are two sides to the political goals and incentives regarding the Norwegian fishery fleet. On one side, fisheries provide significant revenues and employment effects. On the other side, Norwegian fisheries contribute to a large amount of CO2 emissions each year, which has resulted in political provisions to reduce emissions, both nationally through the Norwegian Climate Act and internationally through the EU and UN. Decision-makers must strive to both comply with emission reduction targets and at the same time maintain value creation.

An example of political incentivization of investments in emission-reducing technology is the introduction of Emission Control Area (ECA)s within shipping. When first introduced in 2006, this had a severe impact on the operation and fleet composition of many shipping companies. ECAs enforce a strict limit on SOx emissions from ships in the relevant area. Since 2006, more regions have been added to the list of ECAs, and the limit has become stricter. In order to comply with the sulphur limit in ECAs there are basically three alternatives; switch to low sulphur fuel when entering an ECA (so-called fuel-switching); install an exhaust gas scrubber and continue operations using MGO as usual; or, install LNG compatible machinery (Patricksson et al., 2015). With the ECA zones, the International Convention for the Prevention of Pollution from Ships (MARPOL) utilized an exemption period of 12 months from the date the area entered into force until the emission limits were effective (International Maritime Organization, 2019). Achieving a similar implementation for the Norwegian fishing fleet poses challenges, primarily due to the limited experience in maritime use and technological maturity of propulsion technologies such as electric-fuel cell hybrid vessels, which will be necessary to meet the emissions targets set for 2030 and 2050. However, policy-makers may influence this through subsidies that can, in turn, stimulate demand and technological development, or through the financial support of research and development of low- and zero-emission technology.

Cost and Revenue Considerations

Decision-makers must also consider costs and revenues related to operating and renewing the fishing fleet. All vessels have associated operational costs, including Operation and Maintenance (O&M) costs, fuel costs, CO2 taxation, and regeneration costs. The regeneration cost is defined as a periodic extra cost linked to the replacement of components in the system, e.g. batteries and/or fuel cells (Jafarzadeh et al., 2021). The need to replace certain components comes from wear and tear or ageing and is necessary to maintain the functionality of the system. These costs are periodic and depend on the lifespan of the various components and how much they are used.

In addition to operational costs, there are costs and revenues related to the renewal of the fleet. Typically, decision-makers will take into consideration the characteristics of the existing fleet when determining the better renewal option; replacement or retrofit. The installed propulsion option and age of the vessel may have implications for what option is more reasonable in terms of costs. In this thesis, we define vessel replacement as the acquisition of a new vessel outside the existing fleet. This entails investment in both a hull and propulsion system. The hull is defined as the vessel's watertight enclosure, while a propulsion system is defined as a system that provides a propelling or driving force (Wikipedia, 2023a, Wikipedia, 2023d). When a new vessel is introduced to the fleet, the replaced vessel is salvaged. In this thesis, the salvaging of a vessel is to be understood as the resale of a fishing vessel in a second-hand market. The vessel's salvage value corresponds to the residual value of the vessel in the relevant market and can come from the vessel's useful value as a fishing boat or as scrap value. Furthermore, we define retrofit as changing the propulsion system of an existing vessel in the fleet, implying that the retrofit option only incurs investment in a propulsion system.

Shipyard Capacity and Fuel Access

In addition to political goals, incentives and costs, decision-makers must also deal with external factors such as shipyard capacity and access to fuel.

In 2019, there were just under 70 active shipyards in Norway. According to Menon Economics and Boston Consulting Group (BCG) approximately 49 of the shipyards were repair and/or small shipbuilding yards, while 13 and 6 of the shipyards were medium-sized and large newbuilding yards, respectively. The 6 large newbuilding yards accounted for nearly 60% of the turnover among the shipyards in 2019. The medium-sized newbuilding yards accounted for 25% of turnover, while repair and/or small shipbuilding accounted for the remaining 18% (Haugland et al., 2021). The shipyards in Norway deliver vessels to a range of industries, including the offshore industry, fisheries, ferries, and cargo ships. The various shipyards have an upper capacity limit in terms of how many vessels they can build and retrofit each year. This is determined by a range of factors, including the size and specialization of each shipyard, the demand for their services, and the availability of resources such as skilled labour and materials.

In terms of access to fuel, this is largely dependent on both supply and infrastructure requirements of the specific type of fuel in consideration. In this thesis, we focus on MGO, battery power, as well as hydrogen and ammonia. As previously mentioned, MGO is the primary fuel used in modern fishing fleets, and therefore, the necessary infrastructure and access to this fuel are readily available. In order to install batteries on vessels, the primary infrastructure needed is a suitable charging network. However, the power demand can vary depending on the battery size and required charging times for a specific application. For example, charging 1,000 kWh in 30 minutes necessitates a power demand of 2,000 kW, while charging the same amount of energy in 10 minutes requires 6,000 kW of shore power. This can significantly strain the local electrical network and may necessitate power grid expansions (DNV GL Maritime, 2019). Since there is currently no demand for hydrogen or ammonia as fuel, there is no distribution or bunkering infrastructure for vessels. However, the production of both hydrogen and ammonia are well-known and commercially available technologies suitable for local production as long as adequate electrical energy is available. Another option is long-distance distribution infrastructure (DNV GL Maritime, 2019). In essence, the accessibility of hydrogen and ammonia supply is not constrained as long as suitable production facilities and grid power infrastructure are available. For this thesis, we make the rather strong assumption that we are not limited by access to fuel and that the choice of fuel type has no bearing on the operation of the vessel. This is deemed necessary in order to limit the extent of the real-life problem.

2.3.2 Low- and Zero-emission Propulsion Alternatives

The increasing demand for fuel efficiency and reduced emissions has led to the development of various propulsion systems. Propulsion systems are often categorised as mechanical, electrical or hybrid propulsion (Gabrieli and Jafarzadeh, 2020). The various propulsion options have varying potentials for retrofitting an existing vessel versus requiring the construction of a new one. For a more in-depth overview of the development of vessel propulsion systems, the reader is referred to Geertsma et al. (2017). A simplified illustration of the various propulsion systems presented in this section is given by Figure 2.15. Red indicates the conventional diesel-mechanic propulsion system, yellow indicates low-emission propulsion systems, and finally, green indicates zero-emission propulsion systems. The propulsion systems comprise various components, with the fuel engine, battery, and fuel cell being the focus of this thesis. These propulsion system components have associated energy storage solutions. Finally, it should be noted that vessels may have several combustion engines in order to cover the energy demand.

Diesel-mechanic Propulsion

As of today, the Norwegian fishing fleet predominantly uses a conventional diesel-mechanic propulsion system fueled by MGO. A diesel-mechanic propulsion system, illustrated at the top of Fig-

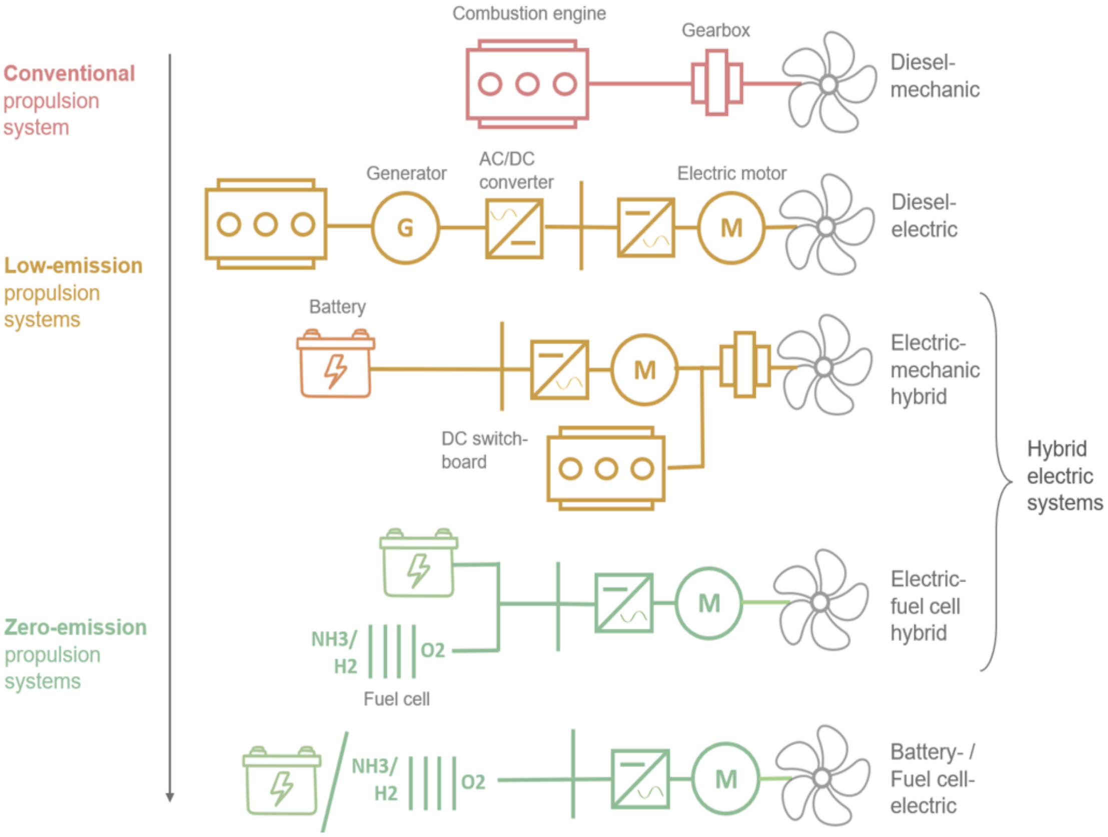


Figure 2.15: Illustration of a conventional diesel-mechanical propulsion system (red), low-emission propulsion systems (yellow) and zero-emissions propulsion systems (green)

ure 2.15, is particularly efficient for speeds between 80-100% of top speed. However, for speeds below 70% of top speed, the fuel efficiency is poor. For vessels operating at low engine load during certain periods, this results in a high specific fuel consumption and related emissions (Gabrieli and Jafarzadeh, 2020). The major advantage of marine diesel-mechanic propulsion is being well-experienced. With this comes well-known operational procedures, highly accessible spare parts, and also advanced global fuel bunkering nets. However, especially environmental concerns and emission reduction targets challenge the participants to think anew when it comes to propulsion technology as it seems difficult to stay below targets using today's technology and diesel fuels (Inal et al., 2022).

Diesel-electric Propulsion

A diesel-electric propulsion system is a transmission system for vehicles powered by combustion engines where the mechanical force of the combustion engine is converted into electrical energy by a generator, driving an electrical motor and thus avoiding the need for a gearbox (Wikipedia, 2023c). The system is illustrated by the second sketch from the top in Figure 2.15. This form of propulsion technology is especially fuel-efficient when the auxiliary power constitutes a significant amount of the propulsion power demand and for vessels with large variations in their operational profile. Especially because of the latter, diesel-electric propulsion is increasingly considered for ocean-going fishing vessels such as bottom trawlers and longliners. The reason for this is that the vessels in question are able to turn off one or more combustion engines so that the remaining engines are operated at high load, which increases fuel efficiency (Gabrieli and Jafarzadeh, 2020). The first diesel-electric coastal fishing vessel was delivered already in 2009. This was a 27.99 m long purse seiner equipped with four combustion engines and two electric motors. Compared to conventional diesel-mechanical propulsion, improved redundancy and reduced fuel consumption were experienced (Gabrieli and Jafarzadeh, 2020).

Hybrid Propulsion

A hybrid propulsion system enables a vessel to be powered in two ways. Using a multi-source energy system allows for optimisation and improvement of vessel power generation. Hybrids come in many configurations and two are presented in short in this section: The electric-mechanic hybrid and the electric-fuel cell hybrid, illustrated third and fourth from the top in Figure 2.15, respectively. Note that the diesel–electric propulsion system previously presented fails the definition of hybrid because the electric drive transmission directly replaces the mechanical transmission rather than being a supplementary source of motive power (Wikipedia, 2023e). Low- and zero-emission hybrid propulsion solutions based on batteries can be implemented as retrofits of existing vessels. The potential is greatest for vessels with a diesel-electric system, as opposed to a conventional diesel-mechanic system, where larger retrofits are required. However, weight and space requirements for battery systems will make it less favourable to retrofit existing vessels. To maximize range and minimize investment costs associated with battery packs, newbuilds offer greater opportunities for optimization, including greater opportunities for various energy efficiency measures (Valland, 2021).

Electric-mechanic hybrid
An electric-mechanic hybrid propulsion system vessel can be operated in three ways. Firstly, pure electric propulsion can be applied for low-speed steaming and low-energy fishing operation. Secondly, the vessel can apply mechanical propulsion for steaming to and from the fishing field and high-energy fishing operations. Finally, hybrid electrical and mechanical propulsion can be applied on occasions with heavy steaming. The electrical components are then used as a booster for the mechanical propulsion (Herdzik, 2013). Generally, economic benefits are to be expected if the fishing vessel operates below 40% of top speed, for a significant amount of time (Gabrieli and Jafarzadeh, 2020). Norwegian-made *Karoline*, a small smack with a length of 11 metres, is the world's first electric-mechanic hybrid fishing vessel and has been in successful operation since 2015. Karoline runs electric-only for almost three hours every day, and the batteries are fully recharged in port overnight (Jafarzadeh et al., 2021). The distance to the fishing field for Karoline is about 4 hours, corresponding to a reduced fuel consumption and CO2 emission of 25%. However, for a fishing vessel with the same battery capacity as Karoline, but with only 30 minutes of steaming to the fishing field, we would see a corresponding reduction of 60% (Aarsæther and Eldby, 2021). Another example of a vessel with an electric-mechanic hybrid system is the 21 metres long netter *Angelsen Senior* from 2019. According to the technical manager, the battery reduces the fuel consumption by 25%, and generator running time by as much as 75%, and it cuts annual CO2 emissions by 200 tonnes (FiskerForum, 2019).

For ocean-going vessels, on the other hand, the reduction in fuel consumption is limited by the necessary size of the battery that would have to be installed. Consequently, the emissions reduction potential for ocean-going vessels is less than for coastal vessels (Valland, 2021). The 81 metres long French pelagic vessel *Scombrus* reported 15-17% fuel and CO2 savings with an electric-mechanic hybrid propulsion system, demonstrating the viability of a hybrid solution for large ocean-going vessels (Bastardie, 2023). In terms of the development of battery technology, this would have to be improbably rapid in order for batteries to become sufficiently energy dense in order to contribute to an even greater emission reduction for energy-demanding ocean-going vessel operations (Wikipedia, 2023f).

Electric-fuel cell hybrid
A fuel cell works in the same way as a battery during discharge except that the reactant in a fuel cell is supplied continuously. Hydrogen or ammonia are widely used as a reactant and can be described as fuel (Holtebekk et al., 2021). The chemical compounds are simple and carbon-free and are converted into electricity without noise and vibrations in fuel cells, thus ensuring the same favourable working environment benefits as with conventional electrification with batteries.

Research on hydrogen fuel cells has spanned several decades, and the technology is mature enough to be rolled out in several applications. However, there is relatively little experience in maritime use, but results from vehicle demonstrations point to higher reliability than for conventional combustion engines (Jafarzadeh et al., 2021). There are two typically challenging aspects related to hydrogen fuel cells. The first is access to fuel. Infrastructure for production and distribution must be established together with the prototypes being tested, which increases the total costs associated with this type of demonstration project (Jafarzadeh et al., 2021). The second is the storage of hydrogen onboard the relevant fishing vessel. Hydrogen must be stored above deck due to its high flammability and consequent regulations. This requires large space above deck, in addition to the fact that fuel takes up more space than in a diesel vessel. Consequently, a hydrogen-electric fishing vessel must be made longer in order to store the hydrogen that covers the necessary energy demand (Høyem et al., 2022). This is not necessarily possible for a coastal fishing vessel due to the restrictions related to fishing quotas. As for ocean-going fleet, the use of hydrogen may be a viable zero-emission solution for vessels with moderate energy storage needs, such as purse seiners and conventional ocean-going vessels (Valland, 2021).

Hydrogen propulsion can be achieved on existing vessels using containerized fuel cell solutions and storage tanks located on the deck. In practice, the use of hydrogen will only be relevant for newbuilds since it entails weight increases, significant space requirements for storage tanks, and extensive system integration. Newbuilds offer greater flexibility than retrofitting existing vessels. As an example, a 28-meter fishing vessel must be extended to 34 meters to accommodate a hydrogen solution that is equivalent to a conventional diesel setup (Valland, 2021).

Ammonia cannot be used in the same type of low-temperature fuel cells as hydrogen but requires high-temperature fuel cells. These are currently less technologically mature and have not yet been used for mobile applications. However, ammonia is a well-known compound that can be easily liquefied, either by moderate cooling or pressurization and is thus easier to store and transport than hydrogen (Jafarzadeh et al., 2021). The challenge of ammonia is the fact that it is toxic, which entails extra investment costs and energy losses associated with facilities for synthesis and reforming (Høyem et al., 2022). The use of ammonia in fuel cells will require extensive retrofits of existing vessels, and the safety hazard associated with the use of ammonia as fuel implies that as of today, the use of fuel cells fueled by ammonia is not sufficiently technically mature (Valland, 2021). However, it is expected that this technology will have reached a maturity level that corresponds to operational operation around 2035 (DNV, 2022).

The goal of Jafarzadeh et al. (2021) was to develop a solution for a 13 metres coastal fishing vessel with hybrid propulsion based on batteries and fuel cells, with both hydrogen and ammonia as fuel. The report presents detailed sketches and thus a proof-of-concept of zero-emission propulsion technology. The estimated possible sea weather, i.e. the time between fuel bunkering, for an emission-free hydrogen vessel is 18 hours, and with the option to bring in a combustion engine, the vessel is able to be used in sea weather for up to three days. The study finds that a vessel with ammonia will be able to have a significantly longer range in terms of emission-free propulsion than a vessel with hydrogen, but that the current technology is not mature enough, nor does there exist a commercially available fuel cell system for ammonia (Jafarzadeh et al., 2021).

Battery/Fuel Cell Electric Propulsion

A pure electric propulsion system, illustrated at the bottom of Figure 2.15, implies that the vessel in question operates solely on batteries charged exclusively with shore grid power, or fuel cells (Gabrieli and Jafarzadeh, 2020). Pure electric propulsion entails both a lower carbon footprint and better working conditions on board the boat in terms of noise pollution. However, there are several challenges related to an all-electric fishing vessel. A battery electric propulsion system is limited by the low energy density (large battery), high weight, the energy needs of the larger vessels and the associated weight and space requirements, large investment costs on both vessels and land, as well as a lack of network and charging capacity in ports (DNV GL Maritime, 2019). Challenges associated with fuel cells and hydrogen and ammonia are as previously mentioned the lack of necessary infrastructure and storage onboard the vessels. Hydrogen is flammable and requires a large deck space, while ammonia is toxic, representing a safety hazard. Nevertheless, perhaps the most important limitation is the sensitivity to changes in load conditions. Fuel cells degrade based on load variation representing idling, rated power, and high-power operating conditions (Chandran et al., 2022). Because of the limiting factors, as of today, there are no examples of fishing vessels with a pure electric propulsion system. Consequently, these propulsion systems be disregarded further in this thesis.

Chapter 3

Related Literature

The aim of this chapter is to present previously applied modelling characteristics and approaches, as well as solution methods to the Parallel Fleet Replacement Problem (PFRP) within road-based and maritime transport. Firstly, Section 3.1 presents the task related to fleet management at a strategic, tactical and operational level, and introduces the Fleet Replacement Problem (FRP). Secondly, Section 3.2 provides an overview of replacement problems, focusing on the modelling characteristics, approaches and solution methods to the PFRP applied in the OR literature. Ultimately, Section 3.3 summarizes the literature on the Parallel Replacement Problem (PRP) and provides the contributions of this thesis.

3.1 Fleet Management

Fleet owners and managers are faced with challenging tasks related to fleet composition, replacement planning, and allocation/assignment across all transport modalities. These tasks are found at all three levels of the decision hierarchy: the strategic, tactical and operational levels (Hoff et al., 2010). The strategic level is concerned with establishing the framework in which the fleet will operate. This involves acquiring or discarding transportation capacity through a fleet of vessels, and the company may or may not have an existing fleet as a starting point. Regardless of the mode of transportation in question, strategic fleet decisions typically entail considerable capital investment. Uncertainty in demand, costs, and revenues related to fleet operations is high even over just a few years. The length of the time horizon over which decisions are made is generally longer in maritime than in road-based transportation due to the long operational lifetime of large vessels (Ksciuk et al., 2022). The tactical level comprises allocating and assigning the capacity, i.e. vessels of the fleet, to routes, contracts, or other types of operations. The operational level comprises the day-to-day operational planning, which generally consists of determining the routing plan of the day (Hoff et al., 2010). In the framework of Operations Research (OR), many mathematical models and methods have been developed in order to provide decision support for fleet management decisions. The focus of this literature review will be on strategic fleet management problems related to fleet replacement.

The Fleet Replacement Problem (FRP)

According to Redmer (2016), a Fleet Replacement Problem (FRP) concerns the decision on how long to exploit particular vehicles in a fleet or when to dispose of, convert or replace them and by what type of vehicles, in order to avoid too high ownership or exploitation costs including a selection of vehicles investment or acquisition option (e.g. to buy on cash, credit, lease or rent). The formulation of a FRP typically includes cost elements such as investment, O&M costs, as well as salvage value (Somboonwiwat, 2001). A fleet of vehicles is rarely homogeneous, i.e., the vehicles have different characteristics due to technological development and the market situation.

Operational, maintenance, and depreciation costs will thus vary over the lifetime of a vehicle (Hoff et al., 2010).

Essentially, Fleet Replacement Problems are Asset Replacement Problems applied to fleets of vehicles or vessels instead of the traditional application on machines or equipment. Asset replacement problems may be categorized as either serial or parallel replacement problems. In Serial Replacement Problems (SRP) each unit is considered to be economically independent and the solution consists of a keep or replace decision of each unit for each period over a horizon. The Parallel Replacement Problem (PRP) on the other hand, considers units that are economically interdependent and operate in parallel. The term *parallel replacement* was first introduced by Vander Veen (1985) who stated that economic interdependence can result from common budget constraints, demand constraints, service requirements or economies of scale in purchase prices. For such problems, the solution includes keep and replace decisions for each individual asset over the horizon.

Consequently, the Fleet Replacement Problem can be formulated as either a serial or parallel replacement problem, depending on whether or not economic interdependence between vessels is introduced. However, as a fleet is typically expected to cover a given demand, or is subject to a common regulatory framework, this literature review will focus on the PRP in terms of model characteristics, formulations and applied solution methods within the OR literature. For a comprehensive review on the SRP the reader is referred to Hartman and Tan (2014), who survey both the serial and parallel replacement problems under a variety of settings, including technological change, variable utilization, tax, and various uncertainties.

3.2 The Parallel Replacement Problem

According to Hartman (1998), effective operation and management of capital equipment are essential to the profitability or efficiency of any business or entity that relies on assets for the production of goods or services. This management includes proper utilization and timely replacement of the equipment, motivated by deterioration, resulting in lower salvage value and increasing O&M costs, or obsolesce, the appearance of new and more technologically advanced alternatives in the market. The PRP spans various applications. This section first presents modelling characteristics and approaches to the PRP by examples of application; generic asset replacement, road-based fleet replacement and maritime fleet replacement. Furthermore, a brief overview of applied solution methods in the OR literature is given.

3.2.1 Modelling Characteristics and Approaches

The purpose of formulating the Parallel Replacement Problem is to determine an optimal replacement schedule for the assets in question. The objective is often to minimize the (discounted) total cost of owning and operating a set of assets over a finite or infinite planning horizon. Throughout the OR literature several modelling approaches have been applied to the Parallel Replacement Problem. Examples are Dynamic Programming (DP), Linear Programming (LP), Integer Programming (IP) and network formulations. Most formulations in the literature are deterministic, but an increasing number of stochastic formulations can be found in recent literature.

Basic Model Formulation

Hartman (1998) presents a LP formulation for the deterministic equipment replacement problem in which multiple assets are required each period and several assets are available for replacement. This formulation is considered to be a basic formulation of the PRP and other formulations can be regarded as extensions.

Parameters

C_{ij}	discounted O&M cost for an i-period old asset in use from the end of time period j to $j+1$
P_{ij}	discounted initial purchase cost for an i-period old asset at the end of time period j
R_{ij}	discounted salvage cost (revenue) for an i-period old asset salvaged the end of time period j
H_i	n_i, i-period old assets available at time period zero
N	maximum asset age limit
T	decision horizon
d_j	demand for time j

Decision Variables

X_{ij}	i-period old asset in use from the end of time period j to $j+1$
B_{ij}	i-period old asset purchased at the end of time period j
S_{ij}	i-period old asset salvaged at the end of time period j

In this cash flow approach, there are no costs incurred on the flow from the initial assets. Additionally, this formulation assumes that the only viable replacement option is the purchase of a new asset. Consequently, the variable B_{ij} is reduced to B_j.

$$\begin{aligned}
\text{min} \quad & \sum_{j=0}^{T-1} P_j B_j + \sum_{i=0}^{N-1}\sum_{j=0}^{T-1} C_{ij}X_{ij} - \sum_{i=1}^{N}\sum_{j=0}^{T} R_{ij}S_{ij} & & (3.1)\\
\text{s.t.} \quad & \sum_{i=0}^{N-1} X_{ij} \geq d_j & j \in \{0,1,...,T-1\} \quad & (3.2)\\
& B_j - X_{ij} = 0 & i = 0; j \in \{0,1,...,T-1\} \quad & (3.3)\\
& H_i - X_{ij} - S_{ij} = 0 & i \in \{1,2,...,N-1\}; j = 0 \quad & (3.4)\\
& H - i - S_{ij} = 0 & i = N; j = 0 \quad & (3.5)\\
& X_{(i-1)(j-1)} - X_{ij} - S_{ij} = 0 & i \in \{1,2,...,N-1\}; j \in \{1,2,...,T-1\} \quad & (3.6)\\
& X_{(i-1)(j-1)} - S_{ij} = 0 & i > 0; j = T \text{ and } i = N; j > 0 \quad & (3.7)\\
& H_i = n_i & i \in \{1,2,...,N\} \quad & (3.8)\\
& H_i, B_j, X_{ij}, S_{ij} \geq 0 & i \in N; j \in T \quad & (3.9)
\end{aligned}$$

The objective function (3.1) minimises the sum of purchase, O&M costs and salvage values over the decision horizon. Constraint (3.2) ensure that the demand is met in every period. Constraint(3.3)-(3.7) are flow balance constraints that preserve the flow at all (i, j) nodes. Constraint (3.8) defines the initial fleet in terms of the number of assets and their age (assumed known information). The final constraint (3.9) is the non-negativity constraint. An integer restriction is omitted in this formulation due to the proven integer solution under common cost assumptions. See Hartman (1998) for more details on this aspect.

Asset Replacement

Jones et al. (1991) consider a Dynamic Programming (DP) formulation of the PRP with both fixed and variable costs associated with replacing machines in the same cluster. Increasing maintenance costs motivate replacements, and the fixed replacement costs provide an incentive for replacing machines of different ages. Adil and Gill (1994) formulate a IP model assuming that purchasing, maintenance, operating, and resale values of the equipment under consideration are all deterministically known. The age is used to determine the present state of the equipment. The model is a relaxation of the binary IP model presented in Bector et al. (1992), and is proven to always yield integer solutions. Karabakal et al. (1994) also formulate a binary IP in which the economic interdependence among the assets is caused by capital rationing. Chen (1998) considers the PRP in which machine investment costs exhibit economy of scale. The model is formulated as a binary

IP, inspired by Jones et al. (1991). Hartman (2000) presents a deterministic Integer Programming (IP) formulation to the generalized PRP with fixed and variable replacement costs, capital budgeting, and demand constraints. In Hartman (2004), on the other hand, demand is considered to be stochastic with discretized levels of asset utilization. The author utilizes a stochastic DP formulation.

Road-based Fleet Replacement

Simms et al. (1984) consider the optimal buy, operate and sell policy for a fleet of vehicles in a deterministic setting and using a DP formulation. Suzuki and Pautsch (2005) examines how motor carriers should adjust their vehicle replacement policies when dramatic changes of vehicle re-sale values and insurance premiums are observed. The vehicle replacement model is formulated as an IP. Büyüktahtakin and Hartman (2016) propose a Mixed-Integer Programming (MIP) approach to the Parallel Replacement Problem under economies of scale. The authors incorporate capacity gains into the model so that newer, more technologically advanced assets have higher capacity than assets purchased earlier. The case study is conducted with data from the United States postal fleet. The formulation is based on the asset replacement model of Hartman (2000).

In recent years, a lot of OR literature related to road-based transport has been published. This may be seen in connection with the ever-increasing focus on the environmental impact of the transport sector, and the transition to electric and alternative-fuel vehicles. Stasko and Oliver Gao (2010) introduces an IP model that minimizes operational costs, plus penalties for emissions, given capital budget constraints. The fleet composes of diesel and hybrid buses and retrofits are incorporated as an alternate method of reducing emissions. Stasko and Oliver Gao (2012) incorporate uncertainty in their formulation and introduce an IP model for making vehicle purchase, resale, and retrofit decisions considering environmental regulations, with a stochastic vehicle breakdown. Kleindorfer et al. (2012) incorporate uncertainty in their formulation of the PRP. The authors examine a fleet of postal delivery (combustion) vehicles and the decision of adopting electric vehicles under uncertainty about future fuel prices and future battery costs. The optimal timing of adopting electric vehicles is found over a 15-year horizon. The model is based on a stochastic DP formulation. Parthanadee et al. (2012) study a fleet of service vehicles that vary in age and cumulative mileage and introduce an IP approach to the PRP. In every replacement decision period, vehicles using either compressed natural gas (CNG) or liquefied petroleum gas (LPG) are included as challengers to the initial fleet consisting of gasoline vehicles. Emiliano et al. (2020) propose an IP model that integrates both budgetary and environmental constraints (CO2 emissions). The study aims to determine the optimal replacement plan for a fleet of diesel buses of different sizes, ages, maintenance costs and emissions rates, with new (less polluting) diesel buses over a time horizon of 50 years. Rajabian et al. (2020) introduce a deterministic MIP model for the PRP under technological change, while also considering environmental aspects in terms of emission regulations by a cap-and-trade system. The model formulation includes both replacement, retrofitting and salvage of a fleet of excavators. Yu (2021) establish a MIP formulation of the PRP regarding a self-driving bus fleet.

Maritime Fleet Replacement

There is also a large amount of OR literature concerning fleet replacement within maritime transport, i.e. shipping. In this literature, the problem is often referred to as the Maritime Fleet Renewal Problem (MFRP) and for an extensive survey on this problem, the reader is referred to Patricksson et al. (2015). The traditional MFRP is a combination of the well-established Maritime Fleet Size and Mix Problem (MFSMP), which considers strategic fleet composition decisions, and the Vehicle Routing Problem (VRP), which involves routing decisions. In its basic version, the MFSMP consists of deciding how many ships of each type to use in order to meet the demand, i.e. designing the optimal fleet of ships. The reader is referred to Pantuso et al. (2014) for a comprehensive survey on the MFSMP. The vehicle routing constraints are included in order to incorporate complete (discounted) life-cycle costs in terms of the acquisition and operation of a fleet of ships. Compared to road-based transport, it is even more important to have adequate cost estimates, including operational costs, for the maritime sector, due to the long life expectancy of ships, large investment costs, and considerable uncertainty in demand, freight rates and operational costs (Patricksson et al., 2015).

Cho and Perakis (1996) propose a MIP model that suggests both optimal routing mixes alternatives, as well as capital investment alternatives (build, purchase or charter) to expand fleet capacity in terms of cost minimization. Later literature also takes uncertainty into account. Alvarez et al. (2011) propose a MIP model of the multi-period fleet sizing and deployment problem, extended into a robust optimization model, considering random fluctuations in the selling and purchasing prices of ships. Pantuso et al. (2016), on the other hand, introduce a stochastic MIP model where future values of demand, new building and second-hand prices, charter rates, travel costs and scrapping values are uncertain. Furthermore, Bakkehaug et al. (2014) proposes a multi-stage stochastic programming formulation and explicitly handles uncertainty in parameters such as future demand, freight rates and vessel prices. The model is node formulated and includes decisions such as when and how to scrap, sell, buy or charter ships.

Also within the maritime sector, participants must deal with new environmental regulations, forcing investments in new propulsion technology. Patricksson et al. (2015) introduce a two-stage stochastic programming model formulated as a MIP, taking into account aspects related to regional limitations in the form of Emission Control Areas (ECA). The authors use a node formulation to describe the discretized possible future scenarios. Zhu et al. (2018) investigates the fleet replacement strategies and resulting CO2 emissions of operators in various scenarios by varying CO2 prices. A stochastic IP model is formulated in order to evaluate the potential impact of an open maritime emissions trading system (METS) on individual containership operators' fleet composition strategies.

3.2.2 Solution Methods

The PRP is combinatorial in nature, and the size of the problem quickly grows with increasing planning horizon, as well as with the number of assets and replacement options. A SRP with k options for replacement in every time period T has a number of $(k+1)^T$ possible solutions. In a PRP, on the other hand, where n assets are required in every time period, the number of possible solutions are given by $\left[\sum_{x=0}^{n} k^x \begin{pmatrix} n \\ x \end{pmatrix}\right]^T$. As a consequence, the solution method applied to the PRP must be chosen in such a way that it matches the problem formulation and the size of the problem instance.

Dynamic Programming have proven useful for solving serial replacement problems. However, when applied to assets considered in parallel, and combinatorics is introduced as a consequence, the problem becomes difficult to solve (Vander Veen, 1985). Richard E. Bellman described the problem caused by the exponential increase in solution space as the *curse of dimensionality* (Wikipedia, 2023b). Consequently, other modelling approaches and solution methods have been applied to the PRP. Exact solution methods such as Branch-and-Bound (B&B), decomposition techniques such as Lagrangian relaxation and Benders decomposition, in addition to (meta)heuristic approaches, are introduced to solve the developed models (Turan et al., 2020).

Exact Solution Methods

In order to solve a DP, either backward or forward recursion is used, depending on the formulation. With backward recursion, in each stage, the optimal way to get to the lowest cost *from* this stage is calculated. With forward recursion, on the other hand, the optimal way to get to the lowest cost *until* this stage is calculated (Lundgren and Ronnqvist. M, 2012). Jones et al. (1991) demonstrates the combinatorial nature of the DP formulation. With 15 machines (in three age groups or clusters), the corresponding problem formulation has over 8.4 billion constraints and over 490,000 variables. The authors however drastically reduce the state space by introducing two simple and intuitive rules. First, it is never optimal to split clusters, and second, newer clusters are never replaced before older clusters. Hartman (2004) uses backward recursion in order to solve a stochastic DP and determine the optimal replacement schedules and utilization levels for two assets that operate in parallel over a finite horizon. The author argues that although DP solutions generally suffer from the curse of dimensionality with an increased number of state variables, the solution method is efficient for two assets despite having four or five state variables, depending on cost assumptions.

Karabakal et al. (1994) develop a B&B algorithm based on Lagrangian relaxation methodology in order to solve the binary IP formulation. Lagrangian relaxation methods are based on the observation that many hard IPs can be viewed as easy problems with a set of "complicating" side constraints. Dualizing such constraints produces a Lagrangian relaxation of the original problem. In order to solve the resulting Lagrangian dual problem, the authors implement a subgradient algorithm. Cho and Perakis (1996) did not apply their model on test instances but suggested Lagrangian relaxation for solving the proposed MIP formulation. Chen (1998) propose an algorithm for solving the binary IP formulation based on Benders' decomposition. The number of subproblems equals the number of groups of machines at the beginning of period 1, where machines in the same group have the same age.

Multiple of the studies papers utilize a MIP solver in order to obtain the optimal replacement schedule (Bector et al., 1992; Adil and Gill, 1994; Hartman, 2000; Suzuki and Pautsch, 2005; Alvarez et al., 2011; Parthanadee et al., 2012; Laksuwong et al., 2014; Patricksson et al., 2015; Pantuso et al., 2016; Zhu et al., 2018;Emiliano et al., 2020; Rajabian et al., 2020). These are PRP with IP formulations, of which most are deterministic programs. These solvers utilize the Simplex method, as well as B&B techniques in order to solve the relevant problem and examples of applied commercial solvers are Gurobi, Xpress and CPLEX. However, evidence suggests that large integer programs can be difficult to solve even for modern commercial solvers due to a large number of decision variables and large state space. Büyüktahtakin and Hartman (2016) first implement a Branch-and-Cut framework with two sets of cutting planes in order to strengthen the model formulation before it is solved with a commercial solver. Hartman (2000), on the other hand, show that the LP relaxation of a restricted subproblem of the PRP has integer extreme points. More specifically, in the author's formulation with economies of scale, if the binary variable that imposes a fixed charge with asset purchase, is fixed, then the optimal solution to the LP relaxation of the resulting formulation is integer-valued. This allows for the solution of large PRPs as B&B procedures are only required for the T binary variables (length of the finite horizon). LP relaxation is also utilized in Adil and Gill (1994).

Heuristics

Simms et al. (1984) formulate a DP structured so that it may be solved by a combination of the optimization techniques of DP and LP. Stasko and Oliver Gao (2010) use an IP approach in combination with a traditional vehicle task assignment algorithm. The formulation is designed to operate in sequence with the algorithm, in order to add emissions and long-term financial cost elements to the objective while maintaining computational tractability and feasible input data requirements. Stasko and Oliver Gao (2012) present an approximate DP approach,i.e. a rolling horizon heuristic, for solving the stochastic IP formulation. The authors argue that stochastic DP can handle the discrete nature of vehicles and accurately represent the dynamic interaction between stochastic breakdown events and fleet owner decisions. Bakkehaug et al. (2014) solves the deterministic equivalent of their stochastic formulation for the current period using a standard MIP solver as a part of a heuristic that utilizes simulation with a rolling-horizon approach. Yu (2021) uses both a commercial solver, as well as a heuristic algorithm to determine the optimal vehicle acquisition and phase-out scheme.

3.3 Summary and Contributions

Table 3.1 summarises the main aspects related to the model characteristic, approach and solution methods of the reviewed literature on the PRP presented in Section 3.2.

Table 3.1: Overview of literature regarding the Parallel Replacement Problem (PRP)

Reference	**Generic**	**Road-based**	**Maritime**	**Emi. Red.**	**Modelling Approach**	**Solution Method**
Simms et al. (1984)		•			DP	Heuristic
Jones et al. (1991)	•				DP	-
Bector et al. (1992)	•				Binary IP	MIP solver
Adil and Gill (1994)	•				(Relaxed) IP	MIP solver
Karabakal et al. (1994)	•				Binary IP	Lagrangian relaxation
Cho and Perakis (1996)			•		IP	Lagrangian relaxation
Chen (1998)	•				Binary IP	Benders' decomposition
Hartman (2000)	•				(Relaxed) IP	MIP solver
Hartman (2004)	•				Stochastic DP	-
Suzuki and Pautsch (2005)		•			IP	MIP solver
Stasko and Oliver Gao (2010)		•		•	IP	Heuristic
Alvarez et al. (2011)			•		Robust IP	MIP solver
Stasko and Oliver Gao (2012)		•		•	IP	Heuristic
Kleindorfer et al. (2012)		•		•	Stochastic DP	-
Parthanadee et al. (2012)		•		•	IP	MIP solver
Laksuwong et al. (2014)		•		•	Single-period IP	MIP solver
Bakkehaug et al. (2014)			•		Stochastic IP	MIP solver + Heuristic
Patricksson et al. (2015)			•	•	Stochastic IP	MIP solver
Pantuso et al. (2016)			•		Stochastic IP	MIP solver
Büyüktahtakin and Hartman (2016)		•			IP	B&C + MIP solver
Zhu et al. (2018)			•	•	Stochastic IP	MIP solver
Emiliano et al. (2020)		•		•	IP	MIP solver
Rajabian et al. (2020)		•		•	IP	MIP solver
Yu (2021)		•		•	IP	MIP solver + Heuristic

For this thesis, we develop an IP model aimed at offering decision support for fleet renewal in the context of a zero-emission fisheries fleet. The existing literature on fleet renewal in the maritime sector is not directly applicable to our case study. This is primarily because the approaches used in maritime studies combine fleet replacement and routing decisions by including VRP constraints, which do not align with the operational characteristics of fishing vessels. Unlike in maritime transportation, fishing vessels do not adhere to predetermined routes in the same manner. As a result, we focus on road-based replacement problems since they align more closely with our specific problem. This approach allows us to consider flow restrictions and opportunities related to vessel purchase, retrofitting, and salvaging. Additionally, we aim to incorporate emission requirements, which pose a constraint applied to the combination of vessels. This introduces additional complexity as it prevents us from decomposing the problem into smaller sub-problems. In the existing literature, similar complexities arise from joint demand or budget constraints that must be fulfilled by the combined fleet.

In summary, our contribution to the OR literature involves expanding the understanding and methodologies in the field by specifically addressing the distinctive constraints and requirements of fleet renewal in the context of a zero-emission fisheries fleet, with a focus on the Norwegian fishing fleet.

Chapter 4

Problem Description

In this chapter, we provide a description of the Fishing Fleet Renewal Problem with Emission Constraints (FFRPEC). The purpose of the FFRPEC is to determine a fishing fleet renewal schedule that satisfies emission constraints over a planning horizon while minimizing the total discounted costs related to the renewal and operation of the fishing fleet.

In the FFRPEC, we have a set of existing fishing vessels, belonging to different sub-fleets. In this context, a sub-fleet refers to a cluster of vessels that use the same primary fishing gear.

This classification is used as the primary fishing gear has implications for the operational profile of the relevant vessel in terms of distance travelled and the energy intensity of the steaming and fishing operation. Consequently, the vessels of different sub-fleets have different energy consumption, making the various sub-fleets heterogeneous in this respect. Vessels that belong in the same sub-fleet, however, are considered homogeneous in terms of energy consumption. Each vessel has associated operational costs and salvage value, as well as CO2 emissions, which numerical values depend on the age of the relevant vessel and the propulsion system installed. The operational costs include expenses related to O&M, fuel, CO2 taxation, and regeneration. Figure 4.1 illustrates both the shared characteristics of the fishing vessels within a sub-fleet and the distinctive features of each fishing vessel due to propulsion system and age.

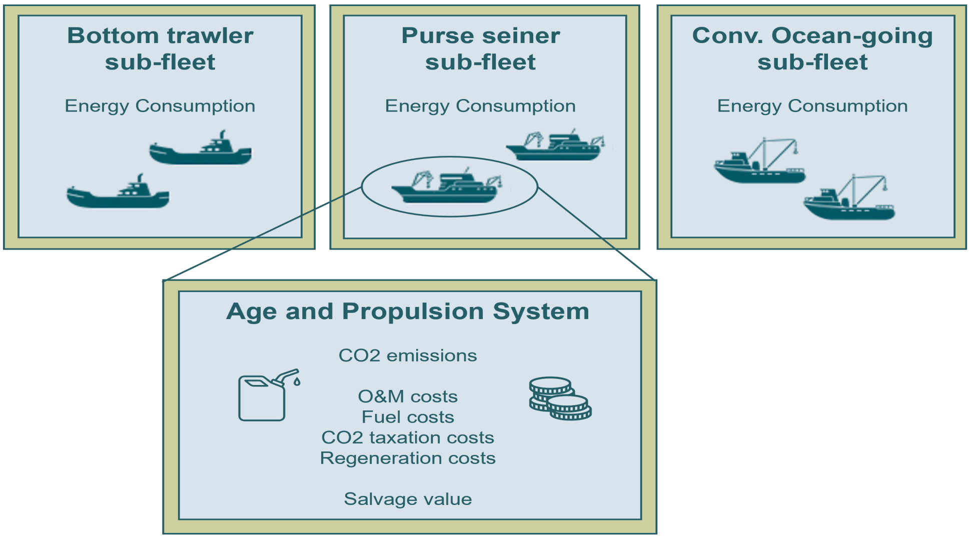


Figure 4.1: Illustration of common characteristics of vessels within the same sub-fleet (energy consumption), as well as distinctive features of each fishing vessel (age and propulsion system).

For every sub-fleet, there exists a set of decisions that describe the renewal options of the fishing fleet. Each of these decisions entails an investment cost, a change in the operational costs, and in the CO2 emissions. The renewal options include retrofitting an existing vessel in the fleet, i.e. changing the propulsion system of the relevant vessel, or replacing a vessel with a new one. Whenever a vessel belonging to a particular sub-fleet is replaced, a new vessel with a specific propulsion system is introduced within the same sub-fleet, while the vessel being replaced is salvaged. This comes from the underlying assumption that the operation of the various sub-fleet is to remain unchanged over the planning horizon. Note that some propulsion systems become available later than others due to lagging technological maturity. Whenever a vessel is salvaged, this entails a revenue corresponding to the salvage value of the vessel. It is common practice to assume a decreasing salvage value with the age of the relevant vessel. Once a vessel reaches the age corresponding to its economic lifetime, the vessel may still be utilized, but at a higher operating cost and with zero salvage value. However, when the vessel reaches the conclusion of its technical lifetime, it must be salvaged.

The FFRPEC also takes into account the limited capacity of the shipyard to retrofit and replace vessels in each period.

The objective of the FFRPEC is to minimize the discounted total costs related to the renewal and operation of the combined fishing fleet. At the same time, the model must comply with emission constraints, such as emission caps that apply over time, necessitating investments in low- and zero-emission propulsion systems. Vessels with a low- and zero-emission propulsion system have lower CO2 emissions compared to conventional diesel-mechanic vessels, either from being more fuel efficient or from using fuels with a lower CO2 footprint, such as battery power, hydrogen or ammonia. The model is responsible for determining the renewal decisions necessary to conform with the emission constraints, including the timing of such decisions.

Chapter 5

Mathematical Formulation

In this chapter, we present our formulation of the FFRPEC. The modelling assumptions we make are presented in Section 5.1, while the notation and a detailed description of the mathematical model for the FFRPEC are presented in Section 5.2 and Section 5.3, respectively.

5.1 Modelling Assumptions

For the sake of limiting the extent of the real-life problem regarding fleet renewal, some assumptions about the nature of the problem have been made in our formulation of the FFRPEC. The assumptions are outlined below.

(1) *The renewal (replacement or retrofit) and salvaging of vessels in a time period applies from the subsequent time period*

Assumption (1) is incorporated to acknowledge the reality that there is a time lag between placing an order for a vessel and its readiness for use, as well as between the decision to salvage a vessel and it being taken out of operation.

(2) *There are no storage options for vessels*

Assumption (2) implies that all vessels are in use, and prevents the construction of vessels that are not used for fishing operations. It is conceivable that this modelling assumption will not affect the results of the model to any particular extent, as the time value of money makes it beneficial to delay investments.

(3) *The number of vessels in each sub-fleet remains constant throughout the planning horizon*

Assumption (3) is included in order to retain the composition of the combined fishing fleet in terms of sub-fleets. By doing so we ensure that any changes made to the fishing fleet do not disrupt the overall structure and operational pattern of the combined fleet.

(4) *When a vessel is replaced, it may only be replaced by a brand-new vessel*

Assumption (4) implies that we disregard the possibility to invest in vessels from a second-hand market. This is considered a reasonable assumption as the emission constraints force investments in vessels with new low- and zero-emission propulsion systems that are not yet available in a second-hand market.

(5) *Retrofit and replacement cost, as well as salvage value, are assumed to be incurred at the beginning of each period, while the O&M, fuel, CO2 taxation and regeneration costs are incurred at the end of the period*

We have included Assumption (5) as this is a widely recognized practice in the OR literature, as demonstrated by Hartman (2000).

5.2 Notation

In this section, we introduce the mathematical notation used in our formulation of the FFRPEC.

Sets

$\mathcal{F}$	Set of sub-fleets
$\mathcal{F}^c$	Set of coastal sub-fleets, $\mathcal{F}^c \subseteq \mathcal{F}$
$\mathcal{F}^o$	Set of ocean-going sub-fleets, $\mathcal{F}^o \subseteq \mathcal{F}$
$\mathcal{I}$	Set of ages
$\mathcal{I}_{fo}$	Set of ages for sub-fleet f with propulsion system o, $\mathcal{I}_{fo} \subseteq \mathcal{I}$, $\mathcal{I}_{fo} = \{0, .., L_{fo}\}$
$\mathcal{O}$	Set of propulsion systems
$\mathcal{O}_{ft}$	Set of propulsion systems for sub-fleet f in time period t, $\mathcal{O}_{ft} \subseteq \mathcal{O}$
$\mathcal{O}_{ft}^{zero}$	Set of zero-emission propulsion systems for sub-fleet f in time period t, $\mathcal{O}_{ft}^{zero} \subseteq \mathcal{O}_{ft}$
$\mathcal{T}$	Set of time periods

Parameters

B_t^c	Shipyard capacity for coastal vessels in period t
B_t^o	Shipyard capacity for ocean-going vessels in period t
C_t	CO2-tax in period t
d_t	Discount factor in period t
E_{fot}	CO2 emissions of a vessel in sub-fleet f with propulsion system o in period t
F_{fot}	Fuel costs of a vessel in sub-fleet f with propulsion system o in period t
H_{foi}	Number of vessels in sub-fleet f with propulsion system o of age i in the initial fleet (period 0)
L_{fo}	Technical lifetime of a vessel in sub-fleet f with propulsion system o
M	Maximum number of replacements within a sub-fleet over the planning horizon given in multiples of the relevant fleet size
O_{foit}	O&M costs of a vessel in sub-fleet f with propulsion system o of age i in period t
P_{foit}	Replacement cost of a vessel in sub-fleet f with propulsion system o of age i in period t
$Q_{fo'oit}$	Retrofit cost of a vessel in sub-fleet f retrofitted from propulsion system o' to propulsion system o of age i in period t
R_{foit}	Regeneration costs of a vessel in sub-fleet f with propulsion system o of age i in period t
S_{foit}	Salvage value (revenue) of a vessel in sub-fleet f with propulsion system o of age i in period t
T_t^{max}	Maximum total emission from the fleet in period t

Decision Variables

v_{foit}	The number of vessels in sub-fleet f with propulsion system o of age i in period t
b_{foit}	The number of vessel replacements made in sub-fleet f with propulsion system o of age i in period t
s_{foit}	The number of vessels salvaged in sub-fleet f with propulsion system o of age i in period t
$r_{fo'oit}$	The number of vessels retrofitted in sub-fleet f from propulsion system o' to propulsion system o of age i in period t

5.3 Mathematical Model

This section provides our formulation of the FFRPEC.

Objective

$$\begin{aligned}\min \sum_{f\in\mathcal{F}}\sum_{t\in\mathcal{T}}\sum_{o\in\mathcal{O}_{ft}}\sum_{i\in\mathcal{I}_{fo}} \Big(& d_t P_{foit} b_{foit} + d_t \sum_{o'\in\mathcal{O}_{ft}\setminus\{o\}} Q_{fo'oit} r_{fo'oit} \\ & + d_{t+1}(O_{foit} + F_{fot} + C_t E_{fot} + R_{foit}) v_{foit} - d_t S_{foit} s_{foit} \Big)\end{aligned} \tag{5.1}$$

The objective function (5.1) minimises the discounted total cost over the planning horizon. The first two terms represent the total discounted investment costs associated with vessel replacement and retrofitting, respectively. The third term is the total discounted costs related to the operation of the vessels of the fleet in all time periods. This includes O&M, fuel, CO2 taxation and regeneration costs. The fourth and final term represents the revenue originating from salvaging vessels. The total cost is calculated with all sub-fleets and associated propulsion technologies. Note that the model formulation requires that the discount factor for time period $d_{|\mathcal{T}|+1}$ be calculated as well.

Flow Balance Constraints

$$v_{foi,0} = H_{foi} \qquad f \in \mathcal{F}, o \in \mathcal{O}_{f,0}, i \in \mathcal{I}_{fo} \tag{5.2}$$

$$\begin{aligned} v_{foit} + b_{fo,i+1,t} - s_{foit} + \sum_{o'\in\mathcal{O}_{ft}\setminus\{o\}} (r_{fo'oit} - r_{foo'it}) = v_{fo,i+1,t+1} \\ f \in \mathcal{F}, t \in \mathcal{T}\setminus\{|\mathcal{T}|\}, o \in \mathcal{O}_{ft}, i \in \mathcal{I}_{fo}\setminus\{|\mathcal{I}_{fo}|\} \end{aligned} \tag{5.3}$$

Constraints (5.2) ascertains that the characteristics of the vessels of the first period equal the initial fleet given by the parameter H_{foi} in terms of sub-fleet, propulsion system and age. Constraints (5.3) ensure the flow balance from one period to the next, illustrated by Figure 5.1. Vessels replaced in the relevant period are available for use in the subsequent period at the age they were bought, while salvaged vessels are no longer available. In the same manner, vessels that are retrofitted from other propulsion technologies to the current propulsion technology become available in the subsequent period, while vessels retrofitted from the current propulsion technology to another propulsion technology are not.

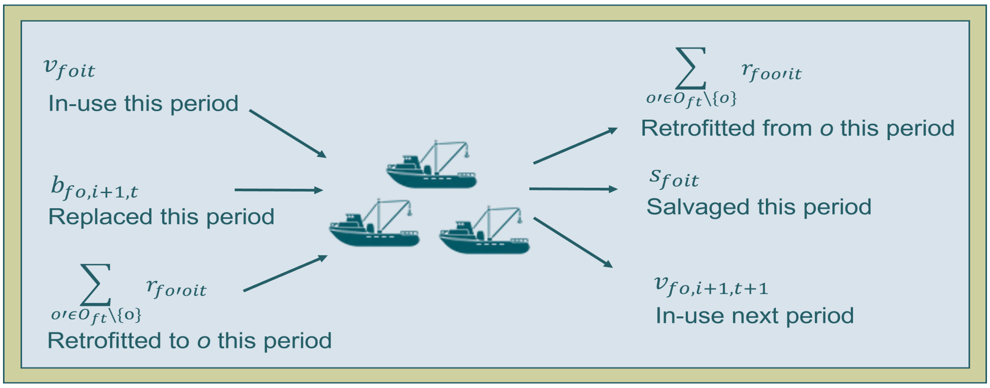


Figure 5.1: Illustration of the flow balance constraints (5.3)

In addition to the traditional flow balance constraints (5.2) and (5.3), we need constraints that ensure a constant size of every sub-fleet, as well as limitations to the vessels, in order to obtain a correct flow of vessels.

$$\sum_{o\in\mathcal{O}_{ft}}\sum_{i\in\mathcal{I}_{fo}} H_{foi} = \sum_{o\in\mathcal{O}_{ft}}\sum_{i\in\mathcal{I}_{fo}} v_{foit} \quad f\in\mathcal{F}, t\in\mathcal{T} \tag{5.4}$$

Constraints (5.4) ensure that the number of vessels in every sub-fleet, irrespective of propulsion technology and age, shall remain unchanged throughout the planning horizon given the initial sub-fleet sizes.

$$\begin{gathered} v_{foit} = 0 \\ f\in\mathcal{F}, t\in\mathcal{T}\setminus\{0\}, o\in\{\mathcal{O}_{ft}|o\notin\mathcal{O}_{f,t-1}\}, i\in\mathcal{I}_{fo} \end{gathered} \tag{5.5}$$

Constraints (5.5) ensure that there can not be vessels of a propulsion technology o in period t that were not available in the previous period.

$$\sum_{o\in\mathcal{O}^{zero}_{ft}}\sum_{i\in\mathcal{I}_{fo}} (v_{foi,t+1} - v_{foit}) \geq 0 \quad f\in\mathcal{F}, t\in\mathcal{T}\setminus\{|\mathcal{T}|\} \tag{5.6}$$

Constraints (5.6) ensure that the total number of vessels with zero-emission propulsion systems within each sub-fleet cannot decrease from one time period to the next.

Replacement Constraints

$$b_{foit} = 0 \quad f\in\mathcal{F}, t\in\mathcal{T}, o\in\mathcal{O}_{ft}, i\in\mathcal{I}_{fo}\setminus\{0\} \tag{5.7}$$

$$b_{fo,0,t} = v_{fo,0,t+1} \quad f\in\mathcal{F}, t\in\mathcal{T}\setminus\{|T|\}, o\in\mathcal{O}_{ft} \tag{5.8}$$

Constraints (5.7) only allow for investments in vessels of age $i = 0$, i.e. brand new vessels. Constraints (5.8) strength constraints (5.3) by ensuring that all new vessels ($i = 0$) must be invested in the previous period.

$$\sum_{t \in \mathcal{T}} \sum_{o \in \mathcal{O}_{ft}} \sum_{i \in \mathcal{I}_{fo}} b_{foit} \leq M \sum_{o \in \mathcal{O}_{ft}} \sum_{i \in \mathcal{I}_{fo}} H_{foi} \quad f \in \mathcal{F} \tag{5.9}$$

Constraints (5.9) ensure that the total number of replacements within a sub-fleet made over the planning horizon is less than or equal to M times the size of the relevant sub-fleet. These restrictions are implemented to approximate real-world scenarios where it is impractical to replace a vessel more than twice within the planning horizon. While our formulation may not allow us to enforce this restriction for each individual vessel, we can ensure that within each sub-fleet, the number of replacements does not exceed twice the size of the relevant sub-fleet. This approach allows us to maintain a reasonable approximation of reality. For this purpose, the value of M is set to 2.

Salvage Constraints

$$\sum_{i \in \mathcal{I}_{fo}} s_{foit} \leq \sum_{i \in \mathcal{I}_{fo}} v_{foit} \quad f \in \mathcal{F}, t \in \mathcal{T}, o \in \mathcal{O}_{ft} \tag{5.10}$$

Constraints (5.10) ensure that we cannot salvage more vessels with a specific propulsion system than there are in the relevant sub-fleet in a specific period.

$$v_{fo,L_{fo},t} = s_{fo,L_{fo},t} \quad f \in \mathcal{F}, t \in \mathcal{T}, o \in \mathcal{O}_{ft} \tag{5.11}$$

Constraints (5.11) ensure that vessels that reach the end of their technical life in period t are salvaged during the respective period.

$$\sum_{f \in \mathcal{F}} \sum_{o \in \mathcal{O}_{f,|\mathcal{T}|}} \sum_{i \in \mathcal{I}_{fo}} s_{foi,|\mathcal{T}|} = 0 \tag{5.12}$$

$$\sum_{f \in \mathcal{F}} \sum_{t \in \mathcal{T}} \sum_{o \in \mathcal{O}_{ft}} s_{fo,|\mathcal{I}_{fo}|,t} = 0 \tag{5.13}$$

The boundary conditions are addressed by constraints (5.12) and (5.13). Constraints (5.12) ensure that the model does not salvage vessels in the last period of the planning horizon, while constraints (5.13) ensure that the model does not salvage vessels of the maximum possible age. The flow balance constraints do not account for this aspect, enabling the model to overlook any future considerations beyond the planning horizon and the ages under consideration. The boundary conditions are necessary to consider for this specific variable as it generates revenues in the objective.

Shipyard Capacity Constraints

$$\sum_{f \in \mathcal{F}^c} \sum_{o \in \mathcal{O}_{ft}} \sum_{i \in \mathcal{I}_{fo}} \Big(b_{foit} + \sum_{o' \in \mathcal{O}_{ft} \setminus \{o\}} r_{fo'oit} \Big) \leq B^c_t \quad t \in \mathcal{T} \tag{5.14}$$

$$\sum_{f \in \mathcal{F}^o} \sum_{o \in \mathcal{O}_{ft}} \sum_{i \in \mathcal{I}_{fo}} \Big(b_{foit} + \sum_{o' \in \mathcal{O}_{ft} \setminus \{o\}} r_{fo'oit} \Big) \leq B^o_t \quad t \in \mathcal{T} \tag{5.15}$$

Constraints (5.14) and (5.15) ensure that the shipyard capacity in terms of the number of vessel replacements and retrofits in period t is not exceeded for the coastal and ocean-going sub-fleets, respectively.

Emission Reduction Constraints

$$\sum_{f \in \mathcal{F}} \sum_{o \in \mathcal{O}_{ft}} \sum_{i \in \mathcal{I}_{fo}} E_{fot} v_{foit} \leq T_t^{max} \qquad t \in \mathcal{T} \tag{5.16}$$

Constraints (5.16) prohibit the total emission of the combined fishing fleet to exceed the emission cap of the relevant period.

Variable Bounds

$$v_{foit}, b_{foit}, s_{foit} \in \mathbb{Z}_0^+ \qquad f \in \mathcal{F}, t \in \mathcal{T}, o \in \mathcal{O}_{ft}, i \in \mathcal{I}_{fo} \tag{5.17}$$

$$r_{fo'oit} \in \mathbb{Z}_0^+ \qquad f \in \mathcal{F}, t \in \mathcal{T}, \quad o, o' \in \mathcal{O}_{ft}, i \in \mathcal{I}_{fo} \tag{5.18}$$

Constraints (5.17) and (5.18) ensure the non-negative integer requirement on v_{foit}, b_{foit}, s_{foit} and $r_{fo'oit}$.

Chapter 6

Case Study

This chapter presents the input data utilized in the Fishing Fleet Renewal Problem with Emission Constraints (FFRPEC). The case study centres around the Norwegian fishing fleet and its compliance with the emission reduction targets of the Norwegian Climate Act and the ZeroKyst project. Fleet renewal decisions are made on an annual basis and the planning horizon runs from 2023 to 2050. In Section 6.1, the sub-fleets and propulsion systems included in the case study are introduced, while Section 6.2 provides an overview of the initial Norwegian fishing fleet's characteristics and lifespan. Section 6.3 covers the calculations of the average annual CO2 emissions of a vessel and the upper limits on the combined fishing fleet's annual emissions. Section 6.4 details the cost calculations conducted, while Section 6.5 provides an overview of the available shipyard capacity for the renewal of the fishing fleet in Norway. Finally, Section 6.6 presents the test instances employed in the computational study conducted in this thesis.

6.1 Sub-fleets and Propulsion Systems

The classification of a vessel as ocean-going or coastal is based on its length. We assume that vessels below 28 metres belong to the coastal fleet, while vessels from and including 28 metres belong to the ocean-going fleet (Johnsen, 2019). Furthermore, the sub-fleet of the vessel is determined by the primary fishing gear used within either the ocean-going or coastal classification. This categorization of vessels is used as the length and primary fishing gear has implications for the vessels' operational profile, such as the distance travelled and energy intensity during fishing and steaming. All vessels within a specific sub-fleet are considered homogeneous with respect to operational patterns and consequently energy consumption. The age and propulsion system of the various vessels within a sub-fleet, on the other hand, are vessel-specific properties. The energy consumption of a vessel must be supplied by a propulsion system. The propulsion systems are classified as either conventional, low-emission, or zero-emission based on the level of CO2 emissions associated with the relevant propulsion system. The sub-fleets and propulsion systems used in this case study are presented in Figure 6.1.

In this case study, we assume that all propulsion systems are available for all sub-fleets in all time periods with the exception of the electric-ammonia hybrid propulsion system. Due to the technical immaturity of the technology, the electric-ammonia hybrid propulsion system is assumed to be available for investment for all sub-fleets starting from 2035 (DNV, 2022).

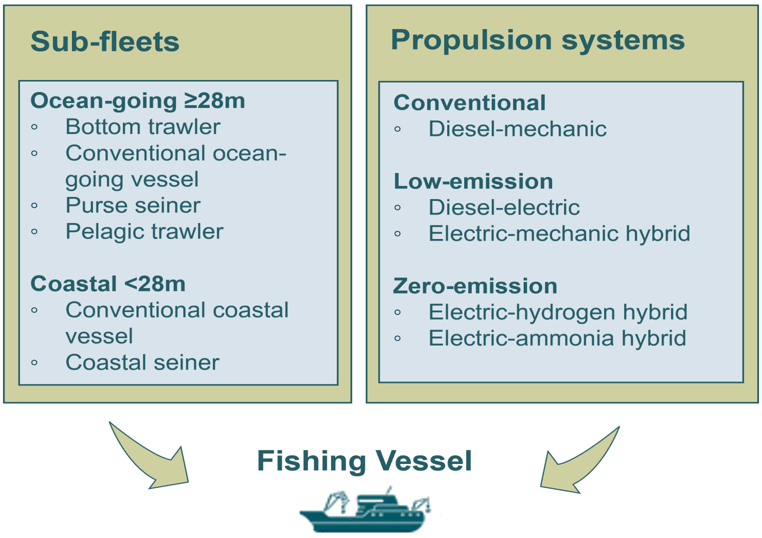


Figure 6.1: The set of sub-fleets and propulsion systems considered in this case study

6.2 Initial Fleet and Vessel Lifetime

A number of assumptions and calculations are made in order to determine the characteristics of the initial fishing fleet in terms of the number of vessels within each sub-fleet, vessel age and installed propulsion systems, as well the economic and technical lifetime of vessels.

6.2.1 Initial Fleet Characteristics

Number of Vessels

The Directorate of Fisheries has large amounts of public data regarding the Norwegian fishing fleet. This data is used to determine the initial fleet composition used in this case study. Statistics on the number of vessels categorized by length group are transformed into the number of vessels that belong to either the ocean-going or coastal fishing fleet (Fiskeridirektoratet, 2022b). Furthermore, to determine the number of vessels in each sub-fleet, we use the distributions between sub-fleets for the ocean-going and coastal fleet as presented in Section 2.1.2. The distributions are obtained from Fiskeridirektoratet (2019) and are based on a population of vessels that exceed a specified minimum requirement for yearly catch income for the relevant vessel group. The resulting number of vessels belonging to each sub-fleet is presented in the second column in Table 6.1.

Vessel Age

To estimate the age of the vessels in the initial fleet, we first utilize statistics provided by the Directorate of Fisheries that detail the number of brand-registered vessels categorized by length group and period of construction as of 2022 (Fiskeridirektoratet, 2023). A brand-registered vessel is a vessel where the owners have the right to participate in fishing and catching with the relevant vessel within Norway's maritime borders (Regjeringen, 1999). Based on these statistics, we estimate the share of vessels that belong to every construction period for the ocean-going and coastal sub-fleets, respectively. The vessels in the various sub-fleets are then distributed accordingly. The distributions between the period of construction for the ocean-going and coastal fleet are presented in Section 2.1.2, and the resulting number of vessels is presented in Table 6.1.

After determining the number of vessels belonging to a construction period for each sub-fleet, the age of the vessels is found by distributing the number of vessels evenly across the corresponding

Table 6.1: Number of vessels divided by period of construction for the initial fishing fleet

		Period of construction					
Sub-fleet	# of vessels	1950-1969	1970-1979	1980-1989	1990-1999	2000-2009	2010-today
Ocean-going vessels							
Bottom trawler	63	3	3	6	11	16	24
Conventional ocean-going vessel	39	2	2	4	7	10	14
Purse seiner	124	6	6	12	22	32	46
Pelagic trawler	33	2	1	3	6	9	12
Coastal vessels							
Conventional coastal vessel	4,698	156	731	1,561	583	667	1,000
Coastal seiner	345	11	54	115	43	49	73

ages, resulting in a discrete uniform distribution per sub-fleet.

Propulsion System

As of today, the Norwegian fishing fleet predominantly uses a conventional diesel-mechanic propulsion system fueled by MGO (Leira, 2018). Consequently, we assume that all vessels in the initial fishing fleet have a diesel-mechanic propulsion system.

6.2.2 Economic and Technical Lifetime

The economic lifetime of an asset can be defined as the time it is profitable to use the asset before it must be replaced. The physical wear and tear of the asset is called capital wear. The economic lifetime takes into account capital wear, but also technological development, market changes, maintenance costs, scrap value, etc. Consequently, the economic lifetime will therefore often be shorter than the technical lifetime, i.e. the time it is technically possible to use the asset (Regjeringen, 2014).

In this case study we use an economic lifetime of 20 years for all fishing vessels, corresponding to the expected economic lifetime of ships, vessels and rigs (SSB, 2014). When a vessel surpasses its economic lifetime, it can still be utilized, but the O&M costs increase. This is discussed in more detail in Section 6.4.2. In terms of technical lifetime, statistics from the Directorate of Fisheries point to the fact that the technical lifetime is considerably longer than the economic one. Based on statistics which detail the number of brand-registered vessels categorized by length group and period of construction as of 2022, we calculate the average age of the ocean-going and coastal vessels (Fiskeridirektoratet, 2023). The calculated average age of vessels in the ocean-going fleet is approximately 20 years, while that of the coastal fleet is around 30 years. Furthermore, the oldest vessels in the ocean-going fleet and coastal fleet (above 15 metres) are about 68 and 78 years old, respectively. Consequently, in this case study, we use that the technical lifetime of vessels in the ocean-going and coastal fleets are 70 and 80 years, respectively, regardless of the installed propulsion system. When a vessel reaches its technical lifetime, it is no longer possible to use the vessel, forcing the replacement of the relevant vessel.

6.3 Emissions Calculations

This section provides the underlying calculations for the average annual CO2 emissions of a vessel, as well as the upper limit on annual emissions, utilized in this case study.

6.3.1 Annual CO2 Emissions per Vessel

To calculate the average annual emissions per vessel we start out by computing the emissions of a vessel with a conventional diesel-mechanic propulsion system for all sub-fleets, hereby referred to as conventional emissions. Furthermore, we make assumptions regarding the percentage reduction in emissions for the other propulsion systems compared to the conventional emissions. We assume that the average annual emissions of a vessel with a specific propulsion system do not vary over the planning horizon.

Conventional Emissions

For the diesel-mechanic propulsion system, we first compute the annual MGO consumption of all sub-fleets based on the calculated annual total catch in 2022 and fuel intensities as of 2019 (step 1) and then convert this into the corresponding CO2 emissions (step 2). Finally, we divide by the total number of vessels within the relevant sub-fleet and obtain the average annual CO2 emissions per vessel. The calculations are illustrated by Figure 6.2.

$$\mathit{Vessel\ CO2\ emissions} = \underbrace{\mathit{Fuel\ Intensity} \cdot \mathit{Total\ catch}}_{\text{Step 1}} \cdot \underbrace{\mathit{Density} \cdot \mathit{Carbon\ Footprint}}_{\text{Step 2}} \cdot \frac{1}{\mathit{Num.of\ vessels}}$$

Figure 6.2: Illustration of the average annual CO2 emissions calculations

In the first step of our calculations, the fuel use intensities as presented in Section 2.2.2, given in litres of MGO per kg catch, is multiplied by a calculated total catch per sub-fleet. This is done in order to estimate the annual MGO consumption of the various sub-fleets (Thompson and Thompson, 2021).

To calculate the total catch of each sub-fleet, we use statistics from the Directorate of Fisheries concerning total catch in 2022 divided by gear, fish species (pelagic, cod and other demersal species) and length group (Fiskeridirektoratet, 2022a). For a specific type of fishing gear, the total catch is summed across species and allocated to the relevant sub-fleet based on length. For example, the total catch of all species using seine for the length groups *below 11 m*, *11-14.99 m*, *15-20.99 m* and *21-27.99 m*, is summed and allocated to the coastal seiner sub-fleet, while the catch of the ocean-going purse seiner sub-fleet equals the catch with seine for the length group *28 m and over*. The total catch using Scottish seine, gillnet and longline is divided between the conventional ocean-going and coastal fishing fleets, with respective allocations of 159,548 and 257,710 tonnes (Fiskeridirektoratet, 2022a). For the trawl gear, it is necessary to distinguish between different types of trawls in order to determine the catch of the bottom and pelagic trawler sub-fleets. From the statistics regarding total catch in 2022 divided by fish gear, species and length group we observe that a negligible amount of catch is obtained by the coastal fishing fleet in comparison to the ocean-going fishing fleet. Consequently, all the catch by trawl is allocated to the ocean-going fleet and the bottom and pelagic trawler sub-fleets. This allows us to use a statistic that distinguished between different types of trawl (but not length group) from the Directorate of Fisheries for determining the total catch (Fiskeridirektoratet, 2022b). The same statistics form the basis for the total catch broken down by fishing gear and fleet in Figure 2.2 in Section 2.1.1 (Fiskeridirektoratet, 2022a, Fiskeridirektoratet, 2022b).

By multiplying the fuel use intensity by the total catch, we find the annual MGO consumption of the various sub-fleets. The fuel use intensities as of 2019 and the calculated total catch in 2022, as well as the resulting MGO consumption of the various sub-fleets, are presented in Table 6.2.

In the second step of our calculations, we use a density of 0.84 to convert from litres to kg of MGO, and a carbon footprint of 3.17 kg CO2 per kg of MGO to estimate the annual CO2 emissions for each sub-fleet. The CO2 conversion factor includes the complete process of producing, distributing and combusting diesel (Winther et al., 2020). Finally, we calculated the average annual CO2 emissions per vessel with a diesel-mechanic propulsion system for all sub-fleets by dividing the annual CO2 emissions for each sub-fleet by the number of vessels in the relevant sub-fleet. The results are presented in the rightmost column of Table 6.2.

Table 6.2: Calculated annual total catch and MGO consumption per sub-fleet and corresponding average CO2 emissions per vessel with a conventional diesel-mechanic propulsion system

Sub-fleet	**Fuel use intensity [litres MGO/kg catch]**	**Sub-fleet total catch [tonnes]**	**Sub-fleet MGO consumption [tonnes]**	**Avg. CO2 emissions [tonnes/vessel]**
Ocean-going vessels				
Bottom trawler	0.46	381,545	147,428	7,418
Conventional ocean-going vessel	0.32	159,548	42,887	3,486
Purse seiner	0.09	731,363	55,291	1,413
Pelagic trawler	0.09	419,461	31,711	3,046
Coastal vessels				
Conventional coastal vessel	0.14	257,701	30,306	20
Coastal seiner	0.07	107,322	6,311	58

Emission Reduction

For all other propulsion systems, we assume a percentage reduction potential in CO2 emissions compared to the conventional diesel-mechanic propulsion system. The perceived percentage reduction potential and resulting annual CO2 emissions in tonnes per vessel are presented in Table 6.3.

The CO2 emission reduction potentials in Table 6.3 are estimates based on reported savings presented in Section 2.3.2, as well as conversations with subject matter experts for the purpose of this case study (Torstein A. Bø, personal communication, March 14, 2023). The reduction in emissions comes either from an assumed fuel efficiency improvement or from installing low- and zero-emission propulsion technology. The diesel-electric propulsion system is especially fuel-efficient for vessels with large variations in their operational profile, such as ocean-going vessels (Gabrieli and Jafarzadeh, 2020). Consequently, we assume an emission reduction potential of 5% for the ocean-going vessels compared to the diesel-mechanic propulsion system and no reduction for coastal vessels. For the electric-mechanic hybrid propulsion system, we assume emission reduction potentials that lie within the range of reported values (Aarsæther and Eldby, 2021, FiskerForum, 2019, Bastardie, 2023). Amongst the coastal vessels, the coastal seiner is expected to achieve the highest emission reduction potential when installing an electric-mechanic propulsion system. This is due to the fact that coastal seiners, which typically operate in close proximity to the coastline or in nearshore waters, benefit from their shorter steaming time to the fishing field. Even though coastal seiners are assumed to be slightly larger than conventional coastal vessels in terms of engine power, their operation in nearshore areas and consequent shorter steaming time is assumed to entail greater emission than for conventional coastal vessels. The coastal seiners require higher engine power compared to conventional coastal vessels because of the more energy-intensive nature of the active fishing gear purse seine compared to passive fishing gear. The final two propulsion systems, the electric-hydrogen and electric-ammonia hybrid, are zero-emission, resulting in a 100% reduction in emissions.

Table 6.3: Emission reduction potential compared to a diesel-mechanic propulsion system and resulting annual CO2 emissions [tonnes/vessel] for relevant sub-fleets and propulsion systems

	Propulsion system								
	Diesel-mechanic	**Diesel-electric**		**Electric-mechanic hybrid**		**Electric-hydrogen hybrid**		**Electric-ammonia hybrid**	
Sub-fleet	Emissions	Red.	Emissions	Red.	Emissions	Red.	Emissions	Red.	Emissions
Ocean-going vessels									
Bottom trawler	7,418	-5%	7,047	-15%	6,305	-100%	0	-100%	0
Conventional ocean-going vessel	3,486	-5%	3,312	-15%	2,963	-100%	0	-100%	0
Purse seiner	1,413	-5%	1,343	-15%	1,201	-100%	0	-100%	0
Pelagic trawler	3,046	-5%	2,894	-15%	2,589	-100%	0	-100%	0
Coastal vessels									
Conventional coastal vessel	20	-0%	20	-40%	12	-100%	0	-100%	0
Coastal seiner	58	-0%	58	-60%	23	-100%	0	-100%	0

6.3.2 Upper Limit on Total Emissions

In accordance with the Norwegian Climate Act and the ZeroKyst project's ambition, we calculate the upper limit on the annual emissions from the combined fishing fleet. Norway's Climate Act states that Norwegian emissions must be cut by 90-95% by 2050, compared to 1990-levels (Norsk Klimastiftelse, 2022). A 95% emission reduction compared to 1990-levels corresponds to an annual emission cap of 40,000 tonnes of CO2 from and including 2050. The goal of the ZeroKyst project is to contribute to a 50% emission reduction compared to 2005 emission levels from fishing and aquaculture vessels by 2030 (ZeroKyst, 2023). This corresponds to an annual emissions cap of 600,000 tonnes from and including 2030. The emission caps which the combined fishing fleet must comply with are illustrated in Figure 6.3.

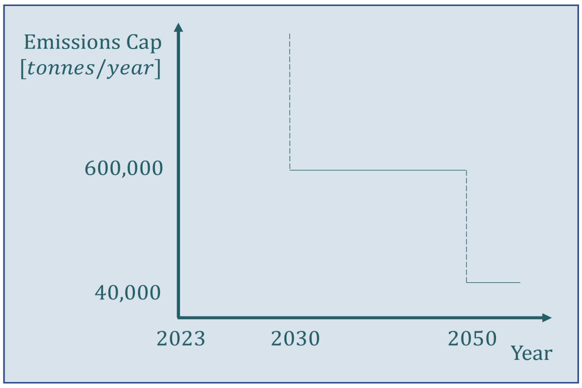


Figure 6.3: Illustration of the upper limit on annual CO2 emissions from the combined fishing fleet over the planning horizon

6.4 Cost Calculations

The cost elements considered in this case study include investment costs, as well as operational costs such as O&M costs, fuel costs, CO2 tax and regeneration costs. In addition, we consider the revenues associated with salvaging a vessel, i.e. salvage revenues. In this section, we go into more detail on each of the cost elements and the calculations behind them.

In order to take into account the time value of money and be able to compare different cost alternatives regardless of when the various costs occur, we convert all costs into present value by a discount factor in the objective function. In this case study, we use we use a discount rate of 4% (Jafarzadeh et al., 2021). The discount factor d in period t with a discount rate r is given by Equation (6.1) (Berk and DeMarzo, 2020).

$$d_t = \frac{1}{(1+r)^t} \tag{6.1}$$

6.4.1 Investment Costs

The model formulation in Section 5.3 allows for two renewal options - retrofitting an existing vessel in the fleet, i.e. changing the propulsion system, or replacing a vessel with e new one. Retrofitting a vessel only entails investment costs related to the propulsion system, while replacing a vessel entails investment costs related to both the propulsion system and the hull of the vessel. However, in Section 2.3.2 we found that hydrogen and ammonia fuel cells will in practice only be a viable option for new vessels. We also found that the potential of retrofit is greatest for vessels with a diesel-electric propulsion system, as opposed to a conventional diesel-mechanic system, where larger retrofits are required. Consequently, the option to retrofit existing vessels is disregarded in this case study. Furthermore, due to the large costs associated with the propulsion system of a vessel, we let the investment cost associated with replacing a vessel correspond to the cost of the propulsion system. The procedure used to calculate the investment costs used in this case study is explained further in this subsection. Finally, which emerges from the model assumptions in Section 5.1, we assume that we only invest in brand new vessels of age zero, i.e. not from a second-hand market.

Investment Cost Calculations

The investment costs in this case study are computed through a bottom-up approach. We first determine the characteristics of the various sub-fleets and propulsion systems in terms of propulsion system components' power or capacity and associated fuel storage. Furthermore, we use unit cost estimates in order to calculate the cost of propulsion system components and associated storage, and then combine this into a total investment cost for the relevant sub-fleet and propulsion system. The combination of components into the propulsion systems in consideration emerges from Section 2.3.2.

Jafarzadeh et al. (2021) investigates three propulsion systems suitable for an 11-meter conventional coastal vessel, including a conventional diesel-mechanic, an electric-hydrogen hybrid and electric-ammonia hybrid propulsion system. In this case study, the coastal vessel analyzed by Jafarzadeh et al. (2021) is assumed to be a generic conventional coastal vessel. This provides us with propulsion system characteristics for the three propulsion systems for the conventional coastal vessel in terms of component power or capacity and fuel storage. Furthermore, Valland (2021) provides standard figures for propulsion system component power and MGO-tank sizes for the ocean-going sub-fleets with a diesel-mechanic propulsion system. The installed power and tank sizes reflect the expected operating profile for the various sub-fleets. The tank size estimates are intended to correspond to the energy demand associated with a typical sea weather, i.e. the time between fuel bunkering. The propulsion system characteristics for the various sub-fleets outlined by Jafarzadeh et al. (2021) and Valland (2021) are presented in the blue cells in Table 6.4.

Table 6.4: Propulsion system characteristics in terms of tank size, propulsion system component power and battery capacity for the various sub-fleets and propulsion systems (Jafarzadeh et al., 2021, Valland, 2021)

	Propulsion system							
	Diesel-mechanic		**Electric-hydrogen hybrid**			**Electric-ammonia hybrid**		
Sub-fleet	MGO-tank [kg]	Combustion engine [kW]	H2-tank [kg]	PEM-cell [kW]	Battery [kWh]	NH3 tank [kg]	SO-cell [kW]	Battery [kWh]
Ocean-going vessels								
Bottom trawler	348,600	5,000	6,562	3,401	7,143	61,067	3,401	7,143
Conventional ocean-going vessel	54,600	1,500	1,028	1,020	2,143	9,565	1,020	2,143
Purse seiner	58,800	2,000	1,107	1,361	2,857	10,300	1,361	2,857
Pelagic trawler	378,000	5,000	7,115	3,401	7,143	66,317	3,401	7,143
Coastal vessels								
Conventional coastal vessel	8,500	294	160	200	420	1,489	200	420
Coastal seiner	9,250	320	174	218	457	1,620	218	457

Where no data was obtained regarding propulsion system characteristics we assume that the values for propulsion system component power, battery capacity and fuel storage can be scaled across the sub-fleets. This means that, for instance, to determine the H2-tank size of the bottom trawler with an electric-hydrogen hybrid propulsion system, presented in Table 6.4, we multiply the H2-tank size of the conventional coastal vessel (160 kg) by the ratio of the MGO-tank size of the bottom trawler (348,600 kg) to the MGO-tank size of the conventional coastal vessel (8,500 kg). The same approach is used for calculating propulsion system component power and battery capacities. The procedure of scaling is inspired by Jafarzadeh et al. (2021) where it is stated that the diesel tank and diesel engine of the 11-meter conventional coastal vessel are scalable values. The calculations for the bottom trawler sub-fleet with an electric-hydrogen hybrid propulsion system are as follows:

$$\text{H2-tank size of bottom trawler} = 160\ kg \cdot \frac{348,600\ kg}{8,500\ kg} = 6,562\ kg$$

$$\text{PEM-cell power of bottom trawler} = 200\ kW \cdot \frac{5,000\ kW}{294\ kW} = 3,401\ kW$$

$$\text{Battery of bottom trawler} = 420\ kWh \cdot \frac{5,000\ kW}{294\ kW} = 7,143\ kWh$$

For the coastal seiner sub-fleet, where no data was obtained regarding propulsion systems characteristics, we assume that for a diesel-mechanic propulsion system, the power of the combustion engine is 320 kW and that the corresponding MGO-tank size is 9,250 kg. For the other propulsion systems, we scale in the same manner as for the other sub-fleets.

For the two missing propulsion systems of our case study, the electric-mechanic hybrid and the diesel-electric propulsion systems, assumptions are made based on input from subject matter experts (Torstein A. Bø, personal communication, March 14, 2023). For the **Electric-mechanic hybrid** propulsion system, we assume a combustion engine of 200 kW and a battery similar to the ones used for the electric-hydrogen and electric-ammonia hybrid systems (420 kWh) for a conventional coastal vessel. The size of the associated MGO tank is found by scaling the tank used in the conventional diesel-mechanical system in relation to engine power. The characteristics of the remaining sub-fleets are then found by scaling based on the conventional coastal sub-fleet. For the **Diesel-electric** propulsion system, we have chosen a different approach to calculating investment costs, compared to the other propulsion systems. Due to the system's similarities to the conventional diesel-mechanical system, but an increase in the number of components, as can be seen in Figure 2.15, we assume a percentage increase in investment cost compared to the diesel-mechanic propulsion system. We assume a 25% and 15% higher investment cost for the ocean-going and coastal sub-fleets, respectively.

Jafarzadeh et al. (2021) also include a techno-economic analysis that offers unit cost estimates on propulsion system component Capital Expenditures (CAPEX) and Operational Expenditures (OPEX), and associated fuel storage. These are presented in Table 6.5.

Table 6.5: Unit cost data on propulsion system components and associated fuel storage (Jafarzadeh et al., 2021)

			Storage	
	CAPEX [NOK/kW(h)]	OPEX [% of CAPEX]	CAPEX [NOK/kg]	OPEX [% of CAPEX]
Combustion engine	10,204	3%	Included	-
PEM-cell*	17,600	3%	5,100	1%
SO-cell	46,750	1%	11.15	-
Battery	5,610	3%	-	-

*Includes electric motor

Utilizing the sub-fleet and propulsion system characteristics partially presented in Table 6.4 and the CAPEXes presented in Table 6.5, the investment costs for all sub-fleets and propulsion systems acquired in the first time period may be calculated. This is presented in Table A.1 in Appendix A. The investment costs include the cost of propulsion system components, in addition to any fuel storage related to combustion engines, fuel cells and/or batteries.

Future Investment Costs

When a greater share of the Norwegian fishing fleet is electrified we expect to see a reduction in the costs of batteries and fuel cells (both PEM and SO) due to a greater maturity in the market and technology. This is referred to as economies of scale. The price of lithium batteries is expected to decrease by 68% by 2050 (Sustainable Truck & Van, 2021), corresponding to a price of 1,795 NOK/kWh by 2050 compared to the price of 5,610 NOK/kWh in 2023. For hydrogen PEM-cells, we expect a decrease from 17,600 NOK/kW today to 3,000 NOK/kW by 2050. Ammonia SO-cells are expected to decrease from 46,750 NOK/kW to 5,000 NOK/kW by 2050 (Jafarzadeh et al., 2021). In order to incorporate this into the FFRPEC we assume that the CAPEX of both batteries and fuel cells decreases linearly over the planning horizon. This means that the investment costs for vessels utilizing propulsion systems with batteries and/or fuel cells will decrease with time, making it profitable to postpone these investments. It is worth noting that this applies to all considered propulsion systems except for the diesel-mechanic system as this system only has a combustion engine.

6.4.2 O&M Costs

Table 6.5 presents percentage estimates for the OPEX on propulsion system components and associated storage. The OPEX does not include fuel costs and can therefore be allocated to the annual O&M costs (Jafarzadeh et al., 2021). For the investment costs, we calculate the cost of both the propulsion system component and associated storage for the various sub-fleets and propulsion systems. This constitutes the percentage basis used to calculate the annual O&M costs of the various propulsion system components and associated fuel storage. These are then combined into annual O&M costs for particular sub-fleets and propulsion systems. The resulting annual O&M

costs for a brand-new vessel acquired in the first time period of all sub-fleets with all propulsion systems are presented in Table A.2 in Appendix A.

Because the CAPEX of batteries and fuel cells depends on the time of investment due to economies of scale, the O&M costs, which is a function of the propulsion system component CAPEX, also depend on the time of investment. The time of investment corresponds to the difference between the current time period and the age of the relevant vessel. For this case study, we assume that a vessel acquired in a specific time period has the same O&M costs every year until a possible renewal. Furthermore, we assume that when a vessel exceeds its economic lifetime, the annual O&M costs are doubled due to an increased need for maintenance. This is done in order to incentivize the replacement of older vessels before younger ones.

6.4.3 Regeneration Costs

As presented in Section 2.3.1, the regeneration cost is defined as a periodic extra cost linked to the replacement of components in the system, e.g. batteries and/or fuel cells, due to wear and tear or ageing (Jafarzadeh et al., 2021). In this case study, the regeneration cost is calculated based on a percentage of the cost of the various propulsion system components. The percentages used, as well as the interval in which the replacement of components occur, are given in Table 6.6 (Jafarzadeh et al., 2021).

Table 6.6: Regeneration cost data (Jafarzadeh et al., 2021)

	Regeneration costs [% of component CAPEX]	**Every X years**
Combustion engine	18%	6
PEM-cell	46%	10
SO-cell	46%	10
Battery	100%	10

For the various sub-fleets and propulsion systems we calculate the cost of the propulsion system components in line with Table 6.5. This cost is the percentage basis we use for calculating the regeneration cost of the various propulsion system components, and furthermore for specific sub-fleets and propulsion systems.

In contrast to the O&M costs, the regeneration cost only occurs at specified intervals after the time of renewal and is equal to zero in the remaining time periods. As the cost of batteries and fuel cells are assumed to decrease over the planning horizon due to economies of scale, the regeneration cost also decreases with time. This indicates that the regeneration cost associated with replacing a battery is lower during the second replacement compared to the initial replacement. Table A.3 in Appendix A presents the regeneration cost of a vessel acquired in the first time period of all sub-fleets with all propulsion systems. Note that the costs occur X years from the first time period.

6.4.4 Fuel Costs

In the same manner as for the investment costs, the annual fuel costs for vessels of a specific sub-fleet and propulsion system are computed through a bottom-up approach. We estimate both the fuel price per unit of energy and the share of the vessel energy consumption covered by a combustion engine, battery and fuel cells for the various sub-fleets and propulsion systems. Subsequently, we calculate the fuel cost by multiplying the unit price by the energy consumption of the specific component, such as the MGO price and energy covered by the combustion engine. We also take into account the efficiency of the relevant propulsion system components.

Firstly, we estimate the fuel price per unit of energy for the relevant fuels. The fuel prices per unit of energy of MGO, hydrogen and ammonia are estimated based on a price per kilogram and an energy density. For MGO we use a price of 9.4 NOK/kg and an energy density corresponding to its

Lower Heating Value (LHV) of 12.75 kWh/kg. This corresponds to a fuel price of 0.74 NOK/kWh. The utilized prices and LHVs for hydrogen and ammonia are 50 and 6 NOK/kg and 33.3 and 5.16 kWh/kg, respectively. The fuel prices are thus equal to 1.50 and 1.16 NOK/kWh (Jafarzadeh et al., 2021). The price of battery power of 0.43 NOK/kWh is obtained from average data for the electricity price in northern Norway, where the majority of the fishing fleet is situated, in the last month as of the 10th of May 2023 (Nord Pool, 2023). The fuel prices per unit of energy used in this case study are presented in Table 6.7.

Table 6.7: Fuel prices per unit of energy (Jafarzadeh et al., 2021)

	Fuel price
MGO	0.74 NOK/kWh
Hydrogen	1.50 NOK/kWh
Ammonia	1.16 NOK/kWh
Battery power	0.43 NOK/kWh

It should be emphasized that these fuel prices are highly uncertain. This is due to several factors, including the volatility of the global oil markets, the rapidly evolving technology and infrastructure for alternative fuels, and shifting government policies and regulations. Over the past year, the average low and high prices in Bergen have been 724 and 1,218 USD per metric tonne MGO. This corresponds to a fuel price of 7.64 and 12.85 NOK/kg and 0.60 and 1.01 NOK/kWh, respectively (Oilmonster, 2023, Norges Bank, 2023). When it comes to the battery power price, i.e. electricity price, this can vary greatly based on the geographical area in which we charge. On 10 May 2023, the day-ahead price at Nord Pool was equal to 0.93 NOK/kWh in southern Norway but equal to 0.34 NOK/kWh in northern Norway. The minimum electricity price in northern Norway in the former month is equal to 0.20 NOK/kWh, while the maximum electricity price equals 0.63 NOK/kWh. The price also depends on the time of year. During Christmas 2022, the electricity price reached a peak of 1.08 NOK/kWh for northern Norway (Nord Pool, 2023). In terms of fuel price of hydrogen and ammonia, Jafarzadeh et al. (2021) also define sensitivities. The price range for hydrogen is between 40 and 60 NOK/kg, corresponding to 1,20 and 1,80 NOK/kWh. For ammonia the price ranges between 4 and 8 NOK/kg, i.e. 0.78 and 1.55 NOK/kWh. These prices are highly dependent on the production method used. For instance, the cost of hydrogen generated via electrolysis will be strongly correlated to the price of electricity.

Secondly, we calculate the average energy consumption per vessel for all sub-fleets in terms of kWh. This is done by multiplying the annual MGO consumption of the respective sub-fleets, presented in Table 6.2, with an energy density factor of 12.75 kWh per kg MGO, and dividing by the number of vessels in the respective sub-fleet (Jafarzadeh et al., 2021). The resulting average vessel energy consumption in kWh is presented in the second column of Table 6.8. In addition to the average vessel energy consumption for the various sub-fleets, we need an energy distribution between the components for the various propulsion systems in order to estimate the fuel costs. We assume an energy distribution between the components for the relevant propulsion systems and sub-fleets as presented in Table 6.8.

The assumed energy distribution corresponds to the emissions reduction potential for the various sub-fleets and propulsion systems presented in Table 6.3. The diesel-electric propulsion system is assumed to be somewhat more fuel-efficient for ocean-going vessels compared to the diesel-mechanic, while the fuel-efficiency, and consequently energy consumption is assumed to be the same for coastal vessels with a diesel-electric and diesel-mechanic propulsion system (Gabrieli and Jafarzadeh, 2020). For the electric-mechanic hybrid propulsion system, the share of battery use corresponds to the emission reduction potential for all sub-fleets (Aarsæther and Eldby, 2021, FiskerForum, 2019, Bastardie, 2023). Furthermore, it is assumed that for the zero-emission propulsion systems, the fuel cells directly replace the combustion engine, i.e. we get an energy distribution identical to that of the electric-mechanic hybrid propulsion system.

Table 6.8: Average annual vessel energy consumption and energy distribution between components for the various sub-fleets and propulsion systems

		Propulsion system							
		Diesel-mechanic	**Diesel-electric**	**Electric-mechanic hybrid**		**Electric-hydrogen hybrid**		**Electric-ammonia hybrid**	
Sub-fleet	Avg. vessel energy consumption [kWh]	Combustion engine	Combustion engine	Combustion engine	Battery	PEM-cell	Battery	SO-cell	Battery
Ocean-going vessels									
Bottom trawler	29,836,663	100%	95%	85%	15%	85%	15%	85%	15%
Conventional ocean-going vessel	14,020,587	100%	95%	85%	15%	85%	15%	85%	15%
Purse seiner	5,685,168	100%	95%	85%	15%	85%	15%	85%	15%
Pelagic trawler	12,252,074	100%	95%	85%	15%	85%	15%	85%	15%
Coastal vessels									
Conventional coastal vessel	82,247	100%	100%	60%	40%	60%	40%	60%	40%
Coastal seiner	233,215	100%	100%	40%	60%	40%	60%	40%	60%

From the average annual vessel energy consumption and energy distribution between propulsion system components presented in Table 6.8, we calculate the energy covered by the combustion engine, the battery, and the hydrogen and ammonia fuel cells for all sub-fleets and propulsion systems. Furthermore, we calculate the fuel cost associated with the individual component. We then take into account the efficiency of the relevant propulsion system component. We assume that the efficiency of the combustion engine is 37%, while the efficiencies of the hydrogen and ammonia fuel cells are 50% and 52%, respectively. For the battery we assume a 100% efficiency (Jafarzadeh et al., 2021). The fuel cost associated with an individual component for a vessel of a specific sub-fleet and propulsion system is then found by the following equation:

$$\text{Component fuel cost} = \frac{\text{Energy covered}}{\text{Component efficiency}} \cdot \text{Fuel price per unit of energy}$$

Furthermore, the annual fuel cost of a vessel of a specific sub-fleet and propulsion system is then found by adding up the different component fuel costs. The results are presented in Table A.4 in Appendix A. We assume that the fuel costs will remain constant over the planning horizon.

6.4.5 CO2 Taxation

In this case study we only consider CO2 emissions that come from the combustion of MGO. Consequently, the costs related to CO2 taxation are found by multiplying the CO2 tax level by the total emissions introduced in Section 6.3.1. In addition to the emissions related to the combustion of MGO, which may be referred to as *direct emissions*, there are also *indirect emissions* associated with the life cycle of the fishery. These indirect emissions do not occur at the point of energy consumption, which is at sea in this case (Miljødirektoratet, 2019). Instead, they arise during various stages of the fishery's life cycle, encompassing activities such as the construction of infrastructure for energy production, the energy production itself, as well as potential transportation of energy to the site for bunkering. Additionally, there are emissions related to the processing and distribution of fish. We disregard the indirect emissions in this case study due to the challenges related to quantifying and assigning these emissions in an accurate manner. However, it is important to note that the exclusion of indirect emissions can result in an incomplete assessment of the overall environmental impact.

The Ministry of Finance has laid down a set of regulations for how CO2 emissions are to be considered in socioeconomic analyzes of government measures. The regulations state that analyses must use annually updated carbon price trajectories from the Ministry of Finance. Despite not being subject to these regulations, we utilize the Ministry of Finance's Medium-price trajectory for the carbon price in this case study, illustrated by the blue line in Figure 6.4 (2023 price level) (Regjeringen, 2022b). The carbon price applies to the price of emissions of one tonne of CO2 for the non-quota-obliged sector, e.g. transport, agriculture, heating in buildings and fisheries (Miljødirektoratet, 2023). The carbon price of 2023 reflects the CO2 tax level as of today, while the trajectory up until 2030 demonstrates a gradual increase in carbon price to 2,000 NOK in 2030 (2020 price level), as discussed in Section 2.2.4. After 2030, the 2,000 NOK tax level is kept constant until 2050. The basis for the medium-price trajectory until 2050 is based on the *Announced Pledges Scenario* of the International Energy Agency (IEA), which is estimated to have a 50% certainty of keeping global temperature rise below 1.7 °C. The trajectory thus aims for a temperature increase that falls within the middle range specified in the Paris Agreement (Regjeringen, 2022b).

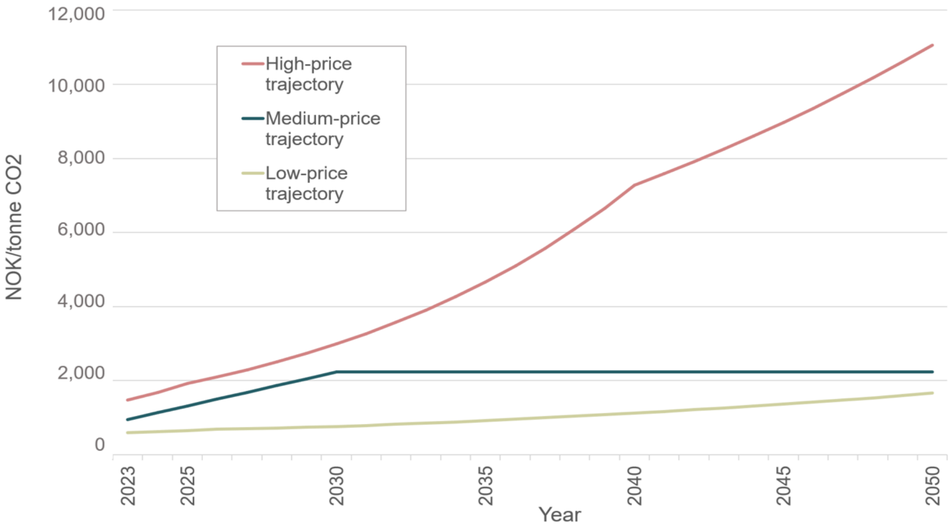


Figure 6.4: Low (yellow), medium (blue) and high (red) carbon price trajectories to be used in socioeconomic analyzes of government measures (Regjeringen, 2022b)

The Ministry of Finance also provides low and high prices to be used for sensitivities in socio-economic analyses for emissions in the years 2023–2100. The low and high prices for 2023-2050 are illustrated by the yellow (Low-price trajectory) and red (High-price trajectory) lines, respectively (2023 price levels) (Regjeringen, 2022b). The low-price trajectory is set to 75% of the emissions trading price in the quota-obliged market in 2023 and then grows with the discount rate for socio-economic analyzes (Regjeringen, 2022b). This is set to 4% for periods spanning 0-40 years (Finansdepartementet, 2021). The high-price trajectory, on the other hand, is based on the UN Climate Panel's assessment of measures required to restrict global warming to 1.5 degrees Celsius (Regjeringen, 2022b).

6.4.6 Salvage Revenues

In this case study we assume that a fishing vessel of a specific sub-fleet with a specific propulsion system, can be sold in a second-hand market for a price equivalent to its salvage value, incurring salvage revenues. The salvage value of all vessels is assumed to start on half the investment cost and then decrease linearly over each period until it reaches zero when the vessel reaches its maximum economic lifetime. The linear decrease in value corresponds to the perceived trajectory of value throughout the economic lifetime of ships, vessels and rigs (SSB, 2014). Furthermore, as the salvage value is a function of the time-varying investment cost, the salvage value depends both on the time of investment and the age of the relevant vessel.

6.5 Shipyard Capacity

As presented in Section 2.3.1, there were just under 70 active shipyards in Norway in 2019. Approximately 49 of these were repair and/or small shipbuilding yards, while 13 and six of the shipyards were medium-sized and large newbuilding yards, respectively (Haugland et al., 2021). The shipyards have an upper capacity limit in terms of how many vessels they can build and retrofit each year. For this case study, we determine these capacities by using statistics that detail the number of brand-registered vessels categorized by length group and period of construction provided by the Directorate of Fisheries (Fiskeridirektoratet, 2023).

The Ocean-going Fleet

The ocean-going fleet is primarily comprised of newer vessels. After 2010, 141 vessels have been built for the ocean-going sub-fleets, corresponding to an average of approximately 10 vessels a year (Fiskeridirektoratet, 2023). This coincides with the number of vessels delivered from large shipyards during the period 2010-2020 (Haugland et al., 2021). As a result, the shipyard's annual capacity is limited to 10 ocean-going vessels in this case study, implying that a maximum of 10 vessels can be acquired each year for the ocean-going sub-fleets combined.

It is important to note that large ocean-going fishing vessels can be constructed outside of Norway, and similarly, not all vessels built in Norway are intended for use within Norwegian maritime borders. For larger fishing vessels, Norwegian shipowners increasingly opt for overseas shipyards. From 2010 until the present day, just below 45% of Norwegian-ordered fishing vessels have been delivered by Norwegian shipyards. Denmark and Turkey account for 25% each, while the remaining 5% are constructed elsewhere. The market share of Norwegian shipyards varies somewhat over time. For deliveries between 2018 and 2020, the market share of Norwegian shipyards was 60%. However, a significant number of orders placed at Turkish shipyards diminishes the market share in the order books to 30% (Haugland et al., 2021). This suggests that the shipyard capacity utilized in this case study might underestimate the actual capacity for ocean-going vessels when considering overseas shipyards.

The Coastal Fleet

The period in which most coastal vessels in today's fishing fleet were built is 1980-1989. During these 10 years, 1,777 coastal vessels were built, an average of approximately 180 vessels a year (Fiskeridirektoratet, 2023). Consequently, the annual shipyard capacity for coastal vessels in this case study is set to 180. Of the 1,777 new vessels, the vast majority belong to the length group *under 11m* with 1,500 vessels.

For the coastal fleet, on the other hand, it applies that customers will predominantly use local and/or national shipyards (Haugland et al., 2021). This is reasonable as investments are smaller, and the nature of the vessels restricts them from covering the same distances as large ocean-going vessels. Traditionally, Norway had a significant shipbuilding industry, but in recent years there has been a decline in the number of shipyards due to changes in market conditions and global competition (Rabbevåg, 2022). Consequently, the shipyard capacity allocated to the coastal fleet in this case study might be an overestimate as it relies on historical data.

6.6 Test Instances

For our computational study, the FFRPEC model is run on the so-called base case as well as alternative scenarios for propulsion system components costs, fuel prices, CO2 tax price trajectory and shipyard capacities. The base case reflects the set of parameter values presented in the previous sections, i.e. the values considered most plausible, of this case study and serves as a reference for evaluating the alternative scenarios. For the alternative scenarios, we use either the base case value or a low or high value for the relevant parameter. Table 6.9 provides an overview of the parameters adjusted in the various scenarios, along with the low, base case and high values.

The costs of the propulsion system components are assumed to decrease linearly between 2023 and 2050, driven by the expected technological advancements of PEM cells, SO cells, and batteries, and the resulting economies of scale over the planning horizon. The component costs for the base case are provided in Section 6.4.1, while the corresponding high and low component costs in 2050 have a range of ±1,000 NOK/kW for the fuel cells and a range of approximately ±200 NOK/kWh for the battery. The fuel prices of both MGO and zero-emission fuels for the base case and the high and low prices are detailed in Section 6.4.4 while the basis for the CO2 tax is presented in Section 6.4.5. Lastly, the shipyard capacities in the base case are described in Section 6.5, while the high capacities represent a 20% increase for both the ocean-going and coastal fleet compared to the base case.

Table 6.9: The base case, low and high values for the parameters adjusted in the scenarios

	Low		**Base case**		**High**	
Component cost [NOK/kW(h)]	2023	2050	2023	2050	2023	2050
PEM cell	17,600	2,000	17,600	3,000	17,600	4,000
SO cell	46,750	4,000	46,750	5,000	46,750	6,000
Battery	5,610	1,600	5,610	1,795	5,610	2,000
Fuel price [NOK/kWh]						
MGO	0.60		0.74		1.01	
Battery power	0.20		0.43		1.08	
Hydrogen	1.20		1.50		1.80	
Ammonia	0.78		1.16		1.55	
CO2 tax [NOK/tonne]	Low-price trajectory		Medium-price trajectory		High-price trajectory	
Shipyard capacity						
Ocean-going fleet	-		10		12	
Coastal fleet	-		180		216	

The technological development of zero-emission propulsion technology influences the propulsion system component costs through economies of scale. This, in turn, influences the investment cost of low- and zero-emission propulsion systems, as well as the O&M costs, regeneration costs, and salvage values. It is a reasonable assumption to anticipate that the costs associated with batteries and fuel cells will undergo comparable advancements over time. This simultaneous technological advancement can be attributed to collaborative research and development efforts, resulting in similar advancements in the costs associated with batteries and fuel cells over time. Consequently, in our scenario analysis, the component cost of PEM cells, SO cells, and battery collectively adhere to either a low, high, or base case value. Furthermore, we assume that the fuel prices of zero-emission fuels such as battery power, hydrogen, and ammonia collectively follow either a low, high, or base case fuel price. This assumption is considered reasonable because the production processes of both hydrogen and ammonia rely on electricity, which creates a mutual interdependence. The fuel price of MGO, on the other hand, is adjusted independently. The same goes for the CO2 tax price trajectory and shipyard capacities.

To succinctly address the various scenarios in the computational study, we have devised a nomenclature, which allows us to describe them in a clear and concise manner. The nomenclature we have devised involves labelling the different scenarios, accentuating the relevant parameter values as either low (L), base case (B) or high (H). We introduce variations in the MGO price (M), CO2 tax (T), zero-emission fuel prices (Z), component costs (C), and finally, shipyard capacity (S).

Below is a concise description of the scenarios with their corresponding label, in addition to our rationale for including them in the computational study. In general, we aim to understand the primary drivers behind fleet renewal: emission reduction requirements or economic considerations.

Making Zero-emissions Less Favourable

The first three scenarios are included in order to observe the results when zero-emission propulsion systems become relatively less favourable compared to conventional and low-emission propulsion systems. To gain insights into the overall favorability of zero-emission propulsion in the base case scenario, we analyze the outcomes obtained when the favorability of zero-emission propulsion decreases. If the results obtained when the favorability of zero-emission propulsion decreases are similar to those in the base case scenario, it implies that fleet renewal is primarily driven by emission reduction requirements. This means that even when the favorability of zero-emission propulsion decreases fleet renewal still occurs due to the necessity of meeting emission reduction targets.

ML-TL-ZB-CB-SB - The price of MGO and CO2 taxation decreases

MB-TB-ZH-CH-SB - The price of zero-emission fuels and propulsion system components costs increases

ML-TL-ZH-CH-SB - A combination of the two preceding scenarios

Making Zero-emissions More Favourable

The next three scenarios are included to observe the effects on the fleet renewal schedule when the inverse holds true, and zero-emission propulsion systems become relatively more favourable. We aim to identify the parameters that drive fleet renewal to be economically motivated, rather than solely driven by emission reduction requirements.

MH-TH-ZB-CB-SB - The price of MGO increases and CO2 tax high-price trajectory

MB-TB-ZL-CL-SB - The price of zero-emission fuels and propulsion system component costs decreases

MH-TH-ZL-CL-SB - A combination of the two preceding scenarios

Increased Shipyard Capacity

The final scenario is included in the computational study to assess how increased capacity influences the choice of propulsion systems utilized for fleet renewal, and the subsequent impact on total emissions and costs. By analyzing the impact of the increased shipyard capacity on fleet renewal, we can evaluate the flexibility to make economically driven choices.

MB-TB-ZB-CB-SH - Increased shipyard capacity

Table 6.10 presents a detailed numerical representation of the test instances. The first three columns display the cost evolution of propulsion system components throughout the planning horizon, measured in NOK/kW(h). Moreover, the fuel prices for MGO, battery power, hydrogen, and ammonia are provided in NOK/kWh, along with the price trajectory of the CO2 tax. Lastly, the shipyard capacity of the ocean-going and coastal fleet is presented in the rightmost columns.

Table 6.10: Test instances for the computational study presented in a numerical format

	Component cost [NOK/kW(h)]						**Fuel price [NOK/kWh]**				**CO2 tax [NOK/tonnes]**	**Shipyard capacity**	
	PEM cell		SO cell		Battery		MGO	Battery power	Hydrogen	Ammonia		Ocean-going fleet	Coastal fleet
	2023	2050	2023	2050	2023	2050							
Base case	17,600	3,000	46,750	5,000	5,610	1,795	0.74	0.43	1.50	1.16	Medium-price trajectory	10	180
ML-TL-ZB-CB-SB	17,600	3,000	46,750	5,000	5,610	1,795	0.60	0.43	1.50	1.16	Low-price trajectory	10	180
MB-TB-ZH-CH-SB	17,600	4,000	46,750	6,000	5,610	2,000	0.74	1.08	1.80	1.55	Medium-price trajectory	10	180
ML-TL-ZH-CH-SB	17,600	4,000	46,750	6,000	5,610	2,000	0.60	1.08	1.80	1.55	Low-price trajectory	10	180
MH-TH-ZB-CB-SB	17,600	3,000	46,750	5,000	5,610	1,795	1.01	0.43	1.50	1.16	High-price trajectory	10	180
MB-TB-ZL-CL-SB	17,600	2,000	46,750	4,000	5,610	1,600	0.74	0.20	1.20	0.78	Medium-price trajectory	10	180
MH-TH-ZL-CL-SB	17,600	2,000	46,750	4,000	5,610	1,600	1.01	0.20	1.20	0.78	High-price trajectory	10	180
MB-TB-ZB-CB-SH	17,600	3,000	46,750	5,000	5,610	1,795	0.74	0.43	1.50	1.16	Medium-price trajectory	12	216

Chapter 7

Computational Study

In this chapter, the results obtained from running the FFRPEC model are presented. We analyze the results of the base case and scenarios corresponding to the test instances presented in Section 6.6. The hardware and software specifications are described in Section 7.1, followed by a presentation of the obtained result of the base case in Section 7.2. The results from the subsequent scenario analysis are presented in Section 7.3, while the deduced managerial insights based on the results and scenario analysis are presented in Section 7.4.

7.1 Technical Aspects of Optimization

The Fishing Fleet Renewal Problem with Emission Constraints (FFRPEC) is written in the programming language Python and solved using the commercial mathematical solver Gurobi Optimizer. We use Gurobi's Python extension module called *gurobipy* that offers convenient object-oriented modelling constructs and an API to all Gurobi features. The specifications of the hardware and software used are presented in Table 7.1. With the specifications listed below, the model's runtime is in the order of seconds.

Table 7.1: Hardware and software specifications

Processor	Intel(R) Core(TM) i7-10700
CPU model	8 cores / 2.90GHz
Memory	16.0 GB
Operating System	Windows 10 Education 22H2
Python version	3.8.8
Gurobi version	10.0.1

7.2 Solution to the FFRPEC

Figure 7.1 illustrates the renewal schedule for the various sub-fleets of the Norwegian fishing fleet over the planning horizon. The graphs show the development in the number of vessels with a particular propulsion system for every sub-fleet throughout the planning horizon. The secondary y-axis denotes the share of the combined fishing fleet represented by the number of vessels. The propulsion systems are illustrated by coloured lines. The blue line represents the conventional diesel-mechanic propulsion system, while the green and purple line represents the diesel-electric and electric-mechanic hybrid propulsion systems, respectively. Finally, the orange and red line represents the zero-emission propulsion systems, i.e. the electric-hydrogen and electric-ammonia hybrid propulsion systems. Initially, all sub-fleets solely comprise vessels with a diesel-mechanic propulsion system.

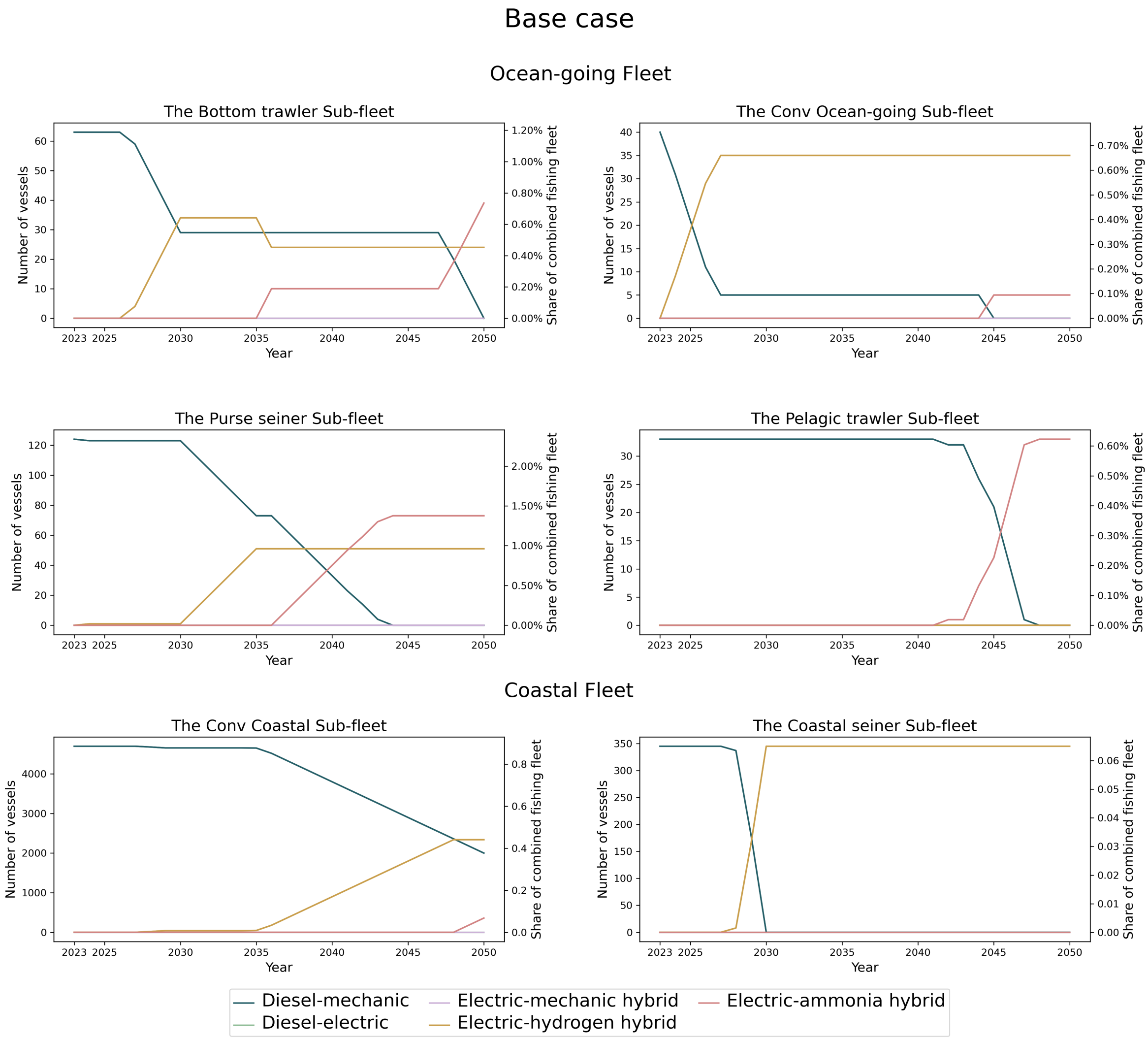


Figure 7.1: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the various sub-fleets over the planning horizon

With the fleet renewal schedule as given by Figure 7.1, the resulting combined emissions, divided between sub-fleets, from the Norwegian fishing fleet over the planning horizon are as shown in Figure 7.2. The bars represent the share of the combined emissions of each sub-fleet. The blue bar represents the bottom-trawler sub-fleet, the green bar represents the coastal seiner sub-fleet, and the purple and orange bar represents the conventional ocean-going and coastal sub-fleets, respectively. Furthermore, the light blue bar represents the pelagic trawler sub-fleet and finally, the red bar represents the purse seiner sub-fleet. In 2023, the combined emissions of the Norwegian fishing fleet amount to 996,089 tonnes of CO2. In 2030 and 2050 the combined emissions amount to 599,984 and 40,000 tonnes, respectively, and thus comply with the emission caps of 600,000 and 40,000 tonnes of CO2.

From the fleet renewal schedule in Figure 7.1 and the associated emissions Figure 7.2, we make some observations. Firstly, we will present the results pertaining to the ocean-going fleet, followed by an examination of the coastal fleet. Lastly, we will present some overall observations concerning the renewal schedule.

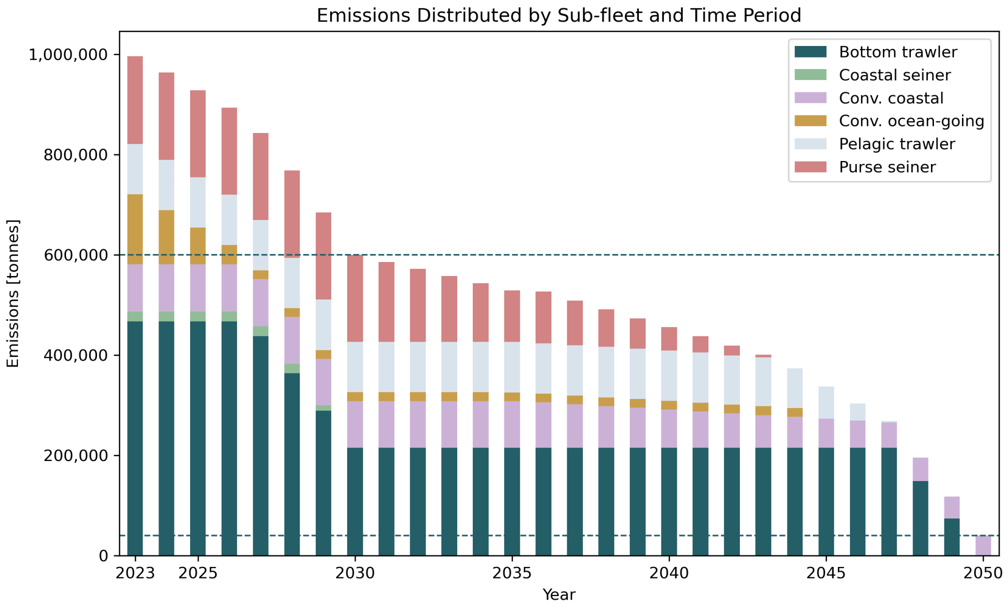


Figure 7.2: CO2 emissions from the combined fishing fleet over the planning horizon divided on sub-fleets

The Bottom Trawler Sub-fleet

Beginning in 2026, the model initiates the process of salvaging diesel-mechanic bottom trawlers. These particular vessels exhibit the most substantial CO2 emissions among all vessel types, by 7,418 tonnes annually. From 2026 to 2029, the model salvages 34 out of 63 bottom trawlers in total. This can be seen in Figure 7.3. All are replaced by vessels with an electric-hydrogen hybrid propulsion system.

From Figure 7.2 it is evident that as of today, the bottom trawler sub-fleets constitute a substantial share of the combined emissions from the Norwegian fisheries fleet, accounting for 46.9% of the total emissions in 2023. This is due to the sub-fleets' relatively high fuel use intensity. As a consequence, the renewal of part of the bottom trawler sub-fleet leads to large emissions cuts from the combined fishing fleet and contributes significantly towards reaching the 2030 emission reduction target. However, the investment cost for a bottom trawler with an electric-hydrogen hybrid propulsion system is substantial. In 2026 the investment cost equals 124,851,013 NOK, while the cost is somewhat reduced in 2029 due to economies of scale, amounting to 116,305,997 NOK. In addition, it pays to postpone these investments for as long as possible due to the time value of money. This is reflected in the results where bottom trawlers fully utilize the shipyard capacity of 10 ocean-going vessels a year in 2027-2029, while only 4 are built in 2026.

As of 2035, the electric-ammonia propulsion system becomes available for investment. For the bottom trawler sub-fleet, the model chooses to replace the 10 oldest electric-hydrogen hybrid bottom trawlers, six 7-year-old and four 8-year-old vessels, with new vessels with an electric-ammonia propulsion system. This implies that in terms of costs, it is sensible to salvage vessels with an electric-hydrogen hybrid rather than a diesel-mechanic propulsion system even though that means that investments must be made in zero-emission propulsion systems later to reach emission reduction targets. By salvaging the electric-hydrogen hybrids the model obtains salvage revenues of 38,725,159 NOK for every 7-year-old vessel and 36,600,902 NOK for every 8-year-old vessel compared to revenues in the range of 6,377,551-0 NOK for the conventional diesel-mechanic bottom trawlers. In terms of operational costs (O&M and fuel), the electric-hydrogen hybrid bottom trawlers entail a cost that is approximately twice that of diesel-mechanic vessels, including CO2 taxation, equivalent to 80,989,420 NOK for the 7-year-old vessels. Additionally, by salvaging the vessels with an electric-hydrogen hybrid propulsion system, the model avoids the substantial regeneration cost. For the 7 and 8-year-old vessels, the next regeneration cost would occur in 2038 and 2037, respectively, amounting to costs of 39,778,025 and 41,633,271 NOK. The significant operational cost savings and salvage revenues justify the double investment in zero-emission propulsion technology from an economic standpoint. In addition, there are economies of scale which means that for a bottom trawler with an electric-ammonia propulsion system, the investment cost is equal to 124,531,079 NOK in 2035 and 49,312,281 NOK in 2047. From a political perspective, one could argue that this trajectory of development is not desirable. It is unfavourable to introduce zero-emission vessels only to subsequently replace them with another zero-emission propulsion system. This is particularly relevant when there is an option to replace conventional diesel-mechanic vessels instead.

Given that the regeneration cost of electric-hydrogen hybrid bottom trawlers only arises once the vessels reach the age of 10, it may seem economically sensible to delay salvaging them until they are 9 years old. However, upon closer examination of the results, it becomes evident that this is not feasible. The model needs to adhere to the emission cap set for 2050, which means there is not enough shipyard capacity available to replace more already zero-emissions electric-hydrogen hybrid vessels in 2035 or subsequent years. Instead, the shipyard capacity must be utilized to replace conventional diesel-mechanic ocean-going vessels to meet the emission targets. By replacing 10 zero-emission bottom trawlers rather than conventional diesel-mechanic vessels, we get a lost emission reduction of 74.18 tonnes of CO2 annually. From 2035 to 2049 this corresponds to 1,039 tonnes of additional CO2 emissions from the bottom trawler sub-fleet.

After the investment in bottom trawlers with an electric-ammonia propulsion system in 2035, the bottom trawler sub-fleet composition remains unchanged until 2047, when the replacement of the remaining vessels with a diesel-mechanic propulsion system is initialized and becomes available for use in the subsequent year. All are replaced by vessels with an electric-ammonia propulsion system and by 2050, all bottom trawlers are zero-emission vessels.

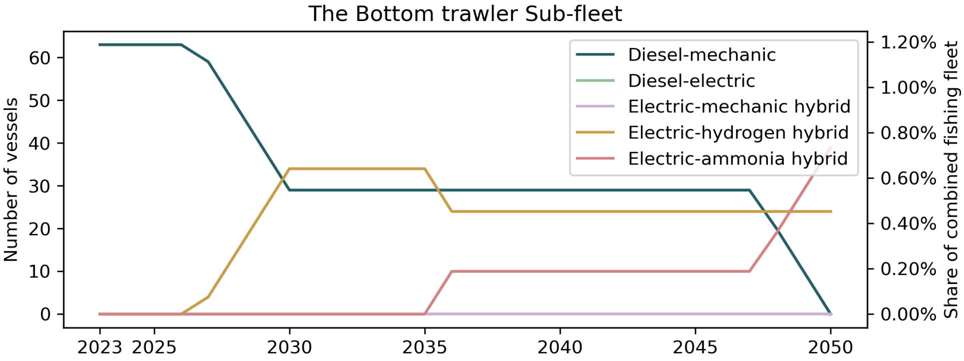


Figure 7.3: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the bottom trawler sub-fleet over the planning horizon

7.2.1 The Ocean-going Fleet

The Conventional Ocean-going Sub-fleet

As can be seen in Figure 7.4, from 2023 to 2026, 35 vessels with a diesel-mechanic propulsion system in the conventional ocean-going sub-fleet are salvaged, while only 5 corresponding vessels are kept until they are also salvaged in 2044. Analysis of the results reveals that the model prioritizes salvaging vessels which in the next period will reach the age corresponding to regeneration rather than vessels that have surpassed their economic life and thus have higher O&M costs. For example, in the first time period (2023), the model salvages an 11-year-old vessel in favour of a 34-year-old vessel. This coincides with the fact that the regeneration interval for a diesel-mechanic propulsion system is every 6th year with a regeneration cost of 2,755,101 NOK, while the increased O&M costs equal 918,366 NOK annually. The 34-year-old vessel is salvaged in the subsequent time period (2024). The number of conventional ocean-going vessels salvaged at a specific age aggregated over the planning horizon is illustrated in Figure B.1 in Appendix B. In several periods, we observe peaks occurring the year prior to the regeneration of the conventional diesel-mechanical propulsion system, which is every 6th year.

In the period 2023-2026, the diesel-mechanic propulsion system is exclusively replaced by vessels with an electric-hydrogen hybrid propulsion system, while in 2044, the model replaces the remaining diesel-mechanic conventional ocean-going vessels with electric-ammonia hybrid vessels. The investment cost of the electric-ammonia and electric-hydrogen hybrid in 2044 equals 20,333,455 and 17,275,606 NOK. However, the operational costs related to O&M and fuel costs correspond to 27,869,013 and 37,106,025 NOK for the electric-ammonia and electric-hydrogen hybrid propulsion systems, respectively. Consequently, despite the higher investment cost associated with the electric-ammonia hybrid, the additional expense is offset within the first year of operation due to lower operational costs. During the period from 2023 to 2026, however, it is advantageous to invest in the electric-hydrogen hybrid propulsion system over the electric-ammonia hybrid propulsion system due to lower investment and operational costs.

Both in the period 2023-2026 and in 2044, it is emission reduction that drives the replacement of the vessels rather than costs. The reason for not retaining the diesel-mechanical conventional ocean-going longer is to postpone the more costly renewal of the bottom and pelagic trawler sub-fleets while still reaching the emission reduction targets of 2030 and 2050. Consequently, in 2046 the sub-fleet is zero-emission. This can be seen in Figure 7.2.

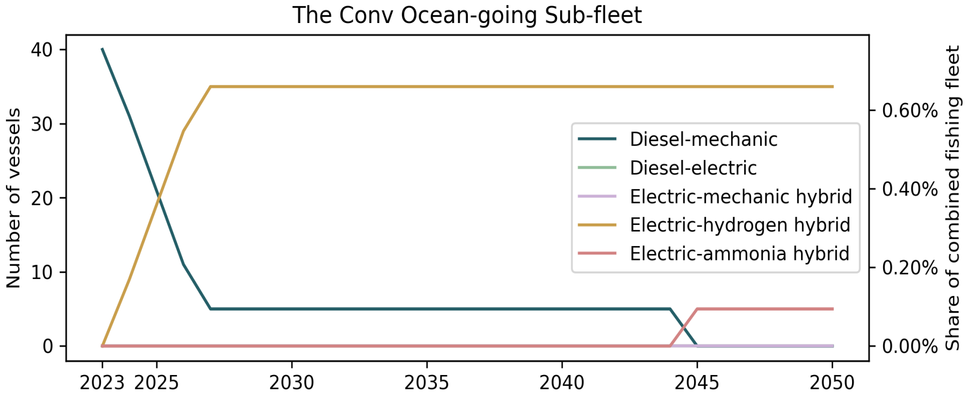


Figure 7.4: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the conventional ocean-going sub-fleet over the planning horizon

The Purse Seiner Sub-fleet

In the renewal schedule of the purse seiner sub-fleet, presented in Figure 7.5, only one vessel with a diesel-mechanic propulsion system is salvaged in 2023. Furthermore, as of 2030, the model starts gradually replacing vessels up until 2043. In this period the remaining 123 purse seiners are replaced by vessels with zero-emission propulsion systems. The diesel-mechanic purse seiners are first replaced by vessels with an electric-hydrogen hybrid propulsion system until 2034, then by electric-ammonia purse seiners as of 2036. From 2030 to 2034 the shipyard capacity for ocean-going vessels is fully utilized by the purse seiner sub-fleet. This is also the case from 2036 to 2040. From 2041 to 2043, shipyard capacity is also delegated to the pelagic trawler sub-fleet. As of 2044, the entire purse seiner sub-fleet is zero-emission.

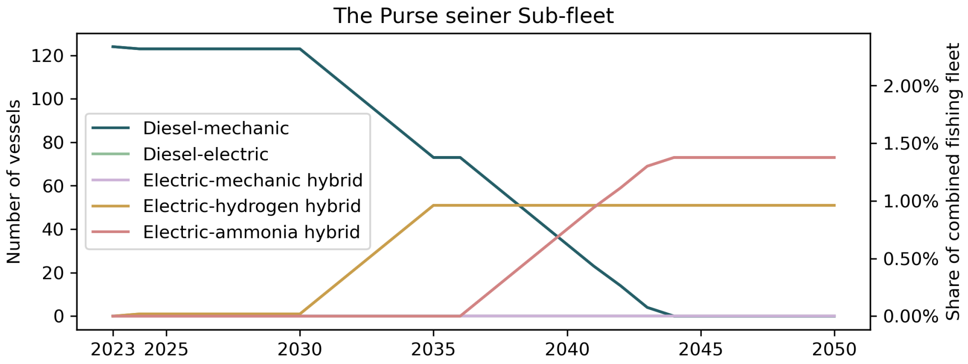


Figure 7.5: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the purse seiner sub-fleet over the planning horizon

The Pelagic Trawler Sub-fleet

For the pelagic trawlers, we observe that the investment in the replacement of vessels is postponed until 2041 when one diesel-mechanic pelagic trawler is salvaged and replaced by a new vessel with an electric-ammonia propulsion system. By closer analysis of the results, it is apparent that this particular vessel is salvaged because it has reached its maximum operational lifetime. The sub-fleet renewal schedule is presented in Figure 7.6. As of 2043, a gradual replacement of the remaining 32 pelagic trawlers with a diesel-mechanic propulsion system is initialized. All are replaced by new vessels with an electric-ammonia propulsion system. In terms of shipyard capacity, the model has the opportunity to postpone these investments for as long as it does, as the pelagic trawlers make up the smallest sub-fleet in terms of the number of vessels. The postponement of investment implies that the costs related to investment are high for this sub-fleet compared to the other ocean-going sub-fleets. This seems reasonable as the costs related to investment, regeneration and O&M costs are the same as for the bottom trawler. What separates the bottom and pelagic trawler sub-fleets is the fuel consumption, and consequently, the fuel cost and potential CO2 taxation, whereas the pelagic trawler sub-fleet has lower costs. The results imply that even though the fuel cost and CO2 taxation are relatively higher for the bottom trawlers than the pelagic trawlers, the model still chooses to replace 34 bottom trawlers before 2030 due to the large emissions associated with the bottom trawlers compared to the pelagic trawlers. A diesel-mechanic bottom trawler emits 7,418 tonnes of CO2 annually, while a diesel-mechanic pelagic trawler emits 3,046 tonnes of CO2. The fuel cost of a diesel-mechanic bottom and pelagic trawler corresponds to 21,997,225 and 9,032,901 NOK, while the associated CO2 taxation corresponds to 16,542,140 and 6,792,580 NOK, respectively.

It should also be noted that by postponing investment in the renewal of the pelagic trawler sub-fleet until 2041, the model and the objective value do not capture the regeneration cost related to the SO-fuel cell and battery that will occur in 2051 for the electric-ammonia propulsion system, equal to approximately 20,000,000 NOK. For reference, this is approximately 11,000,000 NOK more than the regeneration cost of a conventional diesel-mechanic vessel.

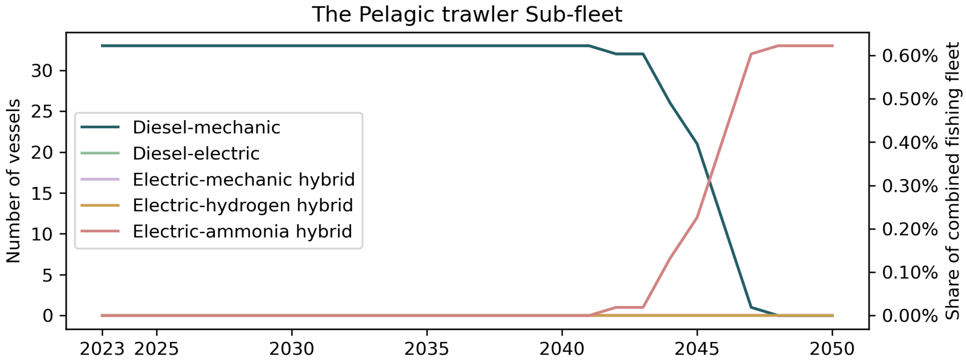


Figure 7.6: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the pelagic trawler sub-fleet over the planning horizon

7.2.2 The Coastal Fleet

The Conventional Coastal Sub-fleet

The conventional coastal sub-fleet is by far the largest in terms of the number of vessels with 4,698 vessels. A first renewal takes place in 2027 and 2028 and a second, more gradual renewal takes place in the period 2034-2049. This is illustrated in Figure 7.7. In 2027 and 2028, 19 and 23 conventional coastal vessels with a diesel-mechanic propulsion system are replaced by vessels with an electric-mechanic hybrid propulsion system. The fact that these vessels are replaced in 2027 and 2028 rather than in 2029, together with the fact that the renewal of coastal seiners uses all the shipyard capacity for coastal vessels in 2029, suggests that from an economic perspective, the model prefers to postpone the renewal of the coastal seiner sub-fleet longer than the conventional coastal sub-fleet. This is reasonable as the investment cost of an electric-hydrogen hybrid coastal seiner equals 6,375,700 NOK in 2028, while the investment cost of a conventional coastal vessel with an electric-hydrogen hybrid propulsion system equals 5,854,737 NOK. In addition to having a lower investment cost than coastal seiners, the operational costs (O&M, fuel) are also significantly lower for conventional coastal vessels. Further analysis of the results thus implies that in terms of costs, the model would preferably replace more conventional coastal vessels earlier, but in order to achieve the emissions reduction target of 2030, the model also replaces coastal seiners. We recall that coastal seiners with a diesel-mechanic propulsion system have an average CO2 emission of only 58 tonnes a year which corresponds to approximately three times as much as a conventional coastal vessel with an annual emission of 20 tonnes of CO2. This implies that despite the higher costs associated with the replacement of a single coastal seine, the model still chooses to replace these first as it would take the replacement of three conventional vessels to achieve the same emission reduction. This suggests that prior to 2030, the need to reduce emissions compels the model to prioritize the replacement of vessels that are more costly to replace.

From 2034, a more gradual renewal process of the conventional coastal sub-fleet is initialized. In 2034 and 2035, 4 and 132 diesel-mechanic conventional coastal vessels are replaced by vessels with an electric-hydrogen hybrid propulsion system, respectively. From 2036 to 2049, the sub-fleet utilizes all the shipyard capacity for coastal vessels of 180 vessels a year. Up until 2048, the vessels are exclusively replaced by conventional coastal vessels with an electric-hydrogen hybrid propulsion system, while in 2048 and 2049, the model invests in electric-ammonia hybrid vessels. The reason for this is that due to the perceived technical maturity development of fuel the SO and PEM fuel cells and consequent economies of scale, the investment cost of a conventional coastal vessel with an electric-ammonia hybrid propulsion system becomes less costly than a corresponding vessel with an electric-hydrogen propulsion system in 2048. The investment costs of a conventional coastal vessel with an electric-hydrogen and electric-ammonia hybrid propulsion system in 2047 are 2,504,885 and 2,507,709 NOK, while in 2048 the investment costs equal 2,337,392 and 2,139,106 NOK, respectively. Consequently, as of 2048, the operational costs (O&M and regeneration) become less for the electric-ammonia hybrid propulsion system compared to the electric-hydrogen hybrid, in addition to the fact that the fuel cost for ammonia is lower than for hydrogen.

For all sub-fleets, the investment cost of a vessel with an electric-ammonia hybrid propulsion system becomes less than that of an electric-hydrogen hybrid at some point in time. The rationale behind this is that the while cost per kW of the SO fuel cell decreases at a faster rate compared to the PEM cell, the cost per kW is not expected to become lower than that of the PEM cell. However, the associated cost of fuel storage, which is an element of the investment cost, is significantly lower for the SO fuel cell and electric-ammonia hybrid propulsion system. The timing at which the electric-ammonia hybrid propulsion system surpasses the electric-hydrogen hybrid propulsion system in terms of investment cost varies among the different sub-fleets. This is due to propulsion system characteristics where the ratio between fuel cell power and tank size is not the same across the sub-fleets.

In 2050, it remains exactly 2,000 conventional coastal vessels with a diesel-mechanic propulsion system in the Norwegian fishing fleet. This implies that despite the fact that the total emissions of the combined fishing fleet are to be reduced by 95% compared to 1990-levels, 42.6% of the conventional coastal sub-fleet still have a diesel-mechanic propulsion system. This corresponds to 39.6% of the coastal fleet and to 37.7% of the combined Norwegian fishing fleet in terms of the number of vessels.

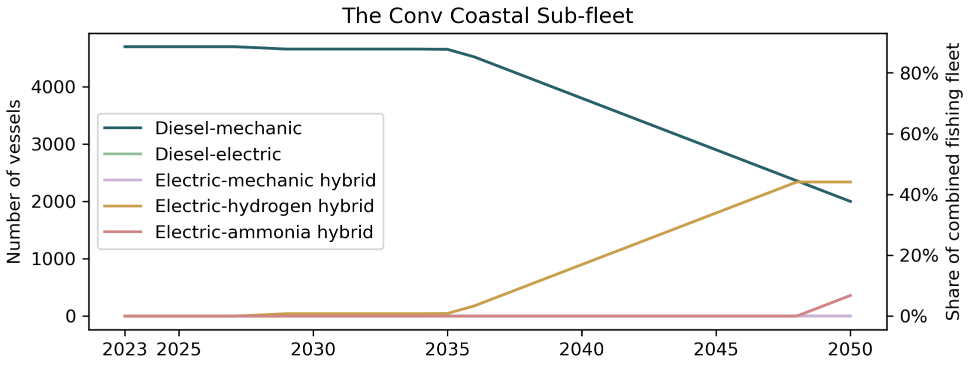


Figure 7.7: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the conventional coastal sub-fleet over the planning horizon

The Coastal Seiner Sub-fleet

From Figure 7.2 it is apparent that the coastal seiner sub-fleet accounts for the smallest share of the combined emissions over the planning horizon despite its relatively large size in terms of the number of vessels. The renewal of the coastal seiner sub-fleet, shown in Figure 7.8, takes place within three years. In 2027 and 2028, 8 and 157 coastal seiners with a diesel-mechanic propulsion system are salvaged and replaced by vessels with an electric-hydrogen hybrid propulsion system. Furthermore, 180 diesel-mechanic coastal seiners are salvaged and replaced in 2029. It is again apparent from the results that the model prioritizes salvaging vessels which in the next period will entail a regeneration cost. The number of coastal seiners salvaged at a specific age aggregated over the planning horizon is illustrated in Figure B.2 in Appendix B.

After 2029, there are no further renewals of the sub-fleet and there are no coastal seiners with a diesel-mechanic propulsion system. As discussed for the conventional coastal vessels, this is due to the relatively higher emission reduction potential for coastal seiners compared to conventional coastal vessels.

7.2.3 Overall Observations

From Figure 7.1 and Figure 7.2, we identify some key observations for the fleet renewal of the Norwegian fishing fleet. The observations are listed in order of perceived importance in addressing

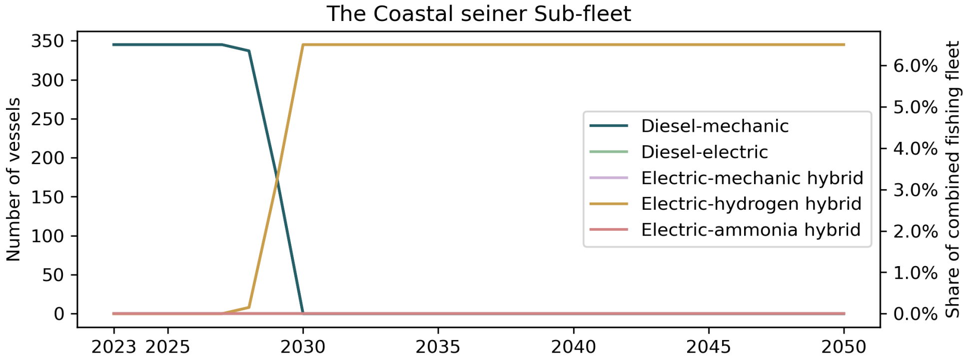


Figure 7.8: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the coastal seiner sub-fleet over the planning horizon

the underlying question - How should the Norwegian fishing fleet be renewed towards 2050?

(1) *The renewal of the ocean-going fleet is initialized before that of the coastal fleet*

Firstly, it is apparent from Figure 7.1 that the renewal of the coastal fleet is not initialized until 2027, in addition to a period from 2030 to 2033 without replacements. For the ocean-going fleet, on the other hand, the renewal is initialized right away. The reason for this is that the emission reduction achieved by renewing coastal vessels is relatively minor when compared to the associated costs. Despite the substantial increase in investment and operational expenses associated with the renewal of an individual ocean-going vessel, the incremental reduction in emissions is considerably higher. For example, if a conventional ocean-going vessel with a diesel-mechanic propulsion system is replaced in 2023 by a corresponding vessel equipped with an electric-hydrogen hybrid propulsion system, the investment cost amounts to 35,217,030 NOK. This replacement results in an annual reduction of 3,485 tonnes of CO2 emissions, which translates to a cost of 10,105 NOK per tonne of CO2 reduced. For a conventional coastal vessel with a diesel-mechanic propulsion system, its replacement with an electric-hydrogen hybrid conventional coastal vessel will incur an investment cost of 6,692,200 NOK and an annual CO2 reduction of 20 tonnes. This corresponds to a cost of 334,610 NOK per tonne of CO2 reduced. In this context, cost-effectiveness pertains to attaining a greater reduction in CO2 emissions per unit of currency (NOK) invested. As a result, directing efforts towards the renewal of ocean-going vessels proves to be more cost-effective compared to coastal vessels when it comes to curbing emissions, as it yields a higher reduction in CO2 emissions per tonne spent. Furthermore, we observe that the conventional coastal sub-fleet is the only sub-fleet that is not fully zero-emission by 2050 with 2,000 diesel-mechanic vessels in 2050. This also points to the fact that, despite the coastal fleet's large number of vessels, there is more to be gained from renewing ocean-going vessels due to the large differences in emissions from a single vessel.

(2) *It is unprofitable to pursue a more gradual transition to zero-emission through low-emission propulsion systems*

From Figure 7.1 we observe that the model consistently avoids investing in vessels equipped with diesel-electric or electric-mechanic hybrid propulsion systems. This choice is made despite the fact that these low-emission propulsion systems have lower investment and operational costs compared to zero-emission propulsion systems, as well as reduced CO2 emissions compared to conventional diesel-mechanic systems. This indicates that the proximity of 2030 and 2050 combined with the limited shipyard capacity makes it unprofitable to pursue a more gradual transition through low-emission propulsion systems. While investing in vessels with electric-mechanic propulsion may be sufficient to meet the 2030 emission reduction target, achieving the 2050 target would likely require an additional replacement. Given the current cost structure, undertaking such a double investment does not offer a worthwhile return. It is conceivable that if we had included the option of retrofitting vessels, we might have witnessed a greater adoption of these propulsion systems.

This would presuppose that the retrofitting costs were sufficiently low so that it could serve as a more gradual transition towards achieving zero emissions. This could lead to significant savings, as the model could delay investment in zero-emission technology and instead wait for technological advancements resulting in lower investment costs.

(3) *Investments are postponed as long as possible with respect to emission reduction targets*

Furthermore, we observe that in general, the renewal investments over the planning horizon are postponed for as long as the shipyard capacity allows. Further analysis of the resulting fleet renewal schedule for the Norwegian fishing fleet reveals that the model postpones investment in zero-emission vessels for as long as possible with respect to emission reduction targets. This can be observed in Figure 7.9 where the utilized shipyard capacity for the ocean-going and coastal fleet is represented by the blue and orange lines, respectively. Here we observe that the utilized capacities are either maximized or only non-zero in the period before it is maximized. Consequently, there is no indication that CO2 taxation costs incentivize renewal beyond the emission caps as of 2030 and 2050, provided the costs associated with low- and zero-emission propulsion systems. An exception arises when four vessels are acquired in 2034, marked by a red circle in Figure 7.9. From the modelling assumptions presented in Section 5.1 we recall that the number of vessels in each sub-fleet is to remain constant throughout the planning horizon. Consequently, every time a vessel is salvaged, a new vessel must be acquired for the same sub-fleet. Upon closer examination of the results concerning salvaged vessels, it becomes evident that the reason for acquiring four vessels in 2034 instead of 2035 is due to the technological lifetime limit being reached for four conventional coastal vessels, necessitating their replacement.

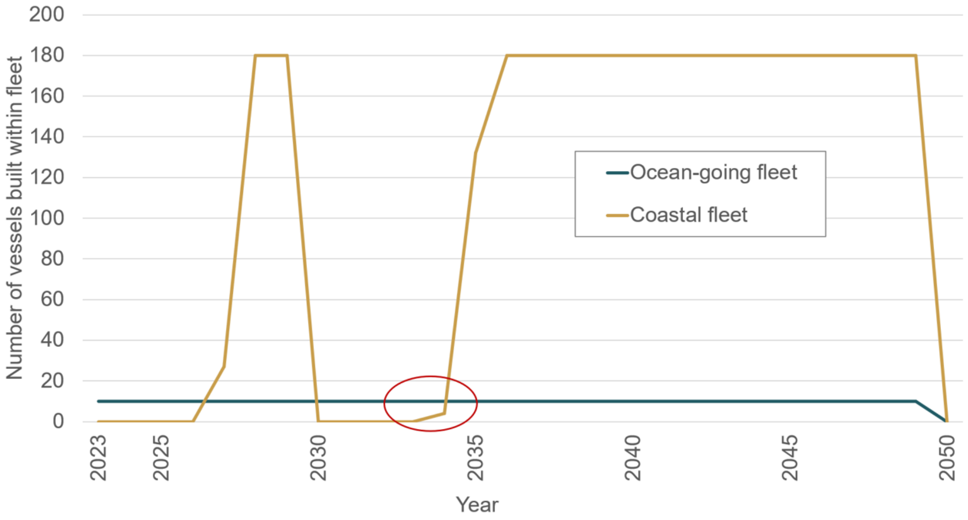


Figure 7.9: Number of vessels built within the ocean-going and coastal fleets every year over the planning horizon

(4) *The shipyard capacities may significantly impact the fleet renewal schedule*

Finally, in Figure 7.9 we observe that for the ocean-going fleet, the utilized shipyard capacity of 10 vessels a year is maximized in all time periods with the exception of 2050. Furthermore, for the coastal fleet, the shipyard capacity of 180 newbuilds a year is not utilized to the fullest until 2028-2029 and in 2036-2049. Recall that a newbuild is available for use from and including the next period. This means that a vessel acquired in 2029 will not be utilized until 2030, and so on. The fact that investments are made so that shipyard capacities are maximized before emission reduction targets in 2030 and 2050 are to be reached, suggests that the shipyard capacity for ocean-going and coastal vessels may significantly impact the resulting schedule.

7.3 Scenario Analysis

In this section, we highlight and discuss the noteworthy results obtained from the computed scenario analysis. The characteristics and nomenclature of the various scenarios are presented in Section 6.6. We compare the fleet renewal schedules of the scenarios to the base case, focusing on the differences and their potential implications. Only partial fleet renewal schedules are presented in this section, while the complete schedules can be found in Appendix C. In Table 7.2, the objective function values, which correspond to the total cost of the fleet renewal schedules and associated cost and revenue elements, are given in billion NOK, as well as the associated total emissions from the Norwegian combined fishing fleet given in tonnes of CO2. For the sake of convenience, the scenarios are numbered.

Table 7.2: Objective function values in terms of the total cost and associated cost and revenue elements in billion NOK and total emissions from the combined fleet over the planning horizon in tonnes of CO2 for all test instances

	Costs and Revenues [billion NOK]							**Total emissions [tonnes]**
	Total cost	Investment	O&M	Fuel	CO2 tax	Regeneration	Salvage	
Base Case	158,1	16.1	20.1	94.0	17.7	10.9	0.66	14,813,785
S1: ML-TL-ZB-CB-SB	143.1	16.1	20.1	88.4	8.2	10.9	0.66	14,813,443
S2: MB-TB-ZH-CH-SB	175.6	16.6	20.2	110.7	17.7	11.2	0.67	14,813,480
S3: ML-TL-ZH-CH-SB	160.6	16.6	20.2	105.1	8.2	11.2	0.67	14,813,480
S4: MH-TH-ZB-CB-SB	185.7	17.2	19.9	108.7	29.7	10.9	0.66	12,611,515
S5: MB-TB-ZL-CL-SB	142.4	15.6	20.0	79.4	17.4	10.7	0.69	14,328,820
S6: MH-TH-ZL-CL-SB	167.4	16.6	19.8	92.0	28.9	10.6	0.63	12,392,034
S7: MB-TB-ZB-CB-SH	152.7	17.3	19.9	87.9	18.5	10.4	1.38	15,579,324

Figure 7.10 illustrates a breakdown of the total costs associated with the base case and the various scenarios over the planning horizon. The bars in the figure indicate the proportion of each cost element relative to the overall cost. The green bar represents the investment costs, the purple bar represents the O&M costs and the orange bar represents the fuel costs. Furthermore, the light blue bar represents the CO2 taxation and finally, the red bar represents the regeneration costs. From Table 7.2 it is evident that the revenues generated from salvaging vessels are of negligible magnitude. Consequently it is not included in Figure 7.10.

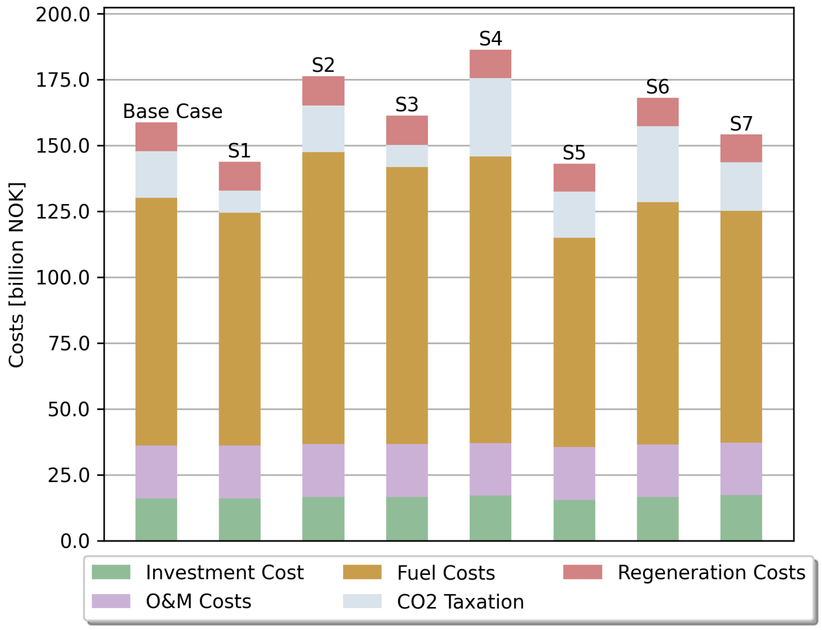


Figure 7.10: Cost breakdown of the total costs associated with the base case and scenarios 1-7

7.3.1 Making Zero-emissions Less Favourable

As presented in Section 6.6, scenarios 1-3 are included in order to observe the results when zero-emission propulsion systems become relatively less favourable compared to conventional and low-emission propulsion systems. Scenario 1 implies a reduced MGO price and CO2 taxation, while scenario 2 implies an increase in the prices for zero-emission fuels as well as an increased component costs of batteries, PEM and SO fuel cells. Scenario 3 combines all these elements. The fleet renewal schedules are found in Figure C.1-C.3 in Appendix C. We recall that based on the established nomenclature, scenarios 1-3 are assigned the following labels:

S1: ML-TL-ZB-CB-SB

S2: MB-TB-ZH-CH-SB

S3: ML-TL-ZH-CH-SB

For scenario 1 there are essentially no changes to the fleet renewal schedule compared to the base case. The reduction in the total cost of 15 billion NOK is expected as the price of MGO and the CO2 tax is reduced. This is also evident from Figure 7.10. The total emissions are reduced by 342 tonnes of CO2. This is presented in Table 7.2. The minor decline in total emissions is due to conventional coastal vessels being retained somewhat longer while replacing the coastal seiner earlier. We recall that a conventional coastal vessel has an annual CO2 emission of 20 tonnes, while a coastal seiner has an annual emission of 58 tonnes. The fleet renewal schedules for the ocean-going sub-fleets in scenario 1 are the same as in the base case.

Scenarios 2 and 3 offer an identical fleet renewal schedule. As for scenario 1, the renewal schedules of the ocean-going sub-fleets are unchanged compared to the base case and investment in conventional coastal vessels is yet again somewhat postponed in favour of coastal seiners. Consequently, we observe a minor reduction in total emissions of 305 tonnes of CO2. The total cost associated with scenario 2 is approximately 11.1% higher than for the base case due to an increase in the prices of zero-emission fuels, and an increased component costs of batteries, PEM and SO fuel cells. However, from Figure 7.10 it is apparent that it is the increase in fuel prices that drive the increase in total cost compared to the base case. The total cost of scenario 3 is somewhat less than that of scenario 2 due to the reduced MGO price and CO2 tax. In Figure 7.10 we observe that the decline is mainly due to the use of the low-price trajectory for the CO2 tax.

Overall, despite the changes made to the various parameter values in scenarios 1-3 to make zero-emission propulsion systems relatively less favourable, the fleet renewal schedules remain largely unchanged compared to the base case. This suggests that, as of today, it is the emission reduction requirements of 2030 and 2050 that drive fleet renewal and investments in zero-emission propulsion technology, rather than economic motives. Despite less favourable circumstances in terms of CO2 tax, fuel prices, and increased component costs of batteries, PEM and SO fuel cells, the Norwegian fishing fleet would in essence still be subject to the same investments and fleet renewal schedule as in the base case. This implies that if we want the model to make changes to the fleet renewal schedule, it will require improvements in terms of fuel prices and technological development for zero-emission propulsion systems beyond the expected values indicated by the base case.

7.3.2 Making Zero-emissions More Favourable

Scenarios 4-6 are included in order to observe the results when zero-emission propulsion systems become relatively more favourable compared to conventional and low-emission propulsion systems. In scenario 4, the price of MGO is increased in addition to the CO2 tax following the high-price trajectory, and in scenario 5, the prices of zero-emission fuels are reduced compared to the base case, as well as the component cost of batteries, PEM and SO fuel cells. Scenario 6 combines all these elements. The fleet renewal schedules may be found in Figure C.4-C.6 in Appendix C. Scenarios 4-6 are assigned the following labels:

S4: MH-TH-ZB-CB-SB

S5: MB-TB-ZL-CL-SB

S6: MH-TH-ZL-CL-SB

S4: MH-TH-ZB-CB-SB

For scenario 4 we observe quite significant alterations to the fleet renewal schedule after 2030 compared to the base case, particularly for the ocean-going fleet. Figure 7.11 presents the base case on the left and scenario 4 on the right for the bottom trawler and conventional ocean-going sub-fleets, whereas Figure 7.12 correspondingly presents the purse seiner and pelagic trawler sub-fleets. In Table 7.2 we observe that the total emissions are reduced by 14.9% compared to the base case, while the total cost sees an increase of 17.5%. The reduction in emissions implies that the increase in the MGO price and high-price trajectory for the CO2 tax incentivises investment in low- and zero-emission propulsion. Additionally, it is worth noting that the driving force behind the incentivized investment in low- and zero-emission propulsion technologies primarily stems from the impact of the CO2 tax rather than the increased MGO price, which contributes significantly to the reduction in emissions. We can confidently assert this fact because the average fuel price per kWh for the zero-emission propulsion systems which use batteries and hydrogen/ammonia as fuel, is consistently higher than the high fuel price of MGO. The cost distribution is presented in Figure 7.10.

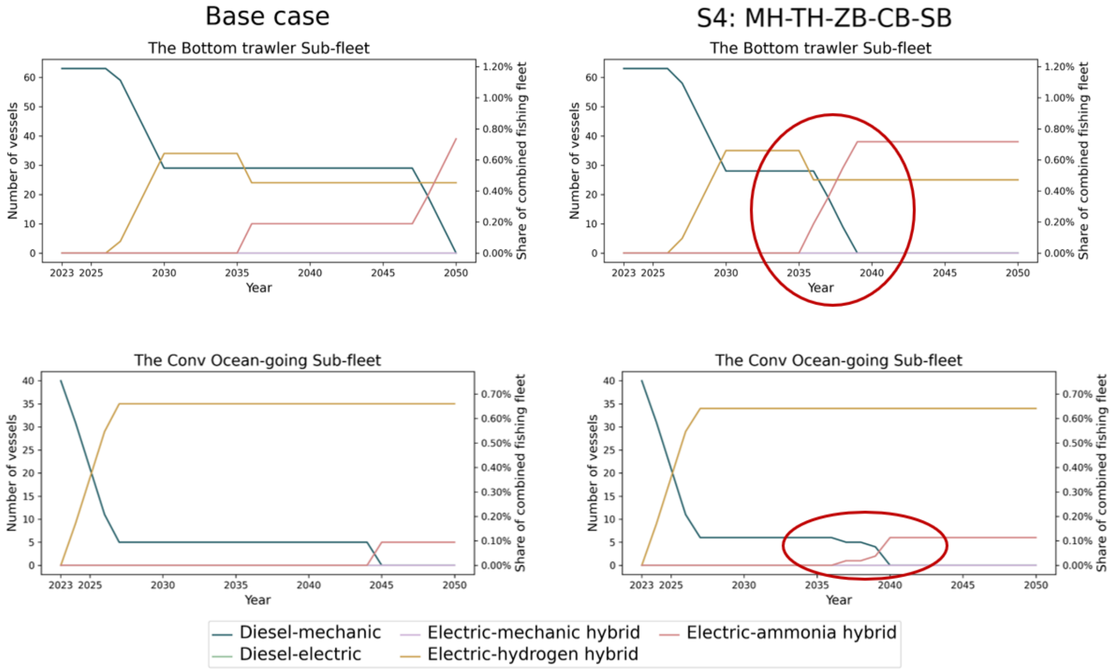


Figure 7.11: Base case and scenario 4: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the bottom trawler and conventional ocean-going sub-fleets over the planning horizon

In Figure 7.11 we observe that the replacement of both diesel-mechanic bottom trawlers and conventional ocean-going vessels is initiated earlier in scenario 4 than in the base case. The bottom trawler and conventional ocean-going sub-fleets, together with the purse seiner sub-fleet, are the sub-fleets with the highest initial emissions in the Norwegian fishing fleet. This is apparent from Figure 7.2. Consequently, when the retention of diesel-mechanic bottom trawlers and conventional ocean-going vessels becomes increasingly expensive, zero-emissions vessels become relatively less expensive. For the bottom trawler sub-fleet, the investment in vessels with an electric-ammonia hybrid propulsion system is intensified earlier in the planning horizon compared to the base case. In scenario 4, all diesel-mechanic bottom trawlers are replaced by zero-emissions vessels by 2038 compared to 2050 in the base case. However, we still observe that 10 electric-hydrogen hybrid vessels are salvaged in favour of new electric-ammonia hybrid bottom trawlers. This is an economically motivated choice as this does not reduce the total emissions. For the conventional ocean-going sub-fleet, the initialization of replacement is now in 2036 rather than 2044 as in the base case, and the sub-fleet is zero-emission by 2039. The total emission reduction for the bottom trawler and conventional ocean-going sub-fleets compared to the base case corresponds to 2,455,358 and 55,760 tonnes of CO2, respectively.

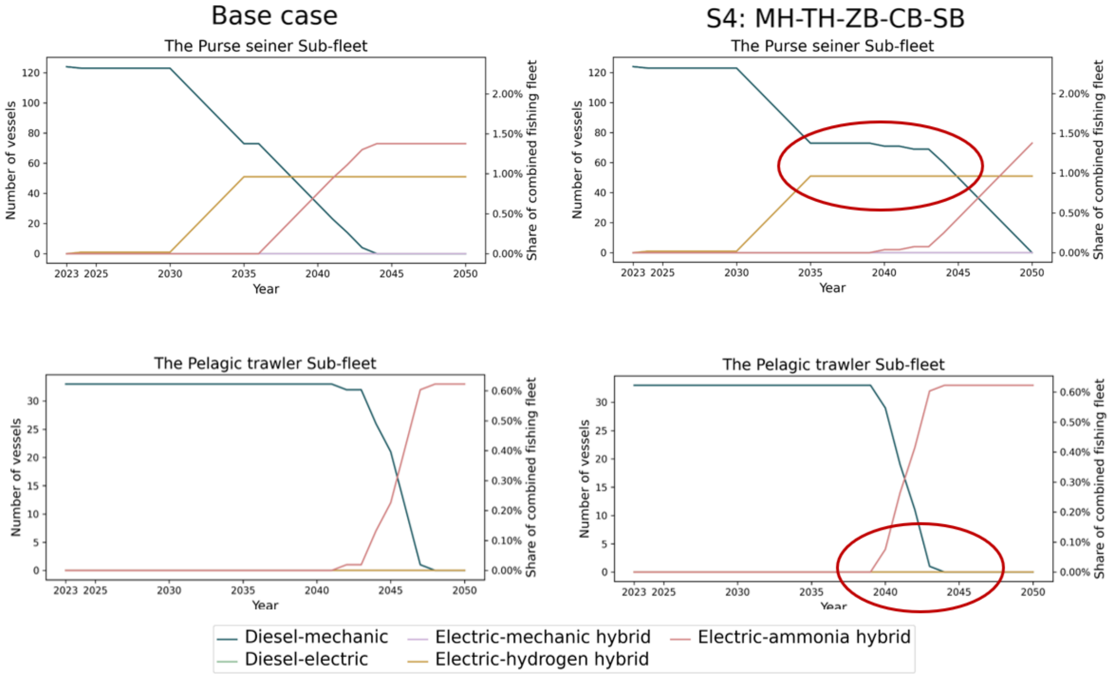


Figure 7.12: Base case and scenario 4: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the purse seiner and pelagic trawler sub-fleets over the planning horizon

In Figure 7.12 we observe that for the pelagic trawler sub-fleet, the investment in zero-emission vessels is expedited compared to the base case, while for the purse seiner sub-fleet, the diesel-mechanic vessels are retained longer in scenario 4 than in the base case. The diesel-mechanic purse seiners are now phased out in 2050 rather than in 2043. Upon closer examination of the results we understand that the reason that we do not observe the same effect for this particular sub-fleet as for the other ocean-going sub-fleets is that in order for the ocean-going fleet to comply with the shipyard capacity limit, some ocean-going vessels must be replaced later in the planning horizon. In other words, the shipyard capacity becomes the bottleneck. The diesel-mechanic purse seiners are the type of vessels with the lowest fuel consumption and consequently lowest emissions amongst the ocean-going sub-fleets with 1,413 tonnes of CO2 a year. The prolonged use of diesel-mechanic purse seiners can thus be attributed to both the limited shipyard capacity for ocean-going vessels and the increase in the MGO price and CO2 taxation.

Also for the coastal fleet, we obtain changes to the fleet renewal schedules for the two coastal sub-fleets. Figure 7.13 illustrates the difference between the base case and scenario 4 for the coastal seiner sub-fleet. We observe that the increase in MGO price and CO2 taxation in scenario 4, prolongs the use of diesel-mechanic vessels within the coastal seiner sub-fleet until 2038 compared to the base case. This is because the model initializes the replacement of conventional ocean-going vessels earlier than in the base case. We recall that a diesel-mechanic conventional ocean-going vessel has a higher fuel consumption than a corresponding coastal seiner and emits 58 against 20 tonnes of CO2 a year. The operational costs related to fuel and CO2 taxation thus shift the replacement within the coastal fleet so that vessels belonging to the conventional ocean-going sub-fleet are replaced earlier than in the base case despite the lost favorability of postponing larger investments.

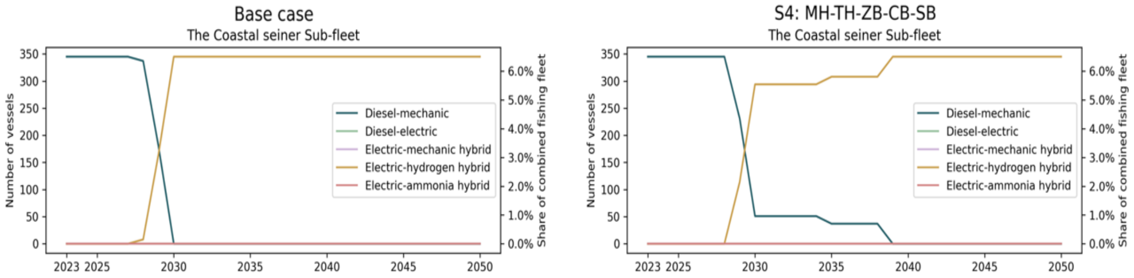


Figure 7.13: Base case and scenario 4: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the coastal seiner sub-fleet over the planning horizon

S5: MB-TB-ZL-CL-SB

For scenario 5, we observe relatively less significant changes to the fleet renewal schedule than in scenario 4 (MH-TH-ZB-CB-SB) compared to the base case. This is also evident from the reduction in total emissions, which is significantly less than in scenario 4, amounting to 484,965 tonnes of CO2. However, the total cost over the planning horizon is reduced by 15.7 billion NOK. This is to be expected as the fact that zero-emission propulsion systems become more affordable which leads to lower investment, O&M and regeneration costs. Figure 7.10 shows that the total fuel costs over the planning horizon are significantly reduced compared to the base case, while the remaining cost elements remain largely unchanged. Figure 7.14 presents a comparison of the base case on the left and scenario 5 on the right for the bottom trawler sub-fleet, whereas Figure 7.15 presents the conventional ocean-going sub-fleet.

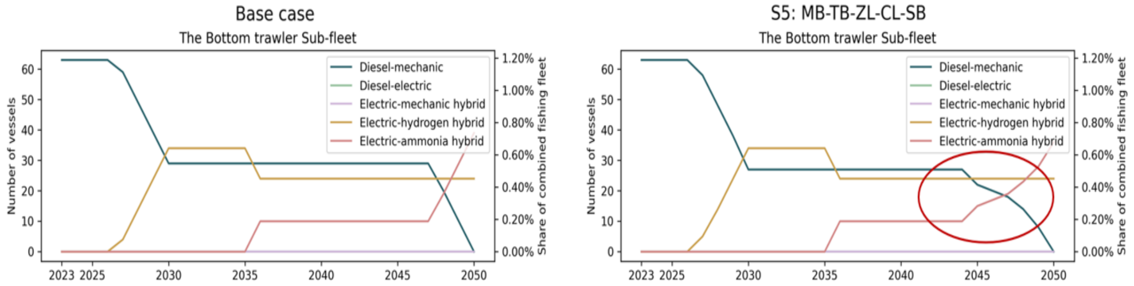


Figure 7.14: Base case and scenario 5: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the bottom trawler sub-fleet over the planning horizon

In Figure 7.14 we observe that compared to the base case, the replacement of diesel-mechanic bottom trawlers with vessels with an electric-ammonia propulsion system is initialized earlier in scenario 5. Both in the base case and in scenario 5, the bottom trawler sub-fleet becomes zero-emission by 2050, but the process of replacement is initialized in 2047 in the base case and in 2044 for scenario 5. This results in a total emission reduction for the sub-fleet of 504,424 tonnes of CO2 compared to the base case.

As can be seen in Figure 7.15, the diesel-mechanic conventional ocean-going vessels are phased out considerably earlier in scenario 5 than in the base case. The sub-fleet is fully zero-emission by 2037 rather than 2045. This corresponds to an emission reduction for the conventional ocean-going sub-fleet of 94,095 tonnes of CO2 compared to the base case. From closer analysis of the results, we observe that the shipyard capacity for ocean-going vessels, as opposed to in the base case, is not utilized to the fullest in all time periods. In 2043, as well as in the period 2045-2048, only 9 ocean-going vessels are built. This implies that the reduced prices of zero-emission fuels, as well as the reduced component cost of batteries, PEM and SO fuel cells, make it economically viable to invest in zero-emission propulsion before emission requirements necessitate it.

The fleet renewal schedules for the ocean-going purse seiner and pelagic trawler sub-fleets, as well as the conventional coastal and coastal seiner sub-fleets in scenario 5, to a great extent, resemble

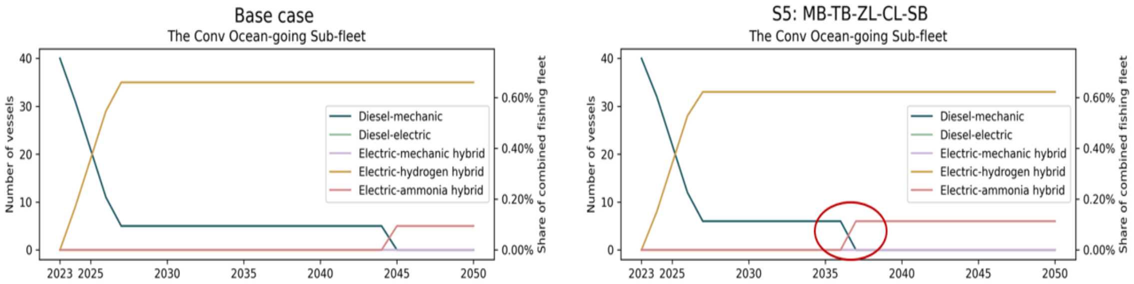


Figure 7.15: Base case and scenario 5: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the conventional ocean-going sub-fleet over the planning horizon

that of the base case. This implies that the reduced prices of zero-emission fuels, in addition to the decrease in component cost of batteries, PEM and SO fuel cells, are not sufficient to incentivize investments in zero-emission propulsion systems. If so, it would require fuel prices to become progressively cheaper to accelerate beyond what is considered in this computational study. In terms of shipyard capacity, the coastal fleet postpones investment in the same manner as in the base case where the shipyard capacity is maximized before 2030 and 2050. This implies that the reduced costs associated with zero-emission propulsion do not incentivize the replacement of the coastal fleet before CO2 emission reduction targets necessitate it. The reason we do not observe the same effect for the coastal fleet as for the ocean-going fleet in terms of replacement decisions being economically driven is the fact that zero-emission propulsion becomes economically favourable later for the coastal fleet than for the ocean-going fleet. This is described in Section 7.2.2.

S6: MH-TH-ZL-CL-SB

In Table 7.2 we observe that the emissions reduction is greatest for scenario 6 compared to the base case with a total reduction of 2,421,751 tonnes of CO2. This is to be expected as the scenario entails both an increase in MGO price and CO2 taxation, as well as a decrease in the price for battery power, hydrogen and ammonia and a steeper technological development for zero-emission technologies. All of these aspects incentivize earlier investments in vessels with zero-emission propulsion systems. The total cost necessarily lies between that of scenario 4 (MH-TH-ZB-CB-SB) and scenario 5 (MB-TB-ZL-CL-SB) as scenario 6 combines the elements of these scenarios. Figure 7.16 presents a comparison of the renewal schedule for the bottom trawler sub-fleet with the base case on the left and scenario 6 on the right.

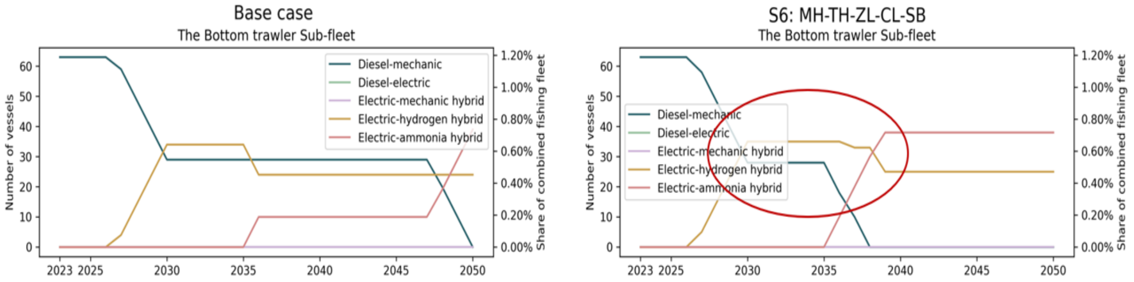


Figure 7.16: Base case and scenario 6: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the bottom trawler sub-fleet over the planning horizon

The fleet renewal schedule of most sub-fleets closely resembles that of scenario 4. This seems reasonable as out of scenarios 4 and 5, it is scenario 4 that significantly alters the fleet renewal schedule. For the bottom trawler sub-fleet, however, the result deviates noticeably from scenario 4 and the base case. In Figure 7.16 we observe that the diesel-mechanic bottom trawlers are salvaged and phased out earlier in scenario 6 than in the base case. Additionally, the salvaging of vessels with an electric-hydrogen hybrid propulsion system is postponed by salvaging 2 vessels in 2036 and 8 vessels in 2037. In both cases, the vessels salvaged are all 9 years old, which implies that salvaging the vessels prevents the regeneration cost that arises when the vessel reaches the age of 10 from incurring.

From the bottom trawler fleet renewal schedule in both the base case and scenarios, it is evident that from an economic point of view, it is worthwhile to salvage electric-hydrogen hybrid bottom trawlers in favour of new electric-ammonia hybrid vessels. This is primarily due to the significantly lower annual fuel costs associated with ammonia. In scenario 6, the operational costs (O&M and fuel) related to a 10-year-old electric-hydrogen hybrid vessel amount to 64,812,269 NOK in 2037, while for the new electric-ammonia the operational costs equal 40,295,120 NOK. If we subtract the salvage value of an electric-hydrogen hybrid bottom trawler, as well as the regeneration cost that otherwise would have been incurred in the subsequent year, from the investment cost of a new electric-ammonia hybrid vessel in 2036, the additional cost of the electric-ammonia hybrid amount to 42,499,417 NOK. We understand that this additional cost can be recovered in less than two years of operating the electric-ammonia hybrid bottom trawler as opposed to an electric-hydrogen hybrid. The salvaging of electric-hydrogen hybrid bottom trawlers also occurs in the base case and other scenarios for the same reason. For scenario 6, the salvaging is only somewhat adjusted due to the decreased attractiveness of retaining diesel-mechanical vessels. The reason why no additional bottom trawlers with an electric-hydrogen hybrid propulsion system are salvaged in favour of electric-ammonia hybrid vessels is the combination of the shipyard capacity for ocean-going vessels and emissions reduction targets necessitates the phasing out of diesel-mechanic ocean-going vessels.

7.3.3 Increased Shipyard Capacity

Finally, scenario 7 is included in order to evaluate the impact on costs and emissions of increased shipyard capacity. The scenario is thus assigned the following label:

S7: MB-TB-ZB-CB-SH

As expected, the model postpones investment in low- and zero-emission propulsion when the shipyard capacities increase and it has the opportunity to replace more vessels at a later point in time while still achieving emissions reduction targets. Consequently, we get a reduction in the total costs corresponding to 5.4 billion NOK, while the total emissions have increased by 765,539 tonnes of CO2. This can be observed in Table 7.2. From Figure 7.10 it is apparent that the cost reduction is due to a relative reduction in fuel costs over the planning horizon compared to the base case. We recall that conventional diesel-mechanic vessels have a lower average price per kWh than zero-emission vessels that utilize battery power and hydrogen/ammonia. Compared to the base case, we observe significant changes to the fleet renewal schedules, especially the bottom trawler sub-fleet and the conventional ocean-going sub-fleet. This can be observed in Figure 7.17 and Figure 7.18 Moreover, substantial alterations are made to the fleet renewal of the coastal fleet, illustrated in Figure 7.19. The complete fleet renewal schedule for scenario 7 is given by Figure C.7 in Appendix C.

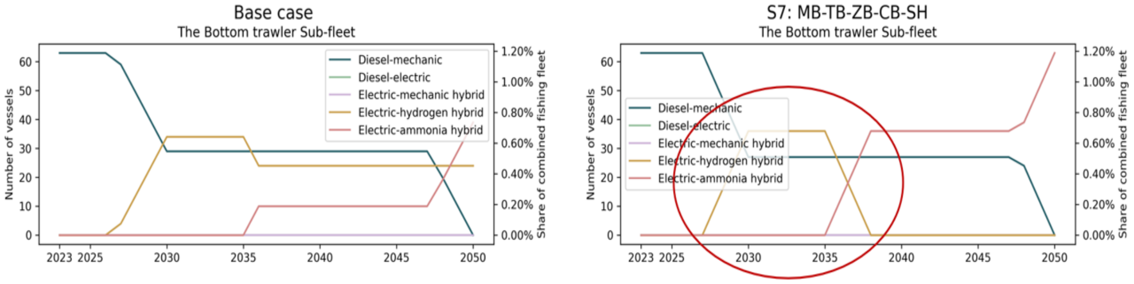


Figure 7.17: Base case and scenario 7: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the bottom trawler sub-fleet over the planning horizon

In Figure 7.17 we observe that like in the base case, bottom trawlers with an electric-hydrogen propulsion system are salvaged in favour of electric-ammonia hybrid vessels, but this time on an even larger scale. This happens despite the fact that there are conventional diesel-mechanic bottom trawlers the model could replace instead. As the electric-ammonia hybrid propulsion system becomes available in 2035, the model now replaces all 36 electric-hydrogen hybrid bottom trawlers that were acquired in the period 2027-2029 over a three-year period. This confirms the observation made for the bottom trawlers in Section 7.2, we stated that examination of the results implied that there is not enough shipyard capacity available to replace more electric-hydrogen hybrid vessels in 2035 or subsequent years, even though it is economically reasonable. The results suggest that for energy-intensive sub-fleets such as the bottom trawler, the electric-hydrogen hybrid propulsion system lacks competitiveness. Once electric-ammonia hybrid propulsion becomes accessible in the market, the economic benefits of replacing the electric-hydrogen vessels with electric-ammonia vessels become apparent. Prior to this development, electric-hydrogen vessels were solely acquired to fulfil the emission reduction target set for 2030. The premature replacement of zero-emission vessels with another zero-emissions propulsion technology signifies a policy that is misguided. This outcome, viewed from a political perspective, directly contradicts the desired objective of reducing overall emissions. To avoid similar consequences, policy-makers should evaluate ways to incentivize the continued use of zero-emission vessels and instead encourage the replacement of conventional diesel-mechanical vessels.

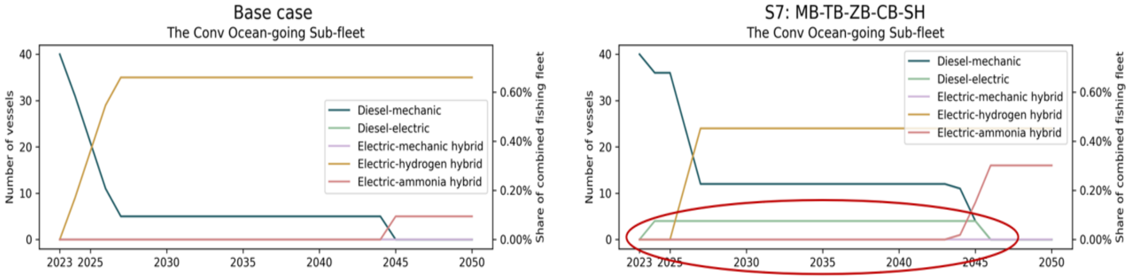


Figure 7.18: Base case and scenario 7: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the conventional ocean-going sub-fleet over the planning horizon

Furthermore, the increased shipyard capacity for ocean-going vessels makes quite significant changes to the fleet renewal schedule for conventional ocean-going vessels compared to the base case. This is pictured in Figure 7.18. Firstly, instead of salvaging 35 diesel-mechanic conventional ocean-going vessels from 2023-2026, as in the base case, the capacity increase makes the model salvage only 28 diesel-mechanic vessels in the same period and replace them with both electric-hydrogen hybrid and diesel-electric vessels. The four diesel-electric vessels are later replaced by electric-ammonia hybrid vessels in 2024. This makes the resulting conventional ocean-going sub-fleet in 2050 comprise of more electric-ammonia hybrid vessels than in the base case (5 and 16). In terms of emissions, the total CO2 emissions of the conventional ocean-going sub-fleet amount to 1,528,543 tonnes of CO2, an increase of 127.3% compared to the base case. From Figure 7.18 it is apparent that the increase in emissions is due to the retention of diesel-mechanic vessels, as well as the introduction of low-emission diesel-electric vessels. The fact that the model chooses to invest in low-emission propulsion systems, such as the diesel-electric implies that the increased shipyard capacity allows for the replacement of more vessels towards the end of the planning horizon, enabling sufficient capacity to invest in low-emission technology, which has lower investment and operational costs than zero-emission technology. With the renewal schedule of scenario 7, the shipyard capacity of ocean-going vessels is utilized to the fullest in all time periods over the planning horizon.

In Figure 7.19 we observe that the fleet renewal schedule of conventional coastal sub-fleet of scenario 7 resembles that of the base case, while for the coastal seiner sub-fleet it is apparent that the increased shipyard capacity makes it possible to postpone investments in zero-emission coastal seiners. Compared to the base case, the combined emissions of the ocean-going fleet are decreased by 0.8% by 2030 in scenario 7, while the emissions from the coastal fleet in 2030 are increased accordingly. Upon closer analysis of the results, we note that for the conventional coastal sub-fleet, the model invests in new diesel-mechanic vessels. In total, the model replaces 38 already diesel-mechanic conventional coastal vessels with new diesel-mechanic vessels. The 38 vessels in

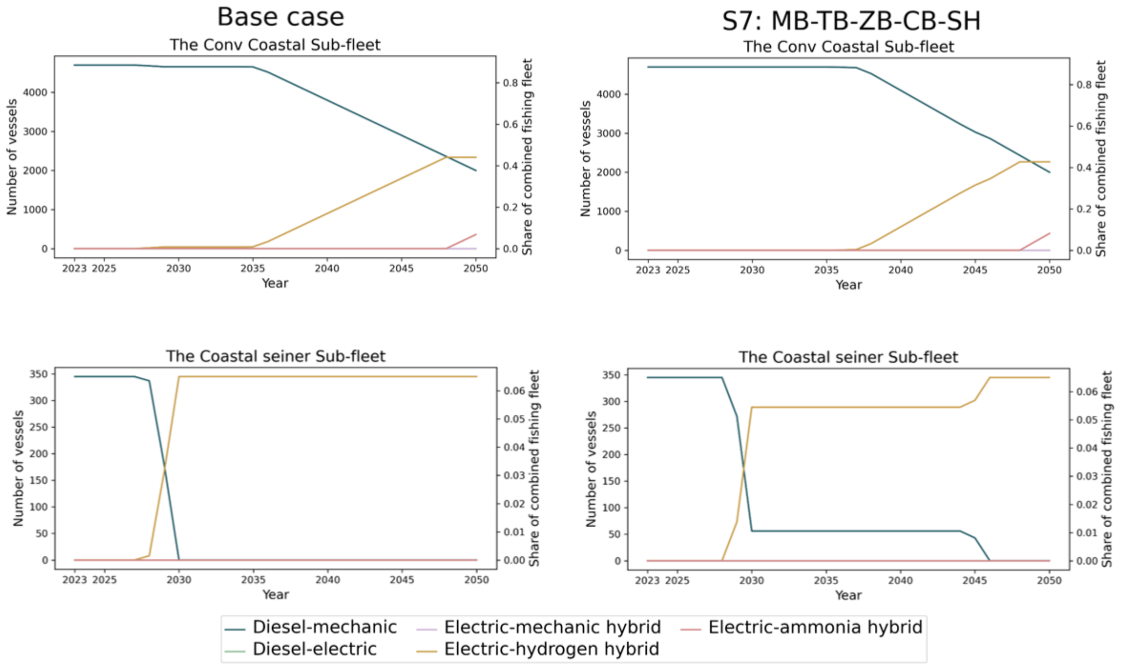


Figure 7.19: Base case and scenario 7: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the conventional coastal and coastal seiner sub-fleets over the planning horizon

question are vessels that either have reached their maximum operational lifetime of 80 years or are 77 years old. The 77-year-old vessels are replaced in order to prevent incurring the regeneration cost that arises when the vessels reach the age of 78 and have only two years left until they need to be replaced due to reaching their operational lifetime. These renewal decisions are definitely economically motivated as emissions remain unchanged. The fact that increased shipyard capacity makes the model invest in new diesel-mechanic conventional coastal vessels when existing vessels need to be replaced rather than low- and zero-emission propulsion, emphasizes that opting for zero-emission vessels is not economically viable given the current investment and operational costs.

7.4 Managerial Insights

In this section, we present our key findings from the conducted computational study. Additionally, we provide an explanation of the limitations inherent in the study and discuss the specific dependencies that have influenced our obtained results.

7.4.1 Key Findings

From running the various test instances presented in Table 6.10 and assessing the changes in the renewal schedule for the Norwegian fishing fleet, we obtain managerial insight that might prove useful to decision-makers in relation to the renewal of the Norwegian fishing fleet. After analyzing the results presented in Section 7.2 and Section 7.3, we have identified several key findings.

(1) *Zero-emission propulsion is economically unfavourable*

From the base case and scenario 7 (MB-TB-ZB-CB-SH), it is apparent that zero-emission propulsion is economically unfavourable. From the base case, it is evident that investments in zero-emission propulsion are driven by the emission reduction requirements of 2030 and 2050, rather than economics. When the shipyard capacity is increased in scenario 7, this leads to investment in both new conventional diesel-mechanic and low-emission vessels, rather than zero-emission. Furthermore, from scenarios 1-3, we have observed that despite less favourable circumstances in terms of CO2 tax, fuel prices, and technological advancements, the Norwegian fishing fleet would in essence still be subject to the same investments and fleet renewal schedule as in the base case. This provides support for the assertion that in the base case, it is the emission reduction targets that are the key driver for replacement, not economic motivations.

Policy-makers hold control over the CO2 tax level, whereas the prices of fuels like MGO and zero-emission alternatives, as well as the costs of zero-emission propulsion technology systems, are primarily determined by market forces. However, authorities have the ability to influence the costs borne by fishermen either directly through subsidies or indirectly through research support and regulations. Policy-makers hold a crucial role in shaping the cost environment that fishermen operate within, while fishermen are likely to be more concerned with the costs associated with investment and operation. As of now, the current costs associated with investing in and operating zero-emission propulsion systems are economically disadvantageous compared to conventional and low-emission propulsion systems. Consequently, we conclude that a transition to zero-emission fisheries will likely require either subsidies related to investment and operation or an increase in costs associated with MGO and CO2 emissions.

(2) *Penalizing the use of conventional fuel incentivizes earlier renewal of the fleet*

In terms of total emissions from the combined fishing fleet, it is apparent from scenarios 4 and 5 that penalizing the use of conventional fuel in terms of increased MGO price and CO2 high-price trajectory, incentivizes earlier renewal of conventional propulsion. This results in a greater reduction in total emissions than reducing the costs associated with zero-emission propulsion. This is particularly because the replacement of fuel-intensive ocean-going vessels such as the bottom trawler is initiated at an earlier stage. However, this comes at the expense of the total costs over the planning horizon, which increase considerably due to increased fuel and CO2 taxation costs. As discussed for scenario 4 (MH-TH-ZB-CB-SB), it is worth noting that it is the high-price trajectory for CO2 tax that is the key driver to the earlier phasing out of vessels with significant emissions, despite relatively increased investment costs, rather than the increased MGO price.

In scenario 5 (MB-TB-ZL-CL-SB) we observe that the diesel-mechanic bottom trawlers are fully phased out by 2050, while in scenario 4 (MH-TH-ZB-CB-SB), the bottom trawler sub-fleet is fully zero-emission by 2038. This implies that the overall cost reduction associated with zero-emission vessels in scenario 5 is not equivalent to the fuel cost increase of conventional diesel-mechanic vessels in scenario 4. In other words, the cost savings achieved through adopting zero-emission propulsion in scenario 5 are not enough to offset the additional expenses incurred in scenario 4 from the increased MGO price and higher CO2 tax. This precisely exemplifies that penalizing conventional technology provides stronger incentives for early fleet renewal than cost reduction of zero-emission propulsion as the bottom trawlers are the most emission-intensive sub-fleet.

(3) *Immediate action must be taken to initiate the renewal of the ocean-going fishing fleet in order to achieve emission reduction targets in a cost-effective manner*

For all test instances, the renewal of the ocean-going fleet is initiated already in 2023 as opposed to the renewal of the coastal fleet which is initiated later. As described in Section 7.2.3, the reason for this is that the emission reduction achieved by renewing coastal vessels is relatively minor when compared to the associated costs. Despite the substantial increase in investment and operational expenses associated with the renewal of an individual ocean-going vessel, the incremental reduction in emissions is considerably higher. Consequently, it is more cost-effective, in terms of emission reduction per unit of currency (NOK) invested, to focus on renewing ocean-going vessels rather than coastal vessels.

the solution to scenario 7 (MB-TB-ZB-CB-SH) implies that the shipyard capacity increase did not result in the postponement of investments in the ocean-going fleet. Instead, the increase allowed for the introduction of low-emission vessels which results in a 3.4% decrease in the total costs, but a 5.2% increase in total emissions of the combined fishing fleet over the planning horizon. From this, we conclude that in order to make informed decisions, it is important for decision-makers to carefully assess the available capacity. The shipyard capacity plays a crucial role in determining the feasibility of different fleet renewal strategies and has direct implications for the choice between a gradual reduction in emissions through the adoption of low-emission propulsion systems or a direct transition to zero-emission propulsion.

7.4.2 Limitations and Dependencies

In conducting this computational study and analyzing the results, it is important to acknowledge the inherent dependence on the costs used throughout the study.

As specific cost data for propulsion systems in terms of investment, O&M, regeneration, and salvage values are limited, the costs and revenues for different sub-fleets and propulsion systems in this study are calculated using a combination of data from various sources, as explained in Chapter 6. Similarly, due to a scarcity of specific data, the fuel consumption and resulting emissions associated with different sub-fleets and propulsion systems are estimated through a bottom-up approach. Consequently, the use of estimated costs and emissions introduces a certain level of uncertainty that can impact the reliability of the results. Furthermore, the data used in this study is obtained from various sources, including industry reports, market data, and expert opinions. While efforts are made to ensure the accuracy and validity of these sources, it is important to acknowledge that some degree of uncertainty and variability may exist in the data.

However, despite these challenges, it is important to note that if the various costs reflect realistic conditions in terms of magnitude, the insights and conclusions drawn from the computational study can be considered highly plausible and directly applicable to the Norwegian fishing fleet in real-life scenarios. In other words, if the study accurately represents the cost dynamics of real-world scenarios, the results and analyses provide valuable and meaningful insights for decision-makers in relation to strategic fleet renewal within the Norwegian fishing fleet.

Chapter 8

Future Research and Concluding Remarks

8.1 Future Research

Through the work of this thesis, we have uncovered several interesting areas for further research. In our opinion, there are mainly two ways in which the work presented in this thesis may be extended. The first one is to a greater extent incorporate vessel operation considerations into the model and the second is to incorporate uncertainty in the model arising from availability of relevant technology and fuel, as well as costs, fuel prices and CO2 tax price-trajectory. This is discussed in Section 8.1.1 and Section 8.1.2, respectively.

8.1.1 Vessel Operation Considerations

Perhaps the most significant problem assumption we make is that a vessel with a low- or zero-emission propulsion system can be operated in the same way as its diesel-mechanic counterpart. However, as of today the range of a vessel with a low- or zero-emission propulsion system is shorter than that of a conventional disel-mechanic vessel. This is because zero-emission fuels like battery power, hydrogen, and ammonia have lower energy density than traditional MGO fuel. Moreover, the size and length restrictions in retrofitting fishing vessels make it challenging to increase vessel size and accommodate additional energy storage. Additionally, the availability of bunkering infrastructure and the time required for bunkering may influence operational planning.

It is important to note that the impact on the operational pattern when transitioning to a low- or zero-emission propulsion system will depend on the design and implementation of the propulsion system, vessel size, fishing practices, and other factors. Possible further development of the work presented in this thesis is, therefore, to include assessments on this aspect, and implement this in the FFRPEC model.

8.1.2 Uncertainty Incorporation

The availability of necessary technology for low and zero-emission propulsion systems remains uncertain. The development and implementation of technologies like hydrogen and ammonia fuel cells for different fishing vessel sub-fleets are still in progress, and widespread availability is not yet achieved. These emerging technologies require further research, testing, and refinement before they can be effectively integrated into practical applications within the fishing industry. Moreover, uncertainty exists regarding access to fuel supply of electricity, hydrogen, and ammonia. The establishment and expansion of the required infrastructure, including bunkering stations and potential production sites for hydrogen and ammonia, pose significant challenges. These endeavours demand substantial investments of time and resources due to the costly and time-consuming nature of infrastructure development. As a result, uncertainties arise regarding the timeline, coverage, and accessibility of the necessary infrastructure to support the adoption of low and zero-emission propulsion systems. Considering these uncertainties, there is an opportunity to further investigate and expand upon the work of this thesis. A comprehensive examination can be conducted to explore various scenarios related to access to technology and fuel, as well as the associated costs of infrastructure.

When there is ambiguity surrounding the development and demand for low- and zero-emission propulsion systems, the costs of relevant propulsion technology are subject to uncertainty. Consequently, this uncertainty extends to the prices of zero-emission fuels, as well as the prices of MGO and the trajectory of CO2 taxes. The unpredictable nature of these factors makes it challenging to forecast and determine their specific prices. To incorporate the uncertainty surrounding costs and prices into the model, an analysis of market trends and scenario-based assessments can be employed to evaluate the potential range of costs and prices for relevant propulsion technology and fuels.

The uncertainty related to the technological development of low- and zero-emission propulsion systems can be addressed either through a flexible or robust approach. In the flexible approach, the worst-case scenario entails that uncertainties in technological development might impede the achievement of emission reduction targets. Consequently, we argue that this uncertainty should be robustly addressed to ensure that fleet renewal strategies align with emission reduction requirements regardless of technological advancements and availability outcomes.

In general, including uncertainty in the FFRPEC, the model can provide more accurate decision-making guidance regarding fleet planning and investment in zero-emission technologies in line with the desired degree of robustness.

8.2 Concluding Remarks

The purpose of this thesis was to provide decision support for decision-makers regarding the transition of the Norwegian fishing fleet to low- and zero-emission propulsion. To achieve this purpose we have developed a mathematical model to solve the Fishing Fleet Renewal Problem with Emission Constraints. The model minimizes the discounted total costs related to the renewal and operation of the combined fishing fleet while meeting emission reduction targets for 2030 and 2050. The model provides a detailed renewal schedule for the replacement of the existing conventional diesel-mechanic fishing fleet. The renewal schedule specifies the timing of replacing a certain number of vessels with a specific propulsion system within a sub-fleet, as well as the propulsion system to be used as a replacement.

The computational study provided valuable managerial insights into the impact of uncertain parameters on the fleet renewal schedule and associated total costs and combined emissions of the Norwegian fishing fleet from 2023 to 2050. Uncertain parameters are fuel prices of MGO, battery power, hydrogen and ammonia, affecting the annual fuel costs of various vessels, in addition to the development in the CO2 tax imposed on the fisheries sector. Furthermore, the technological development of zero-emissions propulsion technology such as batteries and fuel cells is highly uncertain and affects the costs related to investment, O&M, regeneration as well as salvage value. Finally, the available shipyard capacity is also considered. Our objective is to utilize the insights to develop a fleet renewal strategy that satisfies emission reduction targets in an economically viable manner. As mentioned in Section 7.4.1, policy-makers have the possibility to influence the uncertain parameters mentioned, either directly through subsidies or indirectly through funding research on zero-emission technology or implementing regulations.

From our analysis, we highlight three key findings. We found that (1) the transition to zero-emission fisheries will likely require either incentives related to investment and operation or an increase in costs associated with MGO and CO2 emissions. Furthermore, we found that (2) in terms of reducing the overall emissions towards 2050, penalizing the use of conventional fuel in terms of increased MGO price and a high-price trajectory is more effective than reducing the costs associated with zero-emission propulsion. Finally, we concluded that (3) to achieve the emission reduction targets of 2030 and 2050 in a cost-effective manner, it is necessary to initiate the fleet renewal of the ocean-going fleet immediately.

Ultimately, the question arises as to who will bear the financial burden of transitioning the Norwegian fishing fleet to zero emissions. If policy-makers increase the price of MGO and opt for a high-price trajectory for the CO2 tax, the fishermen will bear the costs of the fleet transition. If the operational costs become excessively high and the investment costs for achieving zero emissions are also prohibitively expensive, it may severely impact the overall value creation from the fishing fleet. On the other hand, our analysis indicates that if policy-makers were to solely support research projects to facilitate technological development, while also providing subsidies for the utilization of zero-emission fuels such as battery power, hydrogen, and ammonia, this could inadvertently result in increased overall emissions over the planning horizon. In light of these considerations, a potential solution could be to combine both approaches, finding a balance between increasing the costs of conventional propulsion and financially supporting low- and zero-emission propulsion through subsidies and technological advancements. By strategically combining these two approaches, policy-makers may be able to effectively address the financial challenges of transitioning to zero emissions while promoting sustainable technological solutions and minimizing unintended consequences.

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Appendix A

Cost Calculations

This appendix presents the investment, O&M, regeneration and fuel costs for all sub-fleets and propulsion systems. Note that the investment and O&M costs apply for vessels acquired in the first time period and that the regeneration costs apply for vessels acquired in the first time period and are incurred X years from the first time period, depending on the propulsion system component. The fuel costs are the same for all time periods.

Table A.1: Investment costs of a vessel acquired in the first time period for the considered sub-fleets and propulsion systems

	Propulsion system				
Sub-fleet	**Diesel-mechanic**	**Diesel-electric**	**Electric-mechanic hybrid**	**Electric-hydrogen hybrid**	**Electric-ammonia hybrid**
Ocean-going vessels					
Bottom trawler	51,020,408	63,775,510	74,776,311	133,396,030	199,749,877
Conventional ocean-going vessel	15,306,122	19,132,653	22,430,393	35,217,030	59,813,879
Purse seiner	20,408,163	25,510,204	29,915,525	45,627,070	79,769,365
Pelagic trawler	51,020,408	63,775,510	74,776,311	136,216,330	199,807,299
Coastal vessels					
Conventional coastal vessel	3,000,000	3,450,000	4,397,016	6,692,200	11,722,802
Coastal seiner	3,265,306	3,755,101	4,788,259	7,287,970	12,773,333

Table A.1 presents the investment costs of a vessel acquired in the first time period of the planning horizon. Note that although the cost associated with an electric-ammonia hybrid propulsion system is presented in the table, it is not possible to acquire a vessel with this propulsion system before 2035 due to the lagging technological maturity. The investment cost for vessels with propulsion systems with components such as batteries and fuel cells decreases throughout the planning horizon due to economies of scale.

Table A.2: Annual O&M costs of a vessel acquired in the first time period for the considered sub-fleets and propulsion systems

	Propulsion system				
Sub-fleet	**Diesel-mechanic**	**Diesel-electric**	**Electric-mechanic hybrid**	**Electric-hydrogen hybrid**	**Electric-ammonia hybrid**
Ocean-going vessels					
Bottom trawler	1,530,612	1,913,265	2,243,289	3,332,556	2,792,134
Conventional ocean-going vessel	459,183	573,979	672,911	951,654	837,516
Purse seiner	612,244	765,306	897,465	1,255,898	1,117,100
Pelagic trawler	1,530,612	1,913,265	2,243,289	3,360,759	2,792,134
Coastal vessels					
Conventional coastal vessel	90,000	103,500	131,910	184,446	164,186
Coastal seiner	97,959	112,653	143,647	200,891	178,828

Table A.2 presents the annual O&M costs of a vessel acquired in the first time period of the planning horizon. Since the O&M costs are calculated as a percentage share of the investment cost, acquiring the relevant vessel later in the planning horizon will result in a decrease in O&M cost.

Table A.3: Regeneration costs of a vessel acquired in the first time period for the considered sub-fleets and propulsion systems

	Propulsion system				
Sub-fleet	**Diesel-mechanic**	**Diesel-electric**	**Electric-mechanic hybrid**	**Electric-hydrogen hybrid**	**Electric-ammonia hybrid**
Ocean-going vessels					
Bottom trawler	9,183,673	11,479,591	6,246,734+ 29,979,435	29,979,435+ 19,074,823	29,979,435+ 48,947,317
Conventional ocean-going vessel	2,755,101	3,443,877	1,873,469 + 8,994,250	8,994,250+ 5,720,764	8,994,250+ 14,679,877
Purse seiner	3,673,469	4,591,836	2,499,795+ 11,990,934	11,990,934+ 7,633,294	11,990,934+ 19,587,562
Pelagic trawler	9,183,673	11,479,591	6,246,734+ 29,979,435	29,979,435+ 19,074,823	29,979,435+ 48,947,317
Coastal vessels					
Conventional coastal vessel	540,000	621,000	367,346+ 1,762,755	1,762,755+ 1,121,718	1,762,755+ 2,878,407
Coastal seiner	587,755	675,918	400,408+ 1,918,045	1,918,045+ 1,222,673	1,918,045+ 3,137,464

Table A.3 presents the regeneration costs of a vessel acquired in the first time period of the planning horizon. This cost is not annual but occurs at fixed intervals due to the replacement of propulsion system components. The regeneration cost is broken down per propulsion system component as they can occur at different times. The regeneration cost that occurs when the vessel reaches a certain age is calculated as a percentage share of the investment cost in the relevant propulsion system component. Due to economies of scale, the regeneration cost of vessels with propulsion systems that have components such as batteries and fuel cells decreases over the planning horizon.

Table A.4: Annual fuel costs of a vessel for the considered sub-fleets and propulsion system

	Propulsion system				
Sub-fleet	**Diesel-mechanic**	**Diesel-electric**	**Electric-mechanic hybrid**	**Electric-hydrogen hybrid**	**Electric-ammonia hybrid**
Ocean-going vessels					
Bottom trawler	21,997,225	20,897,364	52,458,632	78,084,114	58,635,473
Conventional ocean-going vessel	10,336,746	9,819,909	24,650,908	36,692,613	27,553,476
Purse seiner	4,191,418	3,981,876	9,995,626	14,878,382	11,172,580
Pelagic trawler	9,032,902	8,581,256	21,541,520	32,064,322	24,077,967
Coastal vessels					
Conventional coastal vessel	60,637	60,637	112,476	162,339	124,495
Coastal seiner	171,939	171,939	246,049	340,308	268,770

Table A.4 presents the annual fuel cost of a vessel. The energy consumption of a vessel is covered by either MGO, electricity, hydrogen and/or ammonia depending on the propulsion system installed.

Appendix B

Salvage Age Distribution

This appendix presents the aggregated age curves for when vessels of selected sub-fleets are salvaged over the planning horizon.

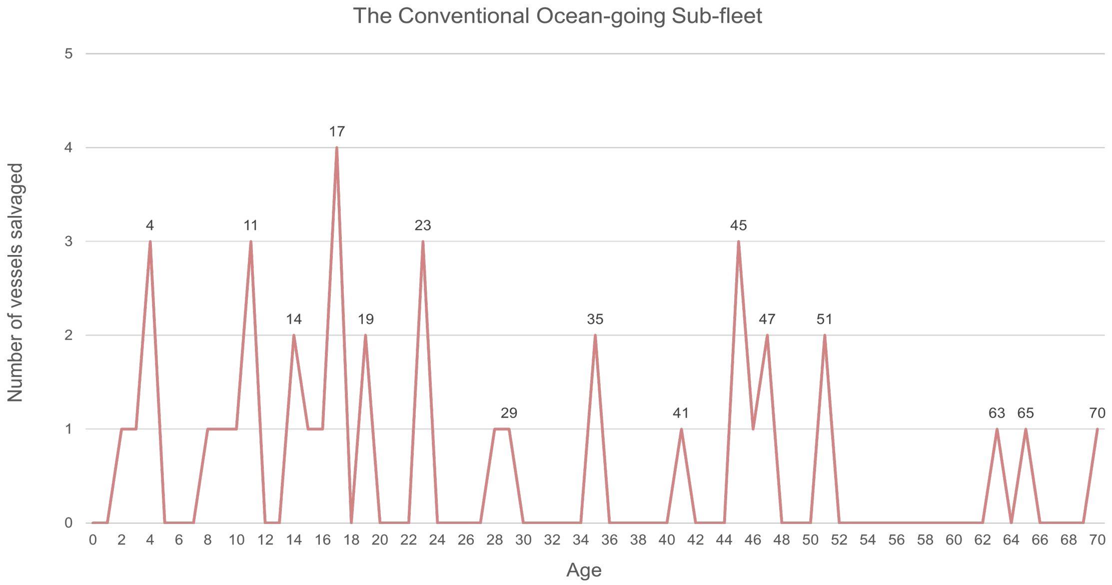

Figure B.1: Number of vessels salvaged at a specific age over the planning horizon for the conventional ocean-going sub-fleet

Figure B.1 shows the number of conventional ocean-going vessels salvaged at a specific age, aggregated over the planning horizon.

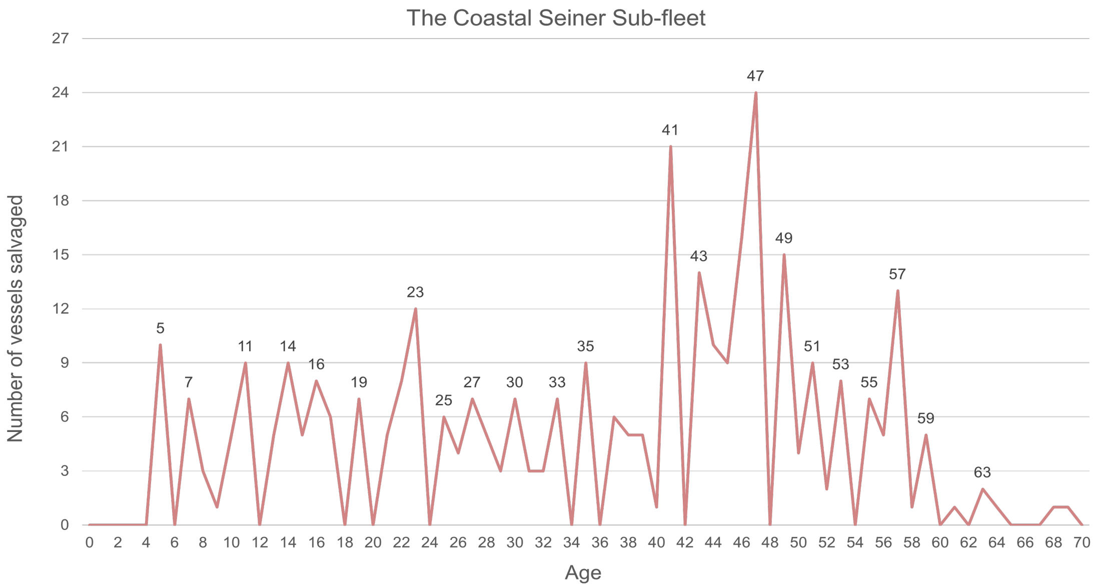

Figure B.2: Number of vessels salvaged at a specific age over the planning horizon for the coastal seiner sub-fleet

Figure B.2 shows the number of coastal seiners salvaged at a specific age, aggregated over the planning horizon.

Appendix C

Scenarios

This appendix presents the complete fleet renewal schedules for the various scenarios in the computational study. The graphs show the development in the number of vessels with a particular propulsion system for every sub-fleet throughout the planning horizon. The secondary y-axis denotes the share of the combined fishing fleet represented by the number of vessels. The propulsion systems are illustrated by coloured lines. The blue line represents the conventional diesel-mechanic propulsion system, while the green and purple line represents the diesel-electric and electric-mechanic hybrid propulsion systems, respectively. Finally, the orange and red line represents the zero-emission propulsion systems, i.e. the electric-hydrogen and electric-ammonia hybrid propulsion systems. Initially, all sub-fleets solely comprise vessels with a diesel-mechanic propulsion system.

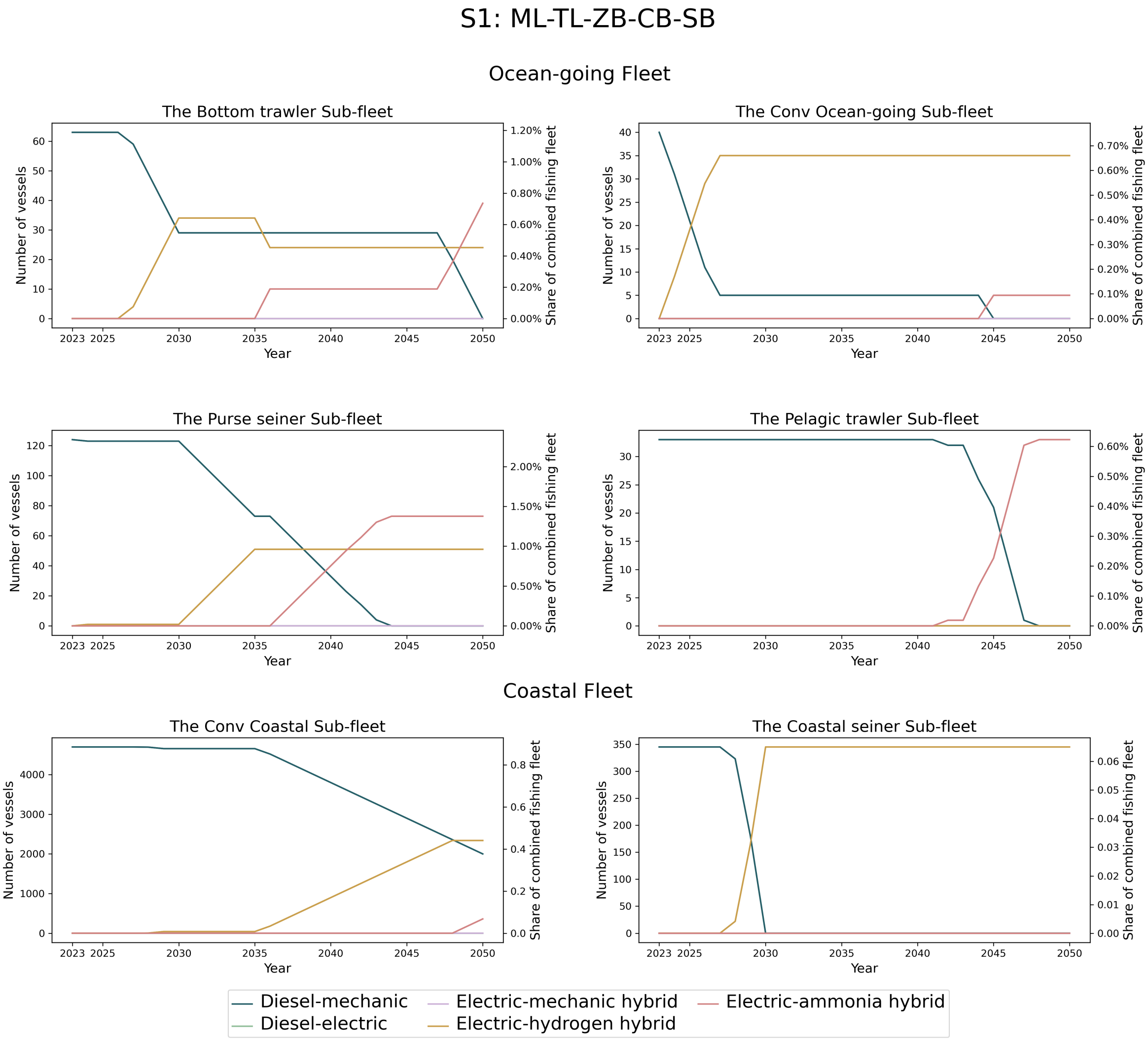

Figure C.1: Scenario 1: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the various sub-fleets over the planning horizon

Figure C.1 illustrates the fleet renewal schedule of the various sub-fleets of the Norwegian fishing fleet over the planning horizon for scenario 1.

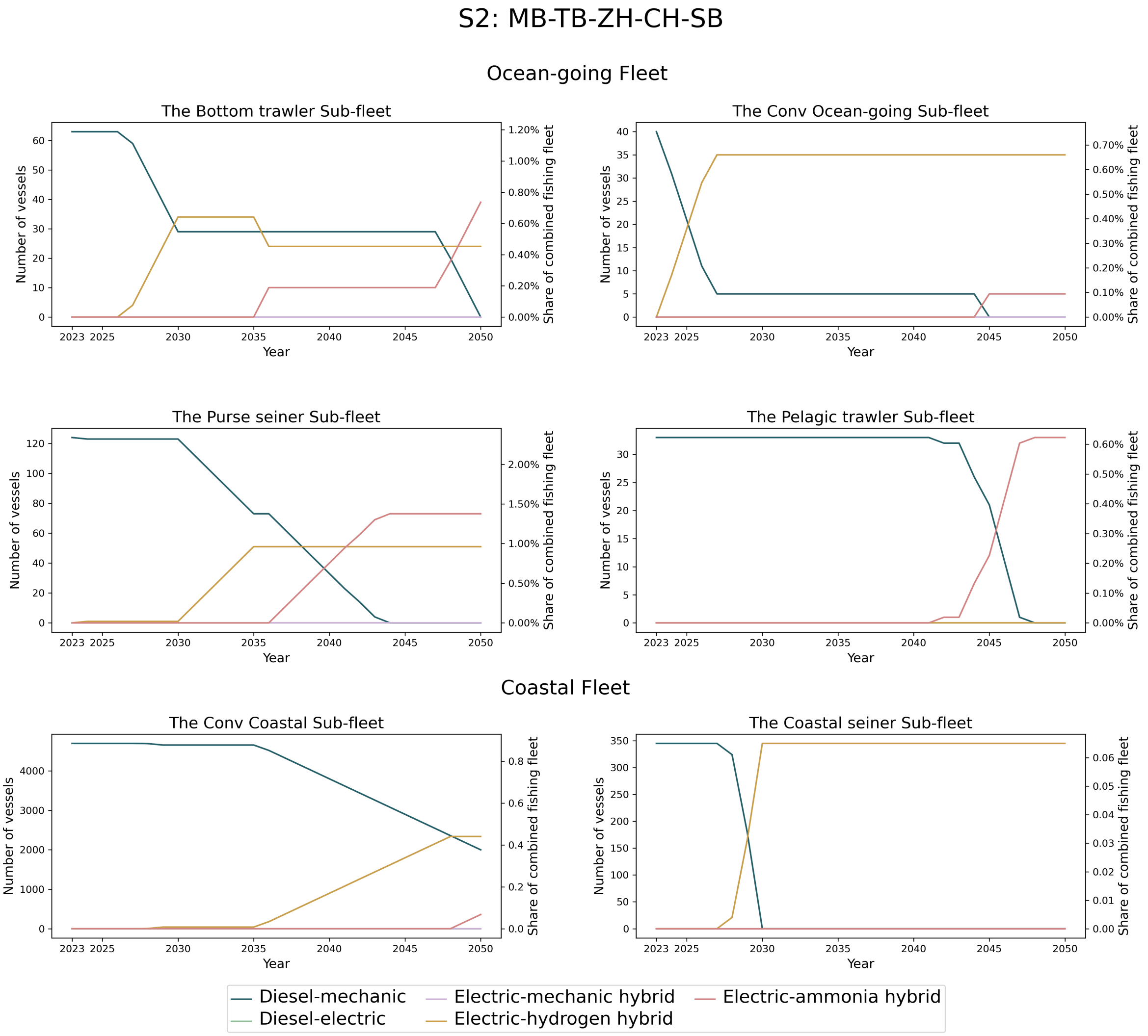

Figure C.2: Scenario 2: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the various sub-fleets over the planning horizon

Figure C.2 illustrates the fleet renewal schedule of the various sub-fleets of the Norwegian fishing fleet over the planning horizon for scenario 2.

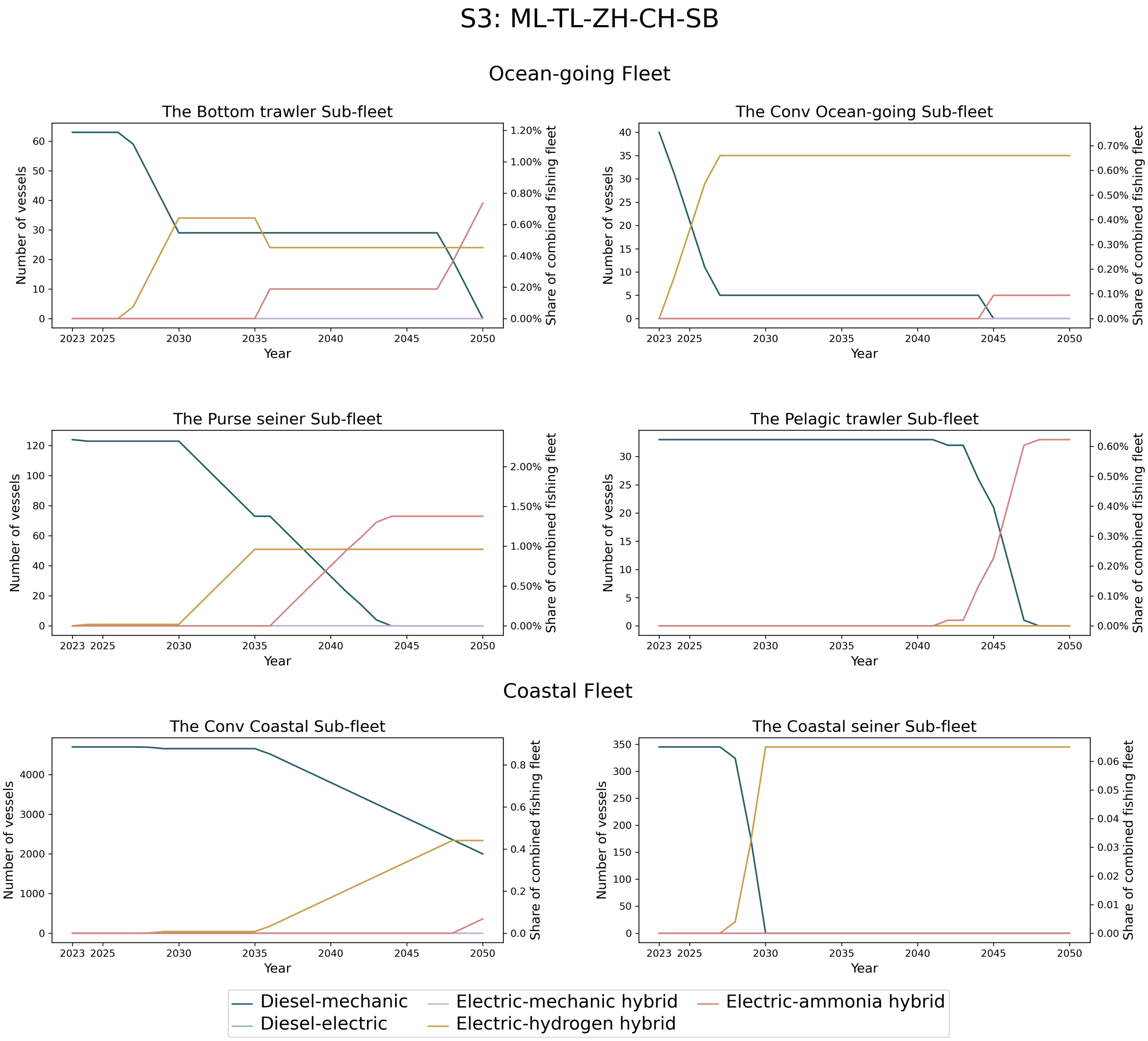

Figure C.3: Scenario 3: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the various sub-fleets over the planning horizon

Figure C.3 illustrates the fleet renewal schedule of the various sub-fleets of the Norwegian fishing fleet over the planning horizon for scenario 3.

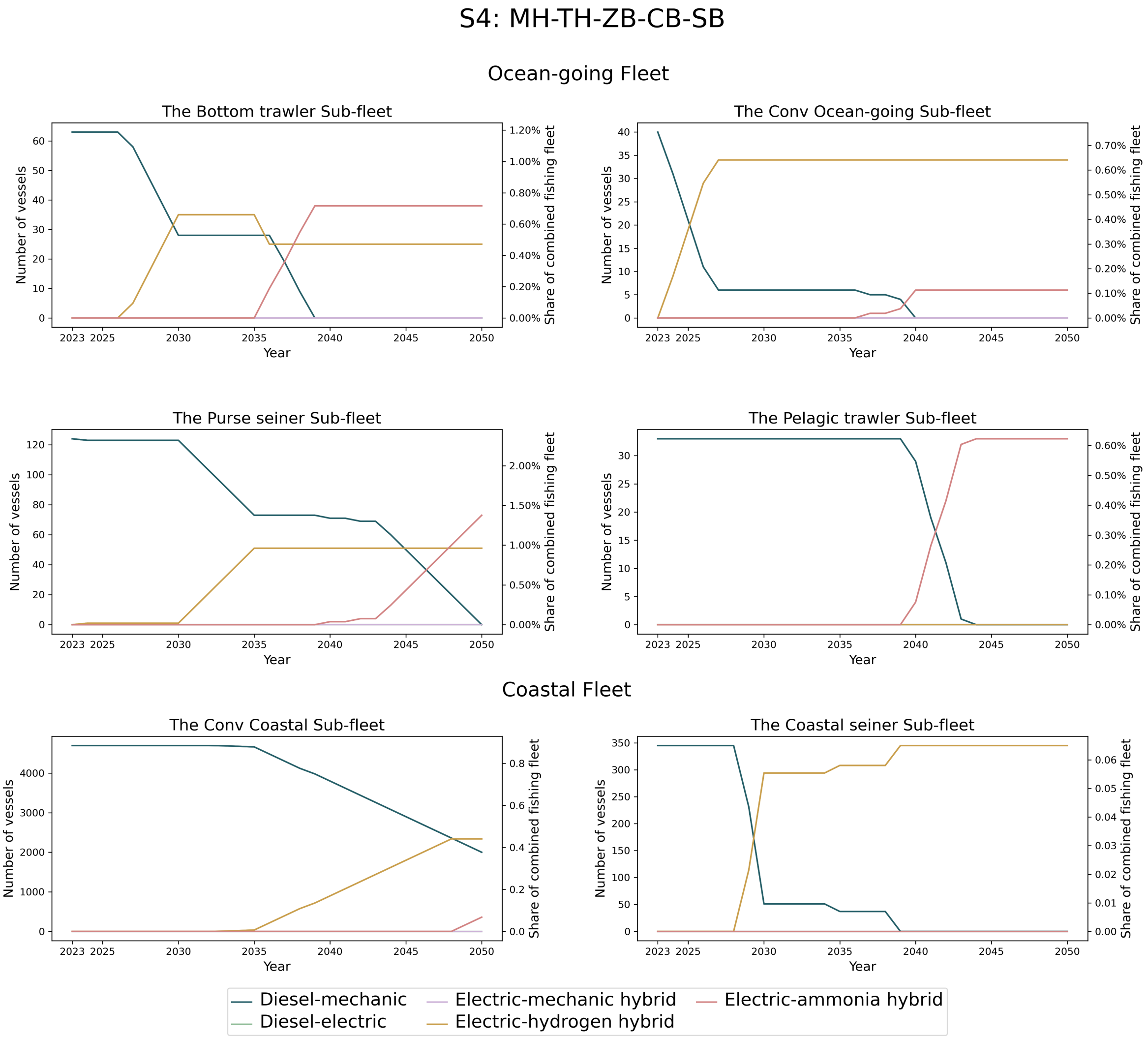

Figure C.4: Scenario 4: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the various sub-fleets over the planning horizon

Figure C.4 illustrates the fleet renewal schedule of the various sub-fleets of the Norwegian fishing fleet over the planning horizon for scenario 4.

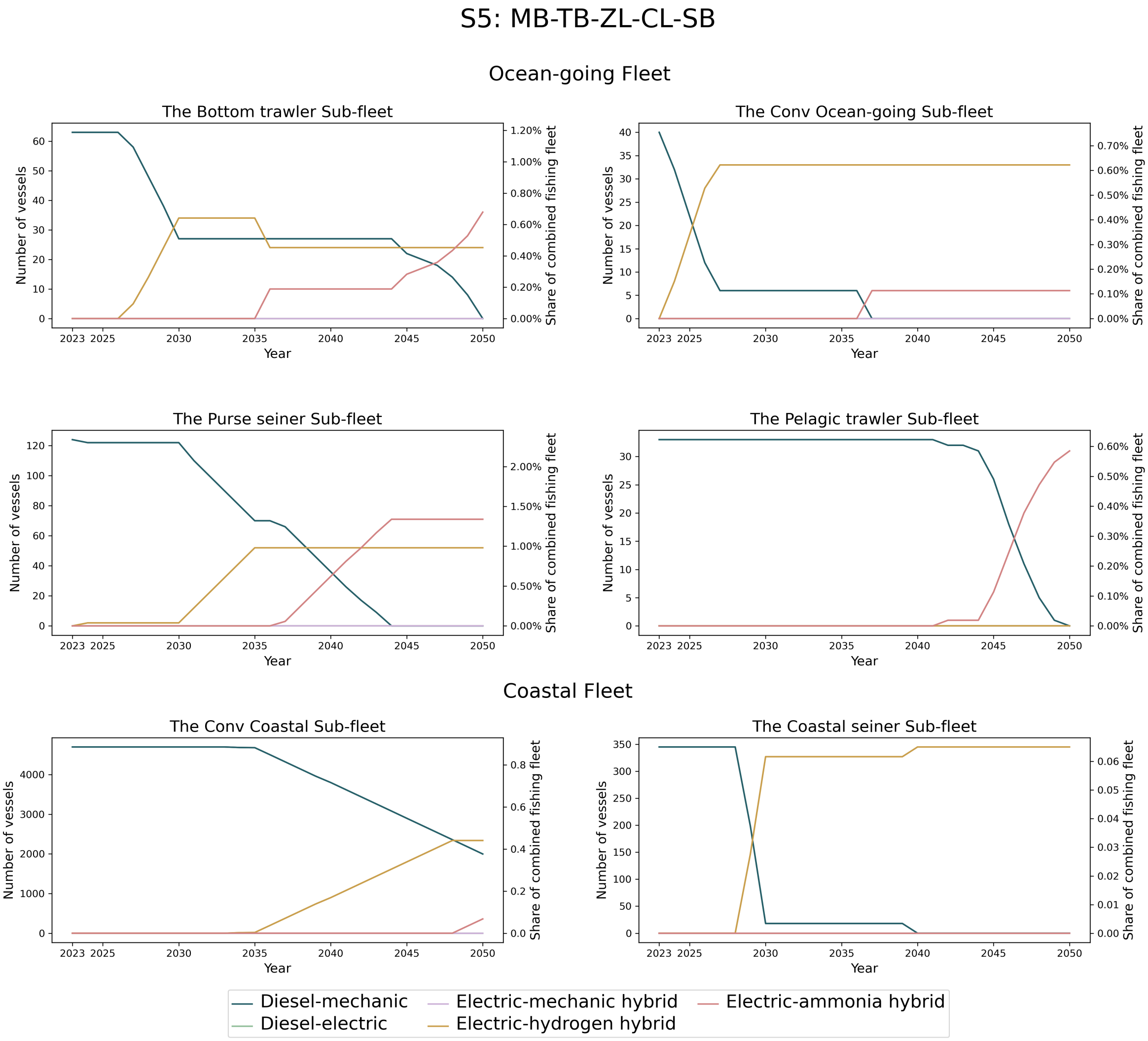

Figure C.5: Scenario 5: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the various sub-fleets over the planning horizon

Figure C.5 illustrates the fleet renewal schedule of the various sub-fleets of the Norwegian fishing fleet over the planning horizon for scenario 5.

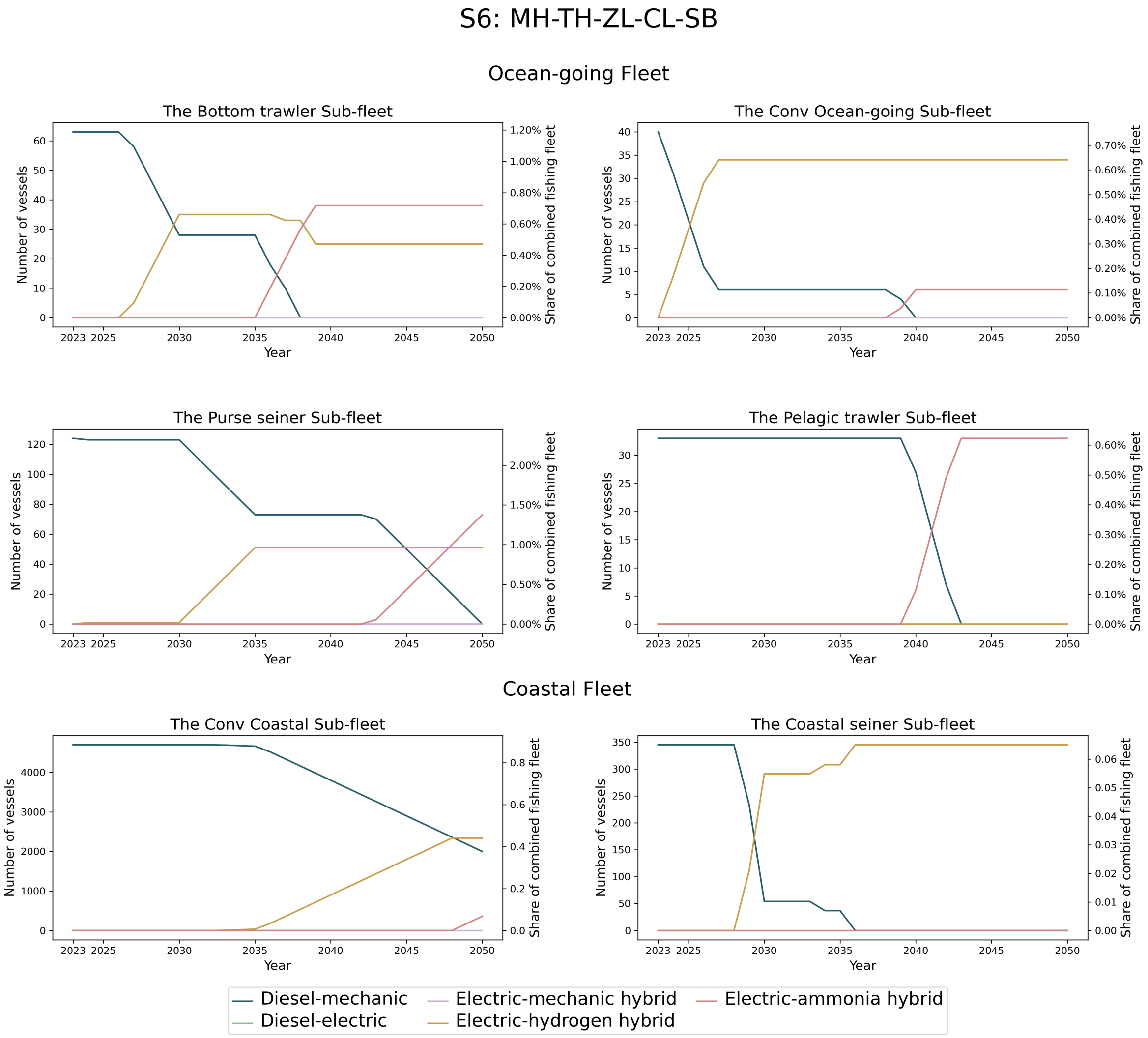

Figure C.6: Scenario 6: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the various sub-fleets over the planning horizon

Figure C.6 illustrates the fleet renewal schedule of the various sub-fleets of the Norwegian fishing fleet over the planning horizon for scenario 6.

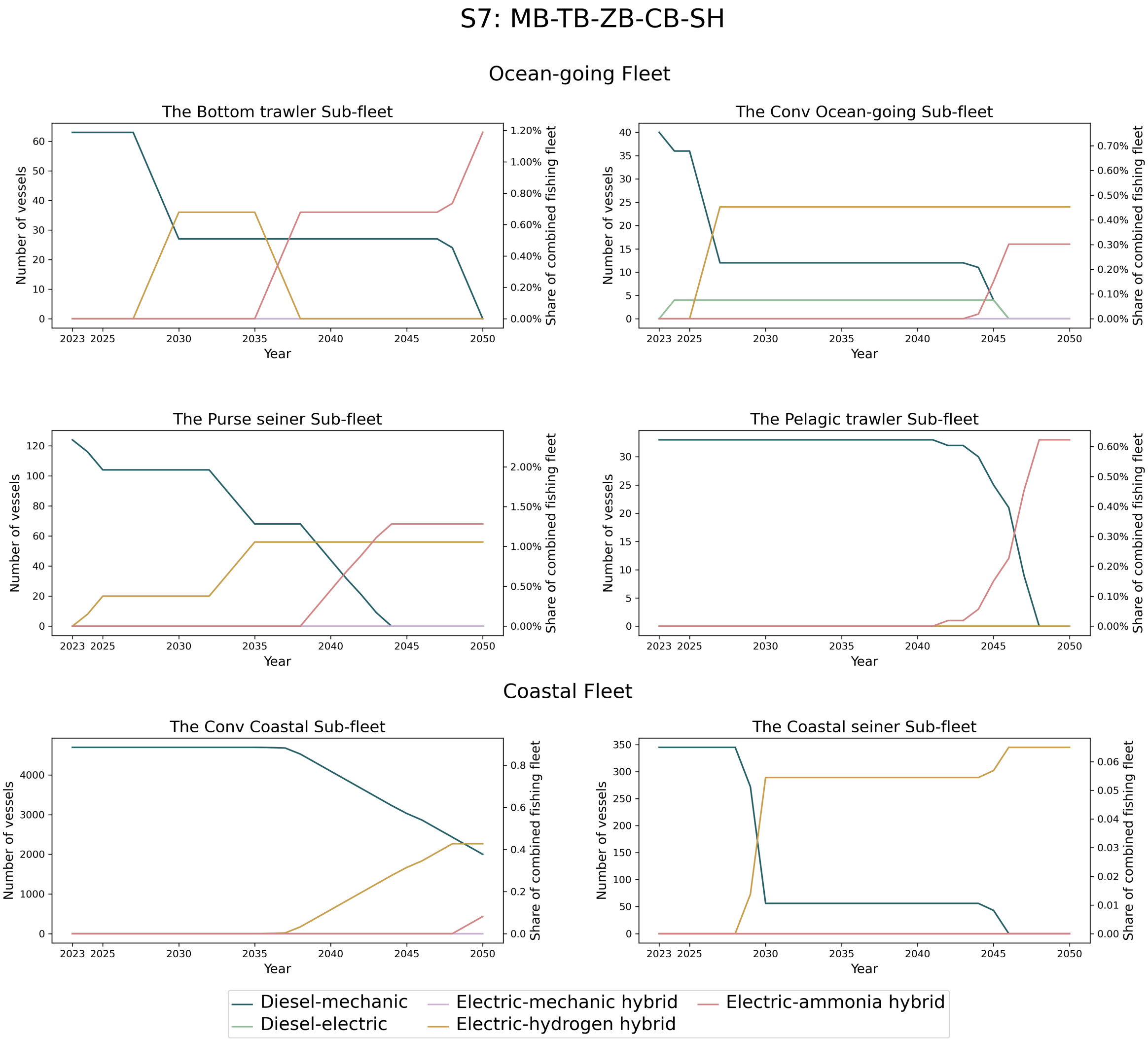

Figure C.7: Scenario 7: Number of vessels and share of the combined fishing fleet with a specific propulsion system for the various sub-fleets over the planning horizon

Figure C.7 illustrates the fleet renewal schedule of the various sub-fleets of the Norwegian fishing fleet over the planning horizon for scenario 7.

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