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Decarbonising Swedish maritime transport: Scenario analyses of climate policy instruments

Lina Trosvik [a,b,*], Selma Brynolf [c]

[a] Swedish National Road and Transport Research Institute (VTI), Gothenburg, Sweden
[b] Department of Architecture and Civil Engineering, Chalmers University of Technology, Gothenburg, Sweden
[c] Department at Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg, Sweden

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ABSTRACT

To analyse the future transition towards fossil-free fuels in the Swedish maritime transport sector, this study develops a scenario modelling tool to assess implications of policy instruments, such as the European Union Emissions Trading System and the FuelEU Maritime regulation. Using data for individual ships and their operational patterns, the model estimates the lowest-cost fuel option for shipowners in different scenarios and calculates the resulting annual fuel consumption and greenhouse gas emissions. Scenario analyses indicate that policy instruments have the potential to affect shipowners' investment choices, but that relatively strong price signals are required for significant effects to arise. Battery-electric propulsion is most common for passenger ferries, ropax ships, and small passenger cruises, while fishing vessels and service ships typically choose conventional fuels across all scenarios. Choices are found to vary between ship segments and scenarios, emphasising the need to consider ship-specific data when analysing effects of policy instruments.

1. Introduction

Maritime transport has a vital role in global trade, and it is projected to continue transporting the majority of long-distance goods the coming decades (ITF, 2019). Although maritime transport generally has low greenhouse gas (GHG) emissions per transport kilometre compared to most other transportation modes (Fraunhofer ISI & CE Delft, 2020), it is estimated to account for about three percent of global GHG emissions annually (IMO, 2020), and about three to four percent of total carbon dioxide (CO_2) emissions in the European Union (EU) (EC, 2021a). Demand for maritime freight transport is projected to increase by about three percent annually through 2050 due to global economic growth, increased international trade activity, and population growth (ITF, 2019), and the International Maritime Organization (IMO) (2020) projects that CO_2 emissions may increase by up to 50 % by 2050 compared to 2018 levels.

Maritime transport can be referred to as a "hard-to-abate" sector due to its high dependence on fossil fuels, limited potential for direct electrification, lack of decarbonisation alternatives, and the forecasted increase in freight demand. Furthermore, ships have a relatively long lifetime of about 20–35 years (Hoffmann, 2020), implying that investments in newbuilt ships made today will have an impact on the possibilities of achieving future climate targets since ships will stay long in the ship fleet. Possible solutions to reduce GHG emissions include both technical and operational measures, such as retrofitting energy-efficient engines, implementing waste

* Corresponding author at: Swedish National Road and Transport Research Institute (VTI), Gothenburg, Sweden.
E-mail address: lina.trosvik@vti.se (L. Trosvik).

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heat recovery systems, improving hull design, reducing speed, and improving routing and scheduling (Bouman et al., 2017; Zhu et al., 2018), as well as changing to renewable fuels (Kanchiralla et al., 2022; Malmgren et al., 2021).

Shipowners' decisions about ship investments are complex and can be affected by numerous factors. The main barriers to transitions towards zero-carbon fuels include significant capital investment, long payback periods, lack of global bunkering infrastructure, high fuel prices, and the additional demand for onboard storage space (DNV, 2022). Furthermore, the ship market is often subject to a volatile environment (Kou & Luo, 2018; Zhang & Yin, 2021) in terms of trade patterns, freight rates, and technological changes (Zhang & Yin, 2021). Information and communication gaps, uncertainty, and imperfect information further increase the complexity and

Table 1
Overview of policy instruments affecting GHG emissions from the Swedish maritime transport sector, sorted by the implementation year.

Level	Name	Year	Emissions addressed*	Short description	Source
IMO	Energy efficiency design index (EEDI)	2013	TTW CO_2	An index applicable for ships above 400 gross tonnage (GT) which is related to the technical design of a ship. It provides a newbuilding standard to ensure a certain efficiency level of ship designs.	IMO (2011)
IMO	Ship Energy Efficiency Management Plan (SEEMP)	2013	Energy efficiency	A tool to assist shipowners in managing the energy efficiency of ships. It consists of three parts: I) Ship management plan to improve energy efficiency (ships above 400 GT), II) Ship fuel oil consumption data collection plan (ships above 5000 GT), and III) Ship operational carbon intensity plan (ships subject to CII, see below).	IMO (2011; 2022)
EU	EU Maritime monitoring, reporting and verification (MRV) Regulation	2018	2018–2024: TTW CO_2 2024-onwards: TTW GHG	Ships of 5000 GT and above, calling EEA ports, are required to monitor and report fuel consumption, CO_2 emissions and transport work per voyage on an annual basis.	EC (2015; 2021c)
IMO	IMO Data Collection System (DCS)	2019		Ships of 5000 GT and above are required to report consumption data for each type of fuel oil they use. The DCS data is the basis for the CII rating and the SEEMP part III.	IMO (2016)
IMO	Carbon Intensity Indicator (CII)	2023	TTW CO_2	The CII applies to all cargo, ropax and cruise ships above 5000 GT. It measures how efficiently a ship transports goods or passengers. The ship is given an annual rating from A to E based on reported IMO DCS data, and too low ratings require shipowners to implement a plan of corrective actions (in SEEMP part III).	IMO (2022)
IMO	Energy efficiency existing ship index (EEXI)	2023	TTW CO_2	An index applicable for ships above 400 GT, which extends the EEDI concept to the existing fleet. The required EEXI standard is determined by the ship type, the ship's capacity and principle of propulsion and describes the CO_2 emissions per cargo ton and mile.	IMO (2021)
EU	EU Emissions Trading System (ETS)	2024	2024–2026: TTW CO_2 2026-: TTW GHG	The current design of the EU ETS is reformed to include emissions from maritime transport. The extension applies to all ships of 5000 GT and above entering EU ports and covers all emissions that occur between two EU ports and half of the emissions from voyages starting or ending outside of the EU. The emissions in scope for surrendering EU allowances (EUA) will be gradually phased in, starting with 40 % of emissions in 2024, 70 % in 2025, and 100 % from 2026 and onwards.	EC (2021c)
EU	FuelEU Maritime Regulation	2025	WTW GHG	The FuelEU Maritime regulation aims to increase the demand and deployment of renewable alternative transport fuels and zero-emission technologies by gradually increasing maximum limits on the yearly GHG intensity of the energy used by a ship. The GHG intensity requirements are set as a percentage reduction relative to a 2020 reference value of 91.16 gCO_2e/MJ. The percentage reduction requirement increases gradually every five years to 2050; 2 % by 2025, 6 % by 2030, 14.5 % by 2035, 31 % by 2040, 62 % by 2045, and 80 % by 2050.	EC (2022; 2023a)
EU	Alternative Fuels Infrastructure Regulation (AFIR)	2025		The regulation aims to set targets for the expansion of infrastructure for alternative fuels. It is proposed that at least 90 % of container and passenger ships above 5000 GT must have access to shore power supply in ports in the main ports by 2030, and that there must be access to liquified natural gas (LNG) bunkering by 2025 at the latest.	EC (2021d; 2023b)
EU	Energy Taxation Directive (ETD)	Not decided		A revision of the ETD is proposed to align the taxation of energy products with EU energy and climate policies. The ETD contains minimum levels of taxation based on the energy content and environmental performance of the fuel. The minimum levels that are proposed for energy products are proposed to be introduced on a lower level in 2023 and to be gradually increased over a ten-year period until 2033.	EC (2021e; 2022)

* TTW: Tank-to-wake, WTW: Well-to-wake.

investment barriers (Malmgren et al., 2023). In addition, ships are highly heterogenous with different operational profiles, power needs, sailing distances, and have different levels of fixed and varying routes, which affect which abatement options that are technologically mature and suitable for different ship segments (DNV, 2022; Mäkitie et al., 2022). For example, the deep-sea segment requires fuels that are globally available, whereas the available options for the short-sea segment are more diverse than for the deep-sea segment (DNV, 2022). Other factors that may affect shipowners' investment decisions include expectations about future trade patterns and demand for maritime transport, prices of new (and second-hand) ships, fuel prices, operating costs, the service capacity (cargo space or passenger seats), and policy instruments (DNV, 2022).

Maritime transport has historically been exempted from both national and international climate policy instruments. However, IMO adopted a GHG strategy in 2018, which was revised in 2023 to include an ambition to reach net zero GHG emissions from international shipping by (or around) 2050 (IMO, 2023a). In the EU, the European Climate Law includes a legally binding climate neutrality target of net zero GHG emissions by 2050 and a target of at least 55 % net GHG emission reduction by 2030 compared to 1990 (EC, 2021b). In addition, the European Commission (EC) proposed a policy package in the European Green Deal in 2019 (EC, 2022), where emissions within the maritime transport sector are targeted in the Fit for 55 package. The package includes four main parts affecting the maritime transport sector: 1) the inclusion of shipping in the EU Emission Trading System (ETS), 2) the revised energy taxation directive (ETD), 3) the FuelEU Maritime regulation, and 4) the revised Alternative Fuels Infrastructure regulation (AFIR). All parts, except the revised ETD, have been decided to be implemented. Several countries have also adopted national targets for GHG emission reductions within the transport sector, which affect emissions from maritime transport. Sweden has the target to reduce GHG emissions from domestic transport (excluding aviation) by 70 % by 2030, compared to 2010 levels, and to reach net zero GHG emissions by 2045 (SOU 2016:47). Due to the global character of maritime transport, the Swedish sector is also affected by targets and policy instruments at a global level and in the EU.

The purpose of this study is to develop a scenario modelling tool that considers individual ships and their operational patterns and which can be used to analyse the future transition towards fossil-free fuels in the Swedish maritime transport sector. The developed model is used to assess implications of climate policy instruments on the energy transition of the Swedish maritime transport sector until 2045. The study focuses on the Fit for 55 policy package but also includes an analysis of a national subsidy of charging infrastructure. The model can estimate which investment options shipowners are most likely to choose in different scenarios, based on the assumption that they will choose the lowest-cost option. The estimations provide scenarios of the fuel consumption and GHG emissions from Swedish maritime transport over the time period 2020–2045 for different ship segments.

Although the literature assessing impacts of policy instruments on maritime transport is growing (Smith et al., 2014; Wang et al., 2015; Smith et al., 2016; Zhu et al., 2018; Gu et al., 2019; Köhler, 2020; Solakivi & Lauri Ojala, 2022; Köhler et al., 2022; Jivén et al., 2022; Rivedal et al., 2022; Vierth et al., 2024), there are, to the authors' knowledge, no studies that model each individual ship in a fleet while accounting for its unique operational pattern, considering the costs of various alternative fuels and propulsion systems, and assessing the effects of policies at an aggregated level (the Swedish shipping fleet). The cost and size of the propulsion systems have, for example, been shown to be especially important for the deployment of battery-electric propulsion (Rivedal et al., 2022), which makes it relevant to include in analyses of shipowners' investment decisions. By considering individual ships and their operational patterns for all ships in and around Sweden and a relatively long modelling time period, this study contributes to the literature by providing a detailed analysis of the effects of policy instruments on shipowners' future deployment of renewable fuels.

2. Regulatory context

The Swedish maritime transport sector accounts for about 7.7 million tonnes of CO_2-equivalent (CO_2e) emissions (in 2022) and the emissions have increased by about 24 % in the last ten years (i.e., compared to 2012 levels). CO_2e emissions from domestic maritime transport have stayed relatively constant around 0.7 million tonnes, while CO_2e emissions from Swedish international maritime transport have continued to increase (Swedish Environmental Protection Agency, 2024a; 2024b).

The majority of Swedish maritime transport travels internationally. For example, 87 % of all cargo handling in Swedish ports in 2022 involved international traffic (Transport Analysis, 2023). It is also at the international level that Swedish GHG emissions from maritime transport are mainly regulated, and there are few nationally implemented policy instruments aimed to reduce their GHG emissions. Due to the international character of the maritime transport sector, it is difficult to limit the analysis to the national level. In the international regulatory context, Swedish maritime transport is affected by policy instruments both at the EU level and at the global level, where the IMO is responsible for regulating global commercial shipping.

Table 1 summarises implemented and proposed policy instruments at the EU and global level affecting Swedish maritime transport, sorted by the year they came into force or are planned to come into force.

3. Literature review

There is a growing literature assessing impacts of climate policy instruments on maritime transport, especially focusing on implications of an ETS implementation (Zhu et al., 2018; Gu et al., 2019; Christodoulo et al., 2021; Flodén et al., 2024; Christodoulo & Cullinane, 2024; Sun et al., 2024; Mao et al., 2024; Vierth et al., 2024). For example, Zhu et al. (2018) investigate the potential impact of a maritime ETS on containership operators' fleet composition strategies and CO_2 emissions and find that it can motivate operators to utilise new technologies, deploy more energy-efficient ships, and even sell or demolish less energy-efficient ships (Zhu et al., 2018). Gu et al. (2019) develop an optimisation model to study the impact of an ETS on fleet composition and deployment. They conclude that, in the short term, the ETS does not lead to CO_2 emission reductions in most scenarios, but in the case of low bunker prices and high allowance costs, a more significant reduction can be expected. Wang et al. (2015) model the economic impacts of an ETS on international shipping, focusing on the container and dry bulk shipping sectors. They find that an ETS will decrease ship speed and fuel consumption for both the container and bulk sectors, but that the different sectors likely will be affected to different degrees. Solakivi et al. (2022) develop a cost projection for different Fit for 55 policies by estimating fuel production costs and their development for 2020–2050 and evaluating alternative fuels for a case ship (a roro vessel). They find that blending biofuels will be the main short-term solution and that e-fuels will be cost-competitive first beyond 2050. Flodén et al. (2024) provide an assessment of the EU ETS on the maritime transport sector's potential GHG emission reductions for different ship types, while their main focus is a qualitative assessment. They suggest that a shift to bio-methanol could occur with EU allowance (EUA) prices of 90–100 EUR/tonne CO_2 and that several low-cost abatement measures, including adjusted routing and logistics systems, could become financially sound. For large-scale fuel shifts they suggest that EUA prices of 150–200 EUR/tonne CO_2 are needed. As the FuelEU Maritime regulation is more recently implemented, there are fewer studies assessing its effects, although Christodoulou and Cullinane (2022) investigate potential fuel pathways for the compliance of FuelEU Maritime regulation using EU maritime monitoring, reporting and verification (MRV) data.

There are also literature considering the Swedish context and assessing implications on marine fuel choices of climate policy measures. Jivén et al. (2022) review cost studies for decarbonisation and find that the proposed package can be expected to increase fuel costs for ships by 80–90 % compared to current costs for fossil fuels. Vierth et al. (2024) use a static time perspective to model three Fit for 55 implementation scenarios and their implications for Swedish freight transport. They argue that a significant part of the CO_2 emissions is missed by only including ships with a minimum gross tonnage (GT) of 5000. Latapí et al. (2024) used the Nordic energy system model to investigate three policy packages and their impact on shipping fuel choices in Denmark, Norway, and Sweden. They study the ferry segments and find that electricity will be the dominant energy carrier in 2045. Salvucci et al. (2019) also use the Nordic energy system model but focus on the whole transport sector and modal shifts from higher carbon taxes. Harahap et al. (2023) develop a set of policy instrument scenarios, such as carbon price, energy tax, and blending mandate to investigate the potential for decarbonising Swedish shipping. They suggest that bio-methanol and hydrogen-based marine fuels could be cost-effective at a carbon price beyond 100 EUR/tonne CO_2 and 200 EUR/tonne CO_2, respectively.

There are also studies simulating global shipping's future development of CO_2 emissions in different ways. For example, the Glotram (Global Transport Model), which is a simulation model of the global shipping system, is used to examine shipowners' decisions of the management and operation of their fleets in response to developments in fuel prices and environmental regulation (Smith et al., 2014; Lloyd's register marine, 2014; Smith et al., 2016). The model uses a profit-maximising approach and simulates effects on the ship fleet and emissions from factors and interactions such as changing fuel prices and transport demand, as well as technical and logistic changes. The MATISSE-SHIP model uses agent-based modelling to simulate investment decisions for new ships and technology changes in the global shipping fleet by including costs and environmental aspects, shipowners' attitudes for new technologies, the need for bunker infrastructure, and operational changes (Köhler, 2020; Köhler et al., 2022). IMO (2020) projects the future CO_2 emissions from the global shipping fleet in various scenarios based on a model that considers factors such as transport work, energy efficiency, and regulatory developments for different ship types and sectors. Although these models take factors such as operating patterns and requirements for different ship segments into account, they have a global perspective and use average ships or groups of ships as input for the modelling. In contrast, this study models the specific energy use and costs for each individual ship in the Swedish model area considering their individual operational patterns and requirements. By modelling each specific ship in the fleet and aggregating results for the Swedish shipping fleet, considering a relatively long modelling time period, and several alternative fuel types and propulsion technologies, this study contributes to the literature by providing an analysis of the effects of policy instruments on individual ships' future deployment of renewable fuels.

4. Methods and data

4.1. Data description and preparation

The developed model in this study uses a dataset of ship movements in Sweden, delivered by the Swedish Meteorological and Hydrological Institute (SMHI) (Windmark, 2020). Using Automatic Identification System (AIS) data, the so-called "Shipair shipping model" was developed by the SMHI to improve statistics on domestic fuel usage and emissions from maritime transport (Windmark et al., 2017) in the Shipair model area (Fig. 1).[1]

The dataset contains information about ship routes for 4331 ships in 2019 in the Shipair model area. For each ship, the data includes routes until the accumulated distance exceeds 90 % of the ships' total travelled distance over the year, or a maximum of ten routes. Hence, the dataset misses some information about the ships' routes and travelled distance, but it can still provide useful information about ships' movements. The dataset consists of both dynamic data, such as position, speed, and operating mode, and static statistical parameters, such as vessel identity, size, and year of vessel construction (Windmark, 2020). Based on the ships' IMO number or maritime mobile service identity (MMSI) number, the Shipair dataset was also matched with information from a commercial database, delivered by IHS Markit (2020), to get additional information about the ships. See the supplementary material (Section S1b)

[1] AIS is a global system that identifies vessels and their movements. Since December 2004, it is mandatory to be fitted with an AIS transceiver for vessels of 300 GT and above engaged in international voyages, cargo ships of 500 GT and above not engaged on international voyages and all passenger vessels (IMO, 2023b). AIS transceivers are also used on most commercial ships and on an increasing number of recreational vessels (Windmark, 2020).

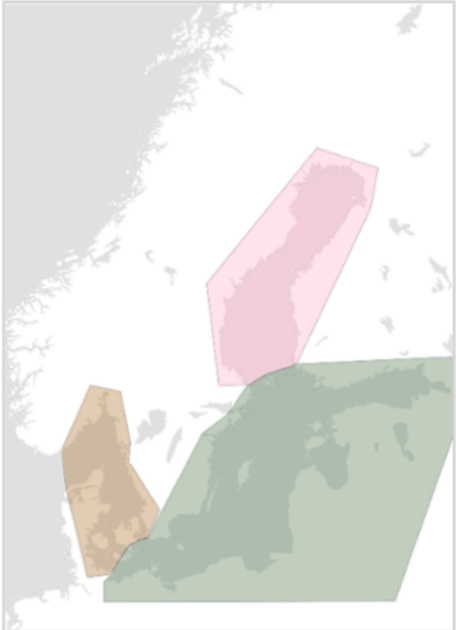

Fig. 1. The Shipair model area, including its three sea basins: North (Baltic Sea, north of Åland), South (Baltic Sea, south of Åland), and West (Skagerrak/Kattegat).
Source: Windmark (2020)

for more details.

The ships are separated into 11 ship types, presented in Table 2, based on the StatCode5 classification, which is the industry-standard ship type coding system (IHS Markit, 2017). Private recreational vessels are not included in the data. In addition to the 11 ship types, this study also uses smaller segments to be able to model different scenarios for different ship segments. More specifically, the ships were divided into six ship segments depending on whether the ship travels in domestic, international or mixed (i.e., both domestic and international) traffic, and whether the ship is above or below 5000 GT. Segments a-c include ships with 5000 GT and above, while d-e include ships below. Segments a and d include domestic traffic, b and e include mixed traffic, and c and f include international traffic. See the supplementary material (section S1b) for more details.

4.2. Scenarios

The policy instrument scenarios, summarised in Table 3, are developed based on the Fit for 55 package in the EU. There are four main scenarios; 1) business as usual (BAU) is a reference scenario, which is a situation in which no new policy instruments are implemented after 2020, 2) base price of EUAs (Base EUA), which assumes that the price of EUAs is constant at 100 EUR/tonne CO_2e, 3) implementation of the FuelEU Maritime regulation (FuelEU), and 4) base price of EUAs and implementation of the FuelEU Maritime regulation (Base EUA FuelEU).

Some assumptions are the same in all scenarios. First, the assumptions about transport demand are based on forecasts by the Swedish Transport Administration (2024) and, for some segments, based on previous trends of the demand (see section S2a in the supplementary material). Second, the assumptions about ship lifetime follow the average scrap age of commercial ships by Hoffmann (2020) (see section S2b in the supplementary material). Finally, the main scenarios are based on the same fuel costs, referred to as base fuel costs, which are further described below in section 4.3.

In scenarios with EUA price, the extension of the EU ETS to maritime transport is assumed to be gradually introduced, starting with 40 % of emissions in 2024, 70 % in 2025, and 100 % from 2026 and onwards. For simplicity, it is assumed to include tank-to-wake (TTW) CO_2e emissions already from 2024 and that it applies to all voyages. Hence, this is different compared to policy instrument, where GHG emissions other than CO_2 are proposed to be included during 2026 and onwards, and where it applies to all ships of 5000 GT and above entering EU ports and covers all emissions that occur between two EU ports and half of the emissions from voyages starting or ending outside of the EU. As indicated in Table 3, all ships of 5000 GT and above are assumed to be affected in all scenarios with EUA price, except one scenario where all ships of 400 GT and above are assumed to be affected.

The CO_2e price component in the EUA is included separately from the fuel costs, and it is estimated for each fuel type by multiplying the emission factor for TTW CO_2e of each fuel with the assumed price of emission allowances.[2] As mentioned, in the Base EUA scenario,

[2] The emission factors are based on Brynolf (2014), Malmgren et al. (2021), and Brynolf et al. (2023).

Table 2
Description of ship types.

Ship type	Abbreviation	StatCode5	Description (according to Statcode5)
Bulk carrier	BU	A2	Including vessels carrying bulk dry, bulk dry/oil, self-discharging bulk dry, and other bulk dry
Cargo ship	CA	A31, A32, A34, A38	Including vessels carrying general cargo, passenger/ general cargo, refrigerated cargo, and other dry cargo
Container ship	CO	A33	Including vessels carrying containers
Fishing vessel	FI	B1	Including vessels for catching fish and other fishing
Passenger cruise	PC	A37A	Including passenger cruise ships
Passenger ferry	PF	A37B	Including passenger ships
Ropax	RP	A36	Including vessels carrying passenger/Ro-Ro cargo
Service ship	SS	B2, B3	Including vessels for offshore supply and miscellaneous (e.g., research vessels, towing/pushing vessels, icebreakers, and dredging vessels)
Tanker ship	TA	A1	Including vessels carrying liquefied gas, chemicals, oil and other liquids
Vehicle carrier	VE	A35	Including vessels carrying Ro-Ro cargo
Other ships	OT	W, X, Y, Z	Including all other ships (W: Inland waterways, X: Nonmerchant ships, Y: Non-propelled ships and Z: Non-ship structures)

Source: Windmark (2020)

the price is assumed to be constant at 100 EUR/tonne CO_2e, which is higher than the price assumed by the EC (2021f) in their impact assessment report. However, the price for emission allowances within the EU ETS has shown a significant increase during the last years. From levels around 15–30 EUR/tonne CO_2 during 2018–2020, the price has reached levels above 100 EUR/tonne CO_2 (around March 2023) (Trading Economics, 2024). Therefore, in the base price scenario, the EUA price is assumed to stay at about the highest reached level of 100 EUR/tonne CO_2. Sensitivity scenarios with lower and higher EUA prices are also modelled. The low-price scenario of EUAs (Low EUA) is assumed to follow the EC (2021f) policy scenario from their impact assessment report including maritime transport in the EU ETS, where the price is assumed to start at 45 EUR/tonne CO_2 in 2021 and average around 55 EUR/tonne CO_2 in 2030 (EC, 2021f). The average yearly price increase is assumed to continue until 2045, which would reach 77 EUR/tonne CO_2 in 2045. The high EUA price scenario (High EUA) is assumed to follow the "Net zero emissions by 2050 scenario for advanced economies" by the IEA (2023), in which the price increases to 215 EUR/tonne CO_2 by 2045. See section S2e in the supplementary material for more details.

The scenarios modelling the FuelEU Maritime regulation are based on a simplified implementation approach. As described in Table 1, the regulation requires a gradual percentage reduction relative to a 2020 reference value of 91.16 gCO_2e/MJ. This study uses this gradual percentage reduction, but does not include the compliance pooling and compliance surplus mechanisms.[3] The gradual reduction is represented by blending lower emission fuel types into the higher emission fuel types, which is described in more detail in section S2e in the supplementary material.

Sensitivity analyses were developed to analyse different fuel costs and infrastructure costs, a subsidy of charging infrastructure, higher battery costs, the inclusion of smaller ships in the EU ETS, higher and lower discount rates, and an adjustment of the model area. More specifically, there are 13 sensitivity scenarios in which different factors are varied, and in 11 of these, the factors are varied together with both the base and high EUA price (see Table 3).

The fuel cost can have a significant impact on the model results. Therefore, the sensitivity scenarios are estimated with alternative fuel costs. "Lower NG" includes lower costs of liquefied natural gas (LNG), natural gas (NG)-methanol, and NG-ammonia with carbon capture and storage (CCS). "Lower Elec" includes lower electricity costs, which also affects the cost of hydrogen, e-methanol, e-methane, and e-ammonia through the fuel production costs. "Lower biomass" includes lower costs of biofuels and liquefied biogas (LBG). "Lower Oil" is used to model a case of fuel oil (FO) rather than marine gas oil (MGO) but could also represent lower crude oil prices. This case should be considered in the lower range as it does not include the increased cost and fuel consumption connected to the use of scrubbers, which is needed to comply with the global sulphur regulations when using FO with more than 0.5 % sulphur content. The "Infrastructure" scenario assumes a higher initial infrastructure cost for new fuel types, but which are declining exponentially until 2045, affecting fuel use costs for all fuels except MGO, LNG, biofuels and LBG. The "Battery" scenario assumes that the cost of batteries used for battery-electric propulsion is 1.5 times higher than in the base case. The assumptions about the base fuel and infrastructure costs are summarised below in section 4.3 and described in detail in section S1a in the supplementary material.

There are also sensitivity scenarios modelling alternative policy designs. First, the "Subsidy" scenario models a case where the infrastructure cost for installing battery charging is subsidised for the shipowners. Second, the "400" scenario models a situation where the EU ETS affects ships of 400 GT and above instead of ships of 5000 GT and above (see section S1b for an overview of ships affected in the different scenarios).

As mentioned in section 4.1, the ship route dataset only includes ship movements within the Shipair model area. This implies that ships that have called Sweden, but which later travel outside of the model area have lower yearly estimated energy consumption than

[3] The FuelEU regulation provides a voluntary pooling mechanism as well as the possibility to bank and borrow from compliance surpluses, which means that ships will be allowed to pool their compliance balance over several ships and bank compliance surpluses to subsequent compliance periods (EC, 2023a).

Table 3
Overview of scenarios.

Scenario	Fuel costs					Infrastructure costs		EUA price*			FuelEU Maritime	Electricity subsidy	Model area adjustment	Higher battery investment cost	Ships affected by EUA price		Discount rate (%)		
	Base	Lower natural gas	Lower electricity	Lower biomass	Lower conven-tional	Base	Declining	Low	Base	High					≥ 5000 GT	≥ 400 GT	3	5	10
Main scenarios																			
BAU	■					■							■		■			■	
Base EUA	■					■			■				■		■			■	
Fuel EU	■					■					■		■		■			■	
Base EUA and Fuel EU	■					■			■		■		■		■			■	
Sensitivity scenarios																			
Low EUA	■					■		■					■		■			■	
High EUA	■					■				■			■		■			■	
Low NG		■				■			S1	S2			■		■			■	
Low Elec			■			■			S1	S2			■		■			■	
Low Bio				■		■			S1	S2			■		■			■	
Low Oil					■	■			S1	S2			■		■			■	
Infrastructure	■						■		S1	S2			■		■			■	
Subsidy	■					■			S1	S2		■	■		■			■	
Battery	■					■			S1	S2			■	■	■			■	
400	■					■			S1	S2			■			■		■	
No adj.	■					■			S1	S2					■			■	
Low r	■					■			S1	S2			■		■		■		
High r	■					■			S1	S2			■		■				■

*S1 and S2 represent that these sensitivity scenarios are estimated with both the base EUA and the high EUA.

in reality. Therefore, all scenarios, except the “No adj“ scenario, include an adjustment where the propulsion system cost is adjusted to match hours of operation in the model area. Hence, the benefits of switching to more energy-efficient options, in terms of reduced energy consumption, are included in the model and the investment costs in the propulsion system are not unproportionally high in relation to the total costs when including fuel costs. The sensitivity analysis “No adj“ includes a situation without this model adjustment. A detailed description of the model area adjustment is presented in section S2d in the supplementary material.

Finally, the choice of discount rate can have a significant impact on the results, where a high discount rate, which could be used by investors to represent risk and underlying investment uncertainties, generally implies that investments with costs arising far into the future will be relatively less expensive than investments that have costs arising closer in time. This reduces the present value of return on investment, and therefore more investment will be postponed (Kou & Luo, 2018). Therefore, sensitivity analyses also model lower (3 %) and higher (10 %) discount rates, compared 5 % which is used in the other scenarios.

4.3. Model development

The dataset described above is combined with different inputs to estimate which investment options shipowners are most likely to choose in different policy instrument scenarios, based on the assumption that they will choose the option with the lowest total discounted cost. These results are used to estimate the total fuel consumption of different fuel types and resulting emissions in the different scenarios, which can be used to analyse tendencies in how policy instruments affect shipowners' investment decisions. The model time period is 2020–2045, where the base year 2020 is based on the dataset from 2019 (hence excluding potential effects from the Covid-19 pandemic) and the end year is chosen based on the Swedish climate target of net zero GHG emissions by 2045.

The model can be divided into five steps, which are summarised below, and described in detail in section S1a in the supplementary material. Fig. 2 presents an overview of the model, summarising the five main steps and main model inputs. The inputs to the model, represented by the rectangles outside the boxes in the figure, include assumptions about future investment costs, fuel costs, infrastructure and distribution costs, energy efficiencies of different propulsion systems (propulsion system efficiencies), emission factors, price of EUAs (where emission factors influence the fuel costs, represented by the dashed arrow in the figure). In addition, assumptions are made for different ship segments regarding transport demand and lifetime of ships.

Shipowners are assumed to renew their current ships with the aim of minimising total costs over the time period included in the model. In the different policy instrument scenarios, it is assumed that the shipowner has perfect foresight and is aware of which policy instruments will be implemented and that these changes will affect their investment decisions through expectations about future fuel costs, EUA price, and subsidies. It is assumed that the ships' voyages and length of voyages are fixed over the time period included in the model, that is, it stays the same as in the base year.

Step 1: Estimation of the energy use per ship in the base year

The first model step consists of an estimation of the energy use per ship for the base year. The estimation uses the ship routes dataset, and the methodology follows the approach in IMO (2020), which considers ship-specific information regarding ship main and auxiliary engine capacity, engine load, design speed, average speed per route, travel time per route, number of trips per route, and the specific fuel oil consumption of conventional fuel (based on engine speed and age of ships). The estimate includes energy use for propulsion (main and auxiliary engines), while energy use at berth and for additional heating (e.g., in boilers) are excluded. The total energy use is validated against the fuel consumption estimated by the Shipair model (see section S1c in the supplementary material).

Step 2: Estimation of energy use for investment options for 2020–2045 per ship

In the second step, the future energy use per ship for all possible investment options in the model is estimated for the time period 2020–2045. To be able to calculate the costs for each investment option in the third model step, an estimate of each ship's future energy use for all investment options is needed. Shipowners are assumed to choose between the investment options presented in Table 4 and the estimation of the future energy use is based on assumptions about propulsion system efficiencies for each investment option. See section S1a in the supplementary material for a detailed description.

When a ship reaches its expected end of lifetime, it will have to choose to invest by the latest that year, but it can also choose to invest earlier.[4] For example, to estimate the future energy use of an investment of conventional fuels in internal combustion engines (ICE) in 2022, the propulsion energy need (from the base year) is divided by the propulsion system efficiencies to estimate the energy use needed for the new propulsion system. Hence, the energy use will for the years 2020-2021 be the same as the base year and the following years 2022-2045 will have the new energy use in that option.

Step 3: Estimation of the discounted costs for each ship and investment option

In the third model step, the costs for each investment option are calculated based on the estimations in step 2, including assumptions of fuel and infrastructure costs, and investment costs for the motor and fuel tank/battery (summarised in Table 5 and Table 6, and described in more detail in section S1a in the supplementary material).[5]

To be able to compare the sum of all costs for each investment alternative, discounted costs, *DC*, are calculated according to equation (1).

[4] The assumed ship lifetime limits the number of investment options, such that in the investment year that the assumed scrap year is reached, the shipowner has to make a decision that year, and the options later in the model are removed. For example, if a shipowner in the base year (2020) owns a 20-year-old ship and the assumed lifetime of that ship type is 25 years, then the shipowner will have the option of making an investment decision during the years 2020–2025, but not later in the model since the ship's lifetime is at an end.

[5] Ship operators are assumed to have the same engine size requirement (in kW) for new investments as for their previous ship.

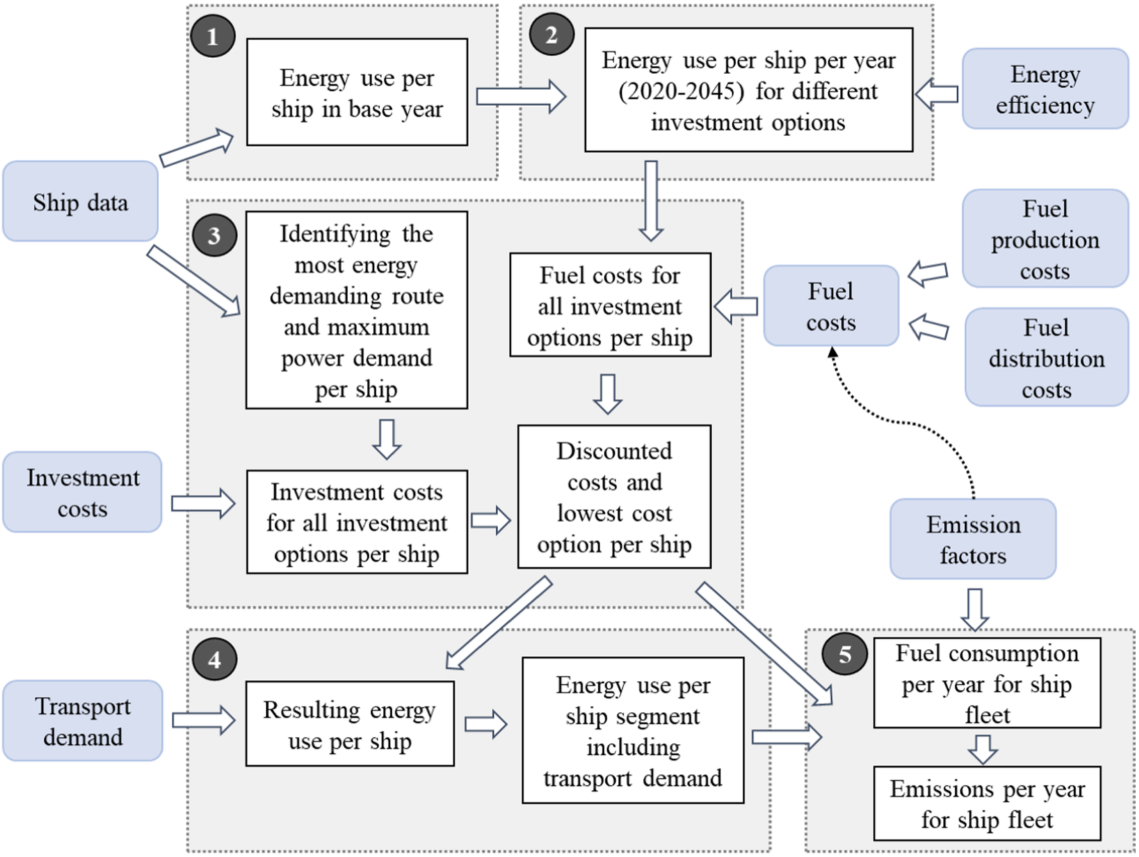

Fig. 2. Model structure overview, describing steps 1–5 in the model (represented by the five boxes) and the inputs to each step (represented by the rectangles outside the boxes). The dashed arrow illustrates that the emission factors also influence the fuel costs in step 3.

Table 4
Investment options in the model, presented together with a description and the assumed propulsion efficiency.

Investment option	Description	Propulsion efficiency [a]				
		SSD	MSD	HSD	BE	FC
Conventional marine fuel	In internal combustion engines (ICE), e.g., MGO, very low sulphur fuel oil (VLSFO)	0.500	0.466	0.442		
Biofuels	In ICE, e.g., hydrotreated vegetable oil (HVO) and bio-methanol	0.500	0.466	0.442		
NG-methanol	In ICE, produced from steam reforming of natural gas	0.500	0.466	0.442		
Electro-methanol (e-methanol)	In ICE, produced from Nordic electricity mix	0.500	0.466	0.442		
Liquified natural gas (LNG)	In ICE	0.500	0.466	0.442		
Liquified biogas (LBG)	In ICE	0.500	0.466	0.442		
Electro-methane (e-methane)	In ICE	0.500	0.466	0.442		
Electro-ammonia (e-ammonia)	In ICE, produced from Nordic electricity mix	0.462	0.431	0.409		
NG-ammonia-CCS	In ICE, produced from steam reforming of natural gas with carbon capture	0.462	0.431	0.409		
Battery-electric propulsion	Nordic electricity mix				0.837	
Liquid hydrogen [b]	In proton-exchange membrane fuel cells (PEM FC)					0.523

[a] SSD: slow speed diesel. MSD: medium speed diesel. HSD: high speed diesel. BE: battery-electric. FC: fuel cell. [b] Hydrogen can be stored onboard ships either as a liquid or as compressed. In this model, we consider liquid hydrogen stored in cryogenic tanks.
Source: IMO (2020),Brynolf et al. (2023)

Table 5
Assumptions of investment costs for the propulsion system.

Energy carrier	Propulsion system component*		2020	2025	2030	2035	2040	2045
Conventional fuels, biofuels	ICE	ICE diesel cost (€/kW)	240	240	240	240	240	240
	Fuel tank	Storage tank liquid (€/kWh)	0.09	0.09	0.09	0.09	0.09	0.09
Electricity	Motor	Electric motor (€/kW)	120	120	120	120	120	120
	Battery	Battery cost base (€/kWh)	500	350	200	187.5	175	150
		Battery cost sensitivity (€/kWh)	750	650	550	450	350	250
Methanol	ICE	ICE MeOH cost (€/kW)	265	265	265	265	265	265
	Fuel tank	Storage tank MeOH (€/kWh)	0.14	0.14	0.14	0.14	0.14	0.14
Liquid hydrogen	Fuel cell	ICE PEM cost (€/kW)	1500	1300	1100	1000	900	800
	Motor	Electric motor (€/kW)	120	120	120	120	120	120
	Fuel tank	Storage tank LH2 (€/kWh)	1.71	1.71	1.71	1.71	1.71	1.71
LNG, LBG, e-methane	ICE	ICE CH4 cost (€/kW)	265	265	265	265	265	265
	Fuel tank	Storage tank LCH4 (€/kWh)	0.2	0.2	0.2	0.2	0.2	0.2
E-ammonia, NG-ammonia CCS	ICE	ICE NH_3 cost (€/kW)	350	350	350	350	350	350
	Fuel tank	Storage tank NH_3 (€/kWh)	0.29	0.29	0.29	0.29	0.29	0.29

*The investment cost is constant for all years except for fuel cells and batteries where we assume a cost reduction. The cost for 2020 is from Lloyd's Register and UMAS (2020), the cost for 2030 is from Kanchiralla et al. (2022) and a continued cost reduction is assumed in line with Whiston et al. (2019).
Sources: Kanchiralla et al. (2022), Lloyd's Register and UMAS (2020), Whiston et al. (2019).

Table 6
Assumptions of distribution infrastructure cost and fuel production cost in the base case, EUR/MWh.

Energy carrier	Fuel distribution infrastructure cost	Fuel production cost					
	2020–2045	2020	2025	2030	2035	2040	2045
Conventional fuels	1.1	43	73	75	78	79	81
LNG	16.9	75	48	53	57	60	63
Electricity	41.7[b]	21	53	41	44	47	51
Liquid hydrogen [a]	41.8[b]	–	–	126	116	107	98
E-methanol [a]	2.2[b]	–	–	157	146	135	126
E-methane [a]	16.9[b]	–	–	157	147	137	130
Biofuels	1.1	200	167	95	96	96	96
LBG	16.9	190	168	114	108	103	98
E-ammonia [a]	4.3[b]	–	–	138	130	123	118
NG-methanol	2.2[b]	75	67	73	78	82	86
NG-ammonia CCS	4.3[b]	86	93	100	105	109	114

[a] Dash symbols are used for years when fuel types are assumed to not be available on the market.
[b] A case with 1.5 times this infrastructure cost with an exponential reduction to this value in 2045 is used in the infrastructure sensitivity analysis.

$$DC_i = \sum_{t=1}^{T} \frac{C}{(1+r)^t} = \sum_{t=1}^{T} \frac{FC_{i,t} + I_{i,t}}{(1+r)^t} \tag{1}$$

For a given investment option, the discounted cost of vessel i is equal to the sum of all costs, C, which includes fuel costs, FC, and investment costs, I, of vessel i at time t, discounted over the lifetime of the investment where r is the discount rate. A discount rate of 5 % is used in all scenarios, except for some of the sensitivity analyses.[6] Fuel costs are based on estimates of fuel consumption in model step 2 and assumptions about future fuel costs, infrastructure and distribution costs and policy instruments.[7] The investment costs for the propulsion system are based on ships' maximum propulsion power, route distances and assumptions about component costs and energy storage margins needed for each ship, while the investment costs for the hull is assumed to constitute 90 % of the total cost of a newbuilt ship using ICE with conventional fuel. Shipowners are assumed to choose the option with the lowest discounted cost.

Step 4: Estimation of energy use per segment including transport demand

The fourth model step is to estimate the total energy use over the time period 2020–2045 including forecasts of the future transport demand. A simplified approach has been used to model the increased demand, where the composition of ships and their operational patterns are scaled based on the assumed growth of each ship segment. The assumed future energy use is estimated by multiplying the energy use of the ships' lowest-cost investment option the previous year with the assumed yearly change in transport demand

[6] The same discount rate is also used in related previous studies, see e.g., Hansson et al. (2020) and Brynolf et al. (2018), but it varies in other studies between 3–11%, see e.g., Zhang and Yin (2021), Pomaska and Acciaro (2022), Yin et al. (2019), and Atari et al. (2019).
[7] All costs are expressed in euros at 2020 values.

(described in section S2a in the supplementary material). The estimations are valid at a ship segment level since it is assumed that all ships in the dataset already have reached their maximum transport capacity and route frequency.

Step 5: Estimation of fuel consumption and emissions

The last model step is to calculate the total fuel consumption of each fuel type, based on the lowest-cost investment option per ship, and the resulting emissions. Emission factors (described in section S2c in the supplementary material) are used to estimate the emissions from the estimated fuel consumption.

Model limitations

All models are simplifications of reality, and this model is no different. To make the model computationally feasible and easy to interpret, a number of simplifications and delimitations have been made. Infrastructure for alternative fuels is assumed to be available for all ships. Market impacts, such as changes in demand for maritime transport in response to changes in fuel prices and regulations as well as fuel price dynamics in response to changes in supply and demand for various fuels, are not considered in the model. However, they are partly analysed through various fuel cost scenarios and by including assumptions about future transport demand for different sectors. Effects on cargo space and ship energy consumption due to different size and weight requirements of propulsion systems are not considered. The size of ships (DWT/GT) and propulsion systems (kW energy conversion and kWh for energy storage) are based on fleet and operational data for 2019 and are kept the same for newbuilt ships for all years. Energy demand for onboard heating, energy use at berth, and other technical and operational improvements than alternative fuel types are not considered since the scope of this study is to analyse effects on the energy mix. Investments in retrofit options are excluded to make the model computationally more feasible. All simplifications and delimitations are further discussed in the discussion section in relation to the results.

5. Results

The outcome of the model estimations is the total discounted costs for all investment options per ship. Shipowners are assumed to choose the lowest-cost investment option, with the restriction that the investment year must be before the ship's assumed maximum age. To demonstrate how different factors influence the model results, scenarios BAU and Base EUA are examined in more detail below, followed by the results for all scenarios.

In the BAU scenario, shipowners of all ship types choose to switch to LNG, where the share varies between about 20–95 % in the investigated ship segments (Fig. 3). The share of ships that choose battery-electric propulsion varies between 0–40 %, where the ship types ropax ships, passenger ferries, and other ships have the highest shares (Fig. 3). Within the segments choosing battery-electric propulsion, it is mainly smaller ships, below 5000 GT, that have battery-electric propulsion as their lowest-cost option, which can be seen in Fig. 4. In the Base EUA scenario, the main difference is that all ship types, except fishing vessels, other ships, and passenger ferries, also have biofuels as the lowest-cost option, where the share varies between 5–80 % between the ship segments. The share of ships choosing battery-electric propulsion also increases slightly, especially for the ropax ship type, which increases from 41 % to 57 %.

Fig. 4 shows that the segments of passenger ferries, ropax ships, and small passenger cruises below 5000 GT are the ship segments that most commonly switch to battery-electric propulsion in all scenarios. There are also some examples in the ship segments of domestic cargo ships below 5000 GT (CA-d), fishing vessels, tanker ships, other ships, and service ships that switch to battery-electric propulsion already in the BAU scenario. Almost all these segments involve smaller ships, below 5000 GT. One explanation for why smaller ships, more commonly than larger ships, have battery-electric propulsion as the lowest-cost option is that they, on average, travel shorter routes, which means that the investment cost for the battery becomes relatively lower than for ships travelling longer routes. In addition, in the scenarios with EUA price, the relative share of the ship investment cost is reduced in comparison to the total cost because the fuel costs increase with a higher EUA price, which increases the number of ships with battery-electric propulsion as the lowest-cost option. Fig. 4 also shows that some ship segments more commonly than others continue to use conventional fuels throughout all scenarios. For example, fishing vessels, other ships, and service ships continue to choose conventional fuels. Several segments that in the BAU scenario choose conventional fuels or LNG are found to switch to biofuels in scenarios with EUA price. In the FuelEU scenario, shipowners only choose conventional fuels, LNG, and battery-electric propulsion. However, when choosing conventional fuels or LNG, they will have to blend in biofuels or LBG as the requirements gradually become stricter within the regulation

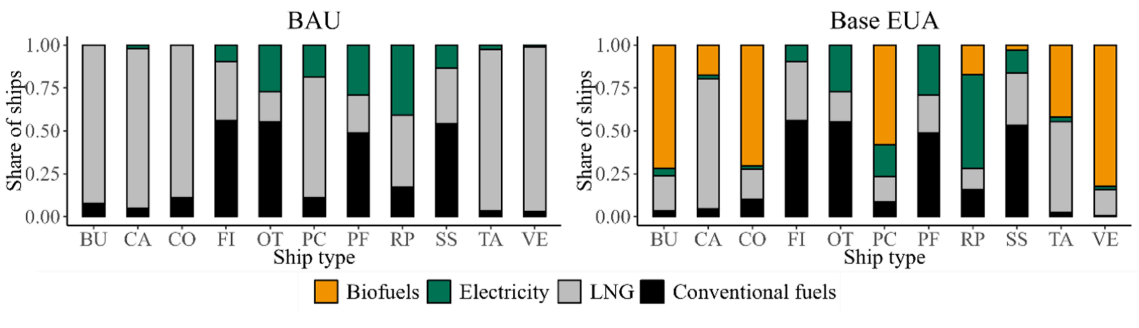

Fig. 3. The share of ships choosing different investment options for each ship type (i.e., their lowest-cost option) in the scenarios BAU (left) and Base EUA (right) in total over the time period 2020–2045. BU: Bulk carrier, CA: Cargo ship, CO: Container ship, FI: Fishing vessel, OT: Other ships, PC: Passenger cruise, PF: Passenger ferry, RP: Ropax ship, SS: Service ships, TA: Tanker ship, VE: Vehicle carrier.

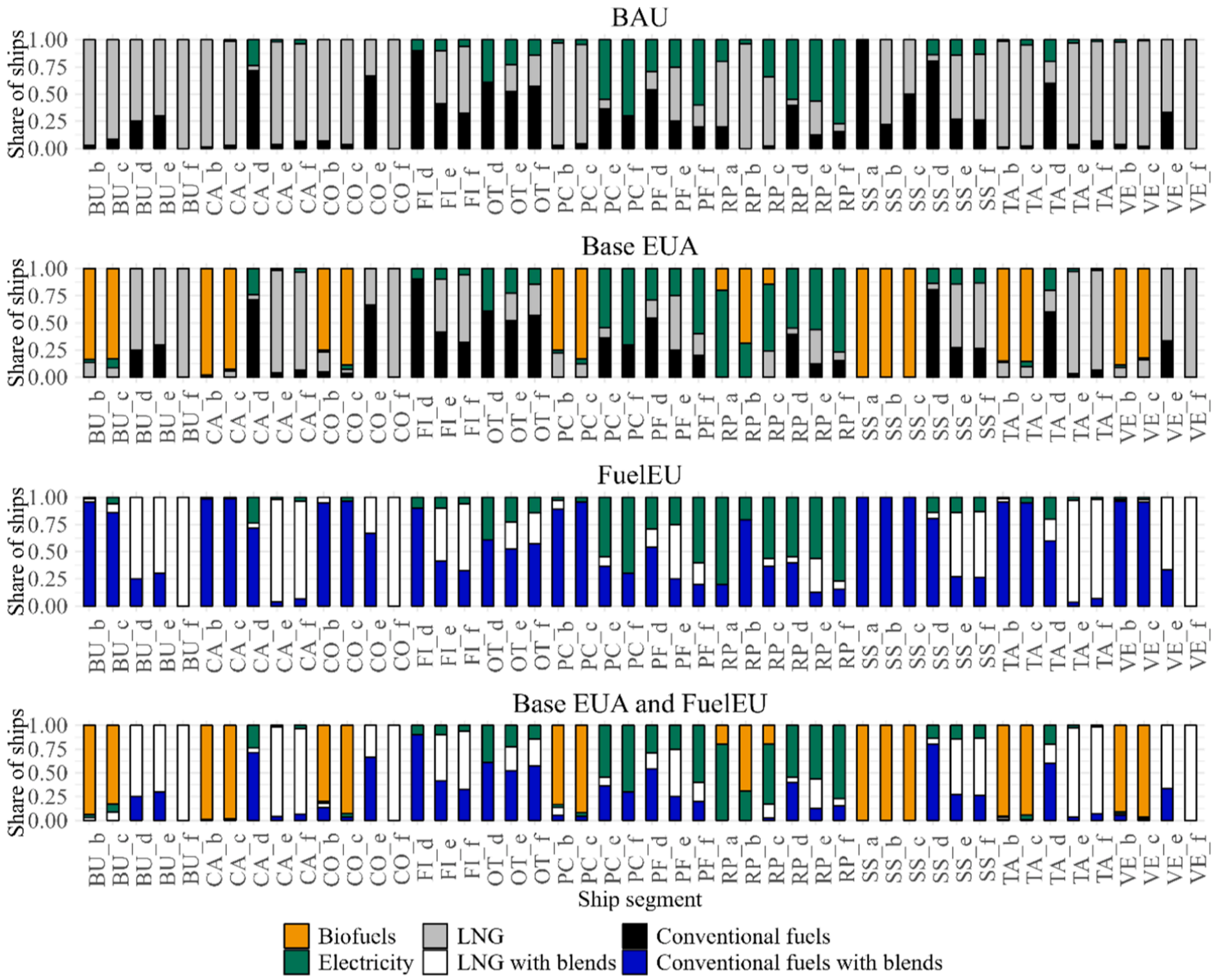

Fig. 4. The share of ships choosing different investment options for each ship segment (i.e., their lowest-cost option) in the main scenarios in total over the time period 2020–2045. BU: Bulk carrier, CA: Cargo ship, CO: Container ship, FI: Fishing vessel, OT: Other ships, PC: Passenger cruise, PF: Passenger ferry, RP: Ropax ship, SS: Service ships, TA: Tanker ship, VE: Vehicle carrier. Segments a-c include ships with 5000 GT and above, while d-e include ships below. Segments a and d include domestic traffic, b and e include mixed traffic, and c and f include international traffic.

(illustrated in Fig. 6 below). When FuelEU is combined with Base EUA price, the lowest-cost investment options are similar to the Base EUA case, where biofuels replace conventional fuels as the lowest-cost option for several ship segments.

In the main scenarios, the most common investment years are 2030 and 2045 (see section S3 in the supplementary material), which partly can be explained by the number of ships that have reached their assumed maximum lifetime by those years and thus must be replaced. Fig. 5 presents boxplots for the main scenarios of the number of ships per investment option and the difference between the chosen investment year and the last possible investment year. The most common chosen investment year is the last possible investment year for all scenarios, although there is a variation across chosen investment options between different scenarios. In the BAU scenario, the investment years for conventional fuels and LNG are close to the last possible investment years, which means that when there are few policy incentives, shipowners choose to wait with investments. However, battery-electric propulsion as investment option has a slightly higher variation, where some choose to invest earlier than necessary. The variation is higher in the scenarios with EUA price, where a higher proportion of the shipowners choose to invest earlier than necessary. In the FuelEU scenario, the result is more in line with the BAU scenario, where fewer shipowners choose to invest earlier than necessary.

Fig. 6 shows the estimated fuel consumption in the main scenarios for the time period 2020–2045 and Fig. 7 presents the estimated reduction of CO_2e emissions. The estimations of the BAU scenario indicate that, if no action is taken, conventional marine fuels will continue to dominate until about 2030. After 2030, an increasing share of LNG can be seen, which by 2045 would be the dominant fuel choice in the Swedish maritime transport sector given the assumptions in the model. This can be explained by that LNG is the lowest-cost option for several ship types, especially in those segments with larger ships (above 5000 GT) (Fig. 4). Although a relatively high share of ships chooses battery-electric propulsion as investment option (see Fig. 4), the energy conversion of electricity only accounts for about five percent by 2045 of the total energy use, which can be explained by that it is mainly smaller ships with lower energy consumption that have battery-electric propulsion as their lowest-cost option and by that battery-electric propulsion is the most

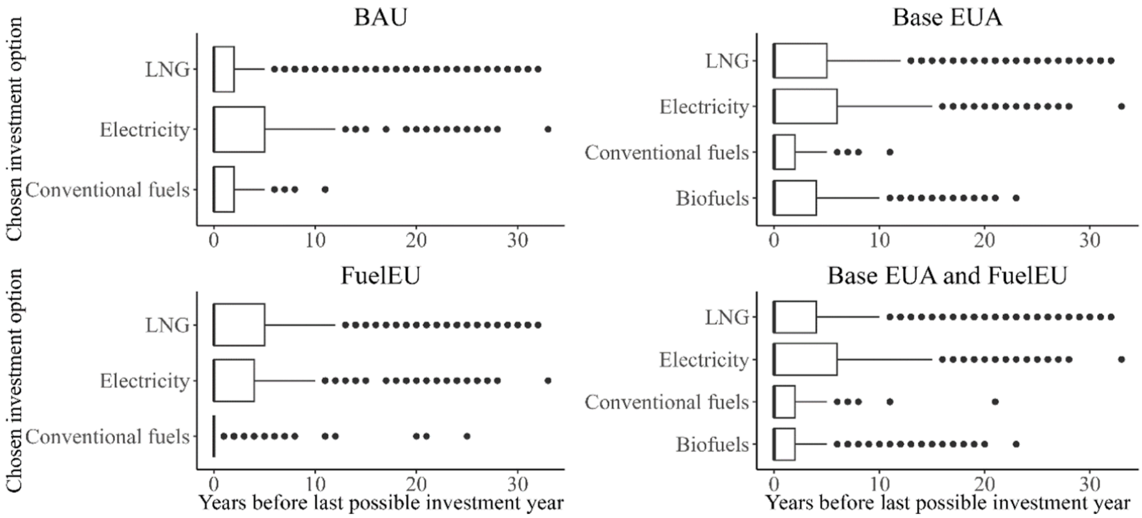

Fig. 5. Boxplot of the chosen investment options and the years before the last possible investment year.

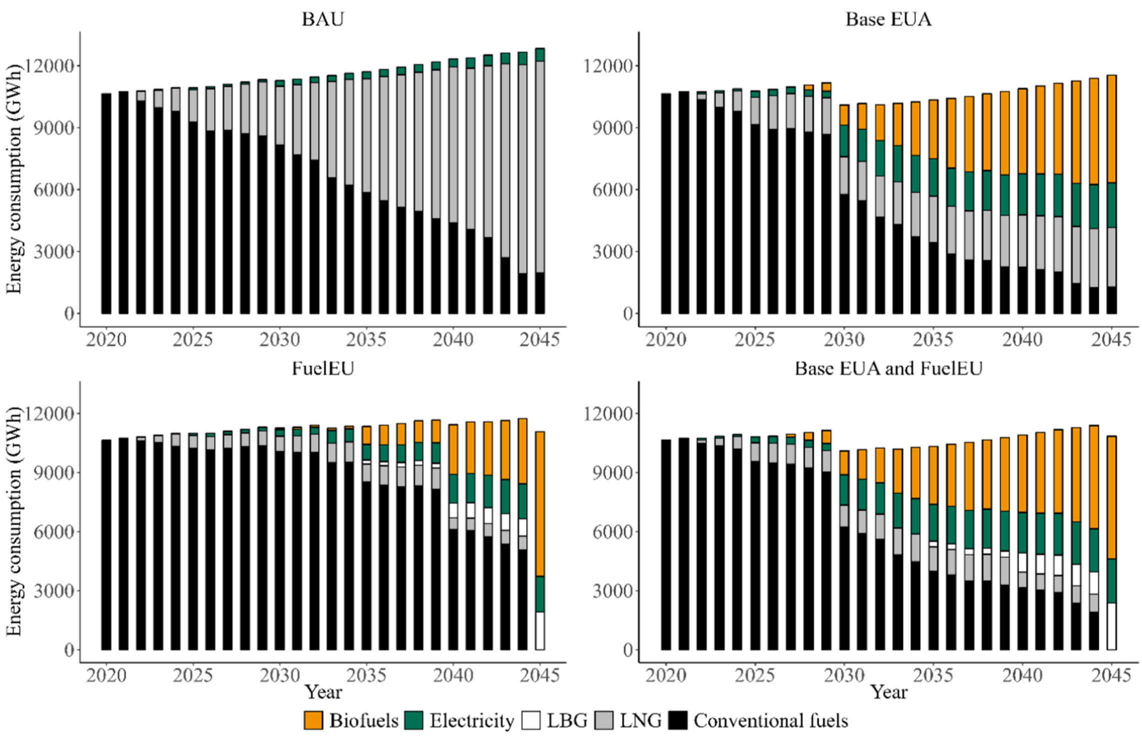

Fig. 6. Estimated fuel consumption in the main scenarios over time.

energy-efficient investment option. The total energy use is expected to increase by about 21 % in this scenario over the model period, which is explained by the assumed increased transport demand. The BAU scenario shows higher CO_2e emissions by 2045 compared to 2020, due to the continued used of fossil fuels and increased transport demand.

The Base EUA scenario indicates that, if the maritime transport sector is included in the EU ETS with the base price of EUAs, this would make biofuels, LNG, and battery-electric propulsion the lowest-cost options for shipowners, where biofuels would account for almost half of the total energy use by 2045. The investments are estimated to happen gradually as the sector is included in the EU ETS. The total energy use is expected to increase by about nine percent over the time period 2020–2045, although it decreases in 2030 due to the adoption of battery-electric propulsion which is more energy-efficient. As can be seen in Fig. 7, Base EUA has a similar development of CO_2e emissions as the BAU scenario until the year 2029, where the emissions are indicated to stay at around the same level as in 2020, followed by a relatively large reduction in 2030. Hence, the base EUA price is indicated to only contribute marginally

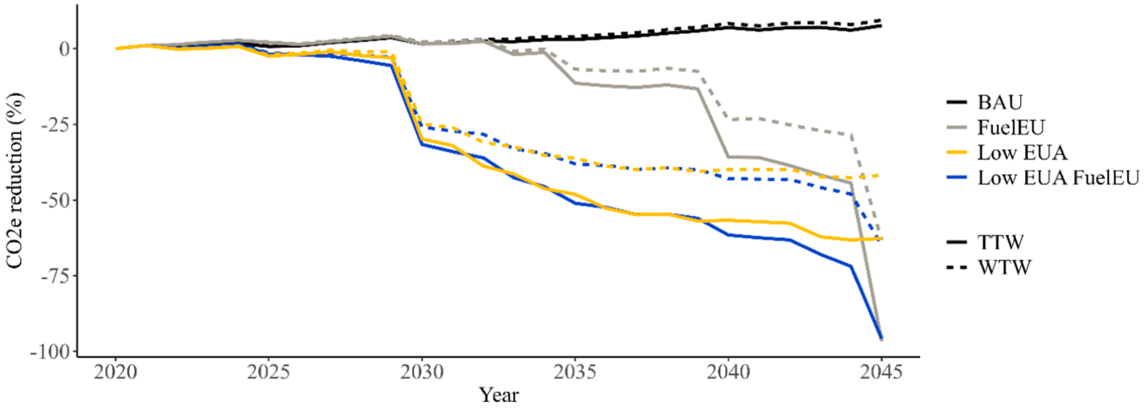

Fig. 7. Estimated reductions of CO_2e emissions in scenarios BAU, Base EUA, FuelEU, and Base EUA FuelEU.

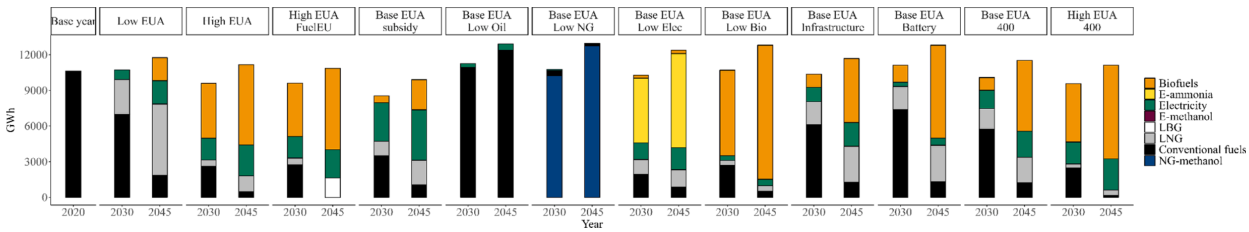

Fig. 8. Estimated fuel consumption in all scenarios for the years 2030 and 2045.

to the achievement of climate targets until 2029 but have a larger influence later in the model period.

The FuelEU scenario is indicated to have marginal effects on investments in alternative fuels by 2030, while the effects are substantially higher by 2045 due to the blending requirements of biofuels and LBG. The total energy use is expected to increase by about five percent in this scenario over the time period 2020–2045. As indicated in Fig. 7, the FuelEU scenario has a similar development of CO_2e emissions as the BAU scenario up until the year 2034, where the emissions are indicated to stay at around the same level as in 2020, followed by larger reductions as the policy requirements are tightened. However, although the CO_2e emission reduction is substantial from a TTW perspective by 2045, the well-to-wake (WTW) perspective indicates almost half of the reduction in 2045. When FuelEU is combined with the EUA price, investments are indicated to happen earlier compared to the case without the EUA price, which results in emission reductions in line with the Base EUA case.

The results from the sensitivity scenarios for the years 2030 and 2045 with the Base EUA are presented in Fig. 8 and Fig. 9, which show a summary of the estimated fuel consumption and the CO_2e emission reductions, respectively. The sensitivity scenarios with higher EUA price (High EUA), no model area adjustment (No adj.), and low and high discount rates (Low R, High R) can be found in the supplementary material (Figures S1 and S2).

The main difference between the Low EUA scenario compared to Base EUA is that fewer ships choose biofuels rather than LNG, which results in smaller CO_2e emission reductions, especially from a WTW perspective. In the High EUA scenario, there is a substantial increase in biofuels and electricity. In addition, the total energy use in the High EUA scenario increases less than in the Base EUA scenario, which mainly can be explained by more ships choosing to invest in battery-electric propulsion. The high EUA price is indicated to result in higher reductions of CO_2e emissions. However, from the WTW perspective, this reduction is about 20 % smaller than from a TTW perspective. When combining FuelEU together with a high EUA price, the main difference compared to the Base EUA FuelEU scenario is that the investments in alternative fuel types happen earlier in the model, which also can be seen in the lower CO_2e emissions reduction by 2030 compared to the Base EUA FuelEU scenario.

The scenario with the subsidy for electricity charging infrastructure (with Base EUA) is estimated to increase the share of electricity energy use by 95 % by 2045 compared to the Base EUA scenario. The difference between the TTW and WTW CO_2e emission reductions is smaller than in the Base EUA scenario without the subsidy, which can be explained by the higher share of electricity and that the emission factor for WTW CO_2e emissions from electricity is lower than for other fuel types.

The fuel cost is shown to have significant effects on the model results. Therefore, the Base EUA scenario is combined with alternative fuel cost scenarios. Two scenarios investigate the impact of lower cost of fossil fuels; "Lower oil" represents a case where fuel oil

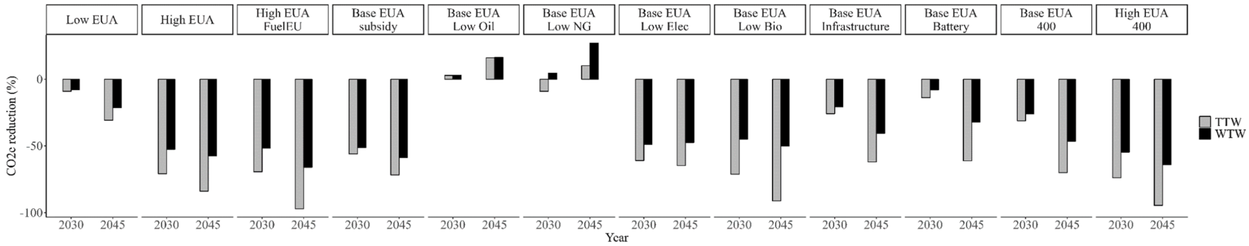

Fig. 9. CO_2e emission reductions of TTW and WTW emissions in all scenarios for the years 2030 and 2045 compared to the base year.

is used instead of MGO (or a case with lower crude oil prices) and "Lower NG" includes lower costs of LNG, NG-methanol, and NG-ammonia-CCS. They result in that fuel oil and NG-methanol are the most common lowest-cost options by 2045 in the "Lower oil" and "Lower NG" scenarios, respectively (Fig. 8). In these cases, the model results indicate that the base EUA price is not high enough to make it cost-effective for shipowners to invest in fossil-free fuel options, resulting in no reduction in CO_2e emissions by 2045 (Fig. 9).[8]

The scenario with "Lower Elec" includes lower electricity costs (25 EUR/MWh), which also affects the costs of hydrogen, e-methanol, e-methane, and e-ammonia through the fuel production cost. With the lower electricity cost, it is cost-effective in the model for shipowners to invest in e-ammonia (and e-methanol, although the energy use is too low to be visible in the figure) and to invest earlier than the last possible investment year (Fig. 8), which is indicated to result in a higher reduction of CO_2e emissions already by 2030 compared to the Base EUA scenario with base fuel costs (Fig. 9). The scenario with "Lower biomass" considers lower costs of biofuels and LBG. Biofuels are indicated to be the lowest-cost option for almost all shipowners, resulting in fewer investments in electricity and higher WTW CO_2e emissions compared to the scenarios with base fuel costs (Fig. 8 and Fig. 9), which can be explained by the higher WTW emission factor for biofuels compared to electricity.

The "Infrastructure" scenario assumes a higher initial cost for infrastructure which declines over time, which affects the fuel use costs for all fuels except conventional fuels, LNG, biofuels and LBG (where the infrastructure costs are assumed to be constant). This scenario results in less transition towards alternative fuels by 2030, but a higher transition by 2045, compared to the scenarios with constant infrastructure costs (Fig. 8). The "Battery" scenario assumes that the cost of batteries used for electric propulsion is higher than in the base case. This scenario results in a substantially lower transition towards battery-electric propulsion, and a higher share of biofuels and LNG compared to the Base EUA scenario (Fig. 8).

In the Base EUA 400 scenario, it is assumed that ships of 400 GT and above are affected by the EUA prices, instead of ships of 5000 GT and above as in the Base EUA scenario. The results indicate that there are more shipowners choosing biofuels and electricity compared to the base case, although the effect is relatively small (Fig. 8). In contrast, in the High EUA 400 price scenario (in Figure S1), the effect of including ships of 400 GT and above is indicated to almost make all shipowners choose alternative fuels rather than conventional fuels. From a TTW perspective, this would result in almost 95 % reduction of all CO_2e emissions (Figure S2). The Base/High EUA 400 are indicated to decrease CO_2e emissions (TTW) by 7–11 % more compared to the scenarios with allowance prices affecting ships of 5000 GT and above (Base/High EUA).

The propulsion system cost is adjusted to match hours of operation in the model area (as described in section 4.3). As a robustness analysis, the scenarios "No_adj" (in Figure S1) model a situation where this adjustment is not included. In both the low and high EUA scenarios, the energy consumption of conventional fuels is higher than in the base case, which is expected as the investment costs are unproportionally high in relation to the total costs when including only a part of the yearly fuel costs (the part connected to the operation within the model area).

Since the choice of discount rate can have a significant impact on the results, sensitivity analyses also model lower (3 %) and higher (10 %) discount rates for the Base and High EUA price scenarios (in Figure S1). In the scenarios with lower discount rates, a higher share of shipowners chooses other fuels than conventional fuels, while in the scenarios with higher discount rates, a lower share of shipowners chooses other fuels than conventional fuels compared to the base cases with 5 % discount rate, which is also to be expected.

The transition of the Swedish maritime transport sector towards renewable fuels increases the demand for renewable fuel production as can be seen in all the investigated scenarios, where biomass and electricity are the main inputs for all the renewable fuels. Table 7 summaries the demand for biomass and electricity that would be needed to produce these fuels by 2045. It should be noted that the model does not consider the fuel consumption of ships when at berth.

6. Discussion

6.1. Model results

The main contribution of the developed model, in comparison with previous maritime modelling studies (Wang et al., 2015; Smith

[8] In the corresponding scenarios with high EUA price, the "Lower oil" scenario also indicates that biofuels and electricity become the lowest-cost options for some shipowners by the end of the model period, while the "Lower NG" scenario still result in NG-methanol being the most common lowest-cost option.

Table 7
Needed supply of biomass and electricity in TWh for the different scenarios in 2045. The share of use of electricity and biofuels in Sweden in 2020 (Swedish Energy Agency, 2022) is shown in parentheses.

Scenario	Biomass TWh	Electricity TWh
BAU	0.6 (0.4 %)	0 (0 %)
Base EUA	2.2 (1.4 %)	9.5 (6.7 %)
FuelEU	1.8 (1.1 %)	16.9 (12 %)
Base EUA FuelEU	2.2 (1.4 %)	15.7 (11.1 %)
Low EUA	2 (1.2 %)	3.5 (2.5 %)
High EUA	2.6 (1.6 %)	12.3 (8.7 %)
Base EUA Low NG	0.1 (0.1 %)	0 (0 %)
Base EUA Low Oil	0.5 (0.3 %)	0 (0 %)
Base EUA Low Elec	15 (9.3 %)	0.5 (0.4 %)
Base EUA Low Bio	0.5 (0.3 %)	20.5 (14.5 %)
Base EUA Infrastructure	2 (1.2 %)	9.8 (7 %)
Base EUA Subsidy	4.2 (2.6 %)	4.6 (3.3 %)
Base EUA Battery	0.6 (0.4 %)	14.2 (10.1 %)
Base EUA 400	2.2 (1.4 %)	10.9 (7.7 %)
Base EUA No adj.	1.6 (1 %)	10.5 (7.4 %)
Base EUA Low R	3.1 (2.0 %)	7.2 (5.1 %)
Base EUA High R	1.3 (0.8 %)	11.2 (8 %)

et al., 2016; Zhu et al., 2018; Gu et al., 2019; Köhler, 2020; Harahap et al., 2023; Latapí et al., 2024), is that it can take into account data for individual ships and their unique operational patterns when estimating the impact of potential policy instruments aggregated to the Swedish maritime transport sector. It is shown that the lowest-cost option differs across different ship segments, which highlights the importance of considering ship-specific factors when analysing the impact of different policy instruments for maritime transport. This is in line with Wang et al. (2015), which find that an ETS will affect different sectors to different degrees, and with Latapí et al. (2024) which find that electrification will dominate the ropax segment.

The scenario analyses indicate a relatively large variation in which fuel types that shipowners choose in the model. For example, in the policy scenarios with low price signals to reduce GHG emissions (e.g., BAU, Low EUA, Fuel EU), conventional fuels and LNG are found to be the most common lowest-cost options for shipowners. Although this study uses a stricter assumption of blend-in by not including the pooling and banking mechanisms in the FuelEU Maritime regulation, the FuelEU scenario without EUA price is indicated to have marginal effects on investments in alternative fuels before 2034, where conventional fuels still is indicated to be the dominant fuel type. When a higher price signal is modelled (e.g., Base EUA, Base EUA FuelEU, and High EUA), a significant transition towards biofuels and electricity is found, and the transition is also indicated to occur earlier in the model compared to the scenarios with lower price signals.

In several scenarios, there is a substantial transition towards alternative fuels, which possibly could result in a supply shortage of those fuels. Logically, that would likely have an increasing effect on the price of those fuel types, which likely would limit the transition towards those fuels. In future research, such fuel price dynamics should be included. For example, in the scenario High EUA, 12.3 TWh of biomass (about 9 % of Swedish biofuel use, see Table 7) and 2.6 TWh electricity (about 2 % of Swedish electricity production, see Table 7) is needed. In the low biofuel cost scenario, the biomass use stands for 20 TWh and about 15 % of the Swedish use of biofuels today.

The fuel costs are likely the most uncertain parameters in the model, making it crucial to examine their impact on the results. The base fuel cost scenario in this study is similar to that of Solakivi et al. (2022), although their results are presented in tonnes of oil equivalents. However, Solakivi et al. (2022) consider a reduction in electricity costs from 80 to 50 EUR/MWh, while this study is modelling it around 50 EUR/MWh in the base fuel costs and keeping it constant at 25 EUR/MWh in the sensitivity analysis with low electricity costs. The scenarios that are found to result in the highest transition towards renewable fuels and the lowest GHG emissions by 2045 are the High EUA Subsidy and High EUA Low Elec scenarios (presented in the supplementary material in Figure S1), which include a subsidy for charging infrastructure and low electricity costs, respectively. Moreover, the low electricity scenarios are the only scenarios where any e-fuel becomes cost-competitive. Both scenarios assume advantageous costs for electricity and e-fuels, where electricity costs are lower than what may be expected in the future (Grahn et al., 2022). However, the scenarios give an indication of how much the relationship between fuel costs and policy instruments' price must change for a significant transition to occur. Hence, if an even higher EUA price would be modelled, it would likely result in earlier investments and a higher transition towards renewable fuels.

The model results are generally in line with findings of previous studies. Zhu et al. (2018) find that a maritime ETS can motivate ship operators to utilise new technologies and to deploy more energy-efficient ships. Moreover, Gu et al. (2019) conclude that an ETS with a low price signal will not lead to significant CO_2 emission reductions in the short term, but that a more significant reduction can be expected in the case of high allowance prices and low prices of alternative fuels. Moreover, Solakivi et al. (2022) find that blending biofuels will be the main short-term solution and that e-fuels will be cost-competitive first beyond 2050, which is in line with the model results for most scenarios.

The assumption of a relatively small storage tank capacity is made because when transitioning to energy carriers with lower energy density, such as hydrogen and batteries, this will have to change to be able to fit the energy onboard the ship (Kersey et al., 2022). All investment options in the model are equally treated in this regard to make a fair comparison (except battery-electric propulsion for ships in international traffic outside of the model area). The investment cost of batteries is a considerable expense, which is indicated in the sensitivity scenario with higher battery cost, where battery-electric propulsion is found to decrease substantially compared to the main scenarios. However, when considering battery-electric propulsion, the operational patterns of ships could change, such as changing routes to be able to charge the batteries more often or a shift to ships specialising in shorter or longer routes. In that case, the fuel margin could be lower than in the base case in the model, which likely would increase the number of ships with battery-electric propulsion as their lowest-cost option.

6.2. Model scope and limitations

The model is based on the assumption that shipowners will choose the lowest-cost investment option. However, in some cases, the difference between the lowest-cost investment option and the second lowest-cost option can be relatively small (see Figure S4 in the supplementary material). If the cost difference is small, shipowners may, in reality, choose to invest in a slightly more expensive option if it fulfils other factors that are considered important. For example, studies using multi-criteria decision analysis have shown that shipowners rank economic factors high but also consider other criteria when selecting marine fuels (Hansson et al., 2019; Ashrafi et al. 2022). Hence, shipowners' choice of propulsion system and fuel type is also affected by other factors, which can influence the results from the model. For example, expectations about future fuel supply and availability of bunker/charging infrastructure, as well as size requirements of different propulsion systems can have a significant influence on shipowners' choices. Nonfinancial factors, such as activities of competing shipping actors, timing, and pressures due to the increasing demand for low-carbon transportation from society are also found to influence shipowners' selection of emission abatement solutions (Balland et al., 2015; Stalmokaitė & Yliskylä-Peuralahti, 2019).

There are some costs that have not been included in the model due to data unavailability. For example, investments in newbuilt ships can affect energy-efficiency, costs, and revenues due to more energy-efficient hull designs and other technical improvements that can reduce energy consumption per tonne-kilometre. Even if this is not considered, the assumptions of high efficiencies of new propulsion systems can partly compensate for this. Additionally, newbuilt ships have a trend of becoming larger, where a higher transportation capacity may affect potential revenues. Yet, different propulsion systems also have other size requirements, which may affect the transportation capacity and the future cash flows. However, according to Korberg et al. (2021), this impact is not shown to be dominating, while Kanchiralla et al. (2023) found some options non-feasible due to the increase in the propulsion systems' volume and weight for a service ship, ropax ship and a tanker ship.

The model does not consider volume and weight constraints of the energy system for new technologies onboard the ships, although a simplified calculation of possible changes in weight and volume is presented in the supplementary material for three examples of ships (Figure S5).[9] For example, for battery-electric propulsion, the weight and size of the propulsion system can be especially challenging. More detailed analyses of the weight and volume requirements for propulsion systems could be included in future model developments.

The ship route dataset only includes ship movements within the Shipair model area. This means that ships that have called Sweden, but which later travel outside of the model area have lower yearly estimated energy consumption than in reality. To address this, the model includes an adjustment where the propulsion system cost is adjusted to match hours of operation in the model area. However, many ships are operating globally and spend a significant time of the year outside of the model area and the EU (i.e., in areas without policy instruments). Such ships are thus likely to have lower incentives to choose alternative fuels because they are less affected by the increased costs from the policy instruments. Hence, for those ships, the investment cost would still be a larger proportion of the total cost compared to ships that only operate within the model area and are affected by policy instruments on all their fuel consumption, which is modelled in sensitivity analyses without the adjustment. In those scenarios, a higher share of the energy consumption comes from conventional fuels compared to the base case.

The fuel consumption at berth is not considered in the model although it is a significant contributor to the GHG emissions in the Swedish maritime transport sector (Windmark, 2020). Traditionally, the same fuels that are used during ship operation also contributes to the energy use at berth, while in the future this might be separated with increasing demand for shore-side electricity. Moreover, a simplified method to estimate ship energy use in the base year is used in the model, where energy demand for onboard heating is not considered. This could change when transitioning from ICEs to fuel cells or battery-electric propulsion as less waste heat will be available. Effects from technical and operational energy-efficiency improvements are not included since the aim of the study is to analyse the future fuel choices. However, the impact from these limitations could be considered in future studies, where potential rebound effects from energy-efficiency measures as well as market dynamics could be analysed.

Another limitation that could affect the model results is the choice of included fuel types. It is assumed, for simplicity, that MGO are used by all ships in the base year. However, there are other conventional marine fuels that should be considered to be included in a future version of the model. For example, heavy fuel oil with scrubber, which currently is the cheapest investment option for many shipowners (Andersson et al., 2020; Hermansson et al., 2024). The possible effects of lower costs of conventional fuels are included in the sensitivity analyses, which indicate a substantially lower transition towards renewable fuels, especially in combination with lower

[9] This calculation only considers typical component weight and volumes of engines, motors, fuel cells, batteries and tanks, but it does not consider additional equipment and variations. Increases in weight will also lead to increases in energy use and an adjustment of energy demand would also be necessary.

EUA price signals. Hence, if the conventional fuels were cheaper (as is the case for heavy fuel oil), the EUA price may have to be even higher than the assumptions in the model for alternative fuels to be cost-competitive and for a transition to occur based on shipowners' lowest-cost options. However, there is an ongoing discussion about the environmental risks from the use of scrubbers (Hermansson et al., 2023), and the Danish Ministry of Environment (2024) recently reached a decision to ban scrubber discharge.

The assumptions about transport demand are the same in all scenarios. However, changed fuel costs and implementations of policy instruments may affect future transport demand. For example, increased costs for shipowners may influence the transport demand and have effects on modal shifts, where if it becomes more expensive for maritime transport, there may be a modal shift to road and rail. In addition, as road traffic transitions towards electricity, the transports of oil will likely decline substantially (Swedish Transport Administration, 2024), which can affect the future demand for maritime transport, especially the tanker ship segment (Sharmina et al., 2017). The main scenario results are also compared in the supplementary material (Figure S3) with a situation of no changes in the transport demand, where a constant transport demand is found to reduce energy use in all scenarios by 2045 due to more energy-efficient propulsion systems.

It is assumed that shipowners have perfect foresight and are aware of future fuel prices and which policy instruments that will be implemented. However, in reality, there are uncertainties about the design of future policy instruments and its effects on future prices. Yet, what the scenario analyses can demonstrate is that if shipowners would have more information about the future development of costs, it would be easier to plan future transitions and to choose alternative fuels to a higher degree. In the long term, there are also other uncertainties for shipowners to take into account, such as uncertainties about which infrastructure and fuels that will be easily available. The sensitivity analyses with high (low) discount rates, which could represent investments as being (less) risky for shipowners, indicate that a lower (higher) share of shipowners choose other fuels than conventional fuels compared to the base cases.

6.3. Policy implications

When implementing policy instruments, it is relevant to ensure that they are cost-effective in terms of having the ability to achieve targets at the lowest possible cost to society. In general, market-based policy instruments, such as such as taxes, subsidies, and emissions trading, have good opportunities to achieve cost-effectiveness since they use market mechanisms to address market failures (such as GHG emissions). More specifically, cost-effectiveness means that the private marginal cost of reducing emissions (i.e., the cost of reducing emissions with an extra unit, e.g., an extra kilo of greenhouse gases) is the same for all actors (Sterner & Coria, 2012).[10] When the marginal cost is the same for all actors, the responsibility is distributed in such a way that actors who can reduce their emissions relatively easily and cheaply reduce their emissions more than actors who find it relatively difficult and expensive to reduce their emissions. The total societal cost of achieving a certain emission reduction can thus be minimised by replacing relatively expensive reduction measures with relatively cheap measures from another actor (Söderholm & Hammar, 2005).

The implementation of maritime transport in the EU ETS has the ability to achieve cost-effective reductions of GHG emissions. However, if only ships of 5000 GT and above are included, all actors will not face the same marginal cost of reducing emissions, which could reduce the cost-effectiveness of the policy instrument. Vierth et al. (2024) recommend that ships with a lower GT should be included in the long term. In a similar way, the model results indicate that an implementation of the EU ETS for ships above 400 GT could decrease CO_2e emissions (TTW) by 7–11 % more compared to the scenarios affecting ships of 5000 GT and above.

In the sensitivity scenarios with lower costs of fossil fuels, the "Lower oil" and "Lower NG" scenarios, the results show only a marginal transition towards fossil-free fuels, although the scenario with high EUA indicates some transitions to occur in the end of the model period. Hence, the difference between the future fossil fuel prices (conventional fuels and LNG) and the renewable fuel options is indicated to impact how high the EUA price signal will need to be for renewable fuel options to become the lowest-cost option for shipowners. Moreover, if the emissions from production of fuels are not included in the EU ETS, or if the fuels are produced outside of the EU and there is no carbon border adjustment, there is a risk of increased emissions because the upstream emissions would not be priced. For example, for fuels that have low emissions during TTW but high emissions during well-to-tank, such as natural gas methanol, the CO_2e price component would not correspond to the emissions that the fuel contributes to. Therefore, it is important to ensure that the upstream emissions during well-to-tank are covered in the EU ETS for all fuel types.

The model results indicate that the WTW CO_2e emissions can be up to double as high as the TTW CO_2e emissions. Although the FuelEU Maritime regulation takes WTW CO_2e emissions into account, the FuelEU scenario results indicate that the emission reductions will occur relatively late in the model. Moreover, since ships have a relatively long lifetime, the investments in newbuilt ships made today will stay long in the ship fleet and have an impact on the possibilities of achieving future targets of GHG emission reductions. The model results indicate that investments in renewable fuel types are found to occur earlier in scenarios with higher EUA prices, implying that the economic lifetime of ships may be reduced with stricter regulations due to increased compliance costs. In the studied model area, these scenarios are indicated to result in emission reductions earlier in time. However, to understand the full implications from shorter economic lifetime of ships, the life-cycle perspective should also be considered. For example, the ship building phase, the scrapping of ships, and if ships are sold and used in areas with less strict regulations could also have implications on the total GHG emissions. In future research, such effects could be studied by modelling shorter ship lifetimes and including the life-cycle perspective.

Policy instruments with a predictable long-term price signal and stability can likely provide better incentives for abatement.

[10] In general, actors' marginal cost is lower for the "first" measures to reduce emissions and higher for reducing the "last" emissions (Söderholm and Hammar, 2005). For example, actors can often use relatively cheap measures to reduce a small part of their emissions (e.g., by slow steaming), while large reductions are often significantly more expensive as they may require investments in new technology.

Without the long-term policy price signal, shipping companies may rather choose to slow down their ships (slow steaming) in order to reduce the fuel consumption than to make substantial investments (Gu et al., 2019). Providing certainty about the possibilities to charge/bunker can likely increase the transition towards alternative fuels, and the Fit for 55 package has the potential to provide long-term price signals and predictability that can give shipowners incentives to make significant investments. For example, the FuelEU Maritime regulation and the AFIR could provide an increased predictability of the regulatory framework and available infrastructure to unlock the "chicken-and-egg" situation between demand and supply of renewable fuels (EC, 2021a). However, the future development of the EUA price can still be uncertain.

7. Conclusions

This study developed a policy scenario modelling tool to analyse the decarbonisation of Swedish maritime transport. The model is used to analyse the implications of climate policy instruments in the EU on the energy transition of the Swedish maritime transport sector over the time period 2020–2045. The main contribution of the developed model is that it can take into account data for individual ships and their unique operational patterns when estimating the impact of potential policy instruments, aggregated to the Swedish maritime transport sector. The model estimates which investment options shipowners are most likely to choose in different scenarios, based on the assumption that they will choose the lowest-cost investment option.

The policy scenarios are mainly used to test the model mechanisms and to analyse tendencies of how different policy instruments can affect shipowners' decisions. The scenarios are not primarily aimed to provide realistic scenarios of the future development of energy use due to the model restrictions of excluding energy use at berth, energy demand for onboard heating, and other technical and operational improvements than alternative fuel types. However, the scenarios can still provide valuable insights about the potential effects of climate policy instruments.

The model results show that the lowest-cost investment options vary between ship segments and different scenarios, which emphasises the need for considering ship-specific data when analysing the effects of policy instruments. As an example, battery-electric propulsion is most common for passenger ferries, ropax ships, and small passenger cruises, while fishing vessels and service ships typically continue to choose conventional fuels across all scenarios. In line with previous studies, the scenario analyses indicate that policy instruments have the potential to affect shipowners' investment choices, but that relatively strong policy instruments are required for significant effects to arise. More specifically, the following results were found from the scenario analyses:

- In scenarios with low EUA price signals, the model results indicate small reductions (or even increases) in CO_2e emissions.
- In the scenarios with higher EUA price, the most common lowest-cost investment options are biofuels and battery-electric propulsion, and investments in renewable fuels are indicated to occur earlier in the model time period compared to scenarios with lower EUA price.
- When costs for conventional fuels and natural gas are assumed to be lower, the EUA price signal will have to be higher for renewable fuels to be cost-competitive.
- The scenario analyses of including smaller ships (of 400 GT and above) in the EU ETS than the current limit (of 5000 GT and above) indicate that CO_2e emissions (TTW) could decrease by 7–11 % more.
- The scenario including the FuelEU Maritime regulation shows relatively small effects in the short run (until about 2030).
- The scenario of a subsidy for electric charging infrastructure is found to almost double the share of electricity use by 2045 compared to the base scenario.

There are numerous factors that can have an impact on shipowners' choice of propulsion system and fuel type. In addition, in some model scenarios, there are small differences between the lowest-cost option and the second-lowest-cost option, which implies that shipowners may, in reality, choose to invest in a slightly more expensive option if it fulfils other factors that are considered important. In future research, the model can be expanded to consider additional factors, such as other emissions than greenhouse gases, scrapping cost, and cost of lost cargo capacity. In addition, it would be relevant to complement the model with a cost-benefit analysis to better understand the total societal cost of implementations of policy instruments and reductions of GHG emissions.

CRediT authorship contribution statement

Lina Trosvik: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Selma Brynolf:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2024.104457.

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