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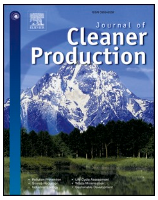

Renewable marine fuel production for decarbonised maritime shipping: Pathways, policy measures and transition dynamics

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ABSTRACT

This article investigates the potential of renewable and low-carbon fuel production for the maritime shipping sector, using Sweden as a case in focus. Techno-economic modelling and socio-technical transition studies are combined to explore the conditions, opportunities and barriers to decarbonising the maritime shipping industry. A set of scenarios have been developed considering demand assumptions and potential instruments such as carbon price, energy tax, and blending mandate. The study finds that there are opportunities for decarbonising the maritime shipping industry by using renewable marine fuels such as advanced biofuels (e.g., biomethanol), electrofuels (e.g., e-methanol) and hydrogen. Sweden has tremendous resource potential for bio-based and hydrogen-based renewable liquid fuel production. In the evaluated system boundary, biomethanol presents the cheapest technology option while e-ammonia is the most expensive one. Green electricity plays an important role in the decarbonisation of the maritime sector. The results of the supply chain optimisation identify the location sites and technology in Sweden as well as the trade flows to bring the fuels to where the bunker facilities are potentially located. Biomethanol and hydrogen-based marine fuels are cost-effective at a carbon price beyond 100 €/tCO_2 and 200 €/tCO_2 respectively. Linking back to the socio-technical transition pathways, the study finds that some shipping companies are in the process of transitioning towards using renewable marine fuels, thereby enabling niche innovations to break through the carbon lock-in and eventually alter the socio-technical regime, while other shipping companies are more resistant. Overall, there is increasing pressure from (inter)national energy and climate policy-making to decarbonise the maritime shipping industry.

1. Introduction

The challenge of decarbonising the maritime shipping sector is a whole systems task requiring cross-sectoral effort (Harahap et al., 2023). Because ships have different characteristics and operating areas, the challenge lies in finding different solutions to ensure that all types of vessels and shipping can become fossil free. Fossil free shipping provides considerable Greenhouse Gases (GHG) emissions reduction compared to shipping with fossil fuels (Fridell et al., 2022). There are a range of different marine fuel options with varying characteristics in terms of availability, cost, energy density, technical maturity and environmental impact. Energy carriers associated with low or zero GHG emissions during their life cycle include different types of biofuels, electrofuels and electricity produced from renewable energy sources such as biomass, hydropower, solar, and wind energy. This article examines the potential of renewable and low-carbon fuel (RLF) production in the maritime sector. The study takes into account the actual production sites and resource availability in Sweden as well as the demand for maritime fuels sold in Sweden.

A growing amount of scientific literature discusses various technical and operational measures regarding the decarbonisation of the maritime shipping industry, essentially focusing on energy efficiency measures or replacing fossil fuels with renewable fuels. Bouman et al. (2017) mapped Carbon dioxide (CO_2) emissions' reduction potentials and measures based on 150 reviewed studies on shipping energy efficiency and GHG emissions and concluded that a more than 75% cut in emissions by 2050

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could be achieved using existing technologies, through a combination of measures and supporting policies. Kanchiralla et al. (2022) assessed the cost-competitiveness and environmental performance of different energy carriers (hydrogen, e-ammonia, e-methanol, and electricity) in different propulsion systems, showing that the selected technologies are promising measures for cutting shipping emissions. Similar to Kanchiralla et al. (2022), Brynolf et al. (2022), Grahn et al. (2022) and Korberg et al. (2021) also analysed the costs and environmental impacts of low-carbon marine fuel production. They concluded that the higher CO_2 mitigation costs of alternative fuels and novel propulsion systems compared to existing options indicate that major incentives are required to facilitate the adoption. A number of techno-economic studies also reached the same conclusion, pointing out that most cost-effective mitigation measures are of an operational and technical nature while alternative fuels could be costly, which highlights the need for economic incentives and policy measures (Irena et al., 2021; Schwartz et al., 2020).

Given the importance of policy measures in combination with technological solutions, several works explored possible regulatory frameworks and policy instruments for decarbonising the shipping industry (Psaraftis et al., 2021; Xing et al., 2020). The most studied policy measures include a bunker/carbon levy (Christodoulou et al., 2021a; Ghaforian Masodzadeh et al., 2022; Psaraftis et al., 2021), an EU Emissions Trading System (EU ETS) (Christodoulou et al., 2021b; Psaraftis et al., 2021), the FuelEU Maritime policy (Christodoulou and Cullinane, 2022), a carbon price (Rojon et al., 2021), and a combination of ship operational measures with market-based measures (MBMs) (Psaraftis et al., 2021). These studies discussed policy effectiveness concerning GHG reduction, compatibility with current regulatory frameworks, potential implementation timelines, commercial impact, as well as practical feasibility, among others. Hansson et al. (2019) explored the different views of stakeholders engaged in maritime shipping and found a mismatch between the aim of ship owners and operators in reducing costs and government agencies in reducing the environmental impact of maritime shipping.

In general there is still limited research on how policies and regulations affect the transition toward renewable fuels (Ampah et al., 2021). Quantitative and qualitative analyses have been widely used to evaluate policy impacts. Energy systems modelling has been extensively applied in scientific studies to address policy questions (Trinh et al., 2021). Within the shipping industry, ben Brahim et al. (2019) and Solakivi et al. (2022) applied a cost optimisation model; Taljegard et al. (2014) used global energy transition model; and a MAC curve-based optimisation model was utilised by Groppi et al. (2022).

Studies examining the impact of policy instruments on the long-term viability of renewable marine fuel and future CO_2 emissions development, considering real production sites, are still limited and thus represent a research gap. This article applies a mixed methods approach, using both quantitative modelling and drawing on qualitative expert interviews. A bottom-up optimisation model was developed incorporating a full supply chain perspective to also investigate the impact of spatial aspects, such as resource availability, plant location and transportation distances, on the total cost of RLF production. In this study, the plant location offers a potential to host the RLF production. The transport distance, transport choice and cost have a major impact on pinpointing the potential location of the RLF production.

The study uses Sweden as a case study and applies the geographically explicit supply chain BeWhere model (IIASA, 2023). Sweden is used as the geographical scope, where there are ambitious climate policies aiming for net zero emissions by 2045, including a milestone target to deep decarbonise the transport sector. Moreover, Swedish shipping has a strong commitment to decarbonisation and is very active in developing many innovative low-carbon shipping projects. Sweden and other Nordic countries have high potential for renewable maritime fuel production due to biomass resource availability, large renewable energy potential and biogenic CO_2, which present real opportunities for global expansion. These countries are also first movers in terms of technology adoption and driving forward an ambitious climate agenda. While the study deals with the Swedish shipping model, the methodology can be applied for other geographical areas as well.

The study further applies socio-technical transitions perspectives. Sustainability transitions in maritime shipping are complex: it is a highly heterogeneous sector, embedded in a global system, with impacts at the global, regional, national and local levels. There is a need to combine techno-economic modelling with socio-technical perspectives to understand better the impacts on the whole system, including links to costs, policies and politics, customer preferences and behaviours, business models, as well as impacts on other sectors (e.g., the forestry sector that delivers resources for biofuels, the energy sector that delivers fuel and electricity for vessels and ports, the transport sector which competes for fuels from road transport and aviation). Scenario analysis in the modelling exercise explores a range of alternative scenarios (e.g., introduction of new policy, uncertainties concerning external prices) to investigate the sensitivity of the results and the impacts on the system analysed.

In the past decade, research aimed at linking quantitative models and socio-technical transition frameworks has emerged (Li et al., 2015). The involvement of local actors is important in the transitions towards fossil-free alternatives. Magnusson et al. (2020) have demonstrated how sustainability transitions can interact with local practice by means of socio-technical scenarios, and it is important to engage key stakeholders in dialogues on transition pathways.

The major novel contribution of this work is therefore threefold. First, a framework that combines supply chain optimisation, scenario analysis and socio-technical perspectives is developed in a unique way, providing the opportunity to thoroughly analyse the socio-techno-economic potential for transitions toward renewable marine fuels in the maritime sector. Model development involves interviews with relevant stakeholders to identify the scope, technologies, and relevant key assumptions. Second, pathways to deep decarbonise the maritime sector employing mixed methods using the case of Sweden are investigated. Finally, the research sheds light on policy impacts as well as develop policy recommendations for incentivising actors to create changes.

In Section 2, the climate and energy policies for the maritime sector are described. Section 3 provides the scope of the model, data inputs, system boundary, the mathematical formulation, and scenario approach are explained. Subsequently, Section 4 presents the modelling results, while Section 5 envisions transition potentials Section 6 discusses conditions for sustainability transitions in shipping sector, and finally, Section 7 concludes the study.

2. Climate and energy policies for the maritime sector

Amidst globally growing momentum for decarbonisation to address climate change, the International Maritime Organization (IMO) has set a target to reduce total GHG emissions from international shipping by at least 50% (compared to 2008 levels) by 2050, following a 40% reduction in carbon intensity by 2030 (IMO, 2020). However, there is increasing political pressure to raise the 50% target to 100% to better align with the Paris Agreement. The International Convention for the Prevention of Pollution from Ships (MARPOL), the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) have been important instruments in reducing GHG emissions from international shipping.

Renewable fuels are likely to play a key role in decarbonising the maritime shipping sector by mid-century. Market-based Measures (MBMs) are currently under discussion at IMO to make low and zero carbon fuels more economically attractive than fossil fuel. The MBMs that have been proposed include global levies on marine fuels, ETS, and other hybrid measures (Psaraftis et al., 2021).

In addition to the IMO Strategy to regulate GHG emissions from ships worldwide, a number of regional, national, local, and industry initiatives have emerged over the past decades. In a regional context, the EU's 'Fit for 55' package, aiming to facilitate a European Union GHG emissions cut of 55% by 2030 (European Commission, 2021a), includes proposed legislative changes among which five proposals would influence the shipping industry:

1. The inclusion of shipping in the EU ETS, starting gradually in 2023 to be fully in place by 2025. This would apply to all ships over 5000 gross tonnes, and the covered ship categories are subject to be reviewed in the coming years. Furthermore, the legislation would cover 100% of the emissions from ships navigating to and from European ports, and 50% of the emissions from voyages to or from a non-EU destinations.
2. The adoption of the FuelEU Maritime Directive limits regarding the *GHG intensity* of the *energy used* on-*board* by *ships* (75% by 2050) by promoting the use of renewable and low-carbon fuels (European Commission, 2021b).
3. The revision of the European Energy Taxation Directive (EU ETD), which would set minimum tax rates for bunker fuel; the rate will increase gradually over 10 years. The minimum tax rate is highest for fossil fuels (€10.75/GJ), and the lowest (€0.15/GJ) applies for electricity, advanced sustainable biofuels and biogas and renewable fuels (European Commission, 2021c). Sustainable fuels will have a zero-minimum tax rate over the transition period to promote the availability of alternative fuels within the EU.
4. A revision of the alternative fuels infrastructure regulation (AFIR) would increase the availability of liquified natural gas (LNG) and hydrogen, and onshore power supply (OPS) for vessels at ports. These requirements are not directly for shipping companies, but this secures the needed infrastructure to support the green transition.
5. The revision of the renewable energy directive (RED II) sets a GHG intensity reduction target in the transport sector of at least 13% by 2030, as well as sub-targets for advanced biofuels and renewable fuels of non-biological origin (European Commission, 2018). RED does not directly influence shipping but sets the sustainability criteria and targets that the more specific measures such as EU ETS, ETD, and FuelEU Maritime aim to fulfil.

In a national context, Sweden aims to shift to a fossil fuel-free transport by 2045, in line with the net-zero emissions target. In the milestone targets, emissions from domestic transport shall be reduced by at least 70% by 2030 compared to 2010, and domestic shipping is included in this goal (Government Offices of Sweden, 2018). For domestic shipping, a number of economic instruments have been introduced or discussed, for instance, Ecobonus incentives, environmentally differentiated fairway dues and port fees, as well as investment support such as the *Klimatklivet* programme.

3. Materials and methods

This research introduces a novel hybrid approach for the optimisation of a renewable marine fuel supply chain. The hybrid modelling approach consists of quantitative energy modelling using the BeWhere model and qualitative socio-technical analysis. The corresponding hybrid-modelling framework is discussed in Section 3.1. Subsequently, Section 3.2 presents the optimisation model used in this study, and Section 3.3–3.4 outline the model input and key parameters used in the model introduction, while Section 3.5 presents investigated scenarios.

3.1. Hybrid modelling approach

A qualitative-quantitative hybrid modelling approach is adopted (see Fig. 1), relying on the strengths of both models to explore a more comprehensive study of how transitions to sustainable marine fuels can be achieved. The overarching research questions are elaborated through an initial study of the current status of international and domestic shipping regarding emissions, fuel use and regulatory environments, informing the focus of the quantitative scenarios and the qualitative case study.

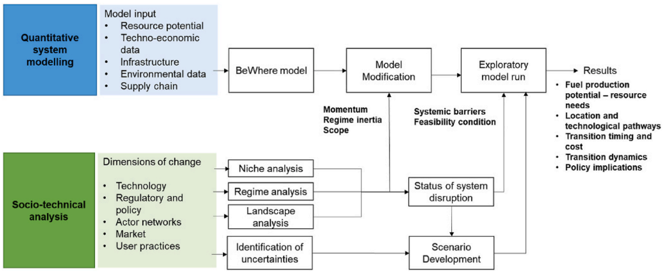

Fig. 1. Hybrid modelling approach.

The development, adoption and diffusion of low carbon technologies is not a straightforward process and may be inhibited by lock-in (i.e., mechanisms which reinforce a certain pathway of development) and path dependency (i.e., the tendency for institutions or technologies to become committed to developing in certain ways) (Nurdiawati and Urban, 2022). Hence, sustainable transitions will involve disruptions of the status quo and transformational changes in multiple dimensions. Moving from the assumption that disruption can facilitate or accelerate sustainability transitions (Kivimaa et al., 2021), the study applies five dimensions of system disruption to analyse the status of low carbon innovations in the maritime sector and future uncertainties related to low-carbon energy transitions, as well as further merge them into an energy system modelling framework. The five dimensions of system disruption were derived by Kivimaa et al. (2021) from the concept of disruptive innovation and socio-technical transitions literature. These include: (1) technology; (2) markets and business models; (3) regulations, policies and formal institutions; (4) actors and networks; and (5) behaviour, practices and cultural issues. The dimensions partly correspond to the socio-technical system elements and constitute the principle mechanisms for change in transition theory as either vectors, barriers or source of uncertainties.

Linking the techno-economic model and socio-technical transition perspectives offers two main advantages:

1. The socio-technical analysis influences the scope for modelling the diffusion of RLF and also provide inputs (e.g., data on fuel preferences, costs, expected price and market developments) on the quantitative modelling, which explores future demands, potentials and impacts in a national perspective. By linking such analysis through the lens of disrupting the quantitative scenario assessment, a more multi-dimensional assessment of transitions as they unfold can be achieved, informing policy, practice and decision making (Turnheim et al., 2015).
2. The case study offers a system's perspective for a more comprehensive understanding of socio-technical low-carbon transitions. The socio-technical perspective broadens the scope of analysis in terms of scale where international, national and local/regional factors and interactions between multiple technologies and sectors are considered (Damman et al., 2021). The analysis provides valuable insights on practical conditions, such as drivers, uncertainties, and tensions occurring during the transitions, as well as stakeholder perspectives on how the transitions can be achieved. Moreover, the socio-technical analysis also reveals transition challenges that may be overlooked or taken for granted as assumptions in quantitative modeling. These include uncertainties among others associated with the expansion of wind and solar power, forest residue availability, lack of hydrogen infrastructure, regulatory barriers, uncertain external prices and policy instruments.

As indicated (Fig. 1), the dimension of disruption is considered as the focal bridge of analysis to evaluate the conditions needed for sustainable transitions. However, the study also borrows some concepts from the Multi-Level-Perspective (MLP) by Geels (2002) and integrate them with the modelling approach to further understand the dynamics of socio-technical transitions in the maritime shipping industry. The MLP is widely applied to analyse innovation processes and their impact on socio-technical transitions within industries, including for sustainability transitions (Geels, 2002; Geels et al., 2016). Energy-intensive industries, the transport sector and the maritime shipping industry are currently under transformation pressure to reduce their emissions and transition from fossil fuels to cleaner, renewable fuels, thereby transforming the socio-technical regime of these industries. Infrastructure, user practices, industry structures, and technological knowledge are aligned and coordinated, which creates stability in the socio-technological regime. These regimes are embedded within the larger context of the socio-technical landscape, a set of external structures. As the landscape changes, however, the changes create an external pressure on the regime and open up for radical innovations, which are developed in protected technological niches. The MLP is therefore a highly relevant framework for understanding these processes and the interactions at the different levels of niche, regime, and landscape.

More details on the quantitative and qualitative approaches are presented below.

3.1.1. *Qualitative analysis*

The socio-technical analysis included in this research relies mainly on qualitative expert interviews to gather information. This research draws on insights from in-depth semi-structured, open-ended interviews. The project team conducted 17 expert interviews in the Nordic countries in 2022. Three types of groups were interviewed: (1) experts from shipping firms and business associations, (2) experts from public authorities and governmental institutions, (3) experts from academia and research institutions. The interviewees were selected to represent a wide range of perspectives on the maritime shipping industry and sustainable marine fuels. The interviewee group represents perspectives from the Nordic countries, particularly Sweden but also Denmark and Norway, and wider international issues that are relevant for IMO. The interviewees are leading experts in their field who were selected based on their long-standing experience, their expertise and knowledge, as well as their important roles in the organizations. The experience of the experts are diverse, as we triangulate the information sources by interviewing key experts in industry, policy and academia. The expert interviews cover the latest insights from industry, policy, and academia. The interviews are not the only source of information, as the quantitative data analysis and modelling plays a major role for this research. The interviews are therefore supplementary, and are providing more detailed qualitative insights into the trends and dynamics of the decarbonisation in the maritime shipping sector to complement the quantitative analysis. The interviews were recorded and stored on digital media then transcribed and analysed using Nvivo. The primary data was supplemented with secondary data. See Supplementary Information (SI) Table 1 for an overview of the interviews.

The interview data were analysed according to a conceptual framework based on socio-technical transitions, using narrative analysis to understand and interpret the findings in detail. To operationalise the regime concept, the study focused on the maritime shipping industry and its current fossil-fuel dominated shipping fleets and related port infrastructure. It observed a 'dynamically stable' organisational field made of actor-networks embedded in shared rules and institutions in their respective countries. Second, to operationalise the niche concept, the study analysed initiatives towards renewable marine fuels, including biofuels, electro-fuels and green hydrogen, as well as the electrification of shipping infrastructure and vessels, all of which have the potential to transform the established regimes. Third, for the landscape concept, the study considered national and international ambitions to reduce greenhouse gas emissions as well as societal pressures related to climate change. Fourth, the qualitative sustainability transitions perspectives with the quantitative energy modelling were integrated.

The role of disruptive innovation, carbon lock-in and path dependency are further important for analysing the industrial dynamics and transition pathways from fossil-based shipping towards an increasing use of renewable marine fuels. According to the Henderson-Clark model, disruptive innovation emerges when there are new technologies in existing markets (Henderson and Clark, 1990). In the case of maritime shipping, new fuels are emerging at the niche level and require a systems change in some cases, with new production and distribution facilities, new supply chains, as well as a change in the design and construction of vessels. These new fuels and technologies have the potential to break through the carbon lock-in and path dependency (Unruh, 2000, 2002), thereby destabilising and altering the current regime and potentially leading to new technological trajectories. Breaking through the carbon lock-in and implementing sustainability transitions not only have environmental and social advantages, they are also beneficial from a business perspective in terms of avoiding stranded assets and financial risks (Unruh, 2019).

3.1.2. *Bewhere model for the marine sector*

The socio-technical transitions approach and the interviews were integrated with quantitative modelling for renewable fuel supply chain based on actual production sites and resource availability. The BeWhere model is a techno-economic optimisation model based on the minimisation of the cost and emission of the supply chain. It is geographically explicit and runs dynamically. It has been widely used for diverse applications in multiple regions, as in biofuel production from forestry-based residuals in Austria, Finland, or on a European scale. The model will identify the optimal use of resources as well as where and when an energy infrastructure can be built at the least cost and minimum emission intensity. This study extends the application of the BeWhere model for analysing the decarbonisation pathways through the production and use of RLF in the case of Sweden and the marine industry.

The BeWhere model is structured to analyse the RLF supply chain from the production of resources (i.e., forest biomass, renewable electricity, and biogenic CO_2), energy plant units, and finally, the ports, as shown in Fig. 2. The model considers existing road networks when evaluating the optimal location for production sites. The different components along the chain are raw materials, technological options, conversion facilities, and demand for the final products. The model relies on logical, mathematical, and mass balance constraints. The constraints assigned in the model configuration are explained in SI.

3.2. *Optimisation model*

The BeWhere model used for this study also follows the Mixed Integer Linear Programming (MILP) principle but includes the spatial and temporal assessment. The model allows least cost solutions for meeting the stipulated demand targets. The original model was originally developed in two studies (Leduc, 2009; Wetterlund, 2010). This

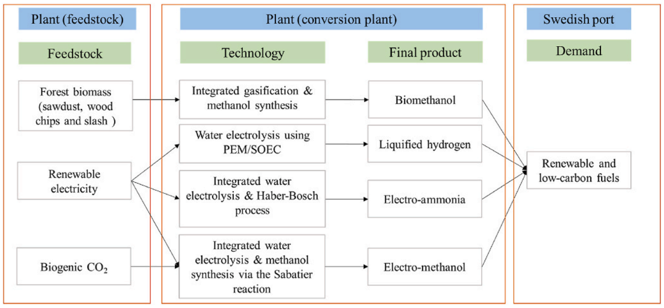

Fig. 2. Diagram of the BeWhere model structure consisting of feedstock, processing plants, technologies, and respective demand.

study adopts the BeWhere framework and develops case-specific mathematical equations as presented in SI. In the MILP, some of the decision variables are constrained to be integer values at the optimal solution, whereas the objective function and all constraints are linear (Harahap et al., 2020).

The model objective function is to minimise the supply chain cost expressed as:

Total Cost = Total Feedstock Cost + Total Technology Cost + Total Transport Cost + Total Carbon Cost + Total Fossil Cost

Total feedstock cost is the market price of resource use for RLF production. The technology cost consists of the annual investment cost and operation and maintenance costs. The transport cost includes the cost of transporting feedstock (biomass and biogenic CO_2) and cost of transporting RLF from the processing plant to the ports where bunker facilities are located. The total carbon cost is the CO_2 eq. emissions resulted from activities along the supply chain multiplied by carbon price. The supply chain emissions consist of emissions from forest biomass, feedstock and RLF production, and fossil emissions. The list of emission factors used in this study can be found in SI Table 4. The cost of carbon is internalised in the model in the form of a CO_2 eq. price. The total fossil cost is the cost of fossil fuel needed to meet the demand.

The constraints assigned in the model are presented in SI.

3.3. Technological pathway

There are a number of alternative RLFs with potentially lower climate impacts, such as electricity, different types of biofuels, hydrogen, ammonia, and electrofuels. Other technologies, such as wind-assisted propulsion, onboard CCS and nuclear marine propulsion, are also currently being explored. Several factors influence the adoption of these RLF alternatives, which vary between different ship segments. This includes technological maturity, the propulsion system, climate performance, and retrofittability, as summarised in Table 1 for RLFs analysed in this study.

3.3.1. Bio-based fuel production

Different biomass type (e.g., forest residue, agricultural residue) and conversion technologies (e.g., gasification, pyrolysis, hydrothermal liquefaction, fermentation, etc.) can be employed for the production of bio-based marine fuels. The study considers only one biofuel type, i.e., biomethanol, in this study. Methanol is emerging as a leading alternative low-carbon, future-proof fuel, which is considered a promising and feasible alternative fuel (DNV, 2023). It is in an early phase of market introduction, but some large shipping companies has been investing substantially in new methanol-fueled vessels. It can be used in pure form or as a blend component in internal combustion engines (ICEs) or fuel cells.

3.3.2. Hydrogen-based fuel production

Three hydrogen-based fuels are considered in this study: liquefied e-hydrogen, e-ammonia and e-methanol. These solutions have been seen as potential low-climate-impact energy carriers when produced from renewable electricity and are currently in different developmental stages. The perspective of different stakeholders (i.e., shipping owners) on their fuel preferences and transition strategies obtained through interviews have also been taken into account in selecting the hydrogen-based fuel type.

Hydrogen is produced using proton-electrolyte membrane (PEM) or solid oxide electrolysis cell (SOEC) electrolysers from water, powered by renewable electricity. In this study, hydrogen is transported and will be used in liquid form, and thereby the liquefaction process is added to increase its volumetric energy density. Hydrogen is also used as feedstock to produce e-fuels including e-ammonia and e-methanol by employing the Haber-Bosch process and methanol synthesis, respectively.

There are other potential alternative energy carriers such as HVO, e-diesel, liquefied biogas, wind-assisted, hybrid or electric propulsion technologies. However, these have not been considered in this study.

3.4. Model input data

3.4.1. Feedstock supply

3.4.1.1. Biomass. Forest biomass, such as sawdust, wood chips and slash (i.e., treetops and branches from forest harvesting) are selected as feedstock for the production of biomethanol. Sawdust and wood chips are by-products from sawmills. Currently in Sweden, the majority of sawdust is sold for wood pellet feedstock, and some are used to meet the internal energy demand of the sawmill. Only sawmills with an annual production capacity higher than 30,000 m^3 of sawn wood are considered in this study to ensure that the availability of raw material is high enough for marine fuel production (Conti et al., 2019). The location and production capacity of the considered sawmills has been listed in a previous study (Conti, 2019).

Slash (treetop and branches) is a by-product from logging activities that is usually left to decompose in the forest. It is primarily used for energy purposes, e.g., as fuel in a combined heat and power (CHP) plant, with around 30% of the total gross potential currently being extracted from Swedish forests (Sandin et al., 2019). The potential of slash in Sweden is around 24−40 TWh/yr (Nurdiawati et al., 2023). The study assumes that slash is homogeneously distributed throughout Sweden aggregated at the municipality level. The potential of slash for each county in Sweden can be found in (Börjesson, 2021).

Considering potential increased competition for forestry by-products in the future, an assumed value of 30% biomass availability was set in the base case. The annual output capacity of sawmills and the potential

Table 1
RLFs included in the analysis and the associated technological conversion pathways.

Fuel	Energy (LHV)[a]	Production Technology (TRL)[b]	Storage method (Aziz et al., 2020)	Propulsion technology	Climate performance (WtP)[c] Fridell et al. (2022)	Retrofittability (Fridell et al., 2022)
Biomethanol	19.9 MJ/kg or 15.8 MJ/L	Integrated gasification (7–8) and methanol synthesis (9)	Ambient (25 °C, 0.1 MPa)	ICE, fuel cell	15.6 g CO_2 eq./MJ (average value)	Possible, but requires adaptation
Liquified hydrogen (e-LH_2)	120 MJ/kg	Water electrolysis using PEM/SOEC (8–9)	Liquefaction (−252.9 °C, 0.1 MPa)	ICE, fuel cell	0–20 g CO_2 eq./MJ	Possible, but costly today
Electro-ammonia (e-ammonia)	18.8 MJ/kg	Integrated water electrolysis (8–9) and Haber-Bosch process (9)	Liquefaction (25 °C, 0.99 MPa)	ICE, fuel cell	0–30 g CO_2 eq./MJ	Low
Electro-methanol (e-methanol)	19.9 MJ/kg	Integrated water electrolysis (8–9) and methanol synthesis via the Sabatier reaction (7–8)	Ambient (25 °C, 0.1 MPa)	ICE, fuel cell	0–15 g CO_2 eq./MJ	Possible, but requires adaptation

[a] Based on lower heating value (LHV), gravimetric energy density (MJ/kg) and volumetric energy density (MJ/L).
[b] TRL = technology readiness levels 1–9 scale, PEM = proton exchange membrane, SOEC = solid oxide electrolysis cell.
[c] WtP = well-to-propeller emissions.

of slash was assumed to be constant for the entire modelling period.

3.4.1.2. Renewable electricity from wind and solar. The electricity supply used in this study has been informed by the literature (Mesfun et al., 2017, 2018). The data are spatially explicit for Europe, considering the grid level, based on a ~40 km × 40 km spatial resolution. Mesfun et al. (2018) focused on the expansion of onshore wind power and solar PV. The maximum capacity is derived based on the highest wind or irradiance under the sample year and based on hourly mean capacity factors for solar and wind technologies. The study integrated biodiversity conservation and the sustainable use of the ecosystem services through avoiding potential environmental impacts and land degradation. The total area of the protected regions and their share within each grid cell are excluded from the available area for installing intermittent renewable technologies. This approach reduces the potential environmental impacts of fuel-based electricity production. In this study, the renewable energy potential from onshore wind and PV is constrained by the potential marine fuel demand in 2050 (described in Section 3.4.2) to avoid overestimating the fuel-based electricity production. The average operating hours for wind onshore is 4000 h/year (IEA, 2019; R.e, 2019) and for solar PV is 1100 h/year (Lindahl, 2016). Considering potential increased competition for renewable electricity in the future, an assumed value of 50% electricity from new added capacity of onshore wind and PV was set in the base case.

3.4.1.3. Biogenic CO_2. Concentrated CO_2 can be supplied from three major sources, which are of fossil origin (e.g., from fossil industrial flue gases like oil refineries), renewable origin (e.g., from biofuel production) and derived from direct capture in the atmosphere. In this study, CO_2 for e-fuels production is assumed from industrial plants through CO_2 capture (Trinh et al., 2021). A capture plant is located at a CO_2 point source to avoid the transportation of flue gas. To avoid reinforcing fossil fuel lock-in, only industries that emit mostly biogenic emissions is considered. Four types of industries are thus selected, including pulp and paper, CHP, biogas upgrading and biofuel plants. A total of 124 industrial facilities were selected as potential locations for e-fuel plant. The list of plant locations, their annual CO_2-release and the associated calculation method can be found in Trinh (2021).

3.4.2. Marine fuel demand

In this study, the marine fuel demand is based on marine fuel sold in Sweden, both for domestic and international shipping, according to what is reported as Swedish GHG emissions. The historical data about the energy demand for international and domestic marine transport registered in Sweden were retrieved from (Swedish Energy Agency, 2023a) and have been analysed to obtain a projection of the fuel demand over the considered timespan. This was done by the extrapolation of historical data assuming the same growth rate (1.4% per year) observed for the past 50 years.

Of all of the total fuel sold for shipping in Sweden, 96% is used by international shipping (Jivén et al., 2016). The majority of all fuel deliveries for shipping in Sweden take place with bunker vessels within the Gothenburg-Skagen sea area, and only about 20% of deliveries occur in the ports along the Baltic Sea coast, mainly by truck (Jivén et al., 2016). Thus, the study assumes that marine fuel will be distributed to the three main port areas in Sweden: the Port of Gothenburg representing West of Sweden and as the major bunkering site (80%); the Port of Stockholm representing the east area (10%); and the Port of Trelleborg representing the southern part of Sweden (10%), see Table 2. The simplification was made amidst high uncertainties concerning future bunkering locations for renewable marine fuel. However, the three large ports selected show a high ambition towards sustainability transitions in their port and are currently experimenting and investing in RLFs.

Table 2
Projected marine fuel demand in assumed bunkering ports in Sweden.

	Projected marine fuel sold in Sweden in Mton/year				
Port	2030	2035	2040	2045	2050
Gothenburg	2.30	2.47	2.64	2.81	2.98
Stockholm	0.29	0.31	0.33	0.35	0.37
Trelleborg	0.29	0.31	0.33	0.35	0.37

3.4.3. Techno-economic parameters

The model timeframe spans from 2030 to 2050 with a five-year time step using the year of 2019 as the baseline. The main financial assumptions for economic analysis are summarised in SI Table S2. An economical lifetime of 20 years and an interest rate of 5% are assumed (give an annuity factor of 0.08). The value of near-term (2030) and long-term (2050) efficiencies and capital expenditure (CAPEX) of hydrogen and e-fuel production mainly refer to a comprehensive review study by Grahn et al. (2022) supplemented with other scientific literature. The values for 2035, 2040 and 2045 were interpolated, as presented in Table S2. The CAPEX data are multiplied by an installation factor of 1.5 to determine the total capital investment (TCI). Further, the annualised CAPEX was estimated by using the annuity factor and TCI. The investment cost of various plants is assumed to decrease over time due to technological improvement and economies of scale, where greater plant sizes are assumed to be built in the future. The plant capacity is determined endogenously by the model. Additionally, the study assumes an efficiency of 65% for the electrolyser in 2030, increased to 74% in 2050 due to technology improvement, in line with various projections and the estimated value in the literature (Grahn et al., 2022; Proost, 2019).

The annual fixed operation expenditures (OPEX) were estimated at 4% of total CAPEX and assumed to be constant over the plant's lifetime. The variable costs were determined based on the utilities required, considering the electricity, water and catalysts, as listed in Table 3. The annual increase in electricity prices was based on the annual increase for the pricing area SE3, as modelled by (Swedish Energy Agency, 2021) in their reference scenario. The revenue from selling by-products, e.g., oxygen, is not considered in this study.

3.5. Scenario development

A set of scenarios are developed to investigate how different parameters affect the production of RLF, listed in Table 4. The scenarios examine changes in the economic parameters (i.e., fossil price, carbon price, and feedstock price) and demand (i.e., introduction of the blending mandate).

3.6. Limitations

The estimation of feedstock availability varies based on the type of feedstock and data availability. The renewable energy potential (Mesfun et al., 2018) and slash quantity as aggregated value (Börjesson, 2021) consider future expansion, whereas sawdust, wood chips (Conti, 2019) and biogenic CO_2 (Trinh, 2021) are based on existing facilities. This study assumed an annual fuel demand increase of 1.4%. Other factors affecting demand fluctuation are not taken into account. This paper is based on a single case study that did not aim for broad empirical generalisation but rather provided valuable insights based on the specific context. However, since maritime shipping is embedded in the international environment, the broader regional and international context was taken into account.

Table 3
Feedstock and utility prices.

Parameter	Unit	2030	2035	2040	2045	2050	Reference
Sawdust	M€/PJ	4.61	4.61	4.61	4.61	4.61	Swedish Energy Agency (2023b)
Slash	M€/PJ	4.90	4.90	4.90	4.90	4.90	Swedish Energy Agency (2023b)
CO_2	€/t CO_2						
From biogas upgrading		0	0	0	0	0	Karlsson et al. (2021)
From biofuel plant		10	10	10	10	10	Karlsson et al. (2021)
From pulp and paper		25	25	25	25	25	Karlsson et al. (2021)
From CHP		50	50	50	50	50	Levihn et al. (2019)
Electricity	M€/PJ						(Swedish Energy Agency, 2021; Trinh et al., 2021)
SE1		3.93	3.93	5.56	5.56	8.55	
SE2		3.93	3.93	5.56	5.56	8.55	
SE3		5.80	5.80	8.18	8.18	12.56	
SE4		7.08	7.08	9.99	9.99	15.32	
Water	€/t	1	1	1	1	1	Grahn et al. (2022)
Carbon price[a]	€/tCO_2	100	130	160	210	270	(Pietzcker et al., 2021) and own assumptions
Fossil price	M€/PJ	10.8	11.3	11.8	12.1	12.5	Solakivi et al. (2022)

[a] Base estimates assume a mid-range 2030 carbon price of 100 €/t CO_2 taking into account the average carbon price at around 80 €/t CO_2 in 2022.

Table 4
List of scenarios developed to investigate the effect of parameter changes on RLF production.

Scenario	Narrative	Parameter change	Year				
			2030	2035	2040	2045	2050
1. Base case (REF)	“Business-as-usual” path based on current policy, market conditions and moderate advances in energy systems and technology		See Table 3				
2. High fossil fuel price (HiFo)	The implementation of EU ETD makes fossil fuels more expensive due to higher tax rates, or the increased price is driven by supply-demand factors	Fossil fuel price (M€/PJ)[a]	20.2	21.0	22.1	22.2	22.6
3. Low fossil fuel price (LoFo)	Less exploration of high-cost new reserves and the continued energy tax exemption of marine fuel lead to a lower fuel price, or the lower price is driven by supply-demand factors	Fossil fuel price (M€/PJ)[a]	6.2	6.5	6.7	7.0	7.2
4. High carbon price (HiC)	The EU’s ambition to reduce GHG emissions creates a strong political signal that translates into a higher carbon price.	Carbon price (€/t CO_2)[b]	130	170	210	270	350
5. Low carbon price (LoC)	A lack of functioning of the EU ETS (e.g., inability to handle market disruptions in the future or due to market and regulatory failures) leads to a low carbon price.	Carbon price (€/t CO_2)[b]	35	50	60	75	100
6. High electricity price (HiEl)	A rapid increase in electricity demand coupled with a transmission bottleneck pushes electricity prices higher.	Electricity price (M€/PJ)[c]	200% base values in Table 5				
7. High biomass price (HiBio)	Increased competition for forest biomass among different sectors leads to a higher biomass price	Biomass price (M€/PJ)[d]	8.9	9.3	9.7	10.1	10.5
8. Blending mandate (BM)	FuelEU Maritime is assumed to be implemented in the form of a blending mandate[e]. The electricity resources are not constrained.						
Scenario mix		See the combination of parameters above					
9. High fossil fuel price & low carbon price (HiFo-LoC)							
10. High fossil fuel price & high carbon price (HiFo-HiC)							
11. Low fossil fuel price & high carbon price (LoFo-HiC)							

[a] Fossil price (M€/PJ_{fuel}) estimate was obtained from Solakivi et al. (2022) considering upper and lower range, which was calculated based on a linear regression of historical crude prices projected with EIA’s long-term and short-term forecasts.

[b] Low and high estimates were obtained from a modelling study by Pietzcker et al. (2021). Carbon price refers to the European Union Allowance (EUA) price (unit in €/t CO_2).

[c] High electricity price scenario reflects an extreme case assuming a doubled base electricity price (unit in M€/PJ_{el}).

[d] The annual increase was estimated based on the increase in biomass prices (M€/$PJ_{biomass}$) for 2030–2050 in Duić et al. (2017).

[e] Share of renewable and low carbon fuels in maritime energy use (in %) based on indicative trajectory presented in the FuelEU Maritime initiative (European Commission, 2021b).

Table 5
Share of RLF of total fuel demand by scenario and by year (%).

Year	Base case (REF)	High fossil fuel price (HiFo)	Low fossil fuel price (LoFo)	High carbon price (HiC)	Low carbon price (LoC)	High electricity price (HiEl)	High biomass price (HiBio)	Blending mandate (BM)	High fossil fuel price & low carbon price (HiFo-LoC)	High fossil fuel price & high carbon price (HiFo-HiC)	Low fossil fuel price & high carbon price (LoFo-HiC)
2030	0%	21%	0%	3%	0%	0%	0%	8%	5%	21%	0%
2035	5%	19%	0%	18%	0%	5%	0%	15%	18%	26%	3%
2040	17%	28%	2%	18%	0%	17%	0%	30%	18%	37%	16%
2045	25%	39%	16%	36%	0%	17%	10%	69%	17%	49%	25%
2050	45%	48%	34%	48%	4%	21%	44%	86%	34%	48%	46%

4. Modelling results

4.1. Production of RLF: resource use, conversion pathways and location sites

This spatio-temporal analysis estimates the optimal production of RLF, using multiple resources available in Sweden (forest biomass, renewable electricity, and biogenic CO_2) and technological pathways (bio-based fuel and hydrogen-based fuels). Details of resources use, RLF production, and the share of RLF in total fuel demand (i.e., marine fuel sold in Sweden) for each scenario are shown in SI and Table 5.

In the base case (REF), biomethanol from forest biomass will become cost-competitive compared to fossil-based marine fuel in 2035, producing 6 PJ_{RLF}/year. By 2050, 67 PJ_{RLF}/year can be produced in Sweden, meeting 44% of the total marine fuel sold in Sweden (see Fig. 3 for the municipalities in Sweden and Fig. 4 for the production share of RLF by technology by municipality). The result shows that carbon prices beyond 100 €/tCO_2 need to be in place to promote biomethanol production. Biomethanol presents a cheaper technology option compared to hydrogen-based fuels. The hydrogen-based fuels (e-LH_2 and e-methanol) become cost-effective at a carbon price of 160 €/tCO_2 and more favourable at a carbon price above 200 €/tCO_2. Higher technology cost, lower conversion efficiency and resource competition with e-LH_2 concerning renewable electricity demand, makes e-ammonia less competitive compared to other technology options.

Fig. 3. Municipalities in Sweden.

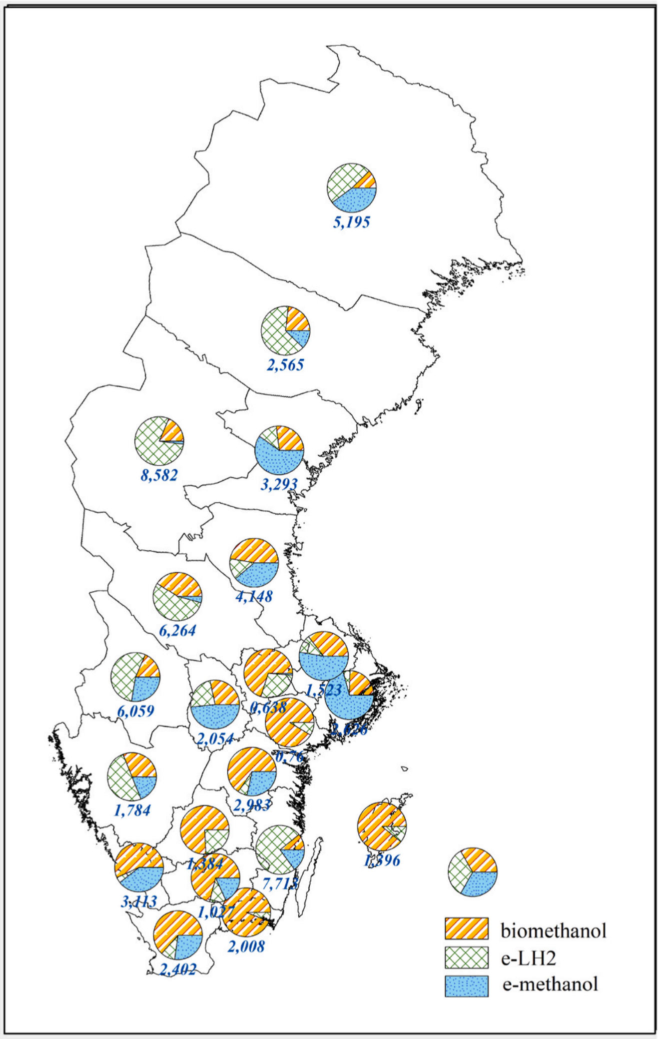

Fig. 4. Production share of RLF by technology (PJ/y), base case scenario, 2050

The high price of carbon (HiC, HiFoHiC) increases the cost competitiveness of RLF, providing opportunities to achieve the share of RLF at 48% in 2050 (see Table 5). High fossil and carbon prices (HiFo-HiC) can push for a higher share of RLF of 21% by 2030, which is higher than the share set by the blending mandate (8%). High prices of biomass and electricity will delay the uptake of biomethanol and eLH_2. Moreover, the production of biomethanol and eLH_2 will be cost-effective, respectively, in 2045 (HiBio) and 2050 (HiEl), a delay of 10 years compared to the base case (REF).

The highest RLF's share of 86% is obtained in the scenario where the blending mandate is enforced. The blending mandate establishes a minimum share of RLF for ships in navigation calling EU ports. In this scenario, the availability of electricity is not constrained when the blending mandate is imposed. To meet 86% of the blending mandate in 2050 consequently requires a significant amount of resources, consisting of 47 $PJ_{biomass}$/y, 159 PJ_{el}/y and 2 $MtCO_2$/y. That amount of electricity is equal to 1.5 fold of the energy supply produced by onshore wind and solar in Sweden in 2020 (104 PJ_{el}/y) (The Swedish Energy Agency, 2022). This shows that such a high blending mandate could create competition with other sectors that have a high demand for green electricity (e.g., road transport, residential heating, heavy industry).

The analysis reveals the optimal technology conversion pathways and plant sites including the size for RLF production (see Fig. 6). The production of RLF is dominated by hydrogen-based fuels (e-LH_2 and e-methanol) in the northern part of Sweden, i.e., Norrbotten, Västerbotten, Västernorrland, and Jämtland, driven by the availability of resources and cheaper electricity prices compared to the southern part of Sweden. In the rest of Sweden, the proportion of bio-based and hydrogen-based RLF is also driven by demand located in the southern part of Sweden.

Fig. 5 maps out the fuel trade flow to meet the marine fuel demand in the selected three ports of Sweden (i.e., Gothenburg, Stockholm, and Trelleborg). Fuels from all parts of Sweden need to be imported to meet the demand in the Port of Gothenburg, which represents 80% of total demand. The RLF demand in the Port of Stockholm can originate from the north and the middle of Sweden, and in the Port of Trelleborg, it can originate from the southern part of Sweden. In the base case scenario (REF), by 2050, 100% of demand in the Port of Stockholm and Trelleborg can be met from RLF, whereas only 40% of fuel demand in the Port of Gothenburg can come from RLF. This means that the Port of Gothenburg needs to import RLF from other countries to meet the entire RLF demand, and at the same time reinforce other mitigation pathways, e.g., energy efficiency improvement and improving management practices.

When it comes to the potential plant location and size (Fig. 6), since the RLF demand is concentrated in the southern part of Sweden, the locations of plant sites with a capacity range between 0.5 and 3 PJ/year are mostly in the middle and southern part of Sweden. The plant size within the aforementioned range covers more than 60% of the total RLF production in Sweden.

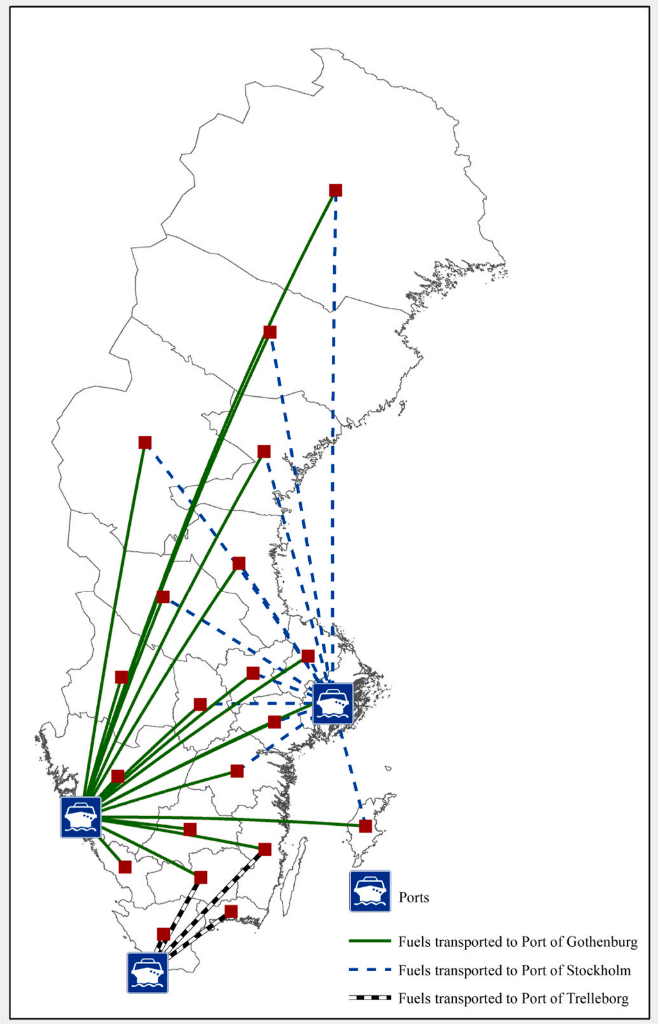

Fig. 5. Fuels transported from production sites to ports, base case scenario, 2050

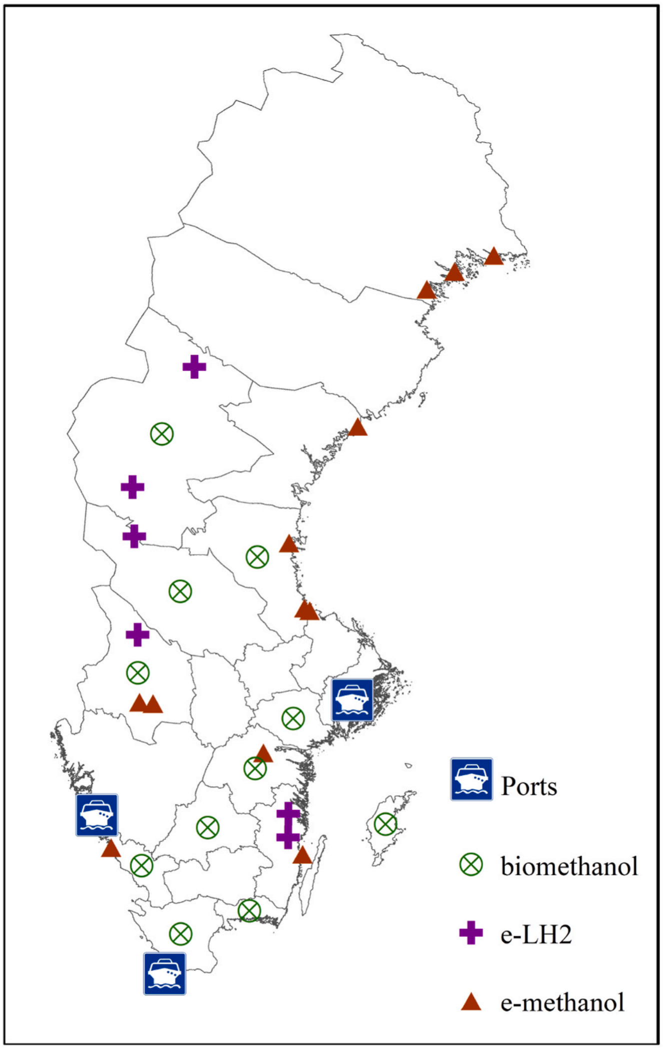

Fig. 6. Potential location sites for RLF production, capacity 0.5–3 PJ/y, base case scenario, 2050

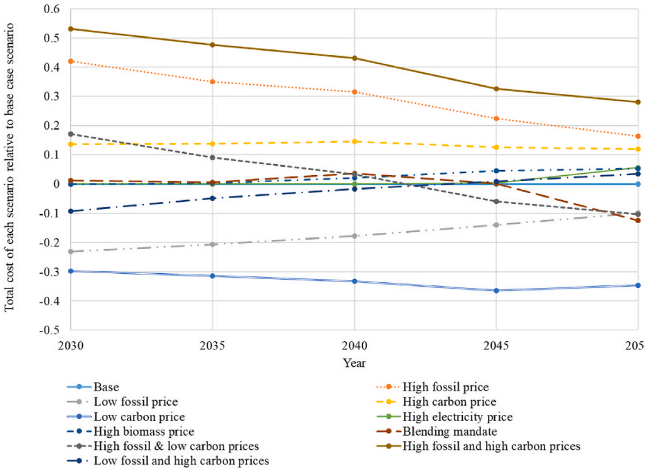

Fig. 7. Total cost of each scenario relative to base case scenario 2030–2050. Total cost is defined in Section 3.2.

4.2. Economic and environmental implications

This section discusses the results of the economic and environmental implications from upscaling the production of RLF in Sweden. Fig. 7 presents the total cost of scenarios relative to the base case scenario in 2030–2050. The total cost, as explained in Section 3.2, encompasses total feedstock, total technology cost, total transport cost, total carbon cost and total fossil cost. It is interesting to highlight that the total cost of the blending mandate scenario is relatively similar to the base case scenario, albeit the highest RLF share is obtained by imposing the blending mandate. A higher RLF share in the blending mandate scenario results in higher feedstock, technology and transport costs, but at the same time lowers the total cost of carbon and fossil fuel due to less fossil fuel being required in the system, compared to the base case. In the scenario with a blending mandate, the RLF (fuel-mix) unit production cost can reach 34 €/GJ, compared to the base case, which is 73 €/GJ, in 2050.

The highest total cost is obtained in the high fossil and high carbon prices scenario, where the cost is 50% higher in 2030 compared to the base case. A cost reduction of 25% in the high fossil and high carbon prices scenario (HiFo-HiC) in 2050 compared to 2030 system cost level (relative to base case scenario), Fig. 7, not only results from the increase of both prices, but also the effect of conversion technology improvement and lower investment cost.

The emissions reduction potential is derived from total fossil fuel replaced by RLF multiplied by the emission factor of marine diesel fuel (90.6 gCO_2/MJ), see Fig. 8. The highest emissions reduction potential is obtained in the blending mandate scenario, with the average annual emissions reduction potential 2030–2050 of 5 $MtCO_2$ eq./y. This is equal to 12% of total CO_2 emissions in Sweden in 2019 (World Bank, 2023). As indicated in Section 4.1., such a high share of RLF in 2050 (80%) requires significant investment in renewable electricity supply and potentially competes with other sectors that have a high demand for renewable electricity.

The study finds that the emissions reduction potential of high carbon price (HiC), 7 $MtCO_2$ eq., is slightly higher than base case (REF), 6 $MtCO_2$ eq. It implies that when other parameters remain the same, with support from technological and market developments, the carbon price at 270 €/tCO_2 and 350 €/tCO_2 in 2050 provides a higher impact in terms of emissions reduction potential.

The study shows considerable emissions reduction from RLF use in the marine sector. It is important to note that the feasibility of RLF application and challenges vary widely for different ship types and segments (Fridell et al., 2022). The choice of RLF depend on among other things the travel distance and speed requirements. For example, the deep-sea shipping which operate over long distance will require larger storage capacity which influence the type of suitable RLF, whereas the short-sea shipping segment can be more efficient with battery-hybrid propulsion system than traditional fuel/propulsion system.

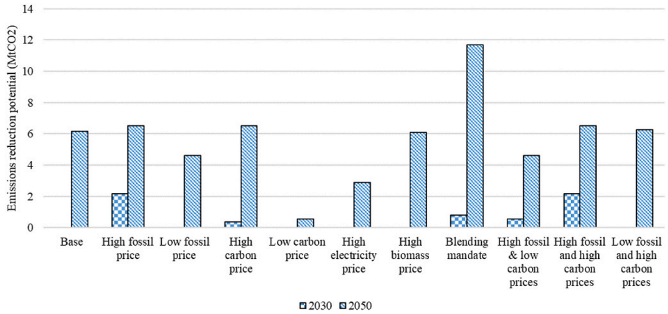

Fig. 8. Emissions reduction potential from RLF production in 2030 and 2050, in $MtCO_2$ eq.

5. Envisioning transition potentials

Although RLFs are potentially beneficial to decarbonising maritime shipping, as discussed in the previous section, the literature has captured that many emerging low carbon technologies struggle to develop and compete with the existing technologies. This section presents complementary perspectives, besides technology and policy, including actor-network, market, infrastructure, attitudes and behaviours towards RLFs, which are relevant to obtain a more nuanced understanding of the transition potential towards low-carbon futures for maritime shipping.

Historically, shipping has transitioned from sail to steam power and then to internal combustion engines over a period of a hundred years. Given the urgent need for transitions towards a low carbon economy, a new wave of innovation in shipping is now emerging. Table 6 summarises five dimensions at which the maritime sector as a socio-technical system may be disrupted.

While biofuels can be considered the most ‘technologically ready’ of existing low-carbon fuel alternatives, hydrogen and electrofuels are building momentum, which could help the shipping industry comply with increasingly stricter emissions rules in the long run. According to the modelling, e-ammonia is less competitive compared to other technology options, primarily driven by high investment cost and lower efficiency compared to e-LH_2. The majority of interviewees also raised concerns about its safety, maturity, and need for different structures for ammonia in terms of bunkering and infrastructure in ports. Other technologies such as wind-propelled propulsion and electric vessels were mentioned by some interviewees; however, all agreed that they would only play a minor role and only for some segments of the shipping industry.

Table 6
Summary of system disruption.

Disruption	Maritime shipping
Dimensions	
Technology	• New advances in energy and propulsion systems for ships • Hydrogen-based fuels are gaining momentum, and there are increased pilot projects in the shipping sector • Methanol is increasingly being used for shipping • Ammonia has potential as a shipping fuel, but there are safety concerns
Actor-network	• Increasing experimentation by big shipping companies having ambitious climate targets and the emergence of niche players (e.g., new technology suppliers) • New alliances and collaborations formed between major cargo owners, ship classification societies, bunker firms and various technology providers • Increased importance of ports as hubs for energy transitions (i.e., providing bunkering systems)
Market and business models	• Pressure to renew incumbent business models in moving away from crude refining’s residue to cleaner fuels • Increased demand from container shipping customers to reduce their transport and logistics (Scope 3) emissions creates synergies in the supply chain’s decarbonisation efforts • Some incumbents invest more in dual-fuel engines for new vessels to reduce the risk of uncertainties
Policies and regulation	• Several regulations at the international (IMO), EU and national levels driving the transitions towards sustainable shipping, with different levels of ambition • Emerging frameworks and standards allow regulators, ship owners and investors to drive decarbonisation • Green shipping corridors initiative to showcase zero-emission fuels and technologies along maritime trade routes
User practices	• Growing sustainability awareness among shipping customers • Wide differences between actors, with some incumbents transitioning more rapidly while others are more reluctant • Different strategies in different segments of the shipping industry (e.g., ferries, container ships, bunker ships, etc.)

The availability of RLF for maritime shipping depends on the availability of resources, scalability, sustainability, cost and demand from other sectors such as aviation. For biofuels, scalability and sustainability are the two main issues that should be addressed. With other industries interested in using biomass and biofuels as part of their transition, this could drive up RLF feedstock prices. While economies of scale are expected to make RLF more cost-effective, the limited availability of feedstock, fuel competition, and sustainability-related issues could push prices in the opposite direction. The result of the modelling shows that high feedstock prices will delay the transition towards sustainable fuels.

Hydrogen-based fuels are considered superior to biofuels in terms of long-term scalability (Dawe et al., 2021). However, they depend on low carbon electricity from renewables and/or nuclear energy for their production. As one interviewee highlighted: *the big question is, where will this (electricity) come from? Because the thing with green methanol, green ammonia, and hydrogen (is that it) requires a lot of green electricity. And there is a lack of electricity, and the lack of green electricity is even worse*" (O3, Association). This uncertainty is also attributed to the fact that there are growing electrification efforts in different sectors. One interviewee further reinforced, "*our biggest concern at the moment is the electricity supply because there is a very big competition about the electricity, including this project in the north of Sweden, about fossil-free steel (production from hydrogen) which needs quite a huge amount of electricity*" (C2, company). Based on the modelling, around 155 PJ_{el} is required to meet 86% of the blending mandate in 2050. These electricity needs for RLFs production (both domestic and international shipping) is comparable to the electricity required to decarbonise Swedish heavy industry (steel, cement, mining, metal, chemical, refinery, and pulp and paper) and road transport according to the estimation by Sweco (2019), which is around 144 PJ_{el}.

The total amount of marine fuel sold in Sweden in 2021 is around 2.4 million metric tons, while the annual global marine fuel consumption is projected to be around 330 million metric tons (Tan et al., 2020). From a global perspective, the scale of the transition is therefore massive. One interviewee illustrated, *"so, we (the shipping company) have 19 green methanol vessels coming into our fleet by 2026. Today the global production of green methanol is 30,000 tonnes a year globally, and we need around 700, 000 tonnes for our first 19 ships. However, we operate over 720 ships (globally)"* (C1, company). Heavy investment is thus needed along the fuel supply chain, especially in fuel production facilities as presented in this study, as well as in a new or retrofitted fleet.

Most interviewees pointed out that regime shifts, while unlocked by technological innovation or behavioural change, are strongly shaped by landscape level pressures. However, some of them expressed concern over the discrepancy between the current IMO targets and the EU ambitions that can be a source of carbon lock-in. Shipping is embedded in the international environment, and the associated fragmented structures along with the different sizes and types of vessels, make consensus about decarbonisation policies difficult. Moreover, there are still uncertainties about future incentives for RLFs/disincentives for fossil fuels, such as energy, carbon taxes and blending mandates, at the regional level. With no incentive to switch to RLF, more and more shipping companies are choosing to invest in LNG-fueled vessels, which risks carbon lock-in and fossil fuel dependency for decades.

Several interviewees pointed out the role of incumbent companies in relation to the RLFs and propulsion technologies development: "*what we can see is that the ship owners and the technology providers experimenting with many different fuel solutions and the number of ships that have a hybrid fuel capability are increasing*" (K3, Academia). However, most interviewees expressed concern that fuel availability and supporting infrastructure are the two main barriers, as one interviewee pointed out, "*you need to be certain that this fuel, whatever fuel we will have in the future, is available in all major ports and bunkering hubs"* (O3, Association). The finding shows that a major shipping company leverages strategic alliances with new players to solve this chicken-and-egg situation, turning this into competitive merit by locking in the RLF supply now. Major companies must make decisions about huge investments and the choice of technology/fuels now to enable a transition in the near to medium future, as vessels have lifetimes of several decades. Regime resistance and thereby delays in investing in new technology and delays in building new business alliances could mean losing out to the competition later. "*I used to say this is the shipping Kodak moment, right? The moment where either we make the wrong choice and we don't exist anymore.*" (C1, company). However, for the majority of shipping companies, inaction and a wait-and-see strategy is a default choice, given the huge uncertainties around the future costs of technologies and fuels, policy landscape, customer demand, and access to capital, among others. This low carbon development also reinforces the port's pivotal role in sustainability transitions of maritime shipping. Technological changes in ship propulsion will result in changes in bunkering requirements at ports of call.

Despite improvements in technology, the fact remains that the nature of the shipping industry shapes the dynamic among different market segments. The operational pattern, visibility to the end consumer, policy, financing landscape, as well as company resources and capability influence the behaviour of the shipping companies in relation to the uptake of RLFs. Those shipping companies that are more exposed to customer visibility seem more likely to transition towards low-carbon technologies than others. Customer awareness is usually higher for local ferries (such as commuter ferries in the Archipelago), as well as global logistics companies that are working with multinational corporations that have high public visibility (e.g., in the fashion industry). Low customer awareness occurs for those shipping segments that have low public visibility and low environmental and social accountability, such as bunkering ships (e.g., oil tankers).

6. Addressing conditions for sustainability transitions in the shipping sector

The targets of the Paris Agreement and particularly the policies and regulations within the EU are driving forces for change in the shipping industry. "*One political driver comes from the European Union, the Green Deal, the Fit for 55 and the inclusion of shipping into the European Emissions Trading Scheme. (…) That is going to put a price on carbon and that's going to change the dynamics in the freight market for all the ships that call in EU ports, which of course, is a very important shipping market*" (K3, Academia). The price of carbon within the EU ETS has been relatively high at the time this study, conducted in 2022/early 2023, ranging between 80 and 100 €/t CO_2. However, shipping experts interviewed for this study estimate that the carbon price needs to be at least about 150 €/tCO_2 to create a financial incentive for shipping companies to avoid polluting. The results of the modelling are in line with the expert's view for creating favourable conditions for the production of hydrogen-based fuels, which requires carbon price at 160 €/tCO_2 (discussed in Section 4.1).

A combination of demand pull-types of instruments, technology-push instruments, and fiscal policies are essential to meet the net-zero emissions in the shipping sector. Demand pull policy, such as a blending mandate, is needed to force investment and mandated renewable fuel off-take. It is cost-effective particularly at the beginning of the transition period, while waiting until the market is further developed. The blending mandate needs to be carefully designed to avoid competing resources use. Technology-push policy, such as investment grants/loans for capital expenditure, can advance technologies along the entrepreneurial and technology development cycle from R&D and piloting to scale-up. Fiscal policies can pass on carbon costs to emitters, reducing carbon-intensive behaviour. Robust carbon prices stimulate innovation and are needed to close the cost gap between conventional fossil-fuel-based technologies and RLF. Operating alongside carbon pricing, energy taxation could drive the change needed for net zero.

Several interviewees advised that the government should stimulate a market for low-carbon products, for example, through public procurement. Overall, investors are hesitant to invest in RLF production, because the technologies are not widely used yet (e.g., hydrogen- or methanol-driven vessels) and because the demand is uncertain. On the other side, shipping companies are reluctant to invest in new technologies and different types of vessels because the RLF supply is limited. Reducing the investment risks requires both fuel producers' and shipping companies' active policy engagement through, for example, subsidies, investments by the state, public-private partnerships, etc. At the same time, strict regulations by policy-makers can provide incentives even for the most reluctant companies, as they aim to avoid fines and other financial penalties. One challenge is that the maritime shipping industry is willing to pay less for sustainable fuel, in comparison to other transportation sectors that are competing for the fuel, such as the aviation industry and the vehicle industry. Low willingness to pay for sustainable fuels is likely to lead to lower volumes supplied to the shipping sector, which may again be used as an argument for not transitioning towards newer, cleaner technologies.

Besides regulatory framework and policy instruments, there is a clear need for infrastructures, including resilient power generation and transmission systems, and robust power system planning to facilitate the production of RLFs, in line with previous research. The study also argues that wider collaboration and synergies are required as decarbonisation in one value chain (e.g., retail business) depends on developments in other chains (e.g., container shipping), which call for firms and other actors in the broader decarbonisation ecosystem to establish effective partnerships. Moreover, in term of human resources, applying the new fuel and propulsion technologies safely demands a re-skilling/upskilling of the maritime workforce, highlighting the need for investment in this area.

From a global perspective, regulating the maritime shipping industry in Sweden and the EU more tightly to achieve sustainability transitions may have some international effects, including knock-on effects where other regions might follow suit. It is likely to lead to front-runner advantages and increased competitiveness in the long run. However, there is also a risk of carbon leakage, with ships calling at Swedish or EU ports but bunkering fuels elsewhere outside of this region. Economic implications for internal trade might occur; however, strong negative economic impacts could be unlikely as Europe is one of the world's largest trading hubs and markets.

7. Conclusions

This article explored the prospects, opportunities and barriers to decarbonising the maritime industry in Sweden, taking into account the actual production sites and resource availability, as well as combining techno-economic modelling and socio-technical transition studies. The study used a mixed methods approach, combining quantitative modelling with qualitative expert interviews.

The study found that there are opportunities for decarbonising the maritime shipping industry by using renewable marine fuels such as advanced biofuels (e.g., biomethanol), electrofuels (e.g., e-methanol) and hydrogen. Other options include battery-electric vessels and wind-powered vessels, although these are unlikely to be an option available for larger vessels and longer distances. As transition fuels, LNG is being used by an increasing number of shipping companies. Ammonia is considered as unsafe by many experts due to its explosiveness and difficulty to handle and store. Methanol is likely to be increasingly used in the future, with one major shipping company investing heavily in new vessels that are adapted to methanol.

Sweden has a tremendous resource potential for bio-based and hydrogen-based RLF production. The results of the modelling shows that Sweden can produce 68 PJ_{RLF}/y by 2050, consisting of 24 $PJ_{biomethanol}$/y, 28 $PJ_{e\text{-}LH2}$/y, and 16 $PJ_{e\text{-}methanol}$/y. Biomethanol presents the cheapest technology option while e-ammonia is the most expensive one. To meet 45% of the projected fuel demand in 2050, Sweden needs to use 30% of the total potential of forest biomass (from sawdust, wood chips and slash) and 41% of the total potential of renewable energy sources from PV and onshore wind. A higher share of RLF consequently lead to more resources. This in turn highlights the importance of operational- and market-based measures to meet net-zero emissions in the shipping sector. Green electricity plays an important role in the decarbonisation of the maritime sector, and the results of the supply chain optimisation pinpoint the location sites and technology in Sweden as well as the trade flow to bring the fuels to where the bunker facilities are located.

Linking back to the socio-technical transition pathways, the authors find the following: 1) there is regime resistance towards change from parts of the incumbent industries; 2) niche innovations are emerging at increasingly competitive prices; and 3) there is increasing landscape pressure from international and national energy and climate policy-making regarding the need to decarbonise the maritime shipping industry. While it is likely that change will be slow, and some actors will be reluctant to decarbonise in the near-to medium-future, others will be actively pushing the transition towards more sustainable fuels in maritime shipping forward. There will then be frontrunners, who are already investing today in a restructuring of their fleets and their operations, whereas there will be laggards who will continue to follow the path dependency of carbon lock-in. As fossil fuel infrastructure is likely to become a stranded asset at some point in the not so distant future, and since economic instruments such as carbon taxes and emissions trading will make it economically attractive to invest in renewable maritime fuels, it will only be a matter of time until the maritime shipping industry decarbonises as well.

The decarbonisation strategies, including the feasibility of alternative fuels and energy efficiency measures, will vary widely for different ship types and segments. Future research can explore decarbonisation pathways in different ship types (e.g., cargo, container, tanker, etc) and segments (deep-sea shipping, short-sea shipping, inner-city transport). Investigating the role of different stakeholders and opportunities for industry and sectoral collaborations are key to overcome barriers for upscaling the RLF. Future research could also explore the sensitivity of the technology costs and technological scaling effect, which are meaningful considering the high uncertainty of future inflation and supply chain risks. The study which focused on developing the sustainability and safety criteria for the development of RLF that takes into account the whole life cycle is meaningful to ensure the positive environmental impact of utilizing the RLF. Finally, future research on the requirement of new infrastructures or adaptation of the existing ones is important to secure adequate access to RLF supply on a global scale.

CRediT authorship contribution statement

Fumi Harahap: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Anissa Nurdiawati:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Davide Conti:** Conceptualization, Data curation. **Sylvain Leduc:** Software, Methodology. **Frauke Urban:** Conceptualization, Data curation, Methodology, Investigation, Funding acquisition, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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