Navigating unchartered waters: Overcoming barriers to low-emission fuels in Swedish maritime cargo transport

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Original research article

Navigating unchartered waters: Overcoming barriers to low-emission fuels in Swedish maritime cargo transport

Elin Malmgren [a,*], Selma Brynolf [a], Linda Styhre [b], Jan van der Holst [c]

[a] Department of Mechanics and Maritime Sciences, Chalmers University of Technology, Gothenburg 412 96, Sweden
[b] IVL Swedish Environmental Research Institute, Gothenburg 411 33, Sweden
[c] Länsstyrelsen i Västmanland, Västerås 721 86, Sweden

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ABSTRACT

The maritime transport sector is often considered hard to abate in the context of greenhouse gas emissions, and the adoption of low-emission marine fuels is slow. Low-emission marine fuels are essential to create a sustainable maritime sector, but to accelerate the speed of adoption, we must understand what hinders their use. This paper outlines the complexity of the marine fuel choice and describes the market landscape. Taking a bottom-up perspective, we investigate the stakeholderś perspective on low-emission marine fuels. Through thematic analysis, barriers and drivers are analyzed for adopting low-emission marine fuels in Swedish maritime cargo transport, using primary qualitative data from 17 semi-structured interviews. The results confirm previously established barriers, such as fuel price, but expand on the current discourse by incorporating qualitative dimensions. We also identified five specific business models for low-emission marine fuel use. Shipping companies trust that investments in sustainable alternatives will eventually pay off. Despite this, the adoption is slow. The themes reveal a sector that wants to transform but often lacks drivers without well-developed legislation. By directing attention to these themes and the underlying complexities, we provide valuable insight to decision-makers and policymakers on what can be done to accelerate the share of low-emission marine fuels.

1. Introduction

Global transportation allows for raw materials and goods to be available across economies, making maritime transport essential in the global economy [1]. However, maritime transport's contribution to climate change is significant as ships emit over 1000 million tonnes of CO_2 equivalents per year, or close to 3 % of the global anthropogenic emissions [2]. Fossil fuels have been the primary marine fuels since the engine overtook the sailing vessel in the 19th century [1], and today, over 99 % of fuels used are fossil [2]. Therefore, the transition to fuels with lower climate impact is a key issue for the maritime industry [2,3].

However, choosing an alternative marine fuel is difficult, as many alternatives to fossil fuel oils have low technical maturity, high costs, and are not available at scale [4]. Moreover, an alternative fuel does not necessarily perform better from an environmental perspective. An attractive fuel must be a low-emission fuel associated with low emissions and pollutants over its entire life cycle. Emissions from fuel use in maritime transport negatively impact the oceans (e.g. [5]), human health (e.g. [6]), the climate (e.g. [2]), biodiversity, ecosystems and more.

The choice of marine fuel is complex as each option has specific characteristics and different technical, economic, environmental, and social performance [3,7,8]. Table 1 outlines the primary characteristics of some suggested fuels/energy carriers for maritime transport and how they depend on the fuel production pathway (i.e., fossil, biogenic, or electricity). The discourse around marine fuels highlights several future propulsion options, such as hydrogen, ammonia, alcohols, wind, and batteries, and stakeholders must weigh different aspect against each other when choosing marine fuel as no option is decisively better for all applications [7,9–15]. Thus, conclusions on “what is the best marine fuel” vary depending on context and preferences. A broader more inclusive set of sustainability criteria for choosing marine fuels has been mapped in the scientific literature, by among others Ashrafi et al. [16] and Andersson et al. [17]. However, as concluded by Ashrafi et al. [16], there is still a lack of understanding of how the different stakeholders in the maritime transport supply chain consider and choose marine fuels and propulsion systems.

The implementation of low-emission marine fuels is slow [3]. Less

* Corresponding author.
E-mail addresses: elin.malmgren@chalmers.se (E. Malmgren), selma.brynolf@chalmers.se (S. Brynolf), linda.styhre@ivl.se (L. Styhre).

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Table 1
Summary of supply, production, and fuel characteristics of different marine fuel pathways. The table gives an overview of some aspects and does not address blue pathways (pathways utilizing CCS). The information presented is based on Malmgren et al. [55] as well as the literature review as described in the method chapter. The table does not consider aspects relevant for energy companies nor fuel producers.

Energy carriers	Energy carrier characteristics	Fossil pathway	Biogenic pathway	Electricity pathway
General properties	The choice of energy carrier is governed by the installed engine system onboard the vessel as one engine only can be run on specific energy carriers	Energy primarily from fossil reservoirs Fuels are often referred to as fossil fuels Directly contributes to global warming Established production, distribution infrastructure, and engine deployment Widely used fuels with a general high social acceptance Fossil energy is a finite resource over the human lifespan Exposed to price fluctuation Contains chemical elements from the geological process which is emitted when combusted if not purified, such as Sulphur and metals [56]	Energy primarily from biomass Fuels are often referred to as biofuels Biogenic fuels have the potential to be climate neutral depending on cultivation practices, equal size harvesting and land use management Zero climate impact requires all support systems to have zero climate emissions The biomass type impacts production pathways and sustainability When waste streams of biomass are used avoided emissions might be accounted for Associated with eutrophication through nitrogen leakages in land management Supply is limited due to the limit on sustainable biomass extraction [57] Land use competition	Energy primarily from electricity Fuels are often referred to as electrofuels Generally, offer emission reductions if produced from low-emission electricity [58–60] Most fuels can be produced from electricity in combination with water electrolysis and additional molecules resulting in synthetic fuels [61] The fewer conversion steps and the less complicated chemical bounds the lower these losses are on average (this is also production process dependent) [61]. Electrofuels not yet available at scale [62] Electrofuels has a comparatively high production cost (not applicable for direct electricity) [58] The emission profile of the fuel is dependent on the original electricity production pathway (low emission amounts in the electricity production corelates to low emissions for the full life cycle of the fuel). [58]
Heavy fuel oil (HFO)	Primary fuel used today High emitter of particulate matter and other regulated, health damaging and environmentally damaging emissions	Produced from crude oil – heavier fractions The main conventional fuel still used in shipping Contains Sulphur resulting in SOx emissions during combustion and associated environmental impacts	–	–
Marine gas oil (MGO)	Primary fuel used today High emitter of particulate matter and other regulated, health damaging and environmentally damaging emissions	Produced from crude oil – heavier fractions The main conventional fuel still used in shipping Contains Sulphur resulting in SOx emissions during combustion and associated environmental impacts	–	–
Diesel	Has a relatively high energy density A flexible fuel which can be used in different mixtures High cetane value Maintains high quality over long periods of time without use	Produced from crude oil One of the main conventional fuels still used in the transport sector at large	Biogenic diesels are like petroleum-derived fuels in their physical properties, but not identical and the properties varies between non-fossil diesels [63]. The final product therefore varies and the chemical structure for diesel is less homogenous than the other fuels Can generate byproducts depending on production pathway Biodiesel fuels most discussed are fatty-acid methyl esters (FAMEs) and hydrotreated vegetable oils (HVO) Several non-fossil diesel options are possible to use as blend-in fuels in automotive engines, and Scania and Volvo have approved HVO for use in their marine engines [64] Biodiesel alternatives for the marine sector, besides HVO and FAME, are at a low TRL level currently, but projects for further development are ongoing Biodiesel is produced from crops high in sugar (starch) or fat	Production of electro-diesel has greater energy loss and therefore higher electricity demand than simpler fuels such as alcohols. Production of electro-diesel have various pathways, including for example FT synthesis [65] Mixable with biogenic and conventional diesel of similar type
Methane	Currently the main alternative fuel in the *ship* order books Is a very potent greenhouse gas and as such all forms of leakages need to be minimized Is a gas at standard temperature and pressure Has a low volumetric density and is therefore most	Produced from natural gas Is associated with similar or higher climate impact than conventional marine fuels dependent on the natural gas supply chain and methane leakages	Produced from dry or wet biomass Bio-methane (other referred to as biogas) has a limited climate mitigation potential when produced from most feedstocks	Electro-methane is produced through the Sabatier reaction, where hydrogen from electrolysis (or other electricity-based hydrogen production) is combined with CO2 from biogenic point sources or direct air capture Limited climate mitigation potential

(*continued on next page*)

Table 1 (*continued*)

Energy carriers	Energy carrier characteristics	Fossil pathway	Biogenic pathway	Electricity pathway
	often stor*ed* in liquified form *using cryogenic storage* Contains carbon, which can be a barrier if regulation will be strictly put on direct emissions from a ship Potential competition with other sectors such as heating and industrial feedstock			
Methanol	Compatible with multifuel marine diesel engines Liquid fuel at ambient temperature, Compatible with existing liquid fuel infrastructure Contains carbon, which can be a barrier if regulation will be strictly put on direct emissions from a ship Potential competition with the chemical sector where methanol is a major feedstock Toxic to humans Biodegradable	Produced from natural gas or coal Significant global production today *Is* associated with similar or l*ower* climate impact than conventional marine fuels depending on fuel production efficiency	Produced from dry or wet biomass Some global production available Reduced climate impact significantly for several production pathway	Electro-methanol is produced through a methanol synthesis, where hydrogen from electrolysis (or other electricity-based hydrogen production) is combined with CO2 from biogenic point sources or direct air capture Pilot production facilities running on Iceland and in China Swedish production planned Has a low climate impact if produced from renewable energy and carbon
Ammonia	Has a low TRL level Safety and risk a concern Highly toxic Is a gas at standard temperature and pressure Stored at ambient temperature at 10 bar, or at ambient pressure at a temperature below −33 °C Potentially high NOx and N_2O emissions, if used in ICE requires additional abatement technology Potential competition with other sectors such as farming and chemical industry	Produced from natural gas Fossil ammonia has a significant global production [66]	Possible to produce from biogas through the Haber–Bosch process	Produced through the Haber–Bosch process from renewable energy through electrolysis The first project to start production in Norway is ongoing with a proposed timeline to start production around 2027
Hydrogen	Has a low TRL level Safety and risk a concern Space requirements for onboard fuel storage is challenging Compressed, cryogenic and cryo-compressed storage alternatives possible No infrastructure available Is a gas at standard temperature and pressure Hydrogen has indirect climate impact and leakages need to be minimized	Produced from natural gas through steam methane reforming and water gas shift Blue hydrogen production with carbon capture possible	Produced from biogenic methane (see methane) through steam methane reforming and water gas shift	Electro-hydrogen is produced from renewable energy through electrolysis Electro-hydrogen has few energy transformations steps from renewable electricity to fuel [67,68]
Electricity	Direct use of electricity in electric drive lines have low emissions, with no direct air emissions from the engine system, and a high life cycle efficiency from power production to use. Space requirements for onboard fuel storage is very challenging especially for ships operating long distances Demand on infrastructure in port is high C*haring* time might be long	Produced from coal, natural gas, and other fossil fuels in power plants	Produced from biomass	Produced using renewable pathways such as wind, solar, and waterpower

than 6 % of the fleet is using any form of alternative fuels [18], with the majority being fossil liquified natural gas (LNG). Only approximately 10 % of the vessel in the global shipbuilding order books constitute an alternative to fossil fuel oil [19]. In contrast, the proportion of renewable energy used in European road and rail transport has increased from 2 % in 2005 to 10.2 % in 2020 [20] and the share of electric drivelines for new cars sold in Europe was 10 % in 2021 [21]. The uptake is so slow that, for example, in Sweden the total greenhouse gas emissions from ships are increasing despite alternative fuel implementation (see Fig. 1). The increase can mainly be explained by the continuous growth in transport work performed in the maritime industry [22–24]. Damaging Sulphur emissions to air have instead decreased as Sulphur regulations have been implemented (purple lines in Fig. 1).

The barriers hindering stakeholders to adopt low-emission marine fuels have been investigated in non-academic literature [27–33], but there is a lack of peer reviewed research. Ghaforian Masodzadeh et al. [34] investigate the issue of transitioning the industry to low-emission fuels from an argumentative standpoint and makes an initial attempt at mapping measures to overcome perceived barriers for implementing low-emission marine fuels in the maritime sector. However, the analysis uses generic market barriers and fails to look at the shipping specific barriers and stakeholders while missing qualitative aspects in the decision-making process. Rehmatulla and Smith [35] argued the market barriers are both sector and industry dependent. Barriers and drivers have been discussed in relation to specific propulsion technologies, such as wind propulsion [36] and biogas [37], and there are some studies which investigate drivers to implement low-emission marine fuels, but are limited to one or two stakeholders [38–42]. The literature is more extensive regarding barriers and drivers for implementing energy efficiency measures in maritime transport [35,43–47]. Barriers hindering the maritime sector in the transition to low-emission fuels, such as cost and technical feasibility, is discussed in the literature today [48], but there is a lack of studies on what drives the fuel choice [16] and how stakeholders interact and collaborate to reduce ship emissions.

Sweden can be considered an early adopter of new fuel technologies [49]. However, with few exceptions the Swedish shipping sector still relies on internal combustion engines (ICE) operated on fossil fuel oils [50]. The total bunkered marine fuel in 2021 in Sweden was 29.9 TWh, of which 700 GWh (2.4 %) was alternative fuels [51]. Natural gas was the most used alternative fuel, but some biogenic fuels were used (primarily hydrotreated vegetable oil (HVO)) and electricity is present in the fuel mix [50,52]. The Swedish electricity grid has a relatively low carbon intensity compared to other nations, with an average of 13–26 g CO2 eq./kWh for used electricity in 2021 (depending on computation method) [53,54], and as such the electricity used can be categorized as low-emission energy in terms of climate emissions.

In this paper, we ask why the uptake of low-emission fuels is slow in maritime cargo transport and how different stakeholders within maritime transport can accelerate the transition. We investigate the uptake of alternative fuels in Sweden's maritime industry, to answer two research questions: i) what barriers do transport stakeholders experience, and ii) how can they overcome barriers to adopt low-emission fuels? The paper focuses on multiple stakeholders to analyze the perception of barriers, drivers, and measures to adopt low-emission fuels from the perspective of both the transporter and the transport buyer. Figure 2presents a simple schematic over the flow of goods between stakeholders. Each stakeholder type can cover several different actors during a single transport.

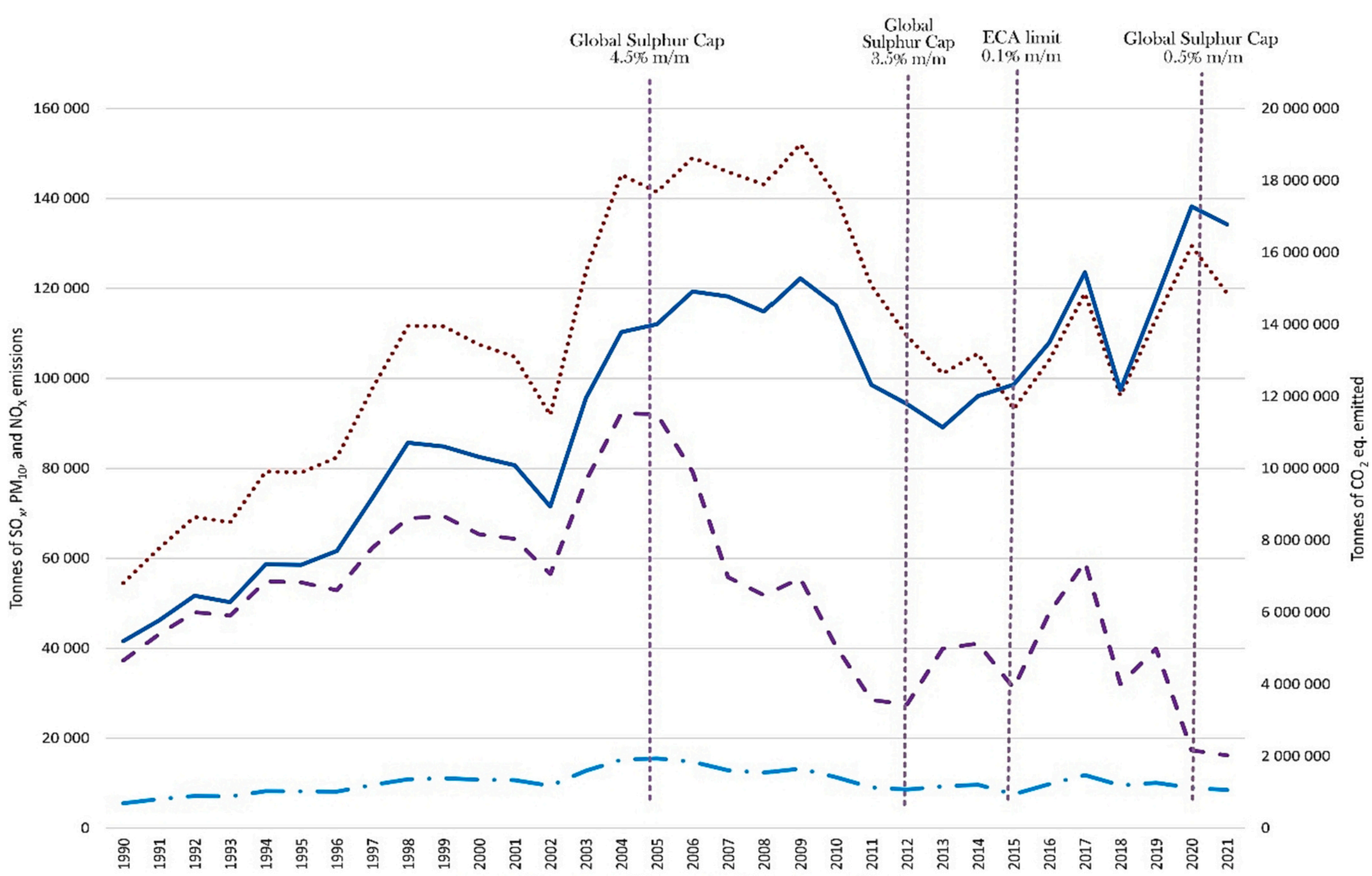

Fig. 1. The yearly emissions of Greenhouse gases (in CO_2 equivalents), Sulphur (in SOx), Nitrogen oxide (in NOx), and Particulate matter (in PM10), from 1990 until 2021 in Swedish shipping [25]. Information on legislation is gathered from The Marine Environment Protection Committee [26].

2. Methods, materials, and analytical framework

The study followed a qualitative research approach, specifically explorative case studies as described by Yin [69]. The analysis is based on sector-relevant data on fuel consumption (conventional and alternative) and fleet characteristics, together with literature, governmental documents, and qualitative data sources. The main research method used was semi-structured interviews analyzed through thematic analysis (TA). A literature review was conducted to detect established barriers to and drivers for low-emission marine fuel to frame the research questions and relate the findings to the state-of-the-art. The search was conducted in Scopus, limited to peer-reviewed papers published from and with the following search string:

TITLE-ABS-KEY ((barrier* OR driver* OR hinder*) AND (sustainability OR fuel OR decarbon*) AND (*maritime* OR "ocean transport" OR "sea transport"))

127 papers were identified and after abstract review 112 papers were found relevant. Additionally, 22 relevant repost were identified through snowballing.

In total, 17 respondents were interviewed divided up in five different stakeholder types: cargo owners, freight forwarders, shipping companies, cargo brokers and ports (Table 2). Characteristics of the interviewed stakeholders are presented in Table 3. The interviewees age ranged from 34 years old to 64, 40 % identified as women and 60 % as men, and they had been at their respective companies between 3 months and their whole working lives. The respondents active in Sweden and its neighbouring countries, from a wide range of cargo segments, and known to have contributed to projects on low-emission marine fuels were asked to take part. All cargo brokers registered with the Swedish shipbrokers' association [70] was contacted for an interview.

The interviewees were informed about the purpose of the interview before accepting. No monetary compensation was given nor were there incentives. All interviewees gave consent to being recorded, as well as were informed that the participation was fully voluntary and that they could withdraw their participation at any point. All gathered data was pseudonymized and treated in accordance with the General Data Protection Regulation.

The topics covered through the semi-structured interview questions were how the agents work with sustainability, what requirements they put on other actors, the current state of low-emission fuels in their business, what barriers they see to adopting low-emission marine fuels, and how they expect the market to develop regarding low-emission fuels. The semi-structured interview guides were tailored per stakeholder type to reflect their roles as transporters, intermediaries, and transportation procurers. Two to three authors and one or two representatives from each company participated in each interview. One author acted as the primary interviewer, while the secondary authors actively listened and added supplement questions. The interviews were conducted through video conferences [71] between November 2022 and February 2023. The audio recordings were transcribed verbatim into text and analyzed.

Interviews were coded using a theoretical framework called reflective thematic analysis, as presented by Braun and Clarke [72] and further developed in Braun and Clarke [73] and Braun and Clarke [74]. In TA, patterns of shared meaning, so called themes, are generated by the researchers to show how different data points relate to a central concept or idea. The themes are used to structure the coded data and tell a story. The tool have been used in a wide spectrum of theoretical frameworks [74]. In this paper, we used a reflective approach, and the results should be interpreted with this in mind. Our research process followed the guidelines of Braun and Clarke [72] for good thematic analysis, including transcription, coding, analysis, and reporting. The identified themes were reviewed systematically, as recommended by Byrne [75], and their coherency discussed with researchers external to the project. The results are built on eight themes, 76 codes, and 1672 code entries. The data set was evaluated for saturation continuously and the number of new codes generated was below 4 % after interview 13 [76].

Table 2
Type of organizations and title of respondents interviewed in the semi-structured interviews.

Interview	Type of organization	Interviewees	Duration (min)
1	Forwarder	Quality (global) and sustainability (regional) manager Ocean transport manager (global)	90
2	Forwarder	Quality (global) and sustainability manager (global) Fleet manager (regional)	75
3	Cargo owner	Logistics manager (regional)	90
4	Cargo owner	Sustainability manager (global)	75
5	Shipping company/ Forwarder	Short sea director (global)	90
6	Shipping company	CEO Fleet manager (global)	90
7	Shipping company	Sustainability manager (global)	90
8	Cargo owner	Sustainability manager	90
9	Port	Sustainability manager	75
10	Cargo owner/ Forwarder	Logistics manager (global) Transportation manager (regional)	90
11	Port	Sustainability manager Sales manager	90
12	Charter broker	CEO	75
13	Shipping company	Sustainability manager (global)	90
14	Charter broker	Broker and Sustainability manager (global)	60
15	Charter broker	Broker (global)	90
16	Shipping company	CEO	75
17	Cargo owner	Shipping manager (regional)	90

3. Barriers to low-emission fuels

The results focus on two subject areas: barriers to implementing low-emission fuels and ways to overcome them. The findings are presented in two chapters: one focusing on barriers (this chapter) and the other on solutions (Chapter 4). Five main themes describing barriers to adopt low-emission marine fuels (Table 4) was identified. These themes are presented in order throughout the chapter below and are summarized in Table 4.

3.1. Communication is challenging

A common theme in the data set was issues caused by communication gaps between stakeholders and within company organizations. The maritime market is often perceived as complicated, with relatively few competing actors, old traditions, and conflicting perspectives, where the physical good flows and information flows form a complicated system (Fig. 2). The shipping company is viewed as the main decision maker, as they are the user of the propulsion system. Still, other actors can set demands (on for example emission levels) and influence the marine fuel choice (by for example filtering information, providing knowledge or information). Cargo owners raised the complex relationship between different stakeholders as one of their main barriers when procuring maritime transport. Charter brokers and some forwarders confirmed this complexity by highlighting the market's intricacy as one of their business objectives; they guide cargo owners in the transport procurement.

The respondents indicated that sustainability became less urgent as the number of stakeholders increased between the shipping company and the cargo owner (Fig. 2). Direct communication between cargo owners and shipping companies is rare, especially if cargo volumes at

Table 3
Area of operations and characteristics for the interviewees regarding market structure and segments. "x" marks areas the company is active in. The vessel and operational area categories have been generalized to maintain the anonymity of the respondents.

Interview	Contract type				Cargo segment					Fleet type	
	Spot	Liner	Time charter contracts	Contract of affreightment	Container	Tank	Rolling cargo	Bulk		Size of vessels	Operational area
								Wet bulk	Dry bulk		
1	x	x	–	–	x	–	x	x	x	–	Global
2	x	x	–	–	x	–	x	–	x	–	Global
3	x	–	x	–	x	–	–	–	x	Up to 5000 dwt in Europe, up to 10,000 dwt in north America	Europe, North America
4	x	x	–	–	x	–	–	–	X	–	Global
5	–	x	–	x	x	–	–	–	–	Up to 5000 dwt	Europe, Northern Africa
6	x	–	x	x	–	x	–	–	x	Up to 20,000 dwt	Northern Europe
7	–	–	–	–	–	x	x	x	x	–	Northern Europe
8	–	x	–	x	x	–	–	–	x	Up to 200,000 dwt	Global
9	–	–	–	–	x	x	x	x	x	Port: open to all sizes	Sweden
10	x	x	x	x	x	–	–	–	x	–	Global
11	–	–	–	–	x	x	x	–	x	Port: open to all sizes	Sweden
12	x	x	x	x	–	–			x	Up to 10,000 dwt	Europe
13	x	x	x	x	x	–	–	–	–	–	Europe
14	x	–	x	x	–	x	–	x	x	Up to 5000 dwt	Europe
15	x	–	x	x	–	–	–	–	x	Up to 20,000 dwt	Global
16	–	x	–	–	x	–	x	–	–	Up to 25,000 dwt	Northern Europe
17	x	x	–	x	x	x	–	–	x	Up to 25,000 dwt	Global

Table 4
Identified themes describing barrier to adopt low-emission fuels.

Themes	Summary
Communication is challenging	It is challenging for stakeholders to aligning their language, definitions, and perspectives to effectively communicate, collaborate, and implement cohesive strategies and initiatives
If someone pays, we can choose better options	There is a lack of agreement of whom should pay for the transition of the maritime industry
There is risk in choosing a low-emission fuel today	There is a tendency to apply nirvana fallacy and continue to look for a silver bullet rather than to make a choice
We lack knowledge and data	There is a lack of relevant knowledge and data regarding low-emission fuel options, technologies, and their implementation as well as uncertainties of how to weigh trade-offs between options
We want to do this, but we need support	There is an agreement among the stakeholders that low-emission fuels are required, but external pressure is needed as there are prohibitive cost and too many uncertainties

sea are not extensive. Forwarders and cargo brokers are primarily used as intermediate parties. Sustainability performance was primarily brought up by shipping companies or cargo owners and not presented by intermediary parties. Hence, the shipping company often has limited insight into how cargo owners' reason, cargo owners have limited knowledge of the maritime sector, and some suggestions or proposals do not reach the shipping company. The limited contact between cargo owners and shipping companies was a concern among the shipping companies:

> " If you have a tanker and you're operating on a spot basis, then you take each load one by one, and in that case, you hardly ever talk to the customer directly. It goes through brokers. So, getting any benefit from the environmental investment, that's really difficult." – interview 16

And cargo owners and shipping companies both identified benefits of having very short communication routes and direct discussions:

> "In certain cases, like with this significant customer, we have actually had direct contact with the shipping companies' head offices [...]. This way, they can have a broader understanding of how it precisely functions, what they offer, what is included, so they can see the entire picture." – interview 2

Consequently, there is a discrepancy in the communication between stakeholders. The cargo owners express a want and need to buy more maritime transport done with low-emission fuels while shipping companies expressed a lack of interest from the cargo owners.

3.2. If someone pays, we can choose better options

The economic cost of moving to a low-emission fuel, and how to cover the cost, was the most discussed topic during all interviews. Low-emission marine fuels have a higher price, and the cost is considered a direct barrier among all stakeholders. The general theme was that better options and technologies are available and can be used, but it is unclear whom should pay. Fuel costs represent a major expense in maritime cargo transport and the interviewees highlighted that the fuel cost today often is transferred over to the cargo owner or freight forwarder.

> "[…] The fuels we use today are extremely cheap compared to other renewable fuels, and we are very... still very... very much focused on cost optimization. " – interview 7

The perspective on whom should pay for the increased fuel cost varied greatly between and among stakeholder types. Several freight forwarders and cargo owners buying container freight argue that a greener shipping industry is not their problem to fix, and that the shipping industry needs to solve this. Other cargo owners and freight forwarders are directly involved in investments in new vessels and pay directly for low-emission fuels to be used onboard. The shipping companies instead emphasized that cargo owners must be prepared to pay more for a low-emission transport service. However, they experienced that most buyers are not interested in this, for example:

> " I think that today, many are somewhat naive and believe that... 'Everyone else should make investments, but not me. I will find the best solution, but I won't invest anything at all or only very little.' And they expect companies around them to make investments. And as a shipping company, we are often the ones expected to make these investments." – interview 5

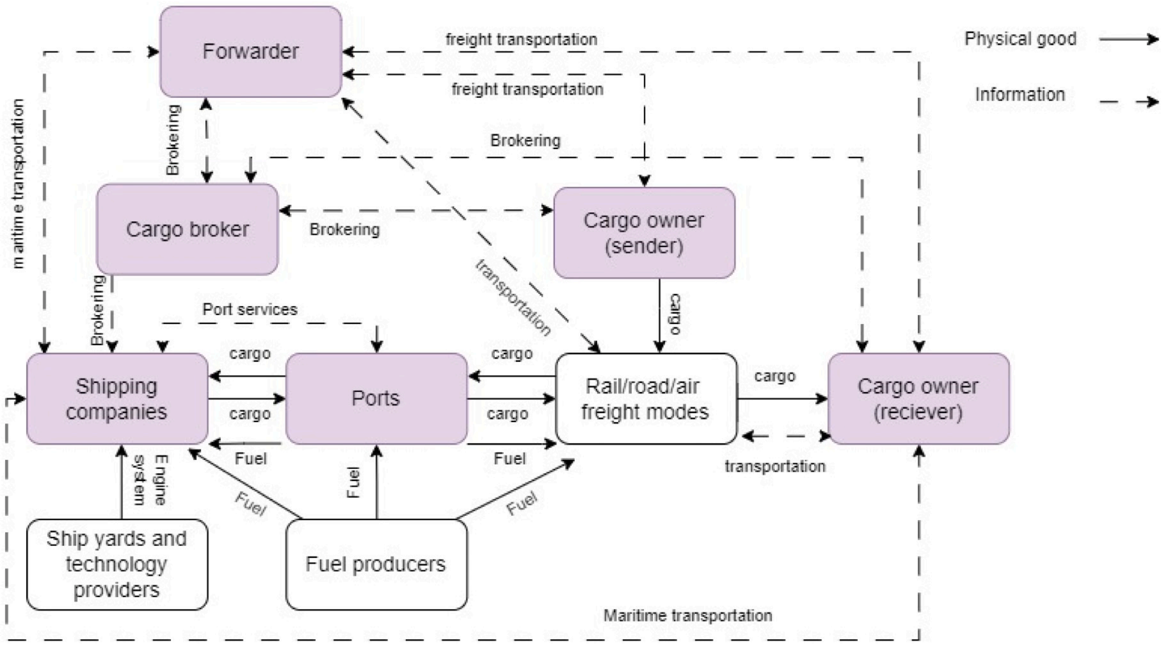

Fig. 2. Cargo and fuel trade flow map of maritime transport as defined in this paper. Lines show the flows of physical goods between stakeholders and maritime transport information exchange. The map is based on information gathered in the interviews as well as with supporting adaptations from Stopford [1] and Ghaforian Masodzadeh et al. [34]. Note that more than one stakeholder of each type can be involved in one cargo transport. Purple boxes show stakeholders interviewed in this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

When asked if there is an interest in environmental performance from the procurer of maritime transport (often forwarders as described in 3.1), some shipping companies points to increased interest in, but still a lack of willingness to pay for low-emission fuels:

> "… I can laugh about it because this is how it goes in every discussion, contract negotiation. It goes like this: 'Can you offer a fully green alternative?' 'Absolutely,' we say. 'How wonderful that you're asking.' And then we start talking about it. [...] Then the customer says, 'Oh, well, I thought maybe we were talking about an extra euro or half a euro.' No, you know, this is not just a slight increase. It's an extreme premium that you have to add, and they can't afford it. They can't afford it." – interview 15

However, it was noted by some that the structure of the problem is also due to old habits among the shipping companies, for example the charter broker who stated:

> "At the same time, there is a certain element of conservatism within the industry, even from the shipowners' side. They naturally find it burdensome with all these additional charges and such... They often have the attitude of, 'Sure, we can make alterations... do things as long as people are willing to pay for it.'." – interview 12

The importance of demand in a functioning market is well-established in the literature, and the need for an active demand was brought up by all the respondents. The view differed on if a demand for low-emission marine fuels exists today, but as stated in interview 8:

> "We notice that when we talk about it, at least something happens." – interview 8

3.3. There is risk in choosing a low-emission fuel today

The uncertainty of which fuel pathway will be the best and if the pathway will be feasible over time was brought up as a barrier by all interviewees. However, the perspective on how significant the barrier is varied greatly, with some stating that from their perspective this makes it impossible to act while others claimed it complicates the choice, but some steps can still be taken. One example is the time perspective:

> "What should I actually procure from a container shipping company? What have they invested in? Well, maybe they have LNG. Then you have a player who has invested in new ships that might come in 2025, using e-methanol, for example, but it's not available here and now." – interview 8

Several interviewees expressed concerns about the maritime industry facing the chicken and egg dilemma: how do we simulate demand for low-emission fuels when they rely on a corresponding supply? The uncertainty of future fuel supply when choosing a propulsion option using a fuel type not yet universally available was a significant concern, keeping stakeholders from adopting low-emission marine fuels. The availability of bunker is a critical factor for shipping companies as the vessels require large amounts of fuel, and the cost of the bunker is a large share of a shipping company's total costs.

> "I believe that the energy issue is extremely difficult to solve for the maritime industry [...] Then there's also the question, and this is the classic chicken and egg dilemma, who will provide them with fuel?" – interview 15

The risks associated with locking-in to a specific fuel were, therefore, especially stressed by shipping companies, as they are directly dependent on the vessel. The cost of investment is large, and it is essential for it to operate over a long period of time. The risk of being unable to operate the ship due to stringent future performance requirements, limited fuel supply, or too high cost is stressed.

> "[…] If you buy a ship, it's supposed to last for 30-40 years. Then you have to try to predict the future. 'But what will the requirements be then?' So you make them as environmentally friendly as possible [...] with today's operations and perhaps try to use technologies that can be built upon."– interview 5

This perspective is linked to the nirvana fallacy; there is no perfect alternative so there is no solution. In the hope of a future, perfect alternative investment is held back. All fuel options have benefits and drawbacks (Table 1), and there is no low-emission marine fuel commercially available today that fully meets the stakeholders' long-term goals, slowing down the adoption of low-emission fuels.

3.4. We lack knowledge and data

There are different views among the stakeholders about what should be considered a low-emission marine fuel or a fuel for the future. When asked what they consider to be a low-emission fuel all respondents considered this to be unclear, illustrated by one shipping company:

> ”Yes, there is still a lot of debate on that. The definition isn't crystal clear […] well LNG is not that in our world […] I don't dare say exactly where the line is drawn today […] ” – interview 17

A reoccurring theme in the interviews is the complexity of the marine fuel choice, which with its various fuel options, engine alternatives, and environmental impact trade-offs, creates a genuine knowledge demand. The interviewees raised the high knowledge level required to make an informed decision as a major barrier. There is a direct need to assess and understand the impact of solutions to implement the best fuels and formulate the correct requirements in the procurement processes. The current knowledge level is viewed as too low to procure sustainable maritime transport, with some stakeholders stating that detailed road-maps of fuels is a must for a transport buyer to figure out how to navigate the issue.

> “Honestly, […] we have quite recently started this. right. So, I would like to say that right now, it's an ongoing screening process. We haven't decided on any specific path; we haven't stated that methanol is better than ammonia or that it has to be fossil-free electricity. […].” – interview 17

Environmental management systems and systematic approaches were highlighted as essential to gain enough knowledge to implement the right solutions and to support the use of the mitigation technologies at different scales and levels. If the stakeholders do not account for emissions, there is no incentive to mitigate them. An overview of the systematic sustainability work taken place in the interviewed companies is shown in Table 5. Seven of the respondents lack goals for emissions from maritime transport entirely while having implemented goals for other transport modes. Most of the shipping companies have goals (Table 5), but not all. Among the respondents, the lack of goals for cargo owners and forwarders was in part attributed to uncertainty of what would be a feasible goal to set. However, three cargo owners noted that so far, they have focused on implementing social sustainability goals rather than environmental in maritime transport procurements.

To include detailed performance parameters in the sustainability work, data is needed. Opinions differ on the amount of data available in the industry, the extent to which it can be shared, the amount that is necessary, and whether other stakeholders are interested in it. However, data on fuel use is available from several of the shipping companies interviewed.

> ”.. We have a lot of data from our ships that we use on a daily basis to understand consumption and so on.” – interview 7

Today, the main method for calculating emissions from transportation options for inclusion in environmental management systems appears to be using default values, where the same number is used regardless of the provider's actual emissions. The respondents highlighted that this leads to a situation where all shipping is treated the same and the environmental issues are de facto not included in the procurement.

> “Then they had a competitor, they shipped with a competitor to us, and we were more expensive, and so we calculated how much better we are at... Because they should include 1,000 kronor per ton of CO_2 in their calculation, and I said, 'But it becomes this much, this many thousands we save, and it's this much money. Suddenly we are competitive.' 'No, but you know we have a flat rate for ro-ro boats in our system.' Well, what the hell, then it doesn't help that we invest

Table 5
Key aspects of the sustainability work at the interviewed companies. “x” marks areas the company is active in. “-“notes no known activity.

Interview	Stakeholder type	Systematic sustainability work			Alternative marine fuels used today	Environmental focus areas in the interview
		ISO or similar system	Science based targets	Includes quantitative goals for maritime transport		
1	Forwarder	x	–	x	LNG	Climate change, energy use
2	Forwarder	x	–	–	Some biofuel, LNG	Climate change
3	Cargo owner	x	–	–	–	Climate change, energy use
4	Cargo owner	x	x	–	Some biofuel	Climate, Clean air
5	Shipping company/ Forwarder	x	–	x	LNG	Climate change, energy use
6	Shipping company	–	–	x	Some LBG	Climate change and emission to air
7	Shipping company	–	–	x	Some biofuel, methanol	Climate change, Emissions to air, water and soil, biodiversity, circularity, energy use
8	Cargo owner	X	X	x	HVO, LNG, LBG	Climate change, emissions to air, biodiversity, and circularity
9	Port	x	–	x	HVO, prepared for LNG	climate change
10	Cargo owner/ Forwarder	x	–	x	LNG	Climate change, emission to air, energy use
11	Port	x	–	x	LNG, methanol, LBG, biomethanol	Climate change, air quality, water quality, energy use
12	Charter broker	–	–	–	–	Climate change and emissions to air, water, and soil
13	Shipping company	x	–	x	LNG	Climate change, Emissions to air, water and soil, energy use
14	Charter broker	–	–	–	–	Climate change and emissions to air, water, and soil
15	Charter broker	x	–	x	–	Climate change, energy use
16	Shipping company	–	–	–	LNG	Climate change, emissions to air, water and soil, waste streams, combustion emissions, energy use
17	Cargo owner	x	x	–	Some electricity, LNG, biofuel	Climate change

one and a half billion in new fancy boats if the dirtiest boats are used in a flat rate. It's quite frustrating, actually." - interview 16

3.5. We want to do this, but we need support

The desire to complete the transition to low-emission fuels is a common theme through the interviews. There is a general agreement among the stakeholders that low-emission fuels are a certainty and necessary. There is also a general agreement that sustainable maritime transport is attractive, with all respondents stating sustainability measures as good for the general public. Despite a general agreement that the transition to low-emission fuels is necessary, the perspective on when and how it will take place differed. Some respondents are more technology-positive and believe there will eventually be a winning option among the low-emission fuels, resulting in all vessels adopting the winning solution. Others favor resilience and a future mix of fuels. The focus of most stakeholders is on the climate concern. All respondents seem to be searching for a way to take actions that will lead to actual effects on the anthropogenic climate impact. The climate change issue was highlighted by all interviewees and other aspects of sustainability were only brought forward by half of the participants (Table 5).

The environmental performance is perceived as difficult to prioritize in the maritime transport procurements due to higher cost (Chapter 3.2), lack of options (Chapter 3.1 and 3.3), and limited knowledge (Chapter 3.4). The availability of sustainable shipping alternatives on the market today is perceived as severely limited. As put by one cargo owner when asked if they had put any direct requirement on environmental sustainability in procurements:

> " No, not yet, we haven't done that. We don't feel that we have really had the opportunity, I mean, the supply hasn't been there for us." – interview 17

When discussing how forwarders and cargo owners can affect the choice of marine fuel several respondents, mainly in the container segment, brought up that they lacked discretion in even deciding which vessel the cargo will be transported with. The primary influence they have on the transport choice is if it goes by ship at all or with another transport mode.

> "Now it's incredibly explicit that we should work extremely hard on environmental issues within all types of transportation, especially maritime. So shipping will be tightened, but we also can't impose such requirements that we can't get the goods moving. We have to work with what we have." – interview 17

This dilemma was also backed up by freight forwarders. Especially for container shipping, the influence on what quality of service you can request is very limited, with one freight forwarder even stating:

> "I have focused on simply getting the cargo on our ships, so choosing ships is not even on the table." – interview 1

There was a clear difference between liner (9 respondents) and spot (9 respondents) shipping, with customers perceiving having far less influence on the fuel choice in liner shipping where the cargo space onboard is divided between a great number of customers.

4. Overcoming barriers to implement low-emission marine fuels

Three themes describing the stakeholders' views on how to overcome barriers were identified in the thematic analysis (Table 6). The first theme emphasizes joint efforts by stakeholders to create opportunities where low-emission fuels can be used. The second relates to external pressures. The third shows how low-emissions marine fuels are implemented today.

Table 6
Identified themes describing drivers and how to overcome barriers as described by the stakeholders.

Theme	Summary
Collaboration creates stability	Involving multiple stakeholders foster communication and innovation, and supports development of comprehensive solutions
You adapt when you must	Change is often driven by necessity rather than convenience or preference. External drivers are needed to successfully navigate towards low-emission maritime transport
Business models exist	There are cases where the barriers are overcome today by singular stakeholders and by groups

4.1. Collaboration creates stability

Finding solutions to overcome the barriers together with others was a common theme throughout the interviews. Collaboration between stakeholders as well as other actors, such as energy companies, was highlighted as key to overcoming several barriers, such as securing fuel supply and sharing the investment risks. The value of mitigating uncertainty was highlighted. For example, collaborative efforts to stimulate fuel supply and thereby solve the chicken and egg dilemma were discussed. One shipping company had already bought fuel without an identified use case:

> " One doesn't need to purchase large quantities, but rather everyone starts buying a small amount so that the fuel producers reach a critical level and can begin producing on a larger scale [...] that's where ship owners can make a significant impact." – interview 7

Other actors have focused on making the low-emission marine fuel option more visible, such as:

> " We have a major procurement coming up next year where we managed to get four different shipping companies on board who could actually provide a price for a reduction when purchasing biofuels, similar to buying green electricity. Currently, there isn't enough availability to meet the demand for a trader like this customer wants, but we offer it whenever the customer requests it." – interview 2

Half the respondents gave examples where continuous discussions between stakeholders enabled the successful implementation of environmental pressure mitigation technologies. Having a shared view of the level of priority for environmental concerns and a shared long-term goal were stated as primary reasons to collaborate. When asked if they collaborate with other companies in the matter of sustainable shipping, all except two answered that they do and try to prioritize collaborations:

> " [...] we have several projects like that and will enter into more of them in the future, so that […] It's the only way to solve this. It's collaborations. " – interview 1

4.2. You adapt when you must

As previously presented, the uncertainty tied to market demand, fuel supply, and future legislation is high. The perspective on how important environmental issues is for a company differed between stakeholders and within each type of stakeholders. Two shipping companies stated that the fleet's longevity depends directly on its environmental performance.

> "For us, there was no other way to go. Investing in old technology when we see what's happening in the world, it was simply unthinkable. [...] It was also a requirement from the owner's side. So there has never been any other discussion." – interview 16

While other shipping companies stated that only direct legal requirements will change the industry's priorities.

> " Yes, the biggest obstacle is that as long as we don't have this global CO_2 price, these conventional fuels that we use today will be so much more cost-effective. [...] It will be difficult to push for a much, much higher cost to decarbonize unless there is an incentive to do it more than just saving the planet." – interview 7

All interviewees highlighted well-developed legislative requirements as an effective and wanted tool to drive change.

> "We are counting on and hoping for there to be even more policy measures regarding this. What we need are policy measures that provide incentives to make this transition faster for all parties involved." – interview 4

Legislation is talked about as a method to mitigate the uncertainties as it must be complied to – if you are forced to adapt, you will. However, the shipping companies stressed that legislation must be equal and fair within each market segment, and it needs to be ensured that pollution sources are not just shifted. The perception was that most of the global maritime cargo transport market adapts exclusively to the lowest cost option which complies with the legal requirements.

4.3. Business models exist

Low-emission fuels are used in Swedish maritime cargo transport despite the barriers (Table 1). In the interview material and literature review five different types of existing business models using low-emission marine fuels today were identified: i) green corridors, ii) public procurements, iii) long-term fleet renewal, vi) cargo owner initiatives, and v) mass balance fuel offsets.

Green corridors are shipping services between two or more ports where a low-emission fuel i.e., "green fuel" is made available for the ship/s. There are examples of these collaborations in discussions around coming projects in the interviews and at least one of the stakeholders is directly involved in a green corridor project. Creating green corridors requires incentives for companies to participate [77], but the structure of liner shipping (i.e. freight transport performed by vessels on a fixed route and time schedule) is particularly suitable for this approach [78].

With public procurements we mean procurement of maritime transport by governmental agencies. This can enable clear procurement processes where demand for environmental performance is directly set. This method has also been highlighted in scientific literature [79] as a way to incorporate other decision factors besides costs of the service (see more in 5.2).

By long-term fleet renewal, we refer to investments by shipping companies in vessels that can use low-emission marine fuels with the aim to be profitable in the future. A ready-for-X fuel option is chosen to make sure that the vessel remains competitive if requirements on environmental performance increase. This type of investment was primarily brought up by family businesses, where the respondents were less motivated by short-term profits. For example, in interview 16:

> " We are not publicly listed. And there is no quarterly economy in our industry, or there cannot be because then you're doomed. You have to think long-term. And we are considering a lifespan of 35 years for these vessels, maybe even 40." – interview 16

A similar argumentation was brought forward around choosing dual fuel engines and preparing for future adaptations when designing the vessel, to make sure the vessels are adaptable:

> "The electrical connection in the ports, everything is ready, the battery room and all the connections are ready, we just need to install the batteries. We chose to wait for it because the development is progressing rapidly here and now. And we also hope to incorporate [Swedish company] batteries in them to have even more Swedish [production] and support our customers." – Interview 16

There are examples where the cargo owners take the initiative and drive the case for low-emission marine fuels. Two main motivations have been identified: meeting their certification requirements for transportation and secure production of fully fossil free products including transport. This type of agreements is currently under discussion and there is a clear vision among some cargo owners:

> "We are going to produce fossil-free [product] by 2030. That's what has been said internally, that if you're not fossil-free as a supplier to [company], then you can't be a supplier to [company]. But maybe that doesn't hold completely true within logistics, just [number] years away." – interview 17

However, the willingness-to-pay for low-emission marine fuels is viewed with some degree of skepticism by the shipping companies:

> "... If you produce green and sell green, then you don't want to ship black. But they have a completely new business idea, and they have a premium product on top of that, so they might be able to afford going green, but it's not certain." – interview 15

Mass balance fuel offsets is when the use of a low-emission fuel is offset against the real use of a conventional fuel. This method is currently used at scale by two interviewed freight forwarders to finance liquified biogas (LBG) use, which is then used in the fuel blend of an LNG propelled vessel. The LNG fueled vessel is on a fixed schedule and service (already with an established demand), and customers have the option to finance the utilization of LBG as a blend-in fuel on the LNG vessel. In principle mass balance fuel offsets ensure that the overall emissions impact of a fuel supply chain is neutral or reduced, even if not every individual unit of fuel used is a low-emission fuel. This creates a reduction in absolute emissions, but an individual cargo owner can't be sure their cargo is shipped directly with the low-emission fuel.

5. Discussion

This study aims to give insight into the interactions between stakeholders. The identified themes are common throughout the data set and describe the perceived barriers and drivers for the adoption of low-emission marine fuels from the perspective of the interviewees. The results paint a picture of a stakeholder landscape with information and communications gaps, diverse goals, uncertainty, and cost concerns, but also with a wish to transform the industry.

Previous research on barriers in maritime energy efficiency [34,35,43–47] corroborate the identified themes. However, the energy efficiency perspective does not include the topics of costs, fuels supply, and the trade-offs between fuels found in this study.

The results presented in this paper are consistent with papers looking at the adoption of low-emission marine fuels from one or two stakeholders' perspectives [37–41]. For example, Dahlgren et al. [37] focus on shipping companies and identify the barrier of high cost as well as a limited willingness-to-pay from the procurer of maritime transport, limited fuel supply, and technology lock-in concerns. Mäkitie et al. [38] looked at Norwegian shipowners and established differences in how low-emission marine fuels are adopted within and between shipping segments, indicating a complex motivational pattern. A similar complex relationship can be seen in this paper, especially in the themes *Communication is challenging* and *We lack knowledge and data*. Ashrafi et al. [16] further confirm this finding and conclude that the maritime decision-making landscape is complex and contains a high level of uncertainty. This supports one of the key claims of our paper: choosing low-emission marine fuel is complex.

5.1. Barriers remain

The five barrier themes (Table 4) are specific to this analysis, but comparable to other studies with a similar focus. Table 7 presents the barrier themes relation to the barriers identified in two previous papers:

Table 7
Barrier themes and their relationship to Ghaforian Masodzadeh et al. [34] framework for barriers and Rehmatulla and Smith [35] barriers analysis.

Themes	Identified barriers in literature
Communication is challenging	Bounded rationality [35] Adverse selection [35] Moral hazards [35]
If someone pays, we can use better options	Asymmetric information [34,35] Market heterogeneity [34,35] Split incentives [34,35] Imperfect competition [34] Principal-agent problem [35]
There is risk in choosing a low-emission fuel today	Credibility and trust [35] Regulatory boundaries [34] Incomplete market [34] Risk [34,35] Behavior and human element barriers [34]
We lack knowledge and data	Imperfect information [34,35] Organizational barriers [34,35]
We want to do this, but we need support	Technical barriers [34] Risk [34,35] Policy barriers [34]

Ghaforian Masodzadeh et al. [34] and Rehmatulla and Smith [35]. Each theme covers two or more barriers, displaying how the barriers are interlinked and interdependent, as previously hypothesized by Mäkitie et al. [38] and Ashrafi et al. [16]. Each of the five barriers were brought up by all different stakeholder types, despite their different roles, levels of knowledge, and levels of interest.

All respondents agree that low-emission fuels are needed (Chapter 3.5), but most argue that someone else should bear the cost of implementation and use (Chapter 3.2). The higher cost associated with low-emission marine fuels appears to be a major concern (Chapter 3.2), which the respondents perceive as a barrier that a company alone cannot overcome, especially in the container segment. However, the respondents did not present increased fuel prices as a problem for the maritime industry at large. Instead, the respondents discussed how the additional fuel cost is large enough to directly affect the transport price, and, therefore, the increased cost must be put on all competing shipping companies, or there must be a demand for the premium service of low-emission transport. Non-fossil fuels are expected to remain at a higher price than HFO for some time, perhaps 2–3 times higher, due to the more complicated process technology and cost of extracting raw material [17]. The investments in capital goods onboard the ships are also substantial [2,4], and it is still unclear who will pay for, for example, the infrastructure investments needed in the ports [80].

Several studies [7,17,81–84] present the fuel cost as the most important barrier for low-emission marine fuels to be competitive. However, we do not reach this conclusion. The production of low-emission fuels and their availability in ports is highlighted as a bigger issue than increased fuel cost by several respondents (Chapter 3.3). We have also identified cases where low-emission fuels are implemented despite their cost (Chapter 4.3), signaling that the higher cost can be overcome today. The cost of low-emission fuel is also expected to decrease over time [17], while the cost of fossil fuel options is expected to increase with the introduction of legislation [62], which may even out the cost difference [62]. However, the characteristics of the maritime transport market make it difficult to take risks in the marine fuel choice [85] as risks are unlikely to pay off.

The marine fuel cost is often paid by the customer, and in the energy efficiency literature the gap between the optimal energy use and the actual energy use in maritime transport is theorized to be due to the principal-agent problem [35,43,45,46]. The principal-agent problem arises in situations where the interests of the principal (e.g., ship owners or operators) and the agent (e.g., ship managers or charterers) are not perfectly aligned [86]. The duality of the cost structure described by the stakeholders in this paper shows similar characteristics. The principal may want to invest in sustainable fuels, while the agent may prioritize cost savings or may not have the knowledge or expertise to evaluate the benefits of low-emission fuels. Poulsen et al. [44] theorized that the decision matrix around maritime energy efficiency contains too many stakeholders for the principle-agent dilemma to be an appropriate model, but it might be a useful framework for some investigations such as specific case studies.

The fuel supply issue relates both to accessibility of an energy carrier, such as being able to bunker methanol in a port, and access to a future low-emission marine fuel. The limited supply of biofuel is a well-documented concern [55,87] for the entire transport sector [88]. However, there are fuel production projects ongoing with the aim to provide low-emission marine fuels in Sweden (see Table 1) and legislation has been brought forward to guarantee LNG and hydrogen access in ports. The difficulties when moving from fossil fuels to a future with sustainable marine fuels should not be downplayed, but many of the identified challenges appear to be due to lack of information rather than future accessibility. Previous qualitative research studies has argued cost and fuel supply as the main barriers to low-emission fuels [89]. Costs and risk of not securing a fuel supply has also been raised in analysis of specific propulsion technologies [36,37]. However, the complexity of the marine fuel choice, the communicative and collaborative aspects are missing in more quantitative studies.

Table 1 presents all fuels mentioned by the respondents during the interviews and displays some key characteristics of each. However, this paper does not directly compare the benefits and drawbacks of different low-emission fuel options or their level of sustainability. Instead, the investigation is focused on barriers to adoption compared to conventional fossil fuels. Some papers investigate quantitative performance between fuel options, for example, Zanobetti et al. [90] and Kanchiralla et al. [91], and show how the vessel type, storage method, production pathway, values, and more affect which fuel is preferred. The theme *There is risk in choosing a low-emission fuel today* highlights this complexity by outlining the stakeholders' concern that no singular fuel has the optimal qualities for all applications.

The themes appear across all types of stakeholders, but the differences between market segments might be significant. There are indications that container shipping companies might premier cost reduction and that very high external demands will be required before container vessels adopt low-emission fuels. On the other hand, stakeholders in the bulk segment have expressed strong interest in transitioning to entirely fossil-free fuels quickly, but the fuels used must be globally available for bunkering.

Another barrier identified through literature [85,92] is that a higher proportion of the investment in green technology must be made by the shipping company rather than the banks. However, two shipping companies in our study opposed this: it is a stronger requirement to show high environmental performance for the banks to be interested in ship investment. Financial institutions have shown interest in lowering the climate impact of shipping, with the most notable example being the Poseidon Principles [93]. The Poseidon principles establish a framework developed to financially incentivize shipping companies currently tied to around 50 % of the global shipping sector. Since the topic was not discussed further no conclusions can be reached, but duality in perspectives is interesting for future research.

5.2. Navigating towards low-emission marine fuels

As barriers remain, the adoption of low-emission marine fuels cannot be expected to accelerate without incentives. Dahlgren et al. [37] looked at drivers and barriers to biogas use across several sectors. The study included the perspectives of shipping companies in Sweden and notes a similar viewpoint on sustainability as brought up in this paper: shipping companies trust that investments in sustainable alternatives will eventually pay off. Despite this, the adoption is slow.

As the economic incentive to shift to a low-emission marine fuel is perceived as low among the respondents (Chapter 3.2), additional drivers are necessary. Cullinane and Yang [94] analyzed the cost of implementing low-emission marine fuels at scale and concluded operational and technical innovations to be insufficient for their implementation, calling for market-based policy measures. The barrier themes relate to both market and non-market failures (Table 7). On a system level, market-related barriers amplify existing market structures [95], which often favors technologies already established on the market, and thereby limits the penetration of low-emission fuels. To overcome the marked-based barriers our paper also highlights the value of market-based policy measures, and all stakeholders specifically call for legislation (Chapter 4.2). The need for efficient legislation is supported further by studies looking at low-emission fuel adoption in other markets [38,96] and singular types of stakeholders [39–41,97]. The established complexity of marine fuel choice for the maritime cargo transport market must be considered in the policy development, something previously argued by Bergek et al. [98], among others. New legislation is being introduced to maritime transport, globally and in the European Union. The coming EU ETS [99] was specifically discussed in the interviews, showing both up-to-date knowledge and interest among the interviewees. The results do, however, stress the design of legislation to be crucial for actual absolute emission reduction to occur. For example, stakeholders raised how the introduction of the Global Sulphur Cap [26] has led to introduction of scrubbers which releases the Sulphur emissions to the water instead of air [100]. The damaging Sulphur emissions are thereby still emitted to nature and not avoided.

The examples of identified business cases where low-emission fuels are adopted are anecdotal, with only singular examples identified in the interview material and general descriptions in the literature (Chapter 4.3). However, for example public procurement with demand on low-emission marine fuel has been confirmed to decrease climate emissions for ferries in Norway [79]. Moreover, long-term investments based on intergenerational thinking in family-owned businesses are rarely identified in literature, but was confirmed in Dahlgren et al. [37]. Green corridors is primarily a concept within freight transport, but public procurements, and cargo owner initiatives (i.e., customer preference and supply chain management) have been confirmed to lead implementation of more sustainable (as defined by the procurer) measures in other sectors (see for example [101–103]).

The three driver themes, *collaboration creates stability, you adapt when you must,* and *business models exist*, do not necessarily reflect efficient solutions nor a complete set of solutions. For example, the theme *collaboration creates stability* suggests facilitating collaborations and communication as solutions moving forward. More research is needed to verify this claim since the approach used in this paper does not assess the efficiency of various measures. However, Bjerkan et al. [42] investigated the role of ports as intermediaries in socio-technical networks and established that the increased advocation and involvement of intermediaries can benefit complex stakeholder networks by providing information and presenting solutions. However, we can see that increased communications steps by using intermediate parties might lead to less focus on sustainability (Chapter 3.1). We also note the need for more knowledge among the cargo owners and that deeper communication between stakeholders is important (Chapter 3.1). Cargo shipping is central to many companies' supply chains, is always a derived demand (i.e., a consequence of the demand for something else), and requires the implementation of legislation on a global scale. Therefore, cargo owners play a central role in whether low-emission fuels are implemented and must interact with other maritime cargo transport stakeholders. Our results reflect interviews with Swedish maritime stakeholders, and the Swedish uptake of low-emission fuel is high compared to the global average [49]. The respondents are, therefore, likely more positive about low-emission fuels than stakeholders in other markets. However, the adoption of alternative marine fuels is increasing globally as well as in individual markets [19]. Hence, the results of this study are likely increasingly applicable for other markets. Several of the interviewed stakeholders operate outside of Sweden as well (Table 3) and act in an international environment where they work with many different types of stakeholders. An example from the Swedish context that differs from previous studies is that the fuel price is viewed as just one barrier among several. Further studies are needed to verify if this is a result linked to the Swedish context, to the markets increasingly positive view on low-emission fuels, or if this is due to differences in research design.

The environmental benefits of low-emission fuels as well as potential cost increase will affect the general public, but this study is limited to companies and company representatives and is not focused on end-consumer preferences or perspectives. The study has also not considered perspectives from fuel producers/energy suppliers and technology providers (Fig. 2). However, the data gathered from the ports connects to the fuel provider perspective, as they act as the bunker point for the ships. No significant differences in discussed themes between ports and other stakeholders were identified.

This paper takes a qualitative approach to clarify and describe what limits the adoption of low-emission marine fuels. By exploring the qualitative aspects of market behaviors, such as attitudes, beliefs, and motivations, thematic analysis can provide a more in-depth understanding of why certain behaviors occur and what factors contribute to them [74]. The descriptions presented here inform analysis within the maritime context which otherwise would have been limited to quantitative aspects, such as cost analysis. Still, the method has clear limitations and is prone to bias [104], and despite measures taken to avoid selection, confirmation, measurement, and reporting bias the results of the study should be considered with this in mind.

We have identified a complex, maybe even wicked, problem in the case of the choice of marine fuel, and the approach taken in this study is not sufficient to describe the full context. The bottom-up approach of this study should be complemented with socio-economic studies and studies of complex or wicked problems. There are methods under development which look more into detail on how to consider multiple criteria in sustainability management of fuel consumption [105]. But, so far, these methods are mainly quantitative and the need for more sociotechnical research remains.

6. Conclusion

This paper examines Swedish maritime cargo stakeholders' perspectives on the adoption of low-emission marine fuels. We identify several interlinked and interdependent barriers hindering the stakeholders from using low-emission marine fuels. *Communication is challenging* among the stakeholders, and *if someone pays, they can choose better options* for human health and the environment, but there is no clear agreement on who should pay for the transition. *There is risk in choosing a low-emission marine fuel today* as it is unclear what will be competitive in the future, and the fuel supply issue is not solved. The degree of complexity in the marine fuel choice is high, and many stakeholders identified a *lack of knowledge and data*. Overall, *they want to do this, but they need support* to overcome the barriers.

We argue that stronger external drivers are necessary for low-emission marine fuel adoption. Emissions from maritime cargo transport are not accounted for in sustainability reporting, and there is a perceived lack of regulatory requirements among the stakeholders. All interviewees viewed the introduction of efficient and fair regulation as positive, as they noted that *you adopt when you must*. Some actions can be, and are, taken by the stakeholders themselves as *collaboration creates stability,* and *business models exist* that can accelerate the adoption. The work performed through this paper gives context to the current discourse on low-emission marine fuels and provides a new foundation to further understand marine fuel choice.

CRediT authorship contribution statement

Elin Malmgren: Conceptualization, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Selma Brynolf:** Conceptualization, Writing – review & editing. **Linda Styhre:** Conceptualization, Investigation, Writing – review & editing. **Jan van der Holst:** Investigation.

Declaration of competing interest

Elin Malmgren reports financial support was provided by Swedish Energy Agency. Linda Styhre reports financial support was provided by Swedish Energy Agency. Jan van der Holst reports financial support was provided by Swedish Energy Agency. Elin Malmgren reports financial support was provided by the Swedish Transport Administration.

Data availability

I have shared some data in the Attached file step. There will be some additional avaiable upon request, but some is confidential due to the nature of the data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.erss.2023.103321.

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