Master's Thesis – Master Sustainable Business and Innovation

THE DECARBONISATION OF THE MARITIME TRANSPORT SECTOR: ASSESSING THE TRANSITION AND SYSTEMIC BARRIERS

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August 18, 2024

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Abstract

The maritime transport sector, plays a significant role in global greenhouse gas emissions, contributing approximately 2.9% of global emissions and 3-4% within the EU (European Commission, 2024). Achieving climate neutrality by 2050 is a critical goal for the European Union, necessitating substantial decarbonisation efforts in the maritime sector, which is categorised as a 'hard-to-abate' (HTA) sector due to its inherent challenges in reducing emissions (Cabot & Villavicencio, 2022).

This study explores the current state of the transition towards decarbonisation within the maritime transport sector, with a specific focus on deep sea freight and bulk shipping. It addresses the complexity of achieving decarbonisation goals set by the European Union and examines the systemic barriers hindering this transition. The research employs a combination of the X-curve framework and the Mission-Oriented Innovation System (MIS) approach to analyse the state of the transition and identify the core barriers and their underlying causes.

The methodology involves qualitative research, including desk research and ten extensive semi-structured interviews with industry- and policy experts. The research uncovers that while there is significant experimentation with sustainable practices and some progress in adopting alternative fuels, the transition is still in its early stages. Major barriers identified include high costs of alternative fuels, the lack of a level playing field, and low societal visibility of the sector's environmental impact. Additionally, the conservative nature of the maritime sector and insufficient short-term regulatory obligations contribute to a slow pace of change.

The findings suggest that while the regulatory frameworks like the FuelEU Maritime Regulation have spurred progress, they are not yet ambitious enough to drive the sector towards rapid decarbonisation. The study concludes that stronger regulatory measures, increased economic incentives, and a shift in industry culture are essential to overcoming the identified barriers and accelerating the transition towards a sustainable maritime transport sector.

This research contributes to the existing body of literature by providing a comprehensive analysis of the current state of the maritime sector's decarbonisation efforts and highlighting the systemic challenges that need to be addressed to achieve climate neutrality by 2050.

Contents

1 Introduction

The build-up of greenhouse gases contributes to climate change and global warming, which can have adverse consequences for lives and livelihood (Park et al, 2023). As the necessity to reduce greenhouse gas emissions increases over time, the European Union's goal of achieving climate neutrality by 2050 (European Commission, 2019) becomes increasingly urgent. This has led to calls from scholars and society to better understand sustainability transitions, including those of the hard-to-abate sectors (Kern & Rogge, 2016; Sovacool & Geels, 2016). Substantial progress has been made in reducing greenhouse gas (GHG) emissions in sectors like power generation, light-duty vehicles (Martin et al., 2023; Yang et al., 2022), and commercial and residential buildings (Gray et al., 2021). Despite increasing efforts towards decarbonisation, there are certain sectors that are more difficult to decarbonise, known as 'hard-to-abate' (HTA) sectors. This category includes international transport, consisting of shipping, aviation, trucking and heavy industries such as refineries, chemicals, steel, aluminium, or cement production (Cabot & Villavicencio, 2022; Warren et al., 2023). Especially in these HTA sectors, large GHG emission reductions are still necessary to achieve climate neutrality by 2050.

One of these HTA sectors is the maritime transport sector, responsible for shipping within and outside of the EU. This sector produces 2.9% of all the carbon emissions worldwide, and 3-4% within the EU (European Commission, 2024). This makes the sector important in the goal of the EU to reduce emissions and obtain climate neutrality. Despite promising developments in this sector, pathways to decarbonisation remain unclear and challenging (Cabot & Villavicencio, 2022; Santos et al., 2022; Grzelakowski et al., 2022). For instance, the long lifespan of the ships, which is 20 to 40 years on average (Jang, 2011), results in a slow phase-out of the current fleet, which has higher emissions than a fleet of new ships. Moreover, the production and deployment of low-carbon fuels has a long lead time (Van Leeuwen & Monios, 2022). Therefore, long-term planning is essential for this sector, as investments in ships with a high carbon intensity can lead to stranded assets, or to continued high emissions by the ships for a long time (Fricaudet et al., 2022). In light of this, realising decarbonisation of the shipping sector requires clear plans of action by industry actors, and a long-term regulatory framework that includes ambitious goals (Van Leeuwen & Monios, 2022).

In previous studies, conducted by Balcombe et al (2019), Gray et al. (2021), Grzelakowski et al. (2022), Martin et al. (2023) and Svanberg et al. (2018), researchers have found that realising ambitious goals for decarbonising the maritime transport sector is expensive and challenging. The actions required, including efficiency measures and alternative fuels such as e-fuels and biofuels, require significant financial investment as well as a level of technological and commercial maturity of solutions that has not yet been obtained (Solakivi et al., 2022). Despite these challenges, there have been promising developments within the sector that could be indicative of relevant first steps towards greener practices (Snijders, 2023). For example, large companies in the sector have placed their first orders for ships capable of using low-carbon fuels (Maersk, 2023; Johnsrud, 2023). Moreover, partnerships between large corporations in the sector are formed together with companies that are part of the value chain, such as refineries producing low-carbon fuels (Port of Rotterdam, 2023). These partnerships aim to expand the use of low-carbon fuels on a larger scale (Grzelakowski et al., 2022). These developments are promising, but realising the goal of decarbonising in the EU remains a challenge.

In response to the challenges around decarbonising the maritime sector, the 'FuelEU Maritime Regulation' (FEUM) entered into force in October 2023 (Council Regulation (EU) 1805/2023; Bureau Veritas, 2023). This regulation aims to curtail GHG emissions from the maritime sector, specifically for ships with a tonnage above 5000 GT (Council Regulation (EU) 2023/1805). Ships above 5000 GT represent approximately 55% of all ships calling ports in the EU, but they represent 90% of CO_2 emissions from the sector (Council Regulation (EU) 2023/1805). The regulation mandates a 2% reduction in GHG intensity by 2025, increasing over time leading up to an 80% decrease in GHG intensity by 2050. These reductions are relative to the GHG intensity levels in 2020 (DNV, 2024). GHG intensity is defined as the amount of emissions per MJ of energy used on board, on a well-to-wake basis (Council Regulation (EU) 2023/1805). The regulation gradually becomes more ambitious to reflect the expected technology development and the increased production and implementation of low-carbon fuels for maritime use (Council Regulation (EU) 1805/2023). To summarise, the FuelEU Maritime Regulation mandates a firmer commitment to a sustainable transition in the shipping sector across EU member states, and can be seen as an important step in the mission of decarbonising the shipping sector. Therefore, the FuelEU Maritime Regulation is seen as crucial in the future of the shipping sector, which makes it a central aspect of this research.

Previous research into the decarbonisation of the maritime shipping sector shows that the primary ways of complying with this regulation involve the use of low- or zero-carbon fuels alongside fuel efficiency measures (Gray et al., 2021; IRENA, 2021). Low- or zero-carbon fuels are mostly used in existing ships as drop-in fuel, or in ships specifically built for the use of fuels such as methanol or ammonia (Gray et al., 2021). However, the production and uptake of these fuels needs to increase to reach the ambitious EU targets, as well as ships capable of using them (Solakivi et al., 2022). While the technical and economic aspects such as the development of alternative fuels in the maritime sector have been discussed in previous studies, Von Malmborg (2023) points out a noticeable gap in the literature concerning the social and transitional dynamics of decarbonisation in the shipping sector. Notably, Harahap et al. (2023) mention a lack of studies on the long-term effectiveness of policy instruments that aim to support the use of renewable marine fuels. Moreover, many studies in recent years have not taken the development and implementation of the FuelEU Maritime Regulation into account due to its novelty, presenting a research gap in understanding its effects. Additionally, there is a research gap regarding the current state of the decarbonisation of the shipping sector and the factors influencing the pace and direction of this, as few studies have addressed this subject. To better understand the state and developments of transitions, Sovacool & Geels (2016) and Kern & Rogge (2016) hypothesise that an understanding of the pace and direction of transitions could be supported by a transition studies perspective. This study aims to add to the existing body of literature on the decarbonisation of maritime transport by adding a transition studies perspective.

Through a transition perspective, this study aims to provide insight into the complexity of achieving the European mission of decarbonising the maritime sector by providing a broad insight into the different factors that influence the transition of the maritime transport sector. To achieve this, the core systemic barriers and their underlying causes are analysed, as well as identifying the 'state' of the transition. The state of the transition refers to the current phase and progress towards the maritime sector's shift towards decarbonisation. The barriers to the decarbonisation of the maritime sector are relevant to research because they can highlight where the focus should be for to decarbonise the sector. To understand these barriers, the current system is analysed, as described in Section 2 and 3. The X-curve framework, as discussed by Hebinck et al. (2022), is used to analyse the state of the transition. This framework was developed to better understand the complex nature of transitions and to help come to "a shared understanding of the dynamics in transitions-in-the-making" (Hebinck et al., 2022). To gain more insight into the core barriers to the decarbonisation of the maritime transport sector, the Mission-oriented Innovation System (MIS) approach is used. The MIS approach "includes a problem-solution diagnosis and an analysis of structural, functional and systemic barriers" (Wesseling & Meijerhof, 2023), which contributes to finding the core barriers in achieving a mission. The study by Wesseling & Meijerhof (2023) illustrated the value of the MIS approach, by using the Dutch mission for sustainable maritime shipping as a case study. Together, the use of the MIS approach and the X-curve contribute to insight in the current state of the transition as well as the core barriers in the transition to decarbonisation.

To further define this research, the scope is described for the case study and the *mission*. The case study in this research is deep sea freight and bulk shipping. Deep sea freight and bulk shipping present an interesting case study, as the market is dominated by a small number of companies (Alphaliner, 2023), and is affected by the FuelEU Maritime Regulation (Council Regulation (EU) 2023/1805). As per the regulation, this includes all ships "calling at a port under the jurisdiction of a Member State" (Council Regulation (EU) 2023/1805). The *mission* that is studied in this paper is defined as follows: "The decarbonisation of the maritime transport sector in the EU by 2050, specifically concerning deep sea freight and bulk carriers".

In conclusion, this study aims to address the research gap in a transitions perspective on the decarbonisation of the maritime transport sector. While there are studies that consider the technical and economic feasibility as very difficult factors in the transition, the core barriers have not been investigated extensively on a European scale. Additionally, this study aims to provide clarity on the current status of the transition. Lastly, it aims to reveal systemic barriers and their underlying causes in the context of the innovation system, which can be useful for improving decarbonisation strategies. The following research questions were formulated:

"What is the current state of the transition towards decarbonisation of the maritime transport sector, and what are the core barriers and their underlying causes hindering this transition?"

Sub-questions:

1. *What is the current state of the transition of the maritime transport sector?*
2. *Which system functions create barriers for the transition?*
3. *What are the underlying causes of these barriers?*

First, the theoretical frameworks are introduced and operationalised in Section 2. Next, the methodology used for this research is discussed in Section 3, explaining the use of semi-structured interviews and desk research in this study. The results are presented in Section 4, providing the current state of the transition of the maritime transport section as well as an analysis of the barriers and their underlying causes. Section 5 includes a discussion of the results, the theoretical implications, as well as the limitations of this study and a discussion of the underlying causes of the core barriers to the transition. Lastly, the research questions are answered in Section 6.

2 Theory

This section outlines the theoretical approach used to achieve the research aim. It starts with an introduction to transition studies, followed by a description of the X-curve and its operationalisation in this study. Next, the Mission-Oriented Innovation System (MIS) approach is explained, including its analytical steps. Finally, this section describes the analytical framework that is based on both theories.

2.1 Transition studies

The field of transition studies is an emerging area of research aiming to integrate innovation studies, economics, social studies and environmental science. Its goal is to create a better understanding of large-scale systemic change in our societal systems. Additionally, it aims to provide options for increasing the speed or direction of change (Geels & Schot, 2007; Hebinck et al., 2022; Loorbach & Geerlings, 2017; Loorbach & Rotmans, 2010). Transition studies can be used to understand past transitions by identifying the patterns and mechanisms that drive change, as well as find systemic problems and increase understanding of current and past transitions. This way, transition studies can be used for guiding or directing transitions towards the desired future state (Hebinck et al., 2022; Loorbach & Geerlings, 2017).

Transitions are a societal process of addressing persistent and complex problems when they cannot be addressed by optimising the existing regime (Rotmans & Loorbach, 2010). Sustainable transitions are a process of simultaneous 'build-up' dynamics of sustainable alternatives and of 'break-down' dynamics of unsustainable practices of the incumbent regime (Bosman, 2022; Hebinck et al., 2022). As pressure from external factors increases and alternatives to unsustainable practices of the incumbent regime become more viable, sudden and radical regime shifts can occur (Bosman, 2022; Hebinck et al., 2022; Loorbach et al., 2017). These shifts are a result of complex and simultaneous developments in the economy, society, ecology and technology that build up towards a radical systemic change over a long period of time (Loorbach & Geerlings, 2017). Steering transitions is complicated by diverse external and internal factors. However, understanding the processes of 'build-up' and 'break-down' in an incumbent regime can provide opportunities to accelerate change (Hebinck et al., 2022; Loorbach & Geerlings, 2017; Silvestri et al., 2022). The X-curve incorporates these concepts and enables visualisation of the current state of the transition.

2.2 The X-curve

The X-curve is used to describe the current state of the transition of the maritime transport sector and to capture complex transition dynamics. It is both a tool and a conceptual framework, which was developed to provide guidance and understanding of sustainability transitions (Hebinck et al., 2022). It can help actors navigate through complex changes when not only the building of a new regime is visible, but the breaking down of the 'old' regime adds to the complexity of the situation (Hebinck et al., 2022; Silvestri et al., 2022). Through the lens of the X-curve framework, these complex processes can be better understood and placed in a broader context (Hebinck et al., 2022; Silvestri et al., 2022). The theory is particularly suitable in multi-stakeholder settings where a multitude of strategies is being explored (Hebinck et al, 2022; Silvestri et al, 2022), making it a relevant framework for the case of maritime shipping, where no definitive decarbonisation pathway has been established yet.

The X-curve provides a simplified depiction of complex systems in transition (Hebinck et al., 2022; Silvestri et al., 2022), as can be seen in Figure 1. It distinguishes 'build-up' and 'break-down' dynamics that are found in transitions. Build-up dynamics encompass patterns of experimentation, acceleration, emergence, institutionalisation and stabilisation, while break-down dynamics involve the patterns of optimisation, destabilisation, chaos, breakdown and phase out. A detailed overview of these patterns of transition can be found in Table 1. These patterns are not linear and can happen simultaneously (Hebinck et al., 2022; Silvestri et al., 2022).

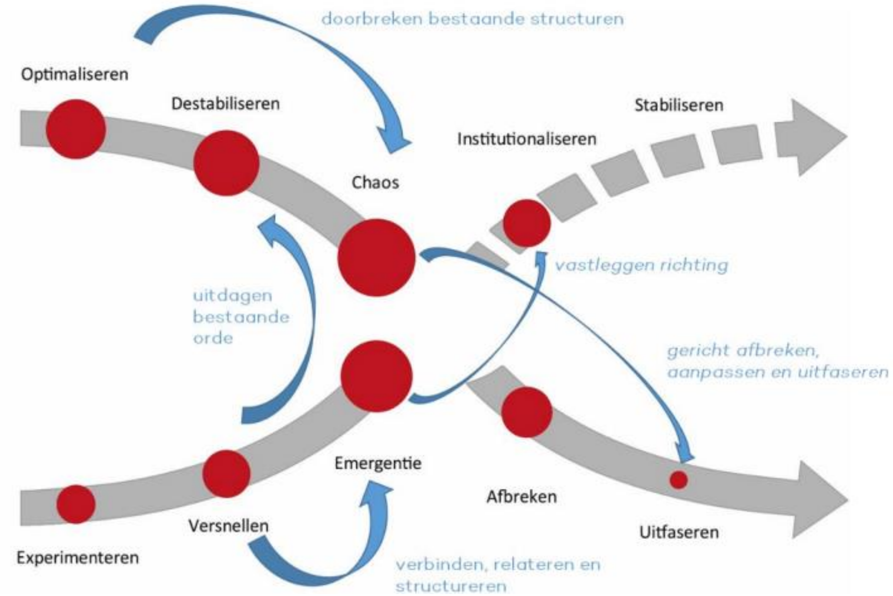

Figure 1: An example of how the X-curve can be used to visualise the state of a sustainability transition. This example is the state of the energy transition in 2017 in the Netherlands, the size of the red circle indicates the degree of activity in a certain transition pattern. Source: Lodder et al. (2017).

Patterns of build-up	**Patterns of break-down**
Experimentation	**Optimisation**
Indicators: • Emergence of radical new practices • Radical new thinking	*Indicators:* • Continuous improving of the existing system • Trust in the existing system
Acceleration	**Destabilisation**
Indicators: • Alternatives to the regime connect… • … and become visible and accessible to an increasing number of people	*Indicators:* • Existing system starts to hamper • Resistance to change increases • More fundamental discussions on future desired state
Emergence	**Chaos**
• Direction of change becomes more clear • Need for transition becomes broadly accepted • New solutions and structures become visible and widely accessible	• Dominant structures, patterns and practices fail • Resistance to change becomes entrenched against looming breakdown • Conflicts and opposing interests emerge
Institutionalisation	**Breakdown**
Indicators: • Change is irreversible • A ‘new normal’ in thinking and doing • New structures solidify • New balance of power	*Indicators:* • ‘Losers’ of a transition become visible • Old structures crumble and disappear
Stabilisation	**Phase-out**
Indicators:	*Indicators:*

• Former radical new practices become embedded into the new dominant system • New practices enter a state of continuous optimisation	• Old status quo is phased out • Saying goodbye to old practices • Losses have been dealt with and accepted

Table 1: The patterns of build-up and breakdown that form the X-curve and their typical indicators. Based on Hebinck et al. (2022) and Lodder et al. (2017).

2.3 Operationalisation of the X-curve

In this study, the X-curve is operationalised by identifying the indicators for each transition pattern as described in Table 1. The presence or absence of these indicators, identified through targeted questions such as those in Table 2, helps to determine the visibility of specific transition patterns. For example, if an interviewee noted that dominant structures are not failing, this would suggest that the transition pattern of chaos is less evident. Additionally, these indicators are used to summarise the developments in the sector within each transition pattern. The summarised findings are organised into a table after obtaining all the results, which serves as the basis for visualising the current state of the transition in the maritime sector. The full interview guide can be found in Appendix 1.

Patterns of the X-Curve	**Exemplary interview questions**
Build-up	-
Experimentation	Have you seen significant experimentation with (producing) sustainable maritime fuels?
Acceleration	In recent years, have you seen a change in pace of the adoption of measures to decarbonise?
Emergence	Is the urgence of adopting decarbonisation strategies widely felt? Are zero/low-carbon strategies becoming dominant in thinking and doing?
Institutionalisation	Are there pathways towards decarbonisation that have created a firm hold on the market?
Stabilisation	Are there zero emission technologies that are here to stay?
Break-down	-
Optimisation	Do incremental improvements in operations have a high priority? Are they seen as more doable compared to moving towards net zero emissions?
Destabilisation	Is it becoming more difficult to be profitable while using conventional maritime fuels?
Chaos	Are large actors in an unsure position? Is a variety of pathways towards net zero competing for investments?
Breakdown	Is conventional maritime fuel seen as an investment risk? Are old technologies incurring losses?
Phase-out	Are 'old' ways of operating disappearing?

Table 2: Exemplary interview questions to find indicators for the different patterns of the X-curve. The interview guide will be tailored to a specific interviewee's field expertise.

2.4 Mission-Oriented Innovation System (MIS) framework

Originating from the Technical Innovation System (TIS) framework, the MIS is a novel approach emerging in innovation studies (Wesseling & Meijerhof, 2023). The MIS is used to analyse transitions that are aimed towards achieving a mission. This mission is often complex and consists of many different factors that influence the outcome of the transition. The MIS takes into account the actors, rules and institutions that play a role in realising a societal mission (Elzinga et al., 2023). In this study, the mission is the decarbonisation of the maritime transport sector. The MIS-concept of the 'societal mission' aligns with the concept of the 'desired future state' in the X-curve. Therefore, this study refers to the 'desired future state' as the *mission*. The MIS framework captures both the build-up of the transition and the breaking down of the old regime, activities and processes (Hekkert et al., 2020; Wesseling & Meijerhof, 2023), making it a good fit with the X-curve. The MIS approach uses the following steps, based on Bours et al. (2022), Wesseling & Meijerhof (2023) and Elzinga et al. (2023):

1. **Structural analysis:** Mapping actors, rules, and institutions contributing to or hindering the sustainability transition: The mission arena.
2. **Problem-solution diagnosis:** Identifying problems and possibilities associated with realizing the future desired state.
3. **Functional analysis:** Evaluating the 7 functions of the MIS, detailed in Table 3. Based on these 7 functions, analyse if the innovation system is sufficiently equipped to achieve its desired state.
4. Analysis of underlying structural problems that result in problematic functioning.

These steps and their application in this research are briefly described.

2.4.1 Structural analysis

In this first step, the actors involved in realising the mission or future desired state are analysed. A distinction can be made between types of actors. First, there are actors that can set the agenda and therefore have a steering role in the direction of the transition. These actors form the mission arena (Wesseling & Meijerhof, 2023). Wesseling & Meijerhof (2023) define the mission arena as "a governance structure where actors formulate and govern the mission, by mobilizing and directing other, preexisting system components". The second type consists of actors that are active in the innovation system, but do not have the same degree of influence over the direction. These actors are part of the overall mission-innovation system. In this step, these actors are analysed and divided between type.

2.4.2 Problem-solution diagnosis

The second step is mapping the problems that need to be solved in order to accomplish the mission, as well as the proposed solutions in a so-called problem-solution diagnosis.

2.4.3 Functional analysis

Developed to study technical innovation systems (TIS), the functions of an innovation system are key processes that take place within the innovation system and can be used to determine the likelihood of an innovation succeeding (Bours et al., 2022; Hekkert et al., 2007). However, according to Bours et al. (2022), Elzinga et al. (2021) and Wesseling & Meijerhof (2023), they are applicable to describe the innovation systems in a certain sector as well. In their 2023 paper, Wesseling & Meijerhof (2023) adapted the system functions in such a way that they can reflect the performance of a MIS within a sector. In Table 3, an overview of the system functions is provided, based on Bours et al. (2022), Elzinga et al. (2021) and Wesseling & Meijerhof (2023). These system functions are analysed for the maritime shipping sector to see which functions perform well, and which might hamper obtaining the mission. This can be used to determine the main barriers.

System function	Description
SF1: Entrepreneurial activities	**Build-up side:** Experimenting with alternatives. **Breakdown side:** Experiments to destabilise actors, institution and networks that cause resistance to change.

SF2: Knowledge development and unlearning	**Build-up side**: Learning by search and 'doing'. This leads to a better understanding of new technical and social knowledge on innovative solutions. **Breakdown side**: Similar learning and development. However, this is aimed at stopping or unlearning harmful practices.
SF3: Knowledge diffusion and network breakdown	**Build-up side**: Stakeholder meetings, conferences, governance structures, public consultations, progress reports and other forms of disseminating knowledge on social and technical aspects of innovative alternatives. **Breakdown side**: Similar forms of disseminating knowledge on destabilisation solutions. This includes breaking down knowledge-sharing networks and increasing societal awareness on harmful practices.
SF4a: Providing directionality to the problem	Incorporates the direction provided to the conceptions of the societal problem, and the level of priority to finding a solution.
SF4b: Solution directionality	The direction that is given to the search and development of solutions. This happens in both the build-up and breakdown side, and includes efforts for coordination within the MIS that are needed to find solutions.
SF5: Market formation and destabilisation	**Build-up side:** Niche markets are created, support for technical and social solutions increases. **Breakdown side:** Existing markets for harmful products or practices destabilise or phase out.
SF6: Resources allocation	**Build-up side**: Includes the mobilisation of resources (human, financial and material) that enable the system to function. **Breakdown side**: Less resources are allocated to markets for harmful products or practices.
SF7: Creation and withdrawal of legitimacy	**Build-up side:** Innovative solutions that contribute to a future desired state need legitimacy to overcome resistance to change and become widely accepted. **Breakdown side**: The MIS needs to create legitimacy for the solving of societal problems over the vested interests of the 'old' regime. This can include lobbying against harmful practices, vocal support for solutions or the mitigation of the power of vested interests.

Table 3: The functions of the MIS, adapted from Bours et al. (2022), Elzinga et al. (2021) and Wesseling & Meijerhof (2023). The build-up side refers to the introduction of alternatives, while the breakdown side refers to the 'old' regime being phased out.

2.4.4 Analysis of structural problems

The systemic barriers that emerge from the functional analysis and the analysis of the patterns of the X-curve are explored iteratively to find interrelatedness between barriers and place them in the context of the system. This iterative process helps to explain the core barriers and their underlying causes. Analysing the interrelatedness is crucial because the root cause of one weak system function may be linked with barriers associated with another system function (Van Arkel, 2021). Similarly, a barrier preventing the institutionalisation pattern of the X-curve to be evident might stem from a lack of destabilisation of current (harmful) practices.

2.5 Operationalisation of the MIS approach

Steps 1 and 2 of the MIS approach involve mapping relevant actors, institutions, and networks, along with possible pathways to achieve the mission. This is done by conducting desk research, for which targets set by different (governmental) organisations, communications from industry actors and other grey literature are used. These steps also help to refine the interview guide and identify potential interviewees. Next, the system functions are analysed. As suggested by Wesseling & Meijerhof (2023) and Wieczorek & Hekkert (2012), the system functions are evaluated using diagnostic questions, which are provided in Table 4. These diagnostic questions are used as the basis for the interview guide.

System function	Operationalisation: Diagnostic questions for evaluating the system function
SF1: Entrepreneurial activities	• Can entrepreneurial activities with new technical or social solutions be identified? • Can different (competing) solutions be identified? Is there a new way of thinking among industry actors?
SF2: Knowledge development and unlearning	• Is the pace of knowledge development high enough to accomplish the mission? • Is knowledge being developed on how to unlearn current harmful practices?
SF3: Knowledge diffusion and network breakdown	• Is knowledge being diffused among different stakeholders? • Are different ways of thinking being connected between stakeholders? • Is knowledge on unlearning harmful practices sufficiently spread? • Are networks that support the old regime starting to hamper?
SF4a: Providing directionality to the problem	• Are the societal problems related to the mission given priority by stakeholders compared to other societal issues and desires? • Do stakeholders associate the missions' societal problems with vested interests? In other words, does solving the problem align with vested interests. • Is the need for transition becoming widely accepted among stakeholders?
SF4b: Solution directionality	• Are stakeholders aware of the necessary actions to take to achieve the goal? • Is there consensus among stakeholders on what the necessary actions are? • What pathways are currently being prioritised? • Is there a dominant pathway emerging?
SF5: Market formation and destabilisation	• Is there support for the transition from formal and informal institutions? • Are innovative solutions being adopted sufficiently? • Is support for supplying the 'new' regime increasing?
SF6: Resources allocation	• Can significant investments in alternative regimes be seen? • Are investments in the 'old' regime becoming harder to obtain?
SF7: Creation and withdrawal of legitimacy	• Can shifting norms, values and paradigms be seen? • Are actors actively lobbying against the 'old' regime? • Is there widespread support for the sustainability transition? • Is the 'old' regime loosing (parts of) its stabilising power? • Is there significant vocal support for the sustainability transition?

Table 4: the MIS system functions and the corresponding diagnostic questions to evaluate them, adapted to better fit the X-curve framework (Based on Wesseling & Meijerhof (2023) and Wieczorek & Hekkert (2012).

2.6 Using the X-curve and the MIS framework

The X-curve and MIS approach are used to create a comprehensive analysis of the transition of the maritime sector. First, the structural analysis and problem-solution diagnosis are conducted as part of the MIS scoping process as described further in Section 3. Following this, the different patterns of the

X-curve are analysed, while simultaneously analysing the system functions. Consequently, the findings from these analyses are used to identify the underlying structural barriers and their underlying causes. This combined approach allows for a clear visualisation of the current state of the transition, the barriers that need to be overcome to advance the transition, and the root causes of these barriers. This process is visualised in Figure 2.

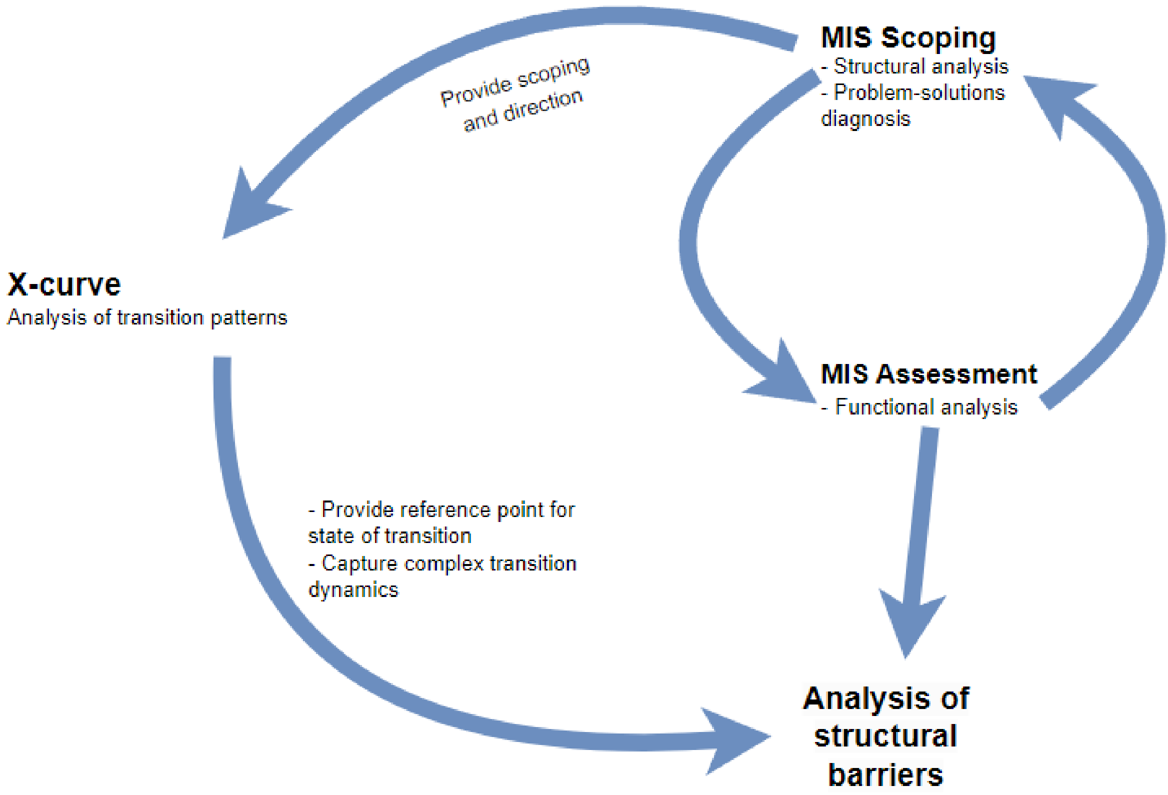

Figure 2: Visualisation of the theoretical framework. The MIS scoping provides scoping and direction to the X-curve analysis and MIS Assessment. In turn, the MIS assessment is used in an iterative manner to improve the scoping. Consequently, the MIS assessment and analysis of transition pattens serve as the context for analysing the structural barriers and their underlying causes.

3 Methodology

In this section, the methodology for answering the research questions is described. First, the research design is explained, including the analytical steps for the MIS approach and the different phases of the X-curve. This is followed by the data collection, which is split into desk research and semi-structured interviews. The data analysis is then explained, after which the section is concluded with a discussion on the validity and reliability of the study.

3.1 Research design

This study employs a qualitative research design, with deep sea freight and bulk shipping as a case study. The research design consists of desk research and semi-structure interviews. The desk research includes press releases, news articles and scientific papers. In addition, ten semi-structured interviews were conducted with both industry actors and experts. These were used to obtain in-depth experiences from the sector, as well as for triangulation of the obtained information from the desk research. Since systems are dynamic and can change rapidly in a transition (Bosman, 2022), the desk research mostly includes recent publications from 2020 onwards. This fits well with the used approach, since the MIS approach captures a transition at a certain point in time (van Raak et al., 2022). After conducting the desk research for the structural analysis and problem-solution diagnosis, results from the interviews were used for triangulation and to add different points of views from the sector to the current state of the transition as well as to the analysis of the system functions. The desk research and semi-structured interviews are further explained in Section 3.2. Below, the analytical steps to answer the research questions are described.

3.1.1 Structural Analysis, Problem-Solution Diagnosis, and Functional Analysis

The structural analysis was conducted to map the key actors, institutions, and networks involved in the transition of the maritime sector. Second, a distinction was made between the actors in- and outside the mission arena, as described in section 2.4.1. This was done by identifying important regulators, industry actors and regulations based on documents in the desk research. Additionally, statements by interviewees on the influence of different actors on others were considered to determine and confirm the mission arena.

Next, the problem-solution diagnosis was performed, which involved identifying the key societal problems and their corresponding solutions. To this end, the data from the interviews and desk research was analysed to identify the different problems and solutions, and how they related to the decarbonisation of the maritime sector. For example, one significant issue identified was the lack of a level playing field for green business models. The primary solution proposed to address this was the implementation of more ambitious policy obligations in the short term. In a similar manner, different issues and solutions are presented in clusters. Therefore, the solutions do not include an extensive list of different technological innovations, and take into account societal implications. The problem-solution diagnosis contributes to the scope and direction of the functional analysis.

Next, the analysis of system functions was conducted by using a set of diagnostic questions as described in Section 2.4.3. The responses from the interviewees were analysed to assess which functions have a positive impact on the transition, and which functions hinder it. The system functions were not described in a quantitative manner, but in a qualitative narrative, which leaves room for nuances and insights into the complexities of the system. The key output of the system functions are systemic barriers that hinder the decarbonisation of the maritime sector. The interrelated underlying causes that are connected to other system functions were discussed in the analysis of underlying structural problems.

3.1.2 Analysis of different patterns of the X-curve

Based on the interviews and desk research, the different patterns of the X-curve were analysed. This was done by analysing the presence of the indicators of each pattern, which are described in Table 1. These indicators were split up between 'negative' and 'positive' indicators, as explained in Section 3.3. The key output of this analysis is developments in the sector, which were attributed to transition patterns. The developments are summarised in a short narrative for each transition pattern. This way, complex transition dynamics are captured. Finally, the 'state' of the transition in connection to the X-curve was visualised in Figure 3. This visualisation serves as a reference point for future research, as it provides a concise overview of activity in each transition pattern. The analysis of the patterns of the X-curve served, in combination with the analysis of system functions, as input for analysing the underlying structural problems.

3.1.3 Analysis of underlying structural problems

Following the analysis of the system functions and the X-curve, the underlying structural barriers were identified as outlined in Section 2.4.4. This process involved examining the interconnections between various barriers that contribute to the malfunctioning of system functions and hinder progress in the transition. To validate these findings, a number of interviewees, including industry and policy experts, was asked to confirm and elaborate on the identified barriers, and desk research was used to ensure triangulation of the results.

3.2 Data collection

3.2.1 Desk research

For desk research, sources such as press releases, policy documents, legislation, news articles, articles written by knowledge institutions and scientific papers were used. These were found using Google Scholar, Google, government databases and knowledge institutions such as the Global Maritime Forum. An overview of used keywords for the desk research can be found in Table 5. This method provided a larger number of different documents, of which 16 papers, 7 reports, 19 press releases and 9 news articles were used. This literature research is useful to obtain knowledge prior to the interviewing process and to strengthen the conceptual basis of the research. Moreover, it is used to triangulate new findings and place them in context of the existing body of literature.

Topic	Keywords
Sustainable marine fuels	Marine fuels, renewable marine fuels, renewable fuels, low-carbon fuels, low- to zero-carbon fuels, maritime fuel transition, ammonia/methanol/hydrogen/LNG in shipping, dual-fuel engines, orderbook dual-fuel engines shipping, *company name* *renewable fuel X/Y/Z*, production of maritime/marine fuels
Decarbonisation of the shipping sector	Marine decarbonisation, wind propulsion shipping, GHG emissions reduction shipping, decarbonisation efforts shipping sector, progress of maritime transition, maritime transition
Social innovations	Sail fast, then wait, Blue Visby, just-in-time arrival, 'company name' sailing speed, marine fuel efficiency, law of general average fuel efficiency

Table 5: List of keywords used in Google Scholar, Google, and knowledge institutes such as the Global Maritime Forum.

3.2.2 Semi-structured interviews

Semi-structured interviews were conducted with relevant actors in the shipping sector, policy experts and energy transition experts to obtain data. The research focuses on the EU but includes international developments due to the global nature of maritime shipping and the influence of global regulators like the IMO, leading to a broader sampling strategy. The sample of interviewees was selected through a purposive sampling approach, meaning the selected interviewees are relevant to the research because of certain characteristics, which are described below. This approach is suitable for selecting information-rich interviewees (Bryman, 2012). The interviews were semi-structured. This is due to the fact that semi-structured interviews make use of an interview guide, but leave room for exploring experiences, motives and attitudes (Barriball & While, 1994), which are very relevant to this study. The semi-structured nature of the interview also leaves room for flexibility and prioritising of topics that the interviewee has knowledge on. The interview guide can be found in Appendix 1.

The interviewees were selected on the basis that they have in-depth knowledge on the policy mix, technology, and economic and cultural characteristics that affect the shipping sector. Moreover, the sample of interviewees included actors actively involved or affected by the transition, as well as 'outside' experts whose expertise lies in policy and legislation. This provided a broad perspective on both developments in the sector and on policy developments. Additionally, the sample includes interviewees from companies involved in alternative fuels such as refineries, bunkering companies and ports. This contributes to a broad view of the transition, which was needed for the analysis of the patterns of the X-curve and the system functions.

In total, 83 individuals or organisations were approached, of which 10 agreed to an interview. Most individuals did not respond, and a number of industry actors indicated that even anonymously, they were not allowed to discuss their strategy in-depth. Of the sample, 5 interviewees can be placed within the mission arena, which is described in Section 4.1. The other 5 interviewees were active in the overall Misson-Innovation System, but were not aligned with an organisation in the mission arena. The individuals and organisations were approached through contact forms, personal email addresses (if publicly available), and through LinkedIn. Additionally, a conference on sustainable shipping was attended to approach additional potential interviewees. The interviews lasted approximately 60 minutes. The interviewees are listed in Table 6.

Interview nr.	Description	Code
1	Carbon market analyst & EU lobbyist	PE1
2	Director of decarbonisation of knowledge institute	NGO1
3	Manager of decarbonisation at major port	IE1
4	Senior consultant maritime decarbonisation	IE2
5	Market analyst renewable maritime fuels	IE3

6	Senior market analyst and policy expert at major shipping company	PE2
7	Senior maritime expert at not-for-profit organisation active in IMO negotiations	PE3
8	Partner at law-firm specialised in maritime law.	PE4
9	Commodity trader specialised in renewable fuels	IE4
10	Sustainable shipping policy expert at knowledge institute	PE5

Table 6: List of interviewees with a short description of their role in the sector (NGO = non-governmental organisation, IE = industry expert, PE = policy expert).

In line with the University Utrecht guidelines, informed consent was provided to interviewees, and interviews were only conducted when consent was given. To ensure interviewees felt free to answer questions, anonymity of interviewees was guaranteed. The right to withdraw at any point was emphasised, as well as the right to withdraw statements at a later time.

3.3 Data analysis

The interviews were recorded to be transcribed verbatim and coded using NVIVO. First, open coding was used for structuring the answers into codes that relate to the indicators and diagnostic questions. These categories are linked to different indicators of the X-curve, and answers to the diagnostic questions stemming from the MIS approach. After the open coding, the codes were structured into categories. These categories are linked to different indicators of the X-curve, and answers to the diagnostic questions stemming from the MIS approach. This contributed to creating structure in the obtained data.

After coding the interview transcripts, the steps of the MIS approach were carried out as described in the previous sections. For the X-curve, the degree of activity attributed to a certain phase was determined by the frequency of indicators and the significance attributed to them by experts. Based on the framework developed by van Raak et al. (2022) and the method developed by Lodder et al. (2017), the following approach was followed:

- For each phase of the X-curve, the indicators found in the data collection are presented.
- Next, the findings are summarised in Table 7. Each development or indicator is market with the symbols ↗ or ↘, to indicate if it is an indicator of the presence of a certain transition pattern, or an indicator of a lack of aspects.
- A short 'narrative' of the phase is presented. This narrative should provide a view of the degree of activity attributed to a certain phase.
- Consequently, Table 7 served as input for Figure 3, as suggested by Lodder et al. (2017).

Using the X-curve, the current system could be described, relating to the first research question. The functional analysis contributed to obtaining the barriers and gaining insight into the underlying causes, relating to the second research question. Using the information obtained in the analysis as described above, the main research question could be answered.

3.4 Reliability and validity

This research uses a qualitative research design. Therefore, reliability and validity should be discussed accordingly. The terms imply that absolute truths about the social world can be known, but there can be multiple truths simultaneously in one system (Guba & Lincoln, 1994), in contrast to some quantitative research designs using numerical empirical data. This is taken into account when discussing this research.

Internal reliability concerns the consistency among different researchers using the same data and the degree of objectivity that is obtained (Bryman, 2012; Guba & Lincoln, 1994). To ensure this with only one researcher, all transcribed interviews were read carefully multiple times to make sure no relevant information was missed through human error, and to identify inconsistencies and patterns in the responses. This increases objectivity (Barriball & While, 1994). However, it should be taken into account that despite these efforts, only one researcher has conducted and analysed the interviews, which makes inter-observer consistency and objectivity more difficult to assure.

External reliability concerns the replicability of the study. For transition studies, this is difficult to obtain because the system can change significantly over time, potentially yielding different results. However, in order to increase the external reliability, all records should be kept carefully in all phases of the research (Bryman, 2012). This makes it possible to see all the responses and any follow-up questions that were not included in the interview guide. This increases external reliability because other researchers are able to see all steps of the research transparently. Lastly, it is important to acknowledge that with a small sample size, interviewees might give contradictory statements, based on their perspective or personal values. To account for this, desk research was used to ensure triangulation.

4 Results

In this section, the results from the interviews and desk research can be found. First, the structural analysis, problem-solution diagnosis and functional analysis are discussed. Next, the different phases of the X-curve are analysed, which is summarised in Table 7. Consequently, the underlying structural problems are discussed. Finally, these structural problems are integrated into the X-curve framework in Figure 3.

4.1 Structural analysis

The maritime sector, often perceived as a conservative and slow-changing industry, has radically changed in its approach to decarbonisation in recent years (Zhang et al., 2022; IE1, IE2, IE3, IE4, PE1, PE2, PE3, PE4, NGO1). This industry, crucial to the global economy, has historically been marked by a resistance to change (IE1, IE2, IE3, PE2, PE3, PE4, NGO1). The maritime sector is a consolidated sector, where a small number of companies has a large market share (Alphaliner, 2024). These large companies have a significant influence over the market, over regulators and they have the capital to invest in technologies on a large scale (NGO1, IE1, IE3, PE1, PE2, PE3, PE4, PE5). Therefore, these companies are considered to be a part of the mission arena.

Regulation in the maritime sector is normally mainly established by the International Maritime Organization (IMO), which sets international maritime safety and environmental standards. While the IMO creates broad regulatory frameworks, enforcement is the responsibility of the governments of its member states (IMO, n.d.). These include 175 countries worldwide. Individual governments can also implement regulations, as well as the EU. In part out of frustration with the inaction of the IMO, the EU implemented the FuelEU Maritime regulation (FEUM), intended to drive the decarbonisation of the maritime sector (Snijders, 2023; IE3). The EU and IMO are considered to be inside the mission arena. Individual member states of the EU and IMO are not considered to be in the mission arena. This is because they do not have the power to influence the decarbonisation of deep sea freight and bulk shipping to a high degree (NGO1, PE3). While they can implement their own policy, they do not have the same ability to steer the transition at the high scale that this study looks at.

The fuel infrastructure used by the maritime sector is dependent on a wide variety of actors, including but not limited to ports, fuel suppliers, refineries and other logistical components. Additionally, knowledge institutes, NGO's lobbying for decarbonisation and financial institutions have an important role in the transition. While these actors are a crucial element in the transition, they are not considered part of the mission arena as they do not have the power to significantly steer the transition on the scale considered in this study (IE1, IE4, PE1, PE5).

To summarise, the mission arena in this study encompasses major European shipping companies, along with the IMO and EU as key regulatory bodies. These organisations have significant influence over the pace and direction of the transition. In the overall MIS, a larger number of actors is considered. This includes individual member states of the EU and IMO, ports, actors active in the supply of marine fuels, knowledge institutes, financial institutions and NGOs. Together, these groups of actors form the context for the analyses conducted in this study.

4.2 Problem-solution diagnosis

Multiple interviewees (NGO1, IE1, IE2, IE3, PE1, PE2, PE3, PE4) indicated that while in their experience the urgency for lowering emissions due to sustainability considerations was widely recognised, this does not translate into immediate action by different industry actors. Multiple interviewees noted that ambitious policy would be needed to incentivise the sector to decarbonise, as the motivation to change is low in the conservative sector (NGO1, IE2, IE3, IE4, PE1, PE2, PE3, PE4, PE5). As mentioned before, the FuelEU Maritime regulation was implemented to drive decarbonisation efforts in the maritime sector. This was followed by the 2023 revised IMO GHG strategy (IMO, 2023). The revised GHG reduction strategy adopted by the IMO aims to reduce GHG emissions from international shipping by 20% by 2030 and 70% by 2030, compared to 2008 levels, with the ultimate goal of achieving net-zero emissions “by or around, i.e., close to 2050” (IMO, 2023).

One of the main problems that was stressed by all interviewees was the need for a level playing field. Currently, implementing competitive green business models is very difficult. As it stands, the FEUM and the individual member states do not provide enough economic incentives to make green business models fully competitive. Taxing emissions is particularly important here (NGO1, PE1, PE3, PE5). From the IMO, there are currently no significant economic incentives. The main solution identified for creating a level playing field is setting more ambitious regulatory obligations (Ulichina, 2024; NGO1, IE1, PE1, PE2, PE3, PE4). Another complication is the importance of the maritime sector to the economy. Severe disruptions of global trade are considered undesirable (NGO1, IE2). However, the impact of ambitious decarbonisation targets for the maritime sector would not lead to an insurmountable increase in costs of transporting goods (Transport & Environment, 2024). Examples of this are the disruption caused by the Covid pandemic and the blocking of the Suez Canal (Prevljak, 2023a). While this did lead to problems with missed delivery times and a shortage of capacity, the enormous cost increase did not cause significant issues (Transport & Environment, 2024). Notably, shipping companies saw their profit margins increase significantly as they were able charge a premium on top of the cost increase (Prevljak, 2023a). Therefore, raising a carbon levy or introducing more ambitious regulatory obligations is considered a viable solution by a number of experts (Ulichina, 2024; NGO1, IE2, IE3, IE4, PE1, PE2, PE3, PE5).

A multitude of technical and social innovations are entering the market. Examples of technical solutions include energy efficiency measures, the use of bio- and e-fuels and on-board carbon capture and storage. Social innovations include ‘just in time arrival’, adjusting sailing speeds and increased incentives for transporting goods as efficiently as possible. While this study does not include an extensive exploration of the different innovations, some examples are highlighted to illustrate the workings of the sector.

To summarise, the most important problems are the inaction in large parts of the sector, the difficulty of competing with oil as an energy carrier and the lack of a level playing field. This is exacerbated by the crucial role of the maritime sector in the world trade, which leads to resistance to any potential disruptions not only from industry actors but also from policymakers.

4.3 Functional analysis

This section includes an extensive analysis of the system functions listed in Table 3. Each function is analysed based on input from interviewees and other data sources, such as press releases, news articles and scientific papers. These were found as described in section 3.2.

Entrepreneurial activities (SF1):

Entrepreneurial activities in alternatives are significant and expanding at a high rate. There is extensive experimentation on different technologies such as wind propulsion, energy efficiency and other innovations. Many technologies are already considered mature technologies, such as the use of methanol (IE3). Notably, some green business models are starting to make sense as different policies come into effect (NGO1, PE1, IE2, IE3, IE4). Especially as the FEUM targets get higher over time, green business models will become more competitive (IE1, IE3, PE1, PE2, PE4). Companies are heavily investing in technologies they used to see as a ‘curiosity’ or annoyance, while potential fuel savings are now increasingly seen as a win by industry actors (NGO1).

On the break-down side, there is activity as well. There are multiple institutions that are working on finding problems that are encountered by companies trying to decarbonise (IE1, IE2, NGO1, PE1, PE3, PE5). This includes developing technical standards by certification societies, the creation of green business models and providing guidance to social innovations.

Knowledge development and unlearning (SF2):
Knowledge development has a high pace. A large number of industry actor is investing in the development of new technologies, as even companies that are not interested in being a frontrunner are investing heavily in new technologies and developing knowledge, even if it is to prevent running behind competitors that have an extensive decarbonisation strategy (Habibic, 2024; PE1, NGO1, IE1, IE2, IE3, PE4).

Signs of 'unlearning' can be seen; there is significant talk of unlearning the 'sail fast, then wait' practice. Combined with positive early experiments, this is an important first step. However, as long as fuel prices are relatively low, there is not enough incentive to force the phasing out of harmful practices (IRENA, 2021; PE1, NGO1, PE2, PE4). Higher fuel prices, either through carbon levies or by mandating a higher uptake of low- to zero carbon fuels would incentivise the sector to increase the rate at which it adopts new practices (IRENA, 2021; PE1, NGO1, IE1, IE2, IE3, PE2). Until this is implemented, it is expected that talk of change is not likely to lead to action (NGO1, IE1, PE4, PE5).

Knowledge diffusion and network breakdown (SF3):
Multiple interviewees have pointed out that knowledge diffusion across the sector is sufficient. For example, IE3 explained the following:

"While a few years ago we had to explain what bio-fuels are and how they work, companies are now coming to us knowing exactly what they want to buy and why. Only on newer developments such as e-fuels are they now asking for our help."

There are multiple annual conferences on the topic of maritime decarbonisation, and public consultations on policy are common in the sector. Additionally, there are large organisations that focus on disseminating knowledge on social and technical aspects of alternatives.

On the breakdown side, interviewees agreed there are hardly any signs of networks breaking down. However, a growing resistance to the status quo can be observed; a growing number of countries and industry actors is actively lobbying for cleaner operations (Laranjeira, 2024; NGO1, PE3, PE4). The societal awareness on the harmful practices has become more present, but the impact on industry actors is still low (NGO1, IE1, PE4). The fact that other sectors have committed to net zero by 2050 helps in pushing for more ambitious goals, as there is a sense that the maritime sector is lagging behind other sectors (NGO1). However, the sector has also been described as 'very conservative' (NGO1, IE1, IE2, IE3, IE4, PE2, PE4, PE5), with a low sense of societal responsibility. These interviewees found it very unlikely that networks would break down in this sector. Notably, as shipping is such a vital component of the global market, regulators are not likely to facilitate a quick breakdown. A majority of interviewees stressed that breaking down the sector or shrinking it should not be a focus, due to the critical function it has in global trade networks.

Providing directionality to the problem (SF4a):
The FEUM has provided direction to the problem both directly and indirectly. Directly, it has set clear targets for the reduction in carbon intensity. The implementation of the FEUM is believed to provide this by mandating a certain percentage of alternative fuels and by providing yearly reduction targets (NGO1, IE1, PE1, PE3, PE4, PE5). The yearly reduction targets are considered particularly important, as it incentivises the adoption of corporate strategies on the short term, beyond vague promises of decarbonising by or around 2050 (NGO1, IE2, PE2, PE4, PE5). However, the targets are still considered

to be too low to encourage the uptake of new technologies sufficiently (Bloomberg, 2024; NGO1, IE1, IE2, IE3, PE1, PE2, PE4, PE5).

Indirectly, the FEUM contributes to providing directionality to the problem by providing economic incentive. The FEUM mandates an increasing percentage of uptake of renewable fuels, which would drive up prices of sailing (NGO1, IE3, IE4, PE3, PE4). This indirectly provides incentives to prioritise fuel efficiency (NGO1, PE2). This incentivises innovations such as wind propulsion, efficient fleet management and slower sailing. IE2, IE3, PE2 and PE3 explained that this improves the competitiveness of green business models significantly, as not lowering the carbon intensity incurs a fine that is substantially higher than the cost of implementing innovative technologies (*Regulation (EU) - 1805/2023*).

Amongst industry actors, the level of priority to finding a solution is high among frontrunners, but not yet in many others (NGO1, PE4, PE5). A lack of corporate citizenship is given as the main reason for companies to delay action (NGO1, IE1, IE2, IE3, IE4, PE1, PE2, PE4, PE5).

The urgency given to the problem by regulators is significant. According to NGO1, IE3 and PE3, the EU has implemented the FEUM partly out of frustration coming from a lack of regulation from the IMO (Snijders, 2023). As a global regulator, the IMO responded to this by radically revising its decarbonisation strategy for 2050 (IMO, 2023). At the same time, pressure from different countries within the IMO has led to more ambitious targets after the most recent negotiations in 2023 (PE3).

Solution directionality (SF4b):
The solution directionality given to the development of solutions can be split into two categories: technical and economical. Between technologies, there is no strong direction dictated by regulators to any specific technologies. Instead, the FEUM is positively technology neutral (McKenney, 2024), while the IMO strategy does not specifically favour any technology over another, according to PE1, NGO1, IE1, IE2 and IE3. PE2 put it as follows:
"The market is innovating very fast and costs are coming down very fast, but it is difficult to predict what technologies will work best. So policy should always be as technology neutral as possible. But it should be more ambitious.'

The solution directionality given to economic solutions is weak (PE1, NGO1, IE1, IE2, IE3, PE2, PE3). The difficulty of competing with oil is one of the main reasons for industry actors to wait with implementing decarbonisation strategies at a large scale (Asmussen et al., 2023; Bloomberg, 2024). PE2 explained this by saying:

"It's simply almost impossible to compete with oil in terms of price, availability and energy density, so the most important thing is price."

As it stands, the FEUM does not provide enough economic incentives to make green business models fully competitive. Taxing emissions is particularly important here. Moreover, looking at the IMO, there are currently also no significant economic incentives. The lack of economic solution directionality is considered an important bottleneck by all interviewees. The current policy mix simply does not incentivise companies enough to decarbonise. This contributes to a lack of long-term planning in the sector.

Notably, Wesseling & Meijerhof (2023) found that a lack of consistent monitoring and reporting emissions was a major shortcoming. Interviewees IE1 and IE3, who are both experts on carbon reporting, stated that there is now a system in place for reporting and monitoring emissions, which is an integral part of the FEUM (Council Regulation (EU) 1805/2023).

Market formation and destabilisation (SF5):

Market formation for sustainable alternatives is gradually increasing. However, multiple interviewees (IE2, IE3, PE1, PE2, PE3, PE4, NGO1) indicated that it is not fast enough to achieve a net zero maritime sector by 2050 (Ulichina, 2024). An important reason for this is the high cost of sustainable alternatives (Asmussen et al., 2023). For a shipping company, it is challenging to decarbonise while there is no level playing field. There is a market emerging for charging a premium for cleaner shipping, and recently many companies have entered this market (CMA CMG, 2024; GoodShipping, n.d.; Hapag-Lloyd, 2023; Maersk, 2023). However, paying this premium is only attractive for a limited number of companies, as the societal visibility of their shipping emissions is limited (NGO1, IE3, PE2, PE5). Therefore, most interviewees agreed that more ambitious policy is needed to create a level playing field. Without this level playing field, green business models cannot compete sufficiently (IRENA, 2021; IE1, IE3, PE2). PE2 characterised the need for a level playing field by stating the following:

"In shipping, it's too far removed from the end customer for them to care about or think about or worry about. So it is very hard to generate the amount of premium they would need on their fuels. The cost gap is just too big and we can't close it through a premium. Therefore, we need policy to step in"

The uptake of innovative solutions on a significant scale has not been not very high (Ulichina, 2024). Despite experimentation being high, large scale implementation of new solutions is not, even though numerous innovations that have been 'mature' for several years (NGO1, IE1, IE3, IE4, PE2, PE5). This problem has been present for several years, as it was already pointed out by Wesseling & Meijerhof (2023). This is in part because many industry actors are waiting to invest until others have 'derisked' a certain technology. This hesitation is caused by the insecurity on the market, on the uncertain future costs of different technologies and on split incentives between different actors (IE1, IE2, IE3, PE1, PE2, PE4). Moreover, a lack of corporate citizenship does little to help the uptake of new technologies, and the low level of pressure from society does not provide incentive to industry actors to implement these technologies (NGO1, IE1, IE3, PE1, PE2, PE4, PE5). Notably, the uptake of low-carbon solutions is considered to be economically viable as long as there is a level playing field. The shipping sector is positioned in a place where it can easily pass on costs to third parties (Transport & Environment, 2024). This is due to their strategic importance, as well as the fact that the costs of shipping are relatively limited compared to the production of goods. In fact, shipping companies have been seen making large surcharges on costs that originate from the EU ETS (Transport & Environment, 2024; NGO1, PE1). Lastly, the low cost of fossil fuel means there has been little economic incentive (NGO1, PE1, PE2, PE4, PE5).

On the breakdown side, there are no visible cases of existing markets for harmful practices being phased out or destabilised. PE4 explained that some companies are currently heavily investing in second-hand ships with a high carbon intensity. An explanation for this is that while it is still profitable, these companies are trying to expand their business without committing to harmful practices for the entire duration of a ships' lifespan (15-25 years). The increasing criticism on the status quo is considered a positive development by multiple interviewees (IE1, IE2, PE1, PE3, PE4, NGO1). Again, multiple interviewees (NGO1, IE1, IE2, IE3, PE1, PE2, PE4, PE5) stressed that without financial incentive and a level playing field, a phase out of harmful practices should not be expected.

To summarise, market formation is gradually increasing, but it is not progressing quickly enough, endangering the goal of decarbonising the maritime sector by 2050. This is largely due to high costs, a lack of a level playing field and low corporate citizenship. Additionally, there are no significant signs of phasing out harmful practices, as some companies continue to invest in high-carbon ships, with interviewees emphasising that without financial incentives and a level playing field, meaningful change is unlikely despite growing criticism of the status quo.

Resources allocation (SF6):

In terms of resource allocation, there was a consensus between interviewees that this should not be a bottleneck for the decarbonisation of the sector. First, multiple interviewees agreed that human capital should not prove a major barrier. While training seafarers in the use of fuels with different safety regulations would take time and money, this is something that the maritime sector is very capable of (NGO1, IE1, IE2, IE3, IE4, PE2). In terms of financial and material resources allocation, most interviewees expected larger companies to find investments through the usual channels without problems (IE1, IE2, IE3, PE1, PE2, NGO1).

However, looking at the supply side of alternative fuels, concerns were voiced by interviewees. There is a risk of a 'chicken and egg problem', as there are extensive plans for the production of e-fuels and bio-fuels for the shipping sector, but many of these plans are at risk due to uncertainty in demand (IE1, IE3, IE4, PE1, PE2, NGO1; Ulichina, 2024). Final investment decisions are delayed or rejected because of this. The reason for this uncertainty is the lack of incentive for shipping companies to purchase e-fuels or bio-fuels up until 2030 (Asmussen et al., 2023; Bloomberg, 2024; Ulichina, 2024). Several interviewees (IE2, IE3, PE1, PE2, NGO1) pointed out that this can lead to GHG emissions that could be prevented.

On the breakdown side, there are signs that less resources will be allocated to harmful practices in the future. In light of the FEUM and the decarbonisation strategy by the IMO, investors seem hesitant to invest in ships that can only sail on conventional marine diesel, until the way forward is clearer (PE1, PE4). PE4 remarked the following on this topic:

"You see some larger companies buying up older second-hand ships, which is likely because they are waiting with investments in newer ships until there is more clarity on the best or cheapest way to decarbonise."

Additionally, the CEO's of five leading shipping companies have publicly called for a clear end date for building fossil-only vessels (Mandra, 2023). This, combined with expectations for a carbon levy (PE1, PE2, PE3, NGO1) makes investments in fossil-only vessels more uncertain, as their business model gradually becomes less attractive. PE1 said the following on how investors should look at the market:

"Investors should be scared of being left with stranded assets, although I'm not sure they are. The goal of the investors should be to make sure that this investment is worth it. It might very well make sense today, but will it, looking at the change of the policy context, still make sense? But it might be too early to tell if this is already happening."

To summarise, there are little definitive signs of decreasing investments in harmful practices, but doubts into their return of interest are rising. PE2 pointed that these doubts can be seen as a positive sign, since that means that the policy changes are working and have put change in motion. Additionally, pressure from pension funds and other financiers to decarbonise more rapidly could have a significant effect on orders for new ships in the short term (IE3).

Creation and withdrawal of legitimacy (SF7):
Political legitimacy is high, as the EU has implemented the FEUM regulation with the goal to drive decarbonise in the sector, as well as putting pressure on the IMO to adopt more ambitious goals (Snijders, 2023; PE3, PE5). Lobbying against harmful practices has grown significantly in recent years, by NGOs and knowledge institutions and by countries that suffer from climate change (PE1, PE3, PE5). The need for the decarbonisation of the maritime sector is recognised broadly. Multiple interviewees pointed out that this has radically shifted over the last years (NGO1, IE1, IE2, IE3, PE2, PE3, PE4, PE5). PE3 summarised this by saying:

"Two years ago there was still a lot of scepticism about the transition. Today, that scepticism, you don't hear it as much. I think that the industry as a whole over the last, I would say five years has transitioned very quickly from 'this is not a thing' to 'how do we fix it'."
Notably, PE4 pointed out that while this is true for a large number of companies, it is not (yet) generalisable across the entire sector, especially outside Northern Europe.

There are significant signs of a withdrawal of legitimacy, but this is different across different regions and companies (Zhang et al., 2022; NGO1, IE2, PE2, PE3, PE4). Additionally, interviewees stated that there is a difference between bulk transport and carrier goods, as bulk transport is less visible to the public and the structure behind it is often very opaque, meaning there is less withdrawal of legitimacy for bulk transport (NGO1, IE3, PE1, PE2). Unfortunately, industry actors experience little pressure from the public (Harap et al., 2023; PE2, NGO1, PE4, PE5). An important reason for the lack of public pressure is the low public visibility and opaque structures of large parts of deep sea shipping (Harahap et al., 2023; NGO1, IE3). Despite the lack of societal pressure, some companies do experience pressure from *within*, from employees, board members and shareholders (PE2).

4.4 Analysis of different patterns of the X-curve

In this section, the different patterns of the X-curve are analysed. This is done based on input by interviewees, supplemented with other sources (news articles, press releases, scientific articles).
The results are summarised in Table 7 as described in Section 3.3, which is used as input for Figure 3.

4.4.1 Patterns of build-up

4.4.1.1 Experimentation

In recent years, experimentation with sustainable practices in the maritime sector has been significant, with high feasibility early action routes becoming more visible (NGO1). A large number of solutions tailored to different situations is being explored (IE1). These range from large scale experiments with efficient sailing in combination with renewable fuels, to modular upgrades that allow smaller companies to transition to alternative fuels (IE2).

Due to the mandated introduction of alternative fuels by the FuelEU Maritime regulation (FEUM), costs are expected to rise as the use of alternative fuels is very expensive (MMMCZCS, 2024). This expected rise in fuel costs has led to a surge in experimentation in fuel efficiency measures and other ways of decreasing emission (NGO1, IE2, PE3). Innovations such as direct carbon capture, wind propulsion, hull cleaning and bubble technology have benefitted from significant R&D investments (NGO1, IE1, IE2, PE2). These methods could significantly reduce emission intensity without relying heavily on vast amounts of renewable fuels (IE1, PE2, PE4, PE5).

A notable focus has been placed on experimenting with diverse alternative fuels and various feedstocks. The production of ammonia in particular is under investigation. While it is widely believed that ammonia is will be cheaper to produce (MMMCZS, 2024; IE1, NGO1, IE2, IE3, PE2, PE4), it is more difficult to transport, store and use (IE2). The safety regulations are still being developed, and it is still considered 'risky' to invest in. Additionally, scaling up for widespread use of ammonia is expected to take years (IE2, IE3).

Innovative operational strategies are also being tested. An example of this is the practice of 'just in time arrival'. The majority of interviewees has highlighted this as a critical step towards decarbonisation. 'Just in time arrival' means a departure from current practice, where ships regularly sail as fast as possible to their destination, just to wait for several days to weeks before unloading their cargo (NGO1, IE2, PE2, PE3). Implementing this at a large scale could achieve a reduction in GHG emissions compared to 2008 (De Andres Gonzalez et al., 2021). A senior policy and market analyst at a major shipping company described it as follows:

"You know, it's amazing how even the most advanced companies still do a lot of their planning on Excel. There has been this pipe dream of optimising fleets with just in time arrival, which could cut fuel use by 20-30%."

Lastly, there has been a radical shift in the policy framework, with the implementation of the FEUM and the 2023 revised IMO GHG reduction strategy for 2050. Interviewees pointed out that this shift has been very influential, although it is considered to be weaker than it should be (IE1, IE2, IE3, NGO1, PE1, PE2, PE3, PE4).

To summarise, there is significant experimentation with new practices, technologies and thinking. While many technologies are not yet economically competitive, this is improving as the goals set by the FEUM become higher over time. The main recommendation that emerged from the interviews and desk research is that policy should be aimed at making green business models make sense. This can be done by a) subsidising sustainable practices and b) making harmful practices more expensive. The consensus among the interviewees was vastly clear that the goals set by the EU and IMO can and should be set higher.

4.4.1.2 Acceleration

The transition of the maritime sector is experiencing a significant acceleration, with key developments entering a phase of rapid progress. A variety of alternatives to conventional marine diesel is connecting to the maritime infrastructure, and has become accessible to an increasingly wide range of actors (IE1, PE2). Ports have invested substantially in providing the infrastructure needed (Prevljak, 2023b; IE1), and the orderbook for dual-fuel engines is growing exponentially (Asmussen et al., 2023). Particularly notable is the swift pace and ambition in Northern Europe, where a number of the largest companies in the sector are based. These companies have taken a proactive approach, and many interviewees consider this to have a substantial impact on the speed of the transition (NGO1, IE2, IE3, PE2). NGO1 explained that the aggressive strategy of companies such as Maersk has incentivised even companies that have no ambition to be a frontrunner now feel the need to actively invest in cleaner practices, as they are afraid of running behind. Large industry actors such as Maersk and Hapag-Lloyd have chosen a possible path for at least the short- to medium term. A mix of e- and bio-fuels that are either used as drop-in fuels or in dual engine vessels will be used to accomplish the short-term goals of the FUEM (Solakivi et al., 2022; IE3, IE4).

According to NGO1, IE3 and PE2, decarbonisation is indirectly pushed ahead by mandating a certain percentage of low- or zero-carbon fuels. This is due to the high price; energy efficiency measures are much more attractive when it is more expensive to burn fuel (NGO1, IE2, IE3).

Considering this, the pattern of acceleration is clearly visible, as alternatives to the regime are visible and have become accessible to a large group of industry actors.

4.4.1.3 Emergence

There are increasing signs of emergence in the transition. First, the need for change is widely recognised, and the agenda has changed radically over the last years (NGO1, IE1, IE3, PE1, PE2). whereas in 2018 the IMO adopted a strategy to reduce emissions by 50% by 2050, this has been changed in 2023, as discussed in Section 4.2. This policy shift is considered a step in the right direction (NGO1, PE3, PE4). This shift was the result of several factors. First, the implementation of the FEUM has sparked fears of different policy mixes in different areas around the world, which would significantly hinder the maritime sector. As more countries considered introducing various policy mixes in response to climate change concerns, the IMO faced increasing pressure to develop a global strategy in line with the Paris Agreement (IE3, PE3). Second, more (developing) countries are realising that there are potential revenues in regulating the maritime sector with a carbon levy, such as African nations and smaller island states in the Pacific and the Caribbean (PE3). These countries have, with support from the UK, Australia and EU member states, become more vocal at the IMO negotiations for the revised 2050 GHG strategy (PE3). This is changing the dynamic at the IMO. As more countries push for decarbonisation, the momentum is increasing (PE3).

Additionally, the agenda of the majority of industry actors is changing rapidly. While the practice of 'wait and see what happens' is still present in the sector (PE4), there are many industry actors that have realised that they have to act. While large emissions reductions are not expected in the short term, many industry actors have taken significant actions for the long term (NGO1, IE1, IE2, PE1, PE2). Even companies that lack ambitious reduction targets are placing orders for vessels with dual-fuel engines, as they do not want to run behind their competitors. These vessels provide a high degree of flexibility in the amount of renewable fuels used by companies, which makes more ambitious regulatory obligations viable (Asmussen et al., 2023).

To summarise, the pattern of emergence is clearly visible as the direction of change becomes clear and the need for the decarbonisation of the maritime sector is broadly accepted.

4.4.1.4 Institutionalisation

Some early indicators of institutionalisation are visible; multiple interviewees noted that a new 'normal' in *thinking* has become widespread. Throughout the sector, thinking of decarbonisation as crucial part of future operations has become common practice (NGO1, IE1, IE2, IE3, PE2, PE4). However, this has not translated into *doing*; while ambitions and promises are high, large-scale change is not yet visible (IE1, IE2, PE2, PE4). Additionally, no signs of a new balance of power were found.

The EU has put into force regulations that force the uptake of zero- and low-carbon fuels in the maritime sector. This has contributed to making (bio-)methanol a stable market factor; trading and hedging in the commodity has become a common practice. There is more regulation on it, the rules are much clearer and it has proven itself as a fuel (IE3).

Overall, some indicators of institutionalisation were found, but the change cannot be considered 'irreversible' based on the data collected for this study.

4.4.1.5 Stabilisation

No clear signs of stabilisation were found. Both policy and different technologies are still subject to change. Instead, many indicators of destabilisation were found. Interviewees indicated that they expected uncertainty and chaos to increase in the coming decade, before stabilisation of a new system can take place (NGO1, PE2, PE3, PE4).

4.4.2 Patterns of break-down

4.4.2.1 Optimisation

Although goals to decarbonise are becoming increasingly ambitious and the urgency is felt, many industry actors still focus on *optimising*. This is done by investing in ships that can use LNG instead of marine diesel, by taking incremental steps in energy efficiency measures for their ships or by slightly increasing operational efficiency (PE1, NGO1, IE1, IE2, PE2, PE4). While there is a growing number that realises this is not a sufficient solution to comply with future policy goals, there are many companies not very good at thinking long term (NGO1, IE1, IE3, PE2, PE4). Rather, they prefer to implement the aforementioned measures and continue as they are as much as possible. This is characterised by NGO1:

"So they may have a long term goal. They recognise that zero is real, but then mostly most of the energy goes to 2026 at the latest, they are focused on what they can do now." (NGO1).

The use of LNG is seen as potentially problematic. While it has lower CO_2 emissions, its potential to reduce GHG emissions is limited due to methane slippage (Spoof-Tuomi & Niemi, 2020; IE1, IE2, PE1, PE2, PE5). While many industry actors claim that they can lower this methane slippage over time, these claims are contested. Multiple interviewees expressed their concerns about the growing investments in LNG ships, as investing in them brings the risk of future stranded assets (IE2, PE1, PE3, PE5). This risk of stranded assets could incentivise actors to actively fight against more ambitious decarbonisation goals (Fricaudet et al., 2021; IE2, IE3, PE1, PE2). As mentioned before, several companies are actively expanding their business by buying older ships (PE4). This is another indication that optimisation is still prevalent.

To summarise, large parts of the maritime sector can still be considered to be *optimising*. While there is a positive trend towards decarbonising, this cannot be said for the maritime sector as a whole. A strong signal from policymakers is needed to convince industry actors of the need to adapt (Asmussen et al., 2023; PE5).

4.4.2.2 Destabilisation

Different actors are increasingly critical of the old system; fundamental discussions on decarbonisation are widespread throughout the sector. While these discussions started much later than in other sectors, the fact that other sectors have been working on it for so much longer seems to have a positive impact on the speed of transition in the maritime sector (NGO1, IE2, PE3).

There are many discussions on how to end unsustainable practices such as the 'sail fast, then wait' practice. NGO1, IE2, IE3, PE2 and PE4 singled this out as a major problem that needs to be addressed. The sail fast, then wait practice means that it is common in the sector for ships to sail very fast to where they need to be, to then wait until they can offload their goods. Since sailing fast is much less efficient, it is estimated that emission reductions of 20% to 40% could be achieved by addressing this (PE4).

On the topic of policy, signs of destabilisation are present. There are fears of a diverse set of rules in different areas. This would make shipping internationally more difficult and expensive. Combined with a number of countries that is motivated to decarbonise shipping, this has already led to more ambitious targets (PE4, PE5). Currently, discussions about a significant global carbon levy are ongoing, which was not considered possible by experts only 4 years ago (NGO1, PE1, PE3).

Lastly, the aggressive strategy that Maersk has pursued over the last years has put pressure on competitors. With a market share of about 15%, Maersk committed reaching net-zero by 2040 (IE3, PE2). As a first step, the company ordered dual-fuel engines that can use both conventional marine diesel and methanol as fuel (IE3). Interviewees agreed that this step surprised the market, and, in combination with the rapidly changing policy field, has incentivised competitors and potential suppliers of renewable fuels to invest in sustainable innovations (NGO1, IE1, IE2, IE3, PE1, PE2).

In short, *destabilisation* is considered to be visible. The expectation is that in the short term, this destabilisation will grow significantly as regulatory obligations for GHG reductions increase (PE3, PE5).

4.4.2.3 *Chaos*

Opposing interests are emerging. In recent negotiations, several emerging economies such as Brazil, South Africa and China have opposed rapid decarbonisation (IE3, PE3. At the same time, countries that are already suffering from climate change have begun an active lobby for more ambitious targets and a possible carbon levy, especially the Pacific and Caribbean island states (Laranjeira, 2024; PE3). At the same time, many African nations are becoming aware of the urgency of decarbonisation of the maritime sector (Laranjeira, 2024; PE3). Frontrunners for decarbonisation are Australia, the UK and New Zealand (PE3). At the same time, the weight of EU regulations has had a major impact on policymaking by the IMO (PE2, PE3). Lastly, PE3 and PE5 described that opposing industry interests also impacted negotiations at the IMO and the EU level, adding further complexity. These opposing interests have resulted in highly contentious negotiations over new regulations (PE3, PE5). As the impacts of climate change become more visible, this is expected to get worse over time.

Additionally, there is a diverse set of options to decarbonise (IE1). Unfortunately, many of these options are not yet used on a large scale, and the use of them is considered risky (IE1, IE2, PE1, PE2, PE4). This leads to a 'wait and see' attitude of many industry actors. Interviewee PE1 explained that while there are multiple mature and viable innovations that can be implemented, industry actors are waiting, as the policy mix that is currently in place is not stringent enough to incentivise them. Uncertainty about the uptake of renewable fuels is a major factor in delaying the development of production sites for renewable fuels, which would risk the decarbonisation of the maritime sector (Ulichina, 2024).

Lastly, multiple interviewees stated that there were no signs of dominant structures failing, or any signs of looming breakdown which could lead to firmly entrenched opposition (NGO1, IE2, IE3, PE2, PE4). Considering this, chaos is present in the transition to a limited extent.

4.4.2.4 *Breakdown*

No indicators of breakdown were found. Interviewees noted that they had not noticed 'old' structures disappearing. Additionally, no indicators of 'losers' in a transition were found. However, multiple interviewees found it likely that the introduction of more ambitious policy obligations might cause a breakdown of parts of the existing system in the period after 2035 (IE1, IE3, PE1, PE2, PE5).

4.4.2.5 *Phase out*

No significant indicators of phasing out old practices on a large scale were found. No signs of the phasing out of the status quo were found, and no losses have been dealt with and accepted. Therefore, the transition pattern of *phase out* is not yet visible.

4.5 The state of the transition

Below, the state of the transition is summarised in Table 7 and visualised in Figure 3. Table 7 includes the 'practice', or key development, in the different phases of the X-curve. The column 'narrative' includes a short summary of the results found for each phase. Table 7 serves as input for Figure 3. Figure 3 provides a visualisation of the current state of the transition. The size of the red circle indicates the degree of visibility of each transition pattern. As can be seen, *optimisation* is still prevalent in the sector. However, *destabilisation* of the current system, as well as early signs of *chaos* are visible. For the build-up side of the transition, many significant indicators of the *experimentation* pattern were found. Additionally, *acceleration* is clearly visible as alternatives to the regime have become available to a wide array of actors.

Build-up phase	**Practice**	**Narrative**
Experimentation	• There are large scale experiments on energy efficiency measures. ↗	In recent years, high feasibility action routes have become increasingly visible. There has been a surge of

	• A growing amount of experimentation in the use of ammonia as fuel. ↗ • First successful tests with voyage optimisation. ↗ • Many activities aimed at decarbonising the sector.	experimentation mainly concerning two topics: Energy efficiency and alternative fuels/propulsion. Efforts to de-risk the use of ammonia are ongoing. The concept of 'just in time arrival' has seen successful tests and has a very high potential to decrease emissions allowing ships to sail slower. Experimentation is clearly present.
Acceleration	• Early action routes are becoming clearer ↗ • Uncertainty in investments ↘ • Large industry actors taking a frontrunner role. ↗ • There have been radical policy shifts at the EU- and IMO-level. Even more ambitious policy is expected. ↗ • A growing number of countries actively lobbies for a faster transition. ↗	The acceleration in this transition is unmistakable. Aside from radical policy shifts, a growing number of alternatives to conventional marine diesel is becoming accessible to a diverse range of actors. The policy implemented by the EU is driving the IMO to make their strategy much more ambitious. Additionally, demands from a growing number of countries is speeding up this process.
Emergence	• Networks increasingly connecting. ↗ • Large industry actors seem to be dictating a pathway. ↗ • Need for change broadly accepted, though not always followed up by the necessary action. ↗ • High price of alternative fuels drives fuel efficiency measures. ↗ • Financial models for sustainable shipping start to make sense. ↗	The sector has seen a significant shift. The IMO has implemented a strategy to achieve near-zero emissions by 2050. Even 'late movers' are investing heavily in new technologies. In order to remain competitive. Networks are increasingly interconnecting, providing a diverse set of industry actors with pathways towards decarbonisation. On the short- to medium-term, a mix of bio- and e-fuels seem to be the dominant solution. The pattern of *emergence* is visible to a degree.
Institutionalisation	• A new 'normal' in *thinking* can be seen in the sector; decarbonisation is a major factor of consideration in almost every aspect of operations. ↗ • (Bio-)Methanol has become a stable market factor. Regulation on it and practices of trading/hedging in it are extensive. ↗ • Despite positive developments, most operations remain the same in practice. ↘	Some early sings of institutionalisation in maritime decarbonisation are becoming visible. First, a new 'normal' in *thinking* can be seen in large parts throughout the sector. Decarbonisation is a topic of importance for a majority of companies. Unfortunately, this is not always followed by actions; the main focus is on the short term. The transition still has a long way to go to become institutionalised.
Stabilisation	• It is far too early for any stabilisation. New practices are constantly being adapted to better suit the market. ↘ • No definitive pathways towards net zero emissions in 2050 have emerged yet. ↘	Currently, there are no significant signs of stabilisation. Rather, the market is expected to destabilise much more than it currently already is. In other words, it will get worse before it gets better. Additionally, there are no definitive pathways towards net zero emissions by 20250 yet. While most industry actors have some form of a short-term strategy, the majority has no concrete plans for the longer term.
Break-down phase		
Optimisation	• Many companies are focused on short term reduction. ↗ • The use of LNG can be seen as optimisation; there are still CO_2 emissions as well as methane slippage. ↗ • A large group of industry actors has adopted a mentality of 'wait and see'. ↗ • Industry actors are waiting for innovations to be derisked. ↗	Despite the growing urgency and increasingly ambitious goals for decarbonisation, many maritime industry actors remain focused on short-term optimisation rather than comprehensive change. Large-scale investments in LNG-power ships is seen as problematic due to methane slippage. This approach reflects a broader trend of adopting minimal changes that allow the industry to continue operating as usual, with many industry actors hesitant to commit to long-term strategies. A mentality of "wait and see" is prevalent, as many industry players are waiting for new technologies to be fully developed and de-risked before investing.
Destabilisation	• There is more resistance against not decarbonising. ↗ • Fundamental discussions on changing the status quo are prevalent. ↗ • There are voices against obligations to use expensive low- to zero carbon fuels, mostly from the smaller industry actors and emerging economies such as China. ↘ • Decarbonisation is increasingly seen as a 'race' where not everyone has an ambition to 'win', but at least wants to stay in the race. ↗	The maritime sector is experiencing growing pressure to decarbonise, with increasing resistance against maintaining the status quo. While smaller industry actors and emerging economies voice concerns over the high costs of low- to zero-carbon fuels, decarbonisation is increasingly seen as a competitive race where industry actors want to stay a part of, if not win. Fundamental discussions on ending unsustainable practices, such as the inefficient "sail fast, then wait" approach, are becoming widespread, with significant potential emission reductions. Policy destabilisation is also evident. This has led to more ambitious global targets, with discussions on a significant global carbon levy—once considered unfeasible—now underway. This trend of

		destabilisation is expected to accelerate as regulatory obligations increase.
Chaos	• It is difficult for companies to decide the right way forward. This is especially true for companies that cannot afford a large strategic team. ↗. • Policy is likely to shift in the coming years. ↗ • There are fears of a diverse set of rules in different areas. This would make shipping internationally more difficult and expensive. ↗ • Opposing interests are emerging. ↗	Many companies in the maritime sector face significant challenges in deciding the best path forward, particularly those without the resources for a large strategic team. The uncertainty around which technologies will ultimately succeed, combined with the likelihood of changing policies in the coming years, adds to this difficulty. There are concerns about the potential for a diverse set of regulations across different regions, which could complicate international shipping and increase costs. Meanwhile, opposing interests are becoming more pronounced. Emerging economies like Brazil and China resist rapid decarbonisation, while countries most affected by climate change, including many African nations and island states, are lobbying actively for more ambitious targets and a global carbon levy. Considering this, chaos is visible to a degree.
Breakdown	• In general, there are no significant signs of breakdown yet. ↘ • However, more stringent policy might force the existing system to shift rapidly over the next decade.	No significant signs of network breakdown are visible.
Phase-out	• As of yet, there are few significant developments that point to a phase-out of old practices on a significant scale throughout the sector. ↘	No signs of phase-out are visible on a large scale.

Table 7: The activity in the different phases of the X-curve.

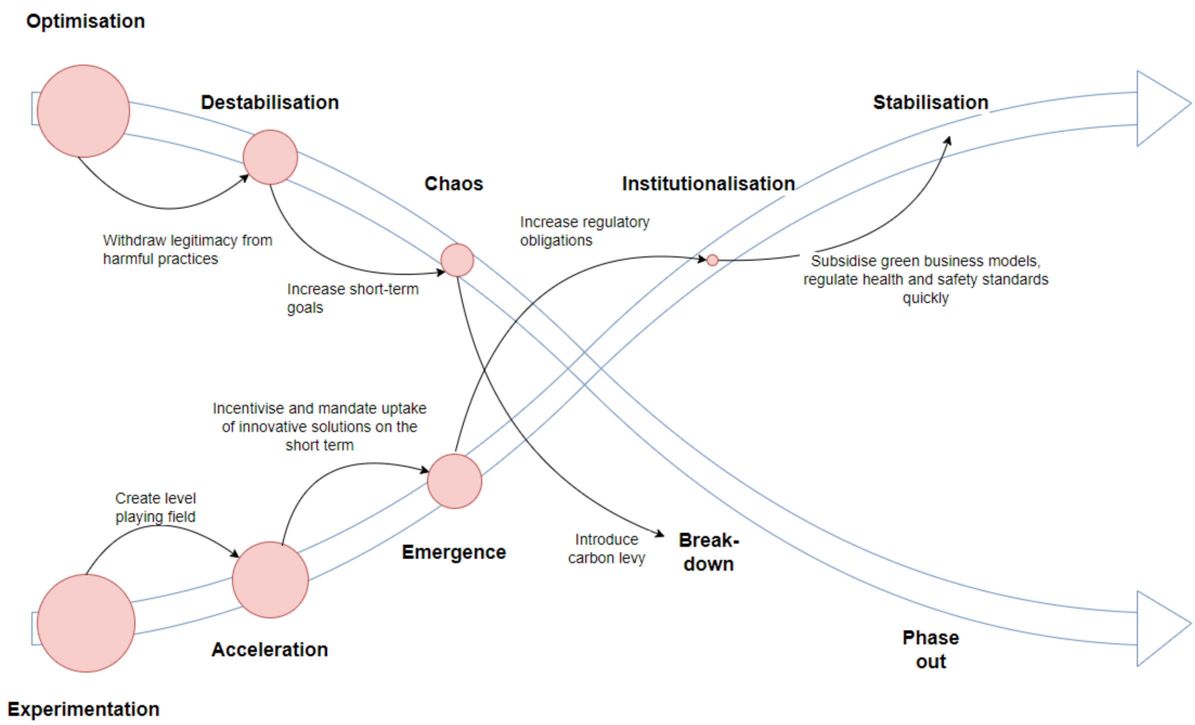

Figure 3: The current state of the transition of the maritime sector, based on the X-curve framework.

4.6 Analysis of underlying structural problems

In this section, the underlying structural problems that lead to problematic functioning of the innovation system are discussed.

A major barrier for decarbonisation that is stressed by all interviewees as well as supporting sources is the high price of alternative fuels. Because of this, competing with oil as an energy carrier is very difficult for most industry actors (Stavroulakis et al., 2023; NGO1, IE3, PE2, PE3). While a segment of the market is willing to pay a premium for green shipping, this is limited (NGO1, IE2, IE3, PE2, PE5). Additionally, the maritime sector is very competitive, making it problematic to raise prices without a level playing field (NGO1, IE3, PE2, PE3). Considering this, it remains very difficult for shippers to recover the difference in cost between renewable fuels and conventional fuels (Asmussen et al., 2023). However, interviewees PE1, NGO1, IE1, IE2, IE3, PE2, and PE5 indicated that they believe that if the targets for decarbonisation were more stringent, this would lead to a much higher pace. The uptake of renewable fuels was characterised by one employee of a global shipping company by stating the following:

"With this kind of engines [dual fuel engines], it is now up to the politicians. If they decide next year we need to go for 10% renewable fuels, we will. If not, we will continue as we are."

The same barrier applies to other innovative solutions. As the price of conventional fuels is relatively low, there is not enough incentive to prioritise fuel efficiency (NGO1, PE2). Additionally, many fuel efficiency measures are expensive and difficult to implement (IE1, IE3, IE4). Therefore, there is no level playing field for green business models based on a combination of fuel efficiency measures and the use of alternative fuels. This is seen as an explanation of why mature technologies such as wind propulsion are not implemented at a larger scale. In order to accelerate the transition further, a level playing field is needed. While the FEUM contributes to this, it does not provide enough guidance in the short term.

Second, there is not enough motivation to decarbonise among industry actors. While there are differences between industry actors, there is a general lack of corporate citizenship (NGO1, PE1, IE1, IE2, IE3, IE3, PE1, PE2, PE3, PE4, PE5). Even though some companies feel both internal and external pressure to decarbonise (IE2, PE2), the most pressure comes from policy, including the FEUM (PE1, IE2, IE3, NGO1). Despite this, many industry actors have translated commitments for net-zero emissions by 2050 to concrete action plans (NGO1, PE2, PE4). More ambitious targets, especially on the short- to medium-term are considered a viable and attainable (Asmussen et al., 2023; Bloomberg, 2024; NGO1, IE2, IE3, IE4, PE1, PE2, PE5). With this in mind, the urgency felt by industry actors could be increased significantly by implementing more ambitious policy. Higher targets would push towards the institutionalisation of the decarbonisation of the shipping sector by signalling to industry actors that the direction of change is irreversible. Additionally, it would benefit the industry actors that adapt best and thereby create a new balance of power between harmful practices and cleaner practices (IE3, PE2, PE3).

Lastly, the withdrawal of legitimacy of harmful practices is insufficient. Due to its crucial function, the maritime sector is given a very high legitimacy. Therefore, many actors believe that decarbonisation should not come at the expense of the functioning of the sector, as this would have far-reaching implications for the global economy. However, it is believed that as long as there is a level playing field, the sector should be able to decarbonise at a higher pace than currently mandated by policy without disrupting global trade (Stavroulakis et al., 2023). While the FEUM goal of 80% reduction in carbon intensity by 2050 is considered ambitious, the short-term goals are considered inadequate to drive uptake of sustainable innovations at a sufficient pace (Asmussen et al., 2023; Bloomberg, 2023; Ulichina, 2024). The insufficient uptake of sustainable innovations threatens the decarbonisation, as final investment decisions for production sites of renewable fuels are postponed (Asmussen et al., 2023; Bloomberg, 2024; Ulichina, 2024; NGO1, PE3, PE5). By revising these goals, policymakers can take an effective step in the right direction in mitigating this 'chicken and egg' problem.

The combination of the aforementioned structural problems leads to behaviour that is characterised as a 'wait and see mentality' in the sector. In this situation, many industry actors seem to prefer inaction until technologies are derisked, properly regulated and available at a large scale for a low cost. At the same time, policymakers are hesitant to implement ambitious policy. The short-term implications of the FEUM are relatively small, the IMO has only recently agreed on an ambitious strategy for GHG reduction targets for 2050. Even though both can be considered radical policy shifts, they are not ambitious enough for the short term (NGO1, IE1, IE2, IE3, PE1, PE2, PE3, PE4).

Therefore, a revision of regulatory obligations is needed. The goal of this revision should be to create a level playing field, incentivise decarbonisation and withdraw legitimacy from harmful practices. Within the mission arena, the EU and IMO are the parties with the power to implement this change. In 2027, a review of the FEUM will take place. This presents an opportunity to implement this change.

5 Discussion

This research investigates the decarbonisation of the maritime transport sector by analysing the state of the transition, as well as systemic barriers that hinder progress and identifying the underlying causes of these barriers. Using the X-curve framework and the Mission-Oriented Innovation System (MIS) approach, the study combines desk research with semi-structured interviews. The discussion section will explore the recommendations that follow from these findings, discuss theoretical implications, highlight limitations of the study, and provide recommendations for future avenues of research.

5.1 Recommendations

From the structural barriers to the decarbonisation of the maritime transport sector, several recommendations emerge from this research. The study identifies key barriers, including the high cost of sustainable innovations and a lack of a level playing field, which, in combination with low regulatory obligations and a lack of corporate citizenship, hinders the uptake of innovative solutions. As discussed in the Section 4.6, the low uptake of these innovative solutions can slow down the decarbonisation of the sector. More ambitious goals would create a stronger incentive for the industry to invest in sustainable innovations and address the prevalent "wait and see" mentality that hinders progress. Economic incentives, such as carbon levies, higher regulatory obligations and subsidies for low-carbon solutions were identified as viable solutions. Notably, the technology neutrality embedded in the FuelEU Maritime Regulation stands out as a best practice, as it allows industry actors to leverage their creativity to find the most viable solutions, reducing resistance to policy measures.

Second, the lack of corporate citizenship and long-term planning by industry actors is a significant barrier. As discussed in Section 4.6, regulatory pressure has been an effective driver of change among industry actors. Therefore, the roles of the EU and the IMO as regulators are crucial in driving the decarbonisation process. While the FuelEU Maritime Regulation represents a significant step toward addressing the lack of long-term planning, this study found that its short- to medium-term targets are not ambitious enough, which endangers the long-term targets, as discussed in Section 4.6.

For industry actors, the use of the X-curve in this research offers valuable insights. As shown in Figure 3, the transition has already begun to challenge traditional practices in the maritime sector, particularly in fuel use and energy efficiency. This destabilisation is likely to intensify, creating challenges and opportunities. To navigate this shifting landscape, companies should prioritise investments in innovative technologies like dual-fuel engines, wind propulsion, and energy efficiency measures. It is important to develop a long-term strategy in anticipation of regulatory changes. Since the transition is also a competitive race, not acting swiftly could cause companies to lag behind more proactive competitors. Adopting a proactive strategic approach would mitigate these risks.

Wesseling & Meijerhof (2023) used the MIS approach before when studying the maritime sector in the Netherlands, focusing on the Dutch ‘Maritime and Inland Shipping and Ports’ Green Deal’. They used a national approach, while this study adds an international component to the use of the MIS approach in this sector. Comparing the results of the two studies provides a perspective on how the results can complement each other and where they differ. For example, Wesseling & Meijerhof (2023) stressed the importance of allowing stakeholders to use their creativity in finding sustainable solutions. Lastly, this study found that the top-down approach of the FuelEU Maritime Regulation (FEUM) has been effective in accelerating the transition, and that its technology neutral design can be considered a good practice for future policy. This design allows stakeholders to creatively implement changes in the most cost-effective manner. The FEUM’s mandate for the uptake of low- to zero- carbon fuels also provides an incentive for the formation of a market for these fuels, even though it does not reach its full potential due to low short- to medium-term targets, as discussed above.

5.2 Theoretical implications

This study contributes empirically by applying the X-curve framework and the MIS approach on the transition of the maritime transport sector. It provides an overview of the current state of the transition, which can serve as a reference point for future research. Additionally, this study shows the core barriers to the decarbonisation of the maritime sector, as well as their underlying causes. Lastly, insights in good practices for future policy are provided.

The MIS approach proved insightful in analysing the core barriers to the transition. During the research, defining the mission arena on an international scale proved challenging. Whereas other studies that analysed a specific mission on a national level could provide a detailed list of actors within the mission arena, this was challenging at the scale studied in this paper. Therefore, defining which actor belonged in the mission arena and which did not, proved to be subjective. Due to the large amount of actors in the international industry, some actors may not have been considered or analysed. Despite this, assessing which actors, rules and institutions belonged to the mission arena provided a useful basis for defining the scope. Furthermore, the relative novelty of the MIS approach presented a challenge, as there are few examples of the MIS being used in international context.

By providing a broad view of the transition of the maritime sector, this study contributes to the existing body of literature. Specifically, this study suggests that more ambitious regulatory obligations as part of the FuelEU Maritime Regulation in the short term could be considered to address the 'wait and see' mentality that is hindering the transition of the maritime transport sector. The results clearly state that regulation should be stricter on the goals in order to increase decarbonisation initiatives. Since decarbonisation is more expensive than business-as-usual, financial incentives to supplement the regulation would help.

While the MIS is suitable in analysing a transition in a sector, finding underlying barriers and providing an overview of possible solutions, it does not provide an overview of the 'state' of the transition. For example, the study by Wesseling & Meijerhof (2023) provides an overview of barriers and proposed solutions, including a low uptake of sustainable innovations, the lack of green business models and a 'wait and see' mentality. Given that this study identified similar systemic barriers, it demonstrates that both in the Netherlands and internationally, a persistent pattern of barriers with minimal improvement can be observed. Capturing the state of the transition, using the X-curve framework provides a more nuanced view as opposed to only analysing the system functions. It provides a view of a transition in its early stages where the acceleration and emergence of new practices is clearly visible. Analysing the transition patterns proved useful for finding best practices in policy, and in finding areas that have been improved. This indicates the benefits of including the use of the X-curve in the MIS approach.

5.3 Limitations and future research

This study focuses on the European mission for decarbonisation of the maritime transport sector, centralising around the FEUM. The context of other regulations and policies, such as the Dutch Green Deal as analysed by (Wesseling & Meijerhof, 2023) is not considered at length in this study. While the FEUM and IMO are taken into account, the national implications of other policies and regulations are not discussed at length. This can create a lack of context, which can be seen as a limitation. For future research, a more extensive analysis of all existing policies could be taken into account. Additionally, comparing results with earlier studies based on the MIS approach could provide a base for finding best practices in transitions. These insights could be used to create a better understanding of how and to what degree transitions can be steered. Unfortunately, this aspect was limited in this study by the number of papers on the maritime sector using the same approach.

This research provides an overview of the current system and the barriers and their underlying causes. However, it does not go into the details and specific role of the different organisations. A limiting factor in this research is the lack of in-depth analysis of the different actors, because the focus was on a system level. Future research could attempt to fill this research gap by doing more detailed analysis on the specific roles of different actors in- and outside of the mission arena to more efficiently decarbonise the marine shipping sector.

Another limiting factor is the novelty of the FEUM. Since the goals for decarbonisation change over the years and the sector are still in an early stage of transition, more information of the effect of the FEUM on the mission of decarbonisation will be available as the industry progresses. However, for this research, only limited documentation on the current effect of the FEUM can be found, creating the need for future research into the progression of the decarbonisation. The analysis of the state of the transition and the system functions provided in this research can serve as a framework for future research.

Finally, this study provides recommendations for increasing the pressure on the sector to decarbonise predominantly on a system level. Concrete recommendations for increasing societal pressure on the maritime transport sector are not provided. The opaque structure of large portions of the sector, which reduces the public visibility of many companies, is identified as a key factor contributing to this issue. Given that this opacity poses a significant barrier to the sector's decarbonization, it presents a compelling area for future research.

6 Conclusion

This study has aimed to provide a comprehensive understanding of the decarbonisation transition within the maritime transport sector, specifically under the FuelEU Maritime Regulation. By employing the X-curve and the Mission-Oriented Innovation System (MIS) frameworks, this research has delved into the structural, functional, and transitional dynamics that influence the sector's shift towards sustainability. Using desk-research and semi-structured interviews, this study has captured the complex transition dynamics and visualised the progress in the transition in Figure 3. Below, the research questions of this study are repeated, along with the answers that resulted from this study.

What is the current state of the transition of the maritime transport sector?

The maritime transport sector is in the early stages of its transition towards decarbonisation, as can be seen in Figure 3. Key industry players have started to invest in sustainable innovations, and decarbonisation has become a significant topic of interest for industry actors. Regulatory shifts, caused by the FuelEU Maritime Regulation and the revised IMO GHG Strategy, have acted as catalysts for change. The transition so far has been categorised as 'revolutionary' compared to 5 years ago, as many industry actors believed that decarbonising the maritime sector would not be necessary. This belief that was reinforced by the previous IMO GHG strategy, which included a reduction target of 50% by 2050. However, despite positive developments, the transition faces significant challenges. In large parts of the sector, *optimisation* is prevalent and no signs of breakdown of the existing system were found. Overall, ways of *thinking* have become widespread in the sector, but new ways of *doing* remain limited. At the same time, the sector remains heavily dependent on fossil fuels, and substantial barriers, including high costs, technological and economic uncertainties and a conservative industry culture, hinder rapid progress. Therefore, while the groundwork for decarbonisation is being laid, the transition is far from complete and faces significant barriers.

Which system functions create barriers for the transition?

Several system functions were identified as barriers to the transition. *Market formation (SF5)* faces significant challenges. Although some sustainable innovations are mature, large-scale uptake remains limited, and future demand for alternative fuels remains uncertain. This causes uncertainty on the supply side of alternative fuels, as final investment decisions for production facilities are postponed or cancelled. As discussed in Section 4.6, this threatens the decarbonisation of the sector in the period after 2030-2035. Additionally, the breakdown side of *SF5* is problematic. Despite increasing criticism, there are not many significant signs of existing markets for harmful practices being phased out or destabilised, with companies continuing to invest in high-carbon ships due to profitability. It was found that without financial incentives and a level playing field for green business models, significant change is unlikely.

Second, *Resources Allocation (SF6)* presents problems. This study found that the allocation of human, financial and material resources should not be problematic for the production of new ships capable of using alternative fuels. However, as with *SF5*, the allocation of capital for production sites of alternative fuels can present a bottleneck. The breakdown side of *SF6* is less problematic. While there are few definitive signs of decreasing investments in harmful practices, rising doubts about their long-term profitability, driven by policy changes and cautious investors, indicate a positive shift towards decarbonisation in the maritime sector. Stronger regulatory obligations could reinforce this positive development and contribute to the breakdown of harmful practices.

Lastly, the system function *Creation and withdrawal of legitimacy (SF7)* presents significant barriers. The maritime sector enjoys high legitimacy and support due to its crucial role in the global economy, which makes it difficult to withdraw legitimacy from harmful practices. The slow uptake of sustainable innovations is partly due to the conservative nature of the sector, where there is a lack of a strong push against the established regime. Additionally, withdrawal of legitimacy for harmful practices in the maritime sector is challenging, due to the low societal visibility and opaque structures of maritime transport, especially deep-sea shipping, resulting in minimal public pressure on industry actors.

What are the underlying causes of these barriers?

The underlying causes of the barriers to decarbonisation of the maritime sector are rooted in several key issues. First, the high costs of alternative fuels make it difficult for sustainable innovations to compete with traditional fossil fuels, particularly in a competitive market, as long as there is no level playing field. This economic challenge is made worse by a lack of motivation among many industry actors, leading to a 'wait and see' mentality, where actors prefer inaction until technologies are fully de-risked or until they are obligated by regulations. The regulatory frameworks, while a step in the right direction, do not include sufficient short-term obligations to drive change at a high pace.

Moreover, the sector's high legitimacy, due to its vital role in global trade, makes it challenging to withdraw support from harmful practices. Additionally, the societal pressure on the maritime sector is minimal due to its often opaque structures and low public visibility.

Concluding, the maritime currently has insufficient economic, societal, cultural, and regulatory incentive to decarbonise. Additionally, decarbonisation is difficult to achieve for motivated industry actors without a level playing field.

What is the current state of the transition towards decarbonisation of the maritime transport sector, and what are the core barriers and their underlying causes hindering this transition?

The sub-questions provide a detailed examination of the different aspects of the research question. The first sub-question reveals that many significant steps in this transition have been made, with regulatory shifts, a new normal in *thinking*, emerging sustainable innovations and a destabilisation of the status quo. This is depicted in Figure 3. However, the transition is far from complete and faces substantial barriers.

The second sub-question delves into the specific system functions that hinder this progress. It highlights that market formation, resource allocation, and the creation and withdrawal of legitimacy are critical areas where the transition is obstructed. These barriers, identified through system functions, explain why the sector's decarbonisation is proceeding slowly. For instance, the high costs of alternative fuels and the lack of a level playing field prevent widespread adoption of sustainable practices.

The third sub-question uncovers the underlying causes of these barriers, linking them back to economic, societal, and regulatory challenges. It shows that the high cost of alternative fuels, a conservative industry culture, and insufficient regulatory pressure create an environment where many industry actors are hesitant to take bold steps towards decarbonisation. This 'wait and see' mentality, combined with minimal societal pressure due to the sector's low visibility, further complicates efforts to drive the transition forward.

To conclude, the decarbonisation of the maritime transport sector is both necessary and challenging. While there is a growing awareness and initial steps have been taken towards reducing GHG emissions, significant systemic barriers remain. To accelerate this transition, strict regulations with higher but feasible targets, better economic incentives to complement regulations and a shift in industry mindset are essential. Overcoming these barriers will require coordinated efforts from all stakeholders to ensure the maritime sector contributes to the decarbonisation that is necessary to combat the effects of global climate change.

7 Reference list

Alphaliner. (2024). PublicTop100. Retrieved March 22, 2024, from https://alphaliner.axsmarine.com/PublicTop100/

Asmussen, M., Ennison, R. E., Furusaki, T., Duff, K., Jameson, P. J., & Verma, S. (2023, December 5). Barriers to scaling Zero-Emission fuel supply in shipping. World Economic Forum. https://www.weforum.org/publications/fuelling-the-future-of-shipping-key-barriers-to-scaling-zero-emission-fuel-supply/

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., & Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies and policies. Energy Conversion and Management, 182, 72–88. https://doi.org/10.1016/j.enconman.2018.12.080

Barriball, L., & While, A. (1994). Collecting data using a semi-structured interview: a discussion paper. Journal of Advanced Nursing, 19(2), 328–335. https://doi.org/10.1111/j.1365-2648.1994.tb01088.x

Bloomberg. (2024, June 18). Scaling up hydrogen: The case for low- carbon methanol | Bloomberg New Economy. Bloomberg New Economy. https://www.bloombergneweconomy.com/news/scaling-up-hydrogen-the-case-for-low-carbon-methanol/

Bosman, R., Loorbach, D., Rotmans, J., & Van Raak, R. (2018). Carbon Lock-Out: Leading the Fossil Port of Rotterdam into Transition. Sustainability, 10(7), 2558. https://doi.org/10.3390/su10072558

Bours, S., Elzinga, R., Pruijn, M., & Hekkert, M. P. (2022). Transitie naar een circulaire kunststof verpakkingenketen. Een missie-gedreven innovatie systeem analyse. In Zenodo (CERN European Organization for Nuclear Research). https://doi.org/10.5281/zenodo.7277672

Bureau Veritas. (2023). FuelEU Maritime. Marine & Offshore Bureau Veritas. https://marine-offshore.bureauveritas.com/sustainability/fit-for-55/fueleu-maritime

Cabot, C., & Villavicencio, M. (2022, September 13). Electrification of the hard-to-abate sectors: implication for Net-Zero power systems in Europe. IEEE Conference Publication | IEEE Xplore. https://ieeexplore.ieee.org/abstract/document/9921125?casa_token=GhJHN37eyHYAAAAA:E_rOovc1D1S1VXH9dcHExcQnQKV_3DllPX88cca_Yi35ic9Fr-GTgyk4BYPHNbbV-DR1382h3nU

CMA CMG. (2024). Reduce your shipments' carbon footprint with ATC+ [Press release]. https://cma-cgm.com/shipping/cmacgm-plus-services/environmental-services

De Andres Gonzalez, O., Koivisto, H., Mustonen, J. M., & Keinänen-Toivola, M. M. (2021). Digitalization in Just-In-Time approach as a sustainable solution for maritime logistics in the Baltic Sea Region. Sustainability, 13(3), 1173. https://doi.org/10.3390/su13031173

DNV. (2024). FuelEU Maritime. https://www.dnv.com/maritime/insights/topics/fueleu-maritime/#:~:text=Calculations%20will%20be%20set%20relative,an%2080%25%20reduction%20by%202050.

Elzinga, R., Negro, S. O., & Hekkert, M. P. (2023). Transitie naar een circulaire autobatterijen keten: Een missie-gedreven innovatie systeem analyse. In circulairekennis.nl. https://circulairekennis.nl/wp-content/uploads/2023/08/O066-Transitie-naar-circulaire-autobatterijen-keten.pdf

ESMA. (n.d.). Classification Societies - EMSA - European Maritime Safety Agency. https://www.emsa.europa.eu/inspections/90-classification-societies.html#:~:text=Classification%20societies%20are%20organisations%20which,and%20inspections%20on%20board%20ships.

European Commission. (2019). 2050 long-term strategy. Climate Action. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en#:~:text=The%20EU%20aims%20to%20be,action%20under%20the%20Paris%20Agreement%20.

European Commission. (2024). Reducing emissions from the shipping sector. climate.ec.eu. https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en

Fricaudet, M., Rehmatulla, N., & Smith, T. (2022). Understanding the scale of the stranded asset risks in the shipping industry. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4181191

Fricaudet, M., Taylor, J., Smith, T., & Rehmatulla, N. (2021). Exploring Methods for understanding stranded Value: case study on LNG-capable ships. UCL Energy Institute. https://discovery.ucl.ac.uk/id/eprint/10156288/1/Fricaudet%20et%20al.%20%282022%29%20Stranded%20value%20-%20case%20study%20on%20LNG-capable%20ships.pdf

Geels, F. W., & Schot, J. J. (2007). Typology of sociotechnical transition pathways. Research Policy, 36(3), 399–417. https://doi.org/10.1016/j.respol.2007.01.003

GoodShipping. (n.d.). Carbon-neutral supply chain with insetting | GoodShipping. https://www.goodshipping.com/insetting

Gray, N., McDonagh, S., O'Shea, R., & Smyth, B. (2021). Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Advances in Applied Energy, 1, 100008. https://doi.org/10.1016/j.adapen.2021.100008

Grzelakowski, A. S., Herdzik, J., & Skiba, S. (2022). Maritime Shipping Decarbonization: Roadmap to meet Zero-Emission Target in shipping as a link in the global supply chains. Energies, 15(17), 6150. https://doi.org/10.3390/en15176150

Habibic, A. (2024, January 30). Masdar and CMA CGM forge green maritime fuels alliance. Offshore Energy. https://www.offshore-energy.biz/masdar-and-cma-cgm-forge-green-maritime-fuels-alliance/

Hapag Lloyd. (2024, January 17). Gemini Cooperation: Hapag-Lloyd and Maersk enter into an operational partnership from February 2025. Hapay-Lloyd. https://www.hapag-lloyd.com/en/services-information/news/2024/01/gemini-cooperation.html

Hapag-Lloyd. (2023, May). "Ship Green": Hapag-Lloyd launches climate-friendly transport solution as part of its digital customer journey. https://www.hapag-lloyd.com/en/company/press/releases/2023/05/-ship-green---hapag-lloyd-launches-climate-friendly-transport-so.html

Harahap, F., Nurdiawati, A., Conti, D., Leduc, S., & Urban, F. (2023). Renewable marine fuel production for decarbonised maritime shipping: Pathways, policy measures and transition dynamics. Journal of Cleaner Production, 415, 137906. https://doi.org/10.1016/j.jclepro.2023.137906

Hebinck, A., Diercks, G., Von Wirth, T., Beers, P. J., Barsties, L. S., Buchel, S., Greer, R., Van Steenbergen, F., & Loorbach, D. (2022). An actionable understanding of societal transitions: the X-curve framework. Sustainability Science, 17(3), 1009–1021. https://doi.org/10.1007/s11625-021-01084-w

Hekkert, M. P., Janssen, M. J., Wesseling, J., & Negro, S. O. (2020). Mission-oriented innovation systems. Environmental Innovation and Societal Transitions, 34, 76–79. https://doi.org/10.1016/j.eist.2019.11.011

Hekkert, M. P., Suurs, R., Negro, S. O., Kuhlmann, S., & Smits, R. (2007). Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change, 74(4), 413–432. https://doi.org/10.1016/j.techfore.2006.03.002

Horvath, S., Fasihi, M., & Breyer, C. (2018). Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040. Energy Conversion and Management, 164, 230–241. https://doi.org/10.1016/j.enconman.2018.02.098

IMO. (n.d.). Introduction to IMO. https://www.imo.org/en/About/Pages/Default.aspx

IMO. (2018, April 13). UN body adopts climate change strategy for shipping. https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx

IMO. (2023, July 7). Revised GHG reduction strategy for global shipping adopted. https://www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx

IRENA. (2021). A pathway to decarbonise the shipping sector. https://www.irena.org/Publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050

Jang, W. (2011). Analysis of Economic Lifespan for Replacement Policy of Container Ship using Fuzzy Interval Numbers. Journal of Korean Navigation and Port Reserch, 35(2), 173–178. https://doi.org/10.5394/kinpr.2011.35.2.173

Johnsrud, I. (2023, August 15). Wallenius Wilhelmsen’s next generation vessels are coming! Wallenius Wilhelmsen. https://www.walleniuswilhelmsen.com/news/wallenius-wilhelmsens-next-generation-vessels-are-coming

Kern, F., & Rogge, K. S. (2016). The pace of governed energy transitions: Agency, international dynamics and the global Paris agreement accelerating decarbonisation processes? Energy Research & Social Science, 22, 13–17. https://doi.org/10.1016/j.erss.2016.08.016

Krupnik, S., Wagner, A., Koretskaya, O., Rudek, T. J., Wade, R., Mišík, M., Akerboom, S., Foulds, C., Stegen, K. S., Adem, C., Batel, S., Rabitz, F., Certomà, C., Chodkowska-Miszczuk, J., Denac, M., Dokupilová, D., Leiren, M. D., Ignatieva, M. F., Estevan, D. G., . . . Von Wirth, T. (2022). Beyond technology: A research agenda for social sciences and humanities research on renewable energy in Europe. Energy Research & Social Science, 89, 102536. https://doi.org/10.1016/j.erss.2022.102536

Laranjeira, A. (2024, July 19). Does the IMO’s revised GHG Strategy hit the mark? — Opportunity Green. Opportunity Green. https://www.opportunitygreen.org/blog/imo-revised-strategy-agreement

Lodder, M., Roorda, C., Loorbach, D., & Spork, C. (2017). Staat van transitie: patronen van opbouw en afspraak in vijf domeinen. In drift.eur.nl. DRIFT. https://drift.eur.nl/nl/publicaties/staat-van-transitie/

Loorbach, D., & Geerlings, H. (2017). Ports in Transition: Strategies, Operations and Perspectives (Vols. 364–378). Routledge.

Loorbach, D., & Rotmans, J. (2010). The practice of transition management: Examples and lessons from four distinct cases. Futures, 42(3), 237–246. https://doi.org/10.1016/j.futures.2009.11.009

Maersk. (2021). Maersk ECO Delivery. https://www.maersk.com/transportation-services/eco-delivery

Maersk. (2023). All the way to net zero. Sustainable Shipping | Maersk. https://www.maersk.com/sustainability/all-the-way-to-net-zero#:~:text=Greener%20fleet%20facts&text=25%25%20of%20Maersk's%20container%20volume,using%20green%20fuels%20by%202030.&text=Green%20methanol%20(e%2Dmethanol%20or%20bio%2Dmethanol).&text=25%20dual%20fuel%20vessels%20on,container%20capacity%20to%2017%2C000%20TEU.

Maersk. (2024). Network of the Future. https://www.maersk.com/network-of-the-future. https://www.maersk.com/network-of-the-future

Mandra, J. O. (2023, December 2). Shipping CEOs call for an end to fossil-only powered newbuilds. Offshore Energy. https://www.offshore-energy.biz/shipping-ceos-call-for-an-end-to-fossil-only-powered-newbuilds/

Martín, J. S., Dimanchev, E., & Neumann, A. (2023). Carbon abatement costs for renewable fuels in hard-to-abate transport sectors. Advances in Applied Energy, 100156. https://doi.org/10.1016/j.adapen.2023.100156

McKenney, T. A. (2024). The impact of maritime decarbonization on ship design: State-of-the-Art Report. IMDC. https://doi.org/10.59490/imdc.2024.907

MMMCZCS. (2024). Fuel cost calculator. Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. https://www.zerocarbonshipping.com/cost-calculator/?s=0

Park, T., Hashimoto, H., Wang, W., Thrasher, B., Michaelis, A. R., Lee, T., Brosnan, I. G., & Nemani, R. R. (2023). What does global land climate look like at 2°C warming? Earth S Future, 11(5). https://doi.org/10.1029/2022ef003330

Port of Rotterdam. (2023, September 20). Partners ondersteunen emissiereducties op de Green & Digital Shipping Corridor Rotterdam-Singapore. https://www.portofrotterdam.com/nl/nieuws-en-persberichten/partners-ondersteunen-emissiereducties-op-de-green-digital-shipping

Prevljak, N. H. (2023a, March 26). Shipping giants reaping high profits from EU ETS, study shows. Offshore Energy. https://www.offshore-energy.biz/shipping-giants-reaping-high-profits-from-eu-ets-study-shows/

Prevljak, N. H. (2023b, December 1). New tool identifies best ports for developing green first-mover initiatives. Offshore Energy. https://www.offshore-energy.biz/new-tool-identifies-best-ports-for-developing-green-first-mover-initiatives/

Regulation - 1805/2023. Regulation (EU) of the European Parliament and of the Council of 13 September 2023 on the use of Renewable and Low-carbon Fuels in Maritime Transport, and Amending Directive 2009/16/EC. (n.d.). http://data.europa.eu/eli/reg/2023/1805/oj

Santos, V. a. D., Da Silva, P. P., & Serrano, L. (2022). The maritime sector and its problematic decarbonization: A Systematic review of the contribution of alternative fuels. Energies, 15(10), 3571. https://doi.org/10.3390/en15103571

Silvestri, G., Diercks, G., & Matti, C. (2022). X-curve: A sensemaking tool to foster collective narratives on system change. DRIFT. https://drift.eur.nl/publications/x-curve-a-sense-making-tool-to-foster-collective-narratives-on-system-change/

Snijders, C. (2023). Analysing the Dynamics of a Global Innovation System: A Case Study on Green Methanol as a Marine Fuel [MA Thesis, Utrecht University]. https://studenttheses.uu.nl/handle/20.500.12932/44678

Solakivi, T., Paimander, A., & Ojala, L. (2022). Cost competitiveness of alternative maritime fuels in the new regulatory framework. Transportation Research Part D Transport and Environment, 113, 103500. https://doi.org/10.1016/j.trd.2022.103500

Sovacool, B. K., & Geels, F. W. (2016). Further reflections on the temporality of energy transitions: A response to critics. Energy Research & Social Science, 22, 232–237. https://doi.org/10.1016/j.erss.2016.08.013

Spoof-Tuomi, K., & Niemi, S. (2020). Environmental and economic evaluation of fuel choices for short sea shipping. Clean Technologies, 2(1), 34–52. https://doi.org/10.3390/cleantechnol2010004

Stavroulakis, P. J., Koutsouradi, M., Kyriakopoulou-Roussou, M., Manologlou, E., Tsioumas, V., & Papadimitriou, S. (2023). Decarbonization and sustainable shipping in a post COVID-19 world. Scientific African, 21, e01758. https://doi.org/10.1016/j.sciaf.2023.e01758

Svanberg, M., Ellis, J., Lundgren, J., & Landälv, I. (2018). Renewable methanol as a fuel for the shipping industry. Renewable & Sustainable Energy Reviews, 94, 1217–1228. https://doi.org/10.1016/j.rser.2018.06.058

Transport & Environment. (2024). Profits Uncontained: An analysis of Container Shipping ETS surcharges. https://www.transportenvironment.org/articles/profits-uncontained-an-analysis-of-container-shipping-ets-surcharges

Ulichina, I. (2024, June 3). Two-thirds of European green shipping fuel projects at risk - analysis. Transport & Environment. https://www.transportenvironment.org/articles/two-thirds-of-european-green-shipping-fuel-projects-at-risk-analysis

Van Arkel, N. J. (2020). Analysis of the Dutch Mission-oriented Innovation System for Sustainable Aviation [Utrecht University]. https://studenttheses.uu.nl/handle/20.500.12932/41078

Van Leeuwen, J., & Monios, J. (2022). Decarbonisation of the shipping sector – Time to ban fossil fuels? Marine Policy, 146, 105310. https://doi.org/10.1016/j.marpol.2022.105310

Van Raak, R., De Geus, T., Van De Lindt, M., & Van Der Have, C. (2022, November). X-curve monitoring transitie naar een Circulaire Economie. DRIFT for Transition. https://drift.eur.nl/nl/publicaties/x-curve-monitoring-transitie-naar-een-circulaire-economie/

Von Malmborg, F. (2023). Advocacy coalitions and policy change for decarbonisation of international maritime transport: The case of FuelEU maritime. Maritime Transport Research, 4, 100091. https://doi.org/10.1016/j.martra.2023.100091

Warren, P., Frazer, M., & Greenwood, N. (2023). Role of climate finance beyond renewables: hard-to-abate sectors. Energy Reports, 10, 3519–3531. https://doi.org/10.1016/j.egyr.2023.10.021

Wesseling, J., & Meijerhof, N. (2023). Towards a Mission-oriented Innovation Systems (MIS) approach, application for Dutch sustainable maritime shipping. PLOS Sustainability and Transformation, 2(8), e0000075. https://doi.org/10.1371/journal.pstr.0000075

Wieczorek, A., & Hekkert, M. P. (2012). Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. Science and Public Policy, 39(1), 74–87. https://doi.org/10.1093/scipol/scr008

Yang, X., Nielsen, C. P., Song, S., & Chen, X. (2022). Breaking the hard-to-abate bottleneck in China's path to carbon neutrality with clean hydrogen. Nature Energy, 7(10), 955–965. https://doi.org/10.1038/s41560-022-01114-6

Yin, R. K. (2017). Case Study Research and Applications: Design and methods. http://cds.cern.ch/record/2634179

Zhang, A., Alvi, M. F., Gong, Y., & Wang, J. X. (2022). Overcoming barriers to supply chain decarbonization: Case studies of first movers. Resources, Conservation and Recycling, 186, 106536. https://doi.org/10.1016/j.resconrec.2022.106536

8 Appendix 1: Interview guide

General information

1a) What is it you currently do and how is it related to the maritime sector?

1b) Could you tell something about the position of your company within the market?

- How would you describe the mission of the company you work for?
  - Could you describe what drives the company in your opinion? *(Mission-driven, goal oriented, etc.)*

1c) From your perspective, how would you describe the maritime sector, and especially over the last 5 years?

Questions related to the X-curve

1) What is your expertise within the topic of sustainable maritime decarbonisation and how would you describe the current developments from your perspective?

2) Can you tell me about the developments you have noticed over the last years?
   a. (What has been your company's role within these changes?)

3) Have you seen significant experimentation with (producing) sustainable maritime fuels?

4) In recent years, have you seen a change in pace of the adoption of measures to decarbonise?
   a) Are alternative options for sustainable operations increasing?

5) Is the urgence of adopting decarbonisation strategies widely felt? Are zero/low-carbon strategies becoming dominant in thinking and doing?

6) From your perspective, can you identify a new balance of power due to the transition?
   a) Are new structures solidifying?

7) Do incremental improvements in operations have a high priority? Are they seen as more doable compared to moving towards net zero emissions?

8) Is it becoming more difficult to be profitable while using conventional maritime fuels?

9) Is the status quo challenged by a growing group of actors? Do you see resistance against the use of harmful practices?

10) Have you noticed resistance to transitioning to more sustainable maritime fuels?
   a) Has this resistance changed for better or worse?

11) Can you see opposing interests emerging?

12) Do you think there is a feeling that the need to lower emissions is recognised across your company/sector? And if so, is there a sense of urgency to it?

13) In light of recent (policy, geo-political etc.) developments, where do you see difficulties, threats and/or challenges arise to successfully decarbonising the maritime sector?
   a) Do you think there are large structures that are failing, are patterns of failure to deliver within a certain time or at a price emerging?
   b) Do you see a large resistance movement against sustainable maritime fuels or other low-carbon solutions? If so, what does this resistance look like?

14) Have you noticed a change in thinking and doing? In the sense that it has become normal to take sustainability into account in all aspects of operations?

15) Are the economic incentives that are currently in place helping speed up the transition?
   a) What other financial tools would be needed?
   b) Is there currently a level playing field? Are companies that operate in the EU at a disadvantage because of stricter policy?

16) In recent years, more and more companies have made statements of their commitment to decarbonising. Some say they aim to become net-zero by 2050, some by 2045 and some even by 2040. What do you make of this?

Questions related to MIS

1) Do you believe there is enough know-how being developed on how to decarbonise the maritime sector?

2) Do you think the sector will be able to unlearn their current (unsustainable) practices?]
   a. Such as the sail hard then wait practice.

3) Have you seen the emergence of networks to support the development of knowledge on the use of sustainable maritime fuels? And do you think that this knowledge is spreading fast enough.

4) From your perspective, is the decarbonisation of the maritime/refinery sector given enough priority by stakeholders?
   a. What are the implications of this for the adoption of decarbonisation strategies?

5) Do you have the impression that decarbonisation is in the interest of large companies or other vested interests? If not, what would be needed to make it in their interest?

6) In order to decarbonise your sector, do you think that actors are aware of the necessary actions to take to achieve this?
   a. Is there consensus on the actions to take?
   b. Can you identify different pathways? For example, is there a clear group of stakeholders lobbying for methanol, while others prioritize the use of ammonia?
   c. Is there a dominant pathway towards decarbonisation emerging?

7) Do you see enough support from informal and formal institutions for the transition?
   a. Where does this support mostly come from? Or if not, where should support come from?

8) From your perspective, can significant investments in decarbonising the sector be seen yet?
   a. And do you think it will become more difficult for companies to find investments for operations that have high emissions in the future?

9) Among people in the sector, have you noticed a shift in what is ‘normal’ ? So do people regard sustainability or sustainable fuels in another light, or do people look differently at the continued use of conventional maritime fuels.

a. Have you heard of or seen lobbying against the use of conventional maritime fuels?
b. Do you think there is widespread support for the decarbonisation of the sector?
c. Has there been significant vocal support for the transition?

10) Are there any question(s) you expected that I did not ask?